Fuel moisture and sustained flaming in masticated fuelbeds

by

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A thesis submitted in conformity with the requirements for the degree of Master of Science in Forestry

Faculty of Forestry
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2014

Abstract

Mastication is a fuel management technique that disrupts the vertical continuity of forest fuels by mechanical shredding of trees and understory vegetation into a highly-compacted surface fuelbed. The particle size distributions, bulk density and arrangements differ from natural and slash fuel types, thus resulting in fuelbeds with potentially different moisture dynamics and fire behaviour. We conducted three experiments, the first of which examined differences in in-stand micrometeorology and fuelbed moisture content between differing levels of stand thinning via mastication. In the second experiment, a fuel moisture model was created, validated with an independent dataset, and compared with pre-existing models that are incorporated in the Canadian Forest Fire Danger Rating System. In the third experiment, we compared the results of standard ignition tests performed on masticated fuelbeds in the laboratory and field to determine probability of sustained flaming, and compared our findings with pre-existing models of ignition for other forest fuels.
Acknowledgments

I would like to take the opportunity to thank my thesis committee for their contributions to this manuscript: B.M. Wotton, D.L. Martell, M.D. Flannigan and D. Schroeder. Additional academic advice was provided by D.K. Thompson. I would especially like to thank S. Hvenegaard for sharing his understanding of wildland fire. Special thanks to R. Ault, R. Hsieh and J. Thomasson for logistical and operational support. Research support was provided by the Natural Sciences and Engineering Research Council (Alexander Graham Bell CGS Scholarship), FP Innovations Wildland Fire Operations Research Group, Canadian Forest Service, Alberta Sustainable Resource Development and the Faculty of Forestry at the University of Toronto.
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1
Introduction

1.1 Fire Management in Canada

Canadian wildland fire management strategies attempt to balance the requirement for fire on the landscape with the need to protect public safety, property, timber resources and recreational values (Martell and Sun 2008). The traditional management paradigm of fire exclusion has changed in recognition that wildfire is an ecologically desirable process that influences forest structure and function in the boreal (Johnson et al. 1998, Johnstone and Chapin 2006). Fire management is gradually allowing more wildfire back onto the landscape, although direct suppression is still necessary where communities and values are threatened.

The wildland-urban interface (WUI) describes an approximate boundary where forested regions meet human settlements. Fire management objectives include reducing the threat of wildfires burning through the WUI into communities, where they can potentially cause property damage and even loss of life. Consideration for the WUI has become increasingly important as population pressures and resource development have expanded communities in northern Canada. Increasing human settlement, particularly in the wildland-urban interface, has intensified pressures put on land managers to reduce risk and losses associated with wildfire (Cohen 2008). In 2011, a wildfire destroyed approximately 400 buildings in Slave Lake, AB and caused an estimated CAD $700 million in damages.

1.2 Fuel Management

Canada’s FireSmart program outlines protection measures designed to: (i) decrease fire behaviour potential; (ii) reduce potential for ignitions, and; (iii) improve
capability of fire suppression resources (Hirsch et al. 2001). Fuel management is practiced in WUI zones because the removal of hazardous fuels should theoretically reduce potential fire behaviour. Fuel management includes reducing surface fuel loads, decreasing crown density, increasing crown base height, and fuel type conversion (Agee and Skinner 2005). Given the extent of the boreal forest and increasing community expansion in forested regions, it is essential to have a strong understanding of how fuel management practices influence wildfire across Canada’s landscape.

Fuel management prescriptions generally aim to retain large, fire-resistant trees, increase live crown height, decrease stem density and reduce surface fuels (Agee and Skinner 2005). Treatments typically require thinning, prescribed fire, or a combination of the two. Noss et al. (2006) describes fuel management as a process that may occur prior to, during and after wildfire. Fuel reductions usually outweigh ecological values within the wildland-urban interface, where human safety and fire-risk mitigation are paramount (DellaSala et al. 2004).

A comprehensive national experiment, called the Fire and Fire Surrogate study (FFS), was designed to investigate consequences of prescribed fire and mechanical fuel reductions at large scales for forest types in the United States (McIver et al. 2013). Collins et al. (2010) summarize the current approaches in fuel reduction treatments, including treatment size, placement and maintenance, as well as important constraints, such as habitat preservation, funding and regulations. Many forest types in Canada and the United States differ in terms of forest structure, ecology and fire regime, and therefore we must be cautious in applying previous research from the United States to the boreal.

The additional goal of restoring stand structure to that of a pre-fire exclusion era is prevalent in fuel management undertaken within the United States, especially for seasonally dry forests of open conifer (including Ponderosa pine and Jeffrey pine) with fire regimes dominated by frequent low-severity surface fires (McIver and Fettig
2010). However, this objective is not generally a consideration in Canada. While some fuel types and associated fire regimes are similar for Rocky Mountain forests in Canada and the United States, the Canadian boreal forest types are centered on regimes of crown fire, and fuel management prescriptions focus on reducing likelihood of crown fire and fireline intensity. Fuel management techniques are being increasingly applied within the wildland-urban interface areas of Canada’s western boreal forest, and this presents an opportunity to investigate novel fuel management techniques in unstudied fuel types.

1.3 Mastication

More recently, fuel management practices have incorporated the mastication (e.g. mulching, chipping, shredding) of thinned trees and understory vegetation left from other fuel management prescriptions. Mastication redistributes aerial and surface fuels into a compacted layer of fractured materials on the forest floor, and is achieved with mechanical equipment that mulches fuels with a rotating drum fitted with cutting teeth. This represents a more economically viable option to reduce surface fuel loads over manual extraction and transport off-site. Mastication re-arranges components of the fuel complex into a layer that covers the forest floor either discontinuously or continuously. These processed fuelbeds likely have different physical properties and moisture responses than naturally-occurring fuels, and thus may exhibit unknown moisture dynamics and fire behaviour.

Mechanical mastication is becoming a popular fuel treatment among land management agencies, especially within the province of Alberta. In addition to the common approach of reducing stem density following a prescribed inter-crown spacing, treatments applied in some boreal spruce forests may alternatively follow a grid pattern arrangement or continuous linear corridors of mulch to disrupt the horizontal continuity of fuels, with residual patches of intact, standing trees and understory. Masticated lines of various widths may also increase accessibility, thereby improving the potential for suppression resources to be effective.
1.3.1 Masticated fuelbeds

Understanding the physical characteristics of a fuelbed is essential to estimating potential fire behaviour and assessing fire hazard. Battaglia et al. (2010) investigated how mulch changed woody material size class distributions across four forest types. Mulching protocols required tree thinning and pruning, which reduced tree density, increased canopy base height and reduced canopy bulk density. The woody surface fuel loading increased 2-3 fold, and was proportional to the reduction in canopy and ladder fuels, thus emphasizing that mulching redistributes fuels. However, mulching also alters size distributions, reducing the proportion of large-diameter fuels and generating fuelbeds that are predominantly composed of small-diameters fuel particles.

Kane et al. (2009) quantified the physical properties of particles and surface fuel loading in masticated fuelbeds. Similar to Battaglia et al. (2010), much of the fuel load was concentrated in the small diameter size classes. Mastication altered fuel diameter shapes from round to irregular and increased particle fracturing. The results of a cluster analysis by Kane et al. (2009) suggested that most masticated fuelbeds differed significantly from natural and slash fuelbeds, owing largely to increased fine fuel loading, high bulk density and greater surface area to volume ratios resulting from mastication.

1.3.2 Moisture dynamics in forest fuels

Moisture plays a critical role in the ignition, sustainability and consumption of forest fuels (Anderson 1970). Fuel moisture is often characterized with respect to diameter-based size classes (Brown 1974). Each size class has a corresponding moisture time lag constant, which is defined as the time required for a dead fuel particle to lose 63% of the difference between the initial and equilibrium moisture content at a constant temperature and relative humidity (Byram 1963). Viney (1991)
and Matthews (2013) provide critical reviews of forest fuel moisture modelling; moisture dynamics have been assessed somewhat extensively within fine fuels.

Kreye et al. (2012) studied the effects of mastication on fuelbed drying rates. They compared desorption for individual fuel particles and fuelbeds for common shrub fuels (*Arctostaphylos manzanita* and *Ceanothus velutinus*), pine dowels and maple dowels. Their results suggested that specific gravity and species play a significant role in moisture dynamics, and increases in fuelbed density with mastication likely dominate moisture response. There was no difference in drying rates between fractured and intact fuel particles; however, each fuel type showed significant differences between desorption of individual surface fuel particles versus the underlying fuels.

1.3.3 Fire behaviour in masticated fuels

The assessment of probability of sustained flaming is critical to understanding mechanisms of fire initiation and spread (Beverly and Wotton 2007). Probability of sustained flaming was historically measured by dropping matches onto fuelbeds of varying levels of moisture under ranges of environmental conditions (Blackmarr 1972). These tests might be conducted in-situ with changing hourly and daily weather conditions, or performed in a controlled laboratory setting where moisture and ambient conditions can be directly manipulated.

Fuel-specific assessments of probability of sustained flaming have been conducted for various fuel types, including grass (de Groot et al. 2005, Leonard 2009, Dimitrakopoulos et al. 2010), gorse shrub (Anderson and Anderson 2010), pine stands (Fernandes et al. 2008) and various other fuels (Plucinski and Anderson 2008, Plucinski et al. 2010, Ganteaume et al. 2009, 2013). Lawson et al. (1997) provided probability of sustained smouldering ignition estimates for various boreal duff fuels. Mastication increases particle fracturing, alters surface area-to-volume ratios and increases small-diameter fuel loads, all of which likely contribute to changes in

Marino et al. (2010) conducted a laboratory experiment to assess the ignition potential of two mechanical fuel treatments, using both flaming and glowing firebrands, across a range of moisture contents. To ensure consistent and representative fuelbeds, the authors reconstructed fuelbeds in aluminum trays, based on bulk density of the upper and lower layers measured in the field. The authors measured time to ignition, flaming duration, fuel consumption and the number of sample-tray sides that were burned during each test. Fuel consumption ratio was the difference between initial and final fuel load. Treatment type and moisture both significantly affected ignition probability and combustion properties.

Mastication changes the physical properties of fuelbeds, which may influence fire behaviour, including rate of spread, flame length and fireline intensity (Kane et al. 2009). Greater fuel load in the high surface area to volume ratio size classes may increase fire behaviour. However the compaction and bulk density of these fuelbeds may act to moderate fire behaviour, although this also increases smouldering combustion, heating duration and smoke production (Busse et al. 2005). Kreye et al. (2011) investigated the effect of particle fracturing on fire behavior for two common shrub species, and their results suggested that fracturing did not increase fire intensity. The findings of that study provide further evidence to the hypothesis that high bulk density of masticated fuels does not inhibit fire (Kobziar et al. 2009, Knapp et al. 2011).

Glitzenstein et al. (2006) measured fire behaviour following chipping of woody understory and large down woody debris in a pine stand. Rate of spread and flame length did not differ between chipped and control plots. However, there was a significant decrease in percent area burned in the chipped treatments. Fire behaviour
prediction models produced relatively accurate estimates of fire behaviour parameters as compared with field observations. The predictions for each model were highly dependent on the effective fuel depth input. The authors concluded that chipping treatments were predicted to have less severe fire behaviour than untreated sites.

Observed and predicted fire behaviour and effects in masticated fuelbeds were also compared by Knapp et al. (2011). The authors used standard fuel models from BehavePlus, and also created customized fuelbed models, altering fuel loading by size class, surface area to volume ratios and fuelbed depth. The results suggest that: i) standard fuel models tended to under-predict flame length and over-predict rate of spread, and; ii) customized fuelbed models were more accurate than standard fuel models. Unexpected fire behaviour has been observed during prescribed burning in masticated fuelbeds (Bradley et al. 2006), and research has emphasized the poor estimation of fire behaviour and fire effects associated with the fuel complex created by this fuel management technique (Kobziar et al. 2009, Reiner et al. 2009, Knapp et al. 2011, Kreye et al. 2011).

Some authors have cautioned against the use of existing fire behaviour prediction models for masticated fuelbeds, as some inputs may be outside the range for which these models were created (Knapp 2011). Glitzenstein et al. (2006) suggested that model predictions based on measured fuelbed properties differ significantly from observed behaviour. Kane et al. (2009) highlighted the importance of collecting detailed fuel loading estimates and developing behaviour and effects models. Battaglia et al. (2010) emphasized that the models should be extensively tested and calibrated against observations from field experiments.

1.4 Thesis structure

In the following chapter (Chapter 2), we examined differences in in-stand micrometeorology and fuel moisture content across multiple levels of stand thinning achieved via mastication. We examined how the Canadian Forest Fire Weather Index
System moisture codes compared with observations of moisture content from surface and deep layers of masticated fuelbeds. This was largely an exploratory study intended to examine the applicability of the Canadian Forest Fire Danger Rating System currently used in fire management operations.

Chapter 3 describes the modification of the hourly Fine Fuel Moisture Code (FFMC), a component of the Canadian Forest Fire Weather Index (FWI) System, to better account for fuel-specific parameters of masticated surface fuels. Model estimates were compared with field observations of surface mulch moisture, and compared with other calibrations of the FFMC.

In Chapter 4, we assessed the probability of sustained flaming in masticated fuelbeds using predictors known to influence the likelihood of successful ignition. Testing was performed under laboratory and field conditions, and the resulting models were compared. We also investigated the utility of the moisture model (developed in the previous chapter), along with several components of the FWI System, and moisture models from the National Fire Danger Rating System.

Chapter 5 summarizes key results from the three studies, briefly proposes some future research directions and provides concluding remarks.
2
Masticated fuelbed moisture and their relation to the moisture codes of the Canadian Forest Fire Weather Index

Abstract. Mechanical mastication is increasingly being applied as a fuel management treatment in the wildland-urban interfaces of western Canada, producing new stand structure and fuelbed characteristics that significantly differ from natural stands, and little is known of the resulting impacts on in-stand micrometeorology and fuel moisture. We measured fire-related micrometeorological variables in-stand and the moisture content of surface and deep (~5-10 cm below surface) layers of masticated fuelbeds under two different thinning levels in north-central Alberta, Canada. We also investigated how well the various moisture indices from the Canadian Fire Weather Index (FWI) System estimate the moisture in these newly generated fuelbeds. Air temperature, solar radiation and wind speed significantly increased with increasing thinning intensity, while relative humidity significantly decreased. Masticated surface fuels under both treatments were significantly drier than control fuels, though between-treatment differences decreased as the fuels became drier. The Fine Fuel Moisture Code (FFMC) followed moisture observed in masticated surface fuels for both treatments, and was the best predictor within the FWI System based on the coefficient of determination ($R^2=0.38-0.54$); however, the FWI indices were not able to estimate moisture for deep layers observed in this study.
2.1 Introduction

Mastication is a fuel management technique that disrupts the horizontal and vertical continuity of elevated and overstory forest fuels by the mechanical shredding (e.g., chipping, mowing, mulching) of trees and understory vegetation into a highly-compacted surface fuelbed composed of small-diameter, fractured particles (Kane et al. 2009, Battaglia et al. 2010). This fuel management approach is commonly implemented in the United States, where mastication, sometimes coupled with subsequent prescribed burning, is performed with the goals of reducing the probability of high-intensity wildfire and restoring historical fire regimes (Stephens and Moghaddas 2005, Bradley et al. 2006, Glitzenstein et al. 2006, Stephens et al. 2012). Mastication is also seeing wider use in Canadian fuel management strategies, particularly as part of operational implementation of the FireSmart program, which outlines protection measures designed to decrease fire behaviour potential, reduce potential for ignitions and improve capability of fire suppression resources in and around the wildland-urban interface. Common hazard reduction fuel management prescriptions in Canadian boreal conifer stands involve either: i) hand-thinning and pruning, followed by mastication, or ii) thinning being achieved directly via the masticator as a result of chipping the stems in place. Although there is mounting evidence to suggest that fuel treatments are effective in reducing fire severity (Pollet and Omi 2002, Strom and Fule 2007, Vaillant et al. 2009, Reiner et al. 2012, Safford et al. 2012), there is still uncertainty regarding the effects of fuels treatments on in-stand micrometeorology and fuel moisture.

The removal of aerial fuels to decrease canopy bulk density and tree connectivity directly affects the openness of the forest canopy, thereby increasing solar radiation incident upon the forest floor and increasing surface wind speed (Agee and Skinner 2005). Increased irradiance lowers relative humidity, increases air temperature, and raises the temperature of dead surface fuels, potentially enhancing the drying of fuels through increased evaporation (Agee et al. 2000). Potential
moderating effects of a more open stand include reduced interception of rain (Whitehead et al. 2006), increasing soil water and foliar water status of retained trees (Samran et al. 1995, Sala et al. 2005, Zou et al. 2008). Open canopies also allow for greater mixing of air between the understory and above-canopy layers that may provide a cooling effect on understory temperatures (Meyer et al. 2001). The effects of stand structure on in-stand micrometeorology have been investigated for various silvicultural thinning treatments (Pook and Gill 1993, Prevost and Pothier 2003, Guan et al. 2006, Weng et al. 2007), natural stands (Biddulph and Kellman 1998, Ray et al. 2005) and more directly for specific fuel treatments (Meyer et al. 2001, Whitehead et al. 2006, Rambo and North 2009, Ma et al. 2010, Bigelow and North 2012).

In addition to the host of alterations produced by stand thinning, the mastication process generates a modified fuelbed that likely has different physical properties and moisture response than naturally-occurring surface fuels. The effect of fuels treatments on fuel moisture has been investigated for conifer-dominated stands in Canada (Whitehead et al. 2006) and the United States (Faiella and Bayley 2007, Bigelow and North 2012, Estes et al. 2012); however, these studies compare treatment-mediated moisture differences with standard moisture dowels, destructive samples of small fuels and repeated measurements of large fuels. The current study employs direct moisture content observations in masticated fuelbeds to compare moisture content differences with control fuels. Aerial fuels are redistributed onto the forest floor, increasing the quantity of surface fuels present, and altering their form to become more irregular (i.e. non-cylindrical) and fractured, increasing the surface area over which moisture is exchanged with the surrounding environment (Kane et al. 2009, Kreye et al. 2011). However, the compactness of a masticated fuelbed may reduce the rates of moisture loss, especially in deeper mulch beds (Kreye and Varner 2007).

Moisture content is a critical element that influences fire behaviour, and is an integral component of most fire behaviour and danger rating systems (Byram 1963, Deeming et al. 1978, Luke and McArthur 1978, Van Wagner 1987). The Canadian
Forest Fire Weather Index (FWI) System produces estimates of fuel moisture of three distinct organic forest floor layers, represented by the following fuel moisture codes: Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC) and Drought Code (DC). In practice, the FWI System moisture codes are applied to a range of forest stands for fire danger forecasting and prescribed burn operations, based on relationships developed for standardized fuel complexes (Stocks et al. 1989). Due to the significant alterations to both stand structure and surface fuels achieved via mastication, surface and ground moisture may not be predicted well with existing operational fire management decision support tools.

The overall objectives of this study were to: i) compare in-stand micrometeorological variables affecting both surface and ground moisture content under differing fuel management treatments; ii) examine differences in moisture content through the masticated fuelbed profile across different levels of thinning and also compare surface mulch moisture in fuel treatments with the more standard naturally occurring litter fuelbeds in an untreated stand; and, iii) assess the applicability of the current FWI System outputs (daily FFMC, DMC and DC) in tracking moisture content of masticated fuelbeds. Understanding the fundamental characteristics of this new fuel type is critical in comparing the trade-offs between altering stand structure and creating new fuelbeds on surface fuel moisture, and thus there is a clear need to investigate this novel fuel management technique in unstudied Canadian forest types.

2.1.1 Background information

The FFMC is one component of the FWI System (Van Wagner 1987) that estimates moisture content changes in fine surface fuels, assuming 1.2 cm layer of pine litter with a fuel load and bulk density of 0.25 kg m$^{-2}$ and 20.8 kg m$^{-3}$, respectively. It is based on a simple exponential model of moisture exchange and although initially designed for a closed canopy of ‘standardized’ jack pine and lodgepole pine, the FFMC is also associated with moisture in other stand types.
Further calibrations are presented by Wotton and Beverly (2007), to better estimate surface litter moisture given stand-specific parameters (forest type, stand density, season) and the Duff Moisture Code. More generally, the FFMC has been found to be a reasonable indicator of moisture content in fine woody fuels (Simard and Main 1982, Rothermel et al. 1986, Trowbridge and Feller 1988). The relationship between FFMC and moisture content is (Van Wagner 1987):

\[ MC_{FFMC} = \frac{147.2 (101 - FFMC)}{59.5 + FFMC} \]  

(1)

The Duff Moisture Code (DMC), another component of the FWI System, is used to track moisture content in the upper layers of pine litter that are starting to decay, assuming a 7.0 cm thick layer with a fuel load and bulk density of 5.0 kg m\(^{-2}\) and 71.4 kg m\(^{-3}\). Similar to the FFMC, the DMC is based on a simple exponential model of moisture exchange with the atmosphere and wetting from rain. The DMC has been found to be well correlated with moisture content in the upper layers organic material in forest floors, and a significant predictor of the sustainability of smouldering ignition in the duff layer (Lawson et al. 1997, Otway et al. 2007). The relationship between DMC and moisture content is (Van Wagner and Pickett 1985):

\[ MC_{DMC} = 20 + e^{(5.6348 \cdot \frac{DMC}{43.43})} \]  

(2)

The Drought Code (DC) was originally developed as an index of soil water storage, and though it was not directly related to a specific fuel component, the DC can represent slow-drying, compact organic matter. The DC assumes an 18.0 cm thick layer with a fuel load and bulk density of 25.0 kg m\(^{-2}\) and 138.9 kg m\(^{-3}\), respectively. The relationship between DC and moisture content (MC\(_{DC}\)) is:

\[ MC_{DC} = 400 e^{DC/400} \]  

(3)

Various fuel- or stand-specific moisture content to moisture code conversion relationships have been developed to compliment the standard moisture codes of the
FWI System, including feathermoss and sphagnum moss below lodgepole pine/white spruce (Lawson et al. 1997), organic layers in white spruce (Lawson and Dalrymple 1996), jack pine in western Canada (Chrosniewicz 1989), duff under black spruce in Alaska (Wilmore 2001) and other common forest types in Canada (Wotton and Beverly 2007).

2.2 Methods

2.2.1 Study site

The study area, referred to herein as the Carldale site, was located approximately 20 km northeast of Hinton, Alberta, Canada (53° 29’ 27.63” N, 117° 23’ 44.25” W) in the Lower Foothills natural subregion (Beckingham et al. 1996). The forested area is a mixedwood stand composed of white spruce (Picea glauca) and trembling aspen (Populus tremuloides), with a minor component (<10%) of black spruce (Picea mariana).

In March 2010, an eight-hectare block of the study area was thinned as part of a community FireSmart hazard reduction program. Thinning was carried out at two different densities and the harvested biomass was mulched and left on site. These two blocks of heavy- and light-thinning, along with an unthinned adjacent control stand, formed the treatments referred to herein (Figure 2.1). The study area was approximately 1050 m in elevation, with a slope of <5% (steeper slopes existed but were excluded from field sampling).

To estimate stand characteristics in the three treatments, a 100 m transect was established in each block, and the point-centered quarter method employed with eight randomly-spaced sampling points. At each sampling point, the nearest tree in each quarter was measured for distance to sampling point, species, diameter-at-breast height (DBH; height of 130 cm; to the nearest 0.1 cm), total height (to the nearest 0.1 m) and live crown base height (LCBH; to the nearest 0.1 m). Canopy openness was
Figure 2.1. Map for Carldale study site with photographs depicting treatments of (a) heavy-thinning, (b) light-thinning and (c) control.
estimated via hemispherical images (n=10 per treatment) that were processed with Gap Light Analyzer 2.0 software (Frazer et al. 1999).

2.2.2 Fuel moisture sampling

The moisture content of masticated woody fuels in each of the study sites was assessed at Carldale on 20 days during the 2012 fire season. Sampling was performed in the centre of each treated block, and always at least 50 m away from any treated area boundaries to minimize the possibility of edge effects. Sample collection always occurred between 1400 and 1530 hours LST, coinciding with the daily FFMC that represents an estimate of moisture content during peak burning hours (~1600 LST). During each sample day, three random locations were chosen within the block and mulched fuel from the surface (top-most 2 cm of mulch material) and from deeper layers (~5-10 cm below the surface layer) at those locations were destructively sampled; correspondingly, in the control site, surface litter was collected (mainly comprised of deciduous leaf litter and conifer needles). Each sample was sealed (airtight) in a metal tin, and transported to a laboratory where it was weighed (within 48 hours), dried at 95°C to a constant weight, dry weight recorded and gravimetric moisture content (i.e. by dry mass) calculated. All moisture contents presented in this chapter are gravimetric moisture expressed as percentages.

2.2.3 Micrometeorological observations

A weather station was installed at the centre of each treatment at the Carldale Site, which consisted of: one multi-channel datalogger (Campbell Scientific CR-1000), one shielded temperature and relative humidity sensor (HC-S3 and 41003-X) at 1.5 m height, one sonic anemometer (Gill 2-D Windsonic sensor) at 2 m height and one solar radiometer (LI200X-20 LI-COR silicon pyranometer) at ground level. Sensors were measured every 30 seconds and recorded as a 20-minute average (or total in the case of rain). Observations initiated July 4, 2013 and continued until September 04, 2013. Additional fuel treatment maintenance was performed within the
light-thinning treatment in early August, and therefore observations from August 1 to September 4 from within that treatment were discarded.

2.2.4 FWI System fuel moisture calculations

We obtained twice-daily (0600 and 1200) observations of air temperature (°C), relative humidity (%), 10-m wind speed (km h⁻¹) and precipitation (mm) from the Alberta Environment and Sustainable Resource Development Obed Lookout Tower (53° 34’ 0.5” N, 117° 30’ 13.0” W) located 11 km from the study site. Weather observations were used to calculate the FFMC, DMC and DC components of the FWI System (Van Wagner and Pickett 1985).

2.2.5 Statistical analyses

Observations of in-stand meteorological variables were first graphically compared. We selected a subset of observations to examine differences in key meteorological variables during only peak fire hours (12:00 to 17:00 LST). For each meteorological variable of interest, we examined its distribution to assess the assumption of normality. Each set of observations failed to meet the assumptions of normality according to the Shapiro-Wilk test (p<0.050), and thus we compared micrometeorological variables across treatments with the Friedman test, a non-parametric equivalent to repeated measures analysis of variance. If the Friedman test indicated significant differences between treatments, pairwise multiple comparisons were performed with the Tukey test.

Average moisture content (n=3) was used in all analyses in an attempt to capture the best estimate of overall moisture content within each treatment at each sampling time. We compared moisture content observations using Pearson’s product moment correlation (r) across surface and deep layers. As all data passed the assumptions of normality and equal variance, we compared average moisture content across the treatments with a One Way Repeated Measures Analysis of Variance, and
investigated any significant differences further with the Tukey pairwise multiple comparison test.

We plotted average observed moisture content and associated FWI System moisture codes over time by treatment to visually compare differences in estimated and observed fuel moisture. We plotted FFMC versus observed surface moisture content along with the FF-scale relationship (Equation 1) to illustrate the relationship to masticated surface moisture and control surface moisture; the same graphical approach was used to compare the DMC and DC with deep mulch moisture content. Correlation and linear regression analysis were employed to assess the significance of the relationship between observed moisture content and the predictions from FWI System moisture code values and to develop a simple calibration to allow direct estimate of mulch moisture from FFMC value.

We obtained FWI estimates from the Obed Tower for the past ten fire seasons (May 1 - October 31, 2004-2013) and applied the newly-developed mulch regressions to compare the annual frequency of days when surface mulch moisture content was estimated to be less than 10, 15 and 20%. The three thresholds were chosen because they represent approximate limits of successful sustained ignition in common forest fuels. All statistical analyses were performed with the R statistical package using an alpha value of 0.05 to determine significance.

2.3 Results

2.3.1 Stand characterization

Light-thinning reduced stem density by 37.7% and basal area by 35.3% relative to the control; heavy-thinning reduced density by 83.2% and basal area by 78.0% (Table 2.1). Canopy openness was nearly doubled in the heavy-thinning treatment relative to the light-thinning and control. Mean DBH was greater in the heavy-thinning treatment because the fuel treatment prescription favoured the retention of larger diameter stems. Furthermore, the proportion of deciduous trees
increased in the heavy-thinning treatment, as deciduous are favoured due to lack of ladder fuels.

Table 2.1. Mean stand characteristics for treatments at Carldale study site (one standard error shown in brackets).  

<table>
<thead>
<tr>
<th>Variable</th>
<th>Light-thinning</th>
<th>Heavy-thinning</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stem density (stems ha(^{-1}))</td>
<td>2061 (246)</td>
<td>557 (70)</td>
<td>3305 (900)</td>
</tr>
<tr>
<td>Basal area (m(^2) ha(^{-1}))</td>
<td>47.9 (3.1)</td>
<td>16.3 (3.0)</td>
<td>74.0 (20.0)</td>
</tr>
<tr>
<td>Diameter at breast height (cm)</td>
<td>16.9 (1.0)</td>
<td>20.1 (0.9)</td>
<td>16.8 (1.0)</td>
</tr>
<tr>
<td>Mean height (m)</td>
<td>15.0 (0.6)</td>
<td>17.0 (0.5)</td>
<td>14.6 (0.6)</td>
</tr>
<tr>
<td>Live crown base height (m)</td>
<td>4.4 (0.6)</td>
<td>4.4 (0.7)</td>
<td>4.8 (0.7)</td>
</tr>
<tr>
<td>Canopy openness (%)</td>
<td>26.6 (1.3)</td>
<td>51.4 (1.1)</td>
<td>24.1 (1.1)</td>
</tr>
<tr>
<td>Percent coniferous (%)</td>
<td>79</td>
<td>65</td>
<td>76</td>
</tr>
</tbody>
</table>

2.3.2 Micrometeorological observations

Pairs of 20-minute mean observations of in-stand air temperature, relative humidity, solar radiation and wind speed are plotted for each combination of treatments in Figure 2.2. There were significant differences in air temperature across treatments (\(\chi^2=511.782\), df=2, p<0.001), and pairwise multiple comparisons via the Tukey-Test indicated significant differences between all treatments (p<0.05). Maximum air temperature over the duration of the experiment was 26.0°C at 15:40 on July 9, 2013 within the heavy-thinning; corresponding air temperatures in the light-thinning and control were 25.3 and 24.7°C, respectively. On average the air temperature observed in the heavy-thinning treatment was 6 and 3% greater than observed in the control and light-thinning, respectively (Table 2.2).

Relative humidity was significantly different across treatments (\(\chi^2=314.680\), df=2, p<0.001), and pairwise multiple comparisons via the Tukey-Test indicated significant differences between all treatments (p<0.05). Minimum relative humidity was observed in the heavy-thinning treatment at 22.4% on July 17, 2013 at 15:00; corresponding humidity values in the light-thinning and control were 31.5 and 34.5%,
Figure 2.2. Mean observations of micrometeorological variables (air temperature, relative humidity, solar radiation and wind speed) compared between all treatment combinations.
Table 2.2. Mean difference and mean ratio comparisons of micrometeorology parameters between treatments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Light vs. Control</th>
<th>Heavy vs. Control</th>
<th>Heavy vs. Light</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Difference</td>
<td>Ratio</td>
<td>Difference</td>
</tr>
<tr>
<td>Temp</td>
<td>0.4 (0.1)</td>
<td>1.03 (0.00)</td>
<td>1.1 (0.2)</td>
</tr>
<tr>
<td>RH</td>
<td>-2.3 (0.3)</td>
<td>0.96 (0.01)</td>
<td>-6.13 (0.22)</td>
</tr>
<tr>
<td>Solar Rad.</td>
<td>0.06 (0.01)</td>
<td>2.30 (0.13)</td>
<td>0.18 (0.01)</td>
</tr>
<tr>
<td>Wind speed</td>
<td>0.1 (0.0)</td>
<td>1.20 (0.01)</td>
<td>0.4 (0.0)</td>
</tr>
</tbody>
</table>

Note: Temp is temperature (°C); RH is relative humidity (%); Solar Rad. is solar radiation (kW m⁻²); wind speed (m s⁻¹). One standard error shown in brackets.
respectively. On average, relative humidity within the heavy-thinning treatment was 11 and 8% lower than observed in the control and light-thinning, respectively.

The differences between treatments were less consistent for solar radiation than all other meteorological variables (Figure 2.2), and are likely attributed to the variability in shading caused by trees at particular sun angles and distances from the sensor location. Solar radiation was significantly different across treatments ($\chi^2=407.851$, df=2, $p<0.001$), and the Tukey-Test indicated significant differences between all treatments ($p<0.05$). Maximum 20-minute average solar radiation was observed in the heavy-thinning treatment at 0.730 kW m$^{-2}$ on July 16, 2013 at 13:40. On the same day maximum of daily average (1200-1700 hrs) solar radiation in the heavy-thinning was observed to be 0.353 kW·m$^{-2}$. Corresponding daily averages in the light-thinning and control treatments were 0.139 and 0.079 kW m$^{-2}$, respectively. Overall average solar radiation observed in the heavy-thinning was 4.7 and 2.9 times greater than in the control and light-thinning, respectively.

Wind speed was significantly different across treatments ($\chi^2=473.099$, df=2, $p<0.001$), and the Tukey test indicated significant differences between all treatments ($p<0.05$). Maximum wind speed was observed in the heavy-thinning treatment at 2.2 m·s$^{-1}$ on July 11, 2013 at 16:20; corresponding wind speeds in the light-thinning and control were 1.1 and 0.9 m s$^{-1}$. Average wind speed observed in the heavy-thinning was 2.04 and 1.73 times greater than in the control and light-thinning, respectively; however, this only amounts to an average difference of 0.44 and 0.37 m s$^{-1}$, respectively.

2.3.3 Surface mulch and control moisture

Observed moisture contents for all treatments and depths are presented in Figure 2.3, along with total daily precipitation and the daily FWI System moisture code values (converted to moisture contents). The study site received frequent precipitation (rain occurred on 41 of the 65 days between June 6 and August 9, 2012
Figure 2.3. Mid-afternoon mulch moisture content at the Carldale treatments during the 2012 fire season and daily FWI System moisture code values (codes are converted to their equivalent moisture contents). Error bars are one standard error.
and there were four events over the duration of sampling where total daily precipitation was greater than 50 mm. The longest rain-free period was observed from July 5 to July 10, 2012. Surface fuels tended to be wetter in the light-thinning and control blocks (Figure 2.3). Fuel moisture records were highly variable immediately following precipitation, and variability decreased as the fuels dried (Figure 2.3; Figure 2.5). The varying degrees of canopy cover between treatments likely further contributed to the variability in moisture content, as well as the fuel composition (i.e. mulch versus mixed leaf/needle litter). Moisture content of surface fuels under both mastication treatments never exceeded ~150% in this study; control moisture content was somewhat more variable than that of masticated fuels.

Maximum absolute decrease in moisture content occurred on June 12, with decreases of 101, 90 and 76% in the control, light- and heavy-thinning, respectively. Conversely, maximum absolute increase in moisture content occurred for the heavy-thinning and control blocks on July 28, with increases of 110 and 94%, respectively, though that precipitation event only increased moisture in the light-thinning by 39%, and was not the greatest increase observed in the light-thinning over the duration of sampling (99% increase on August 6). It is possible that greater differences might have been observed on days when fuel sampling did not take place.

Surface moisture content was significantly different across treatments (p<0.001), and the Tukey test indicated significant differences between all treatments (p<0.05). Surface mulch was drier than control fuels under both treatments, with a mean difference in the heavy- and light-thinning treatments of 52.7 (s.e.=7.8) and 23.1% (s.e.=9.0), respectively. The heavy-thinning had drier surface mulch than light-thinning, with a mean difference of 29.6% (s.e.=6.0). Surface moisture in the heavy- and light-thinning treatments were highly correlated with the control treatment (r=0.81, p-value<0.01 and r=0.72, p-value<0.01, respectively; Table 2.3); the heavy- and light-thinning treatments were also highly correlated (r=0.78, p-value<0.01).
Table 2.3. Correlation matrix for average daily moisture content of the five treatment levels at the Carldale site (n=20 per group).

<table>
<thead>
<tr>
<th></th>
<th>Heavy-thinning</th>
<th>Light-thinning</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface</td>
<td>Deep</td>
<td>Surface</td>
</tr>
<tr>
<td>Heavy-thinning</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface</td>
<td>1.00</td>
<td>-0.01</td>
<td>0.78**</td>
</tr>
<tr>
<td>Deep</td>
<td>1.00</td>
<td></td>
<td>-0.01</td>
</tr>
<tr>
<td>Light-thinning</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface</td>
<td></td>
<td></td>
<td>1.00</td>
</tr>
<tr>
<td>Deep</td>
<td></td>
<td></td>
<td>1.00</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: * indicates significance at α=0.05; ** indicates significance at α=0.01.

Figure 2.4. Mean fuel moisture observations between all treatment combinations (n=20).

2.3.4 Surface moisture content and FFMC

Figure 2.5 shows observed surface moisture content from each treatment versus daily FFMC, as well as the standard relationship between FFMC and litter moisture content used in the FWI System (Equation 1). Additionally, predicted versus observed surface moisture content is presented for all treatments. Moisture estimates from the FFMC were well correlated with the surface mulch moisture under light-thinning (r = 0.75, p-value<0.001), heavy-thinning (r = 0.64, p-value=0.003) and control (r=0.59, p-value=0.007). There was a tendency of the FFMC model to under predict moisture content for both light-thinning and control treatments. There is high variability in mean surface mulch moisture under fuel treatments and the control, however observed moisture content and FFMC estimates tend to converge at the extreme dry end of FFMC values.
Figure 2.5. Comparison of mean surface fuel moisture versus FFMC and observed versus predicted (FFMC estimate) moisture content. The standard FFMC is relationship presented as a solid line. Bars indicate one standard error.
Table 2.4 summarizes regression parameters between mulch moisture content under each thinning treatment and the FWI System’s FFMC (converted to moisture content). Linear regression analysis suggested that the FFMC was a significant predictor of surface moisture in all three treatments (p-value<0.01 for each). We identified one outlier that was systematically present in all three treatments, and determined that it had a significant influence on regression results. The data point was observed on June 19, and examination of meteorological data leads us to suspect that additional rain was received at the Obed Tower but not on site, thus resulting in calculated FFMC values indicating much higher levels of moisture than observed at each of the three sample sites. That day was dropped from the regressions, improving the coefficient of determination values.

Table 2.4. Regression coefficients and summary statistics for a linear model relating mulch moisture content to moisture content from the FFMC (n=19). One standard error shown in brackets.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Predictor</th>
<th>β0 (s.e.)</th>
<th>β1 (s.e.)</th>
<th>R²</th>
<th>RSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy-thinning</td>
<td>mc(FFMC)</td>
<td>-2.21 (16.69)</td>
<td>1.01 (0.29)</td>
<td>0.376</td>
<td>30.77</td>
</tr>
<tr>
<td>Light-thinning</td>
<td>mc(FFMC)</td>
<td>15.33 (15.40)</td>
<td>1.26 (0.27)</td>
<td>0.535</td>
<td>28.39</td>
</tr>
<tr>
<td>Control</td>
<td>mc(FFMC)</td>
<td>33.31 (26.44)</td>
<td>1.40 (0.46)</td>
<td>0.311</td>
<td>48.74</td>
</tr>
</tbody>
</table>

Note: All regressions significant at p<0.01. RSE is residual standard error.

2.3.5 Historical weather analysis

The relationships between FFMC and surface layer moisture in each treatment block allowed us to look historically at the weather received at the Carldale site to examine how frequently surface moisture content in these stands might exceed important thresholds for ignition and spread. We estimated the annual frequency of days when surface moisture content was less than 10, 15 and 20% given historical records of FWI from Obed Tower and the newly-developed mulch moisture relationships based on heavy-, light-thinning and control treatments (Figure 2.6). The FFMC estimated 3.5 (s.e.=1.7) days per fire season where the estimated moisture content was less than 10%; the heavy-thinning calibration estimated 10.0 (s.e.=2.6)
Figure 2.6. Boxplots comparing annual frequency of days when surface moisture content was estimated to be less than 10, 15 and 20% based on the FFMC and heavy-thinning regression model.

days per fire season, and was significantly greater than number of days estimated by the FFMC, according to the t-test (p-value=0.01). The FFMC and heavy-thinning calibration estimated 23.8 (s.e.=3.2) and 32.2 (s.e.=3.8) days per fire season where the moisture content was less than 15%, however this difference was only marginally significant (p-value=0.06); FFMC and heavy-thinning calibration estimated 39.6 (s.e.=3.9) and 43.5 (s.e.=4.0) days per fire season where moisture content was less than 20%, which was found to not be significantly different (p-value>0.05). Interestingly, the light-thinning and control calibrations (Table 2.4) estimated zero days per fire season for all three levels of moisture content.

2.3.6 Deep mulch moisture

Moisture content of deep mulch fuels under both mastication treatments never dried below approximately 150% in this set of observations (Figure 2.3). A maximum
absolute increase in moisture of 50% occurred in the heavy-thinning treatment on July 10, and maximum increase in the light-thinning was 57% on August 4. Maximum absolute decrease in moisture was 37% in the heavy-thinning treatment on August 6, and 56% in the light-thinning on August 5. Mean deep mulch moisture content was lower under the heavy-thinning treatment as compared to the light-thinning treatment, with a mean difference of 22.5 (s.e.=5.2). Deep mulch moisture in the heavy- and light-thinning were not significantly correlated (r=0.35, p-value>0.05; Table 2.3, Figure 2.7).

Figure 2.7. Comparison of mean deep layer moisture between heavy- and light-thinning treatments (n=20).

Figure 2.8 shows observed deep mulch moisture content versus DMC under both mastication treatments, as well as the standard relationship between DMC and moisture content from the FWI System (Equation 2). DMC was not significantly correlated with moisture content in the deeper mulch layer in either heavy-thinning (r=0.163, p-value>0.05) or light-thinning treatments (r =0.102, p-value>0.05).
Figure 2.8. Comparison of mean deep mulch moisture versus DMC, with the standard DMC relationship presented as a solid line (left panels), and observed versus predicted (DMC estimate) moisture (right panels). Bars indicate one standard error.

Figure 2.9 shows observed deep mulch moisture content versus DC under both mastication treatments, as well as the standard relationship between DC and moisture content from the FWI System (Equation 3). DC was not significantly correlated with moisture content in the deeper mulch layer in either heavy-thinning ($r = -0.24$, p-value>0.05) or light-thinning treatments ($r = -0.02$, p-value>0.05) and correspondingly, we observe no relationship in Figure 2.9.
2.4 Discussion

2.4.1 In-stand micrometeorology

Significant differences in micro-climate variables were observed across fuel treatments in this study; these differences became greater with increased thinning intensity and the resultant increased canopy openness. Observed increases in solar radiation with intensity of thinning (Table 2.2) was observed in similar studies
conducted in partially-cut mixedwood stands (Prevost and Pothere 2003) and thinned lodgepole pine stands (Whitehead et al. 2006). Both Whitehead et al. (2006) and Bigelow and North (2012) reported increased wind speed within thinned fuel treatments, but no detectable differences in screen-level air temperature and relative humidity. Conversely, Rambo and North (2009) found significant differences in daily ranges of temperature and vapour pressure deficit (a function of air temperature and relative humidity) in thinned mixed-conifer stands.

The aforementioned studies tended to indicate some observable differences in micrometeorology variables between treatments, though the statistical significance of these differences was not always strong. Weather observations from this study might be autocorrelated due to frequency of sequential sampling (i.e. every 20 minutes); this would violate the assumption of independence for statistical testing. The differences in micrometeorology would still be observable; however we might not be able to suggest that these differences are significant in a statistical sense. This would be congruent with other authors who report differences in micrometeorology between fuel treatments, though they are not statistically significant (e.g. Bigelow and North 2009). More importantly, we should evaluate how these differences (whether statistically significant or not) influence aspects of fuel drying and potential fire behaviour. Bigelow and North (2009) examined this using fire spread simulation, and reported only minor changes increases in rate of spread and flame length. Our study and others suggest that fuels treatments will have minor micrometeorology-mediated effects on fire behaviour given the small absolute changes observed between treatments.

Bigelow and North (2012) recorded micrometeorological variables before and after fuel treatments were applied, and their analysis compared the difference between treatment and control blocks after fuel prescriptions were applied against the difference before prescriptions were applied. The current study did not have this experimental consideration, and we cannot confirm that small differences between blocks were entirely absent prior to treatment.
2.4.2 Surface mulch moisture

Alterations to stand structure may have minor effects on the drying process; however, the creation of a new fuelbed may have a considerably greater influence on surface fuel moisture than stand-thinning alone (i.e. though micrometeorological variables haven't changed significantly, the mulch fuelbeds respond differently than naturally occurring fine fuels). Many authors have hypothesized that increasing exposure associated with fuel treatments should intensify drying rates of forest fuels (Agee et al. 2000, Agee and Skinner 2005). However, recent studies of thinning effects on fuel moisture have suggested that this concern is largely unwarranted (Whitehead et al. 2006, Faiella and Bailey 2007, Bigelow and North 2012, Estes et al. 2012).

Surface mulch under heavy- and light-thinning treatments had the lowest minimum moisture contents; however the magnitude of differences in moisture content between treatments decreased as the fuels became drier. Pook and Gill (1993) found that between-treatment differences for thinned and pruned radiata pine (Pinus radiata D. Don) and control decreased with drier fuels and increasing fire danger. Decreasing differences in moisture content between thinned and unthinned stands was also observed in the study by Whitehead et al. (2006), and they considered the known difference to be insignificant in any practical fire management applications, including ignition probability and crowning potential. This convergence is also reported by Faiella and Bailey (2007) and Estes et al. (2012). We observed a similar trend (Figure 2.5), as surface moisture content and FFMC begin to converge at higher FFMC values (>80 FFMC) across treatments.

Due to frequent precipitation received at the study site and limited destructive sampling, we were unable to observe more days where fuels were extremely dry and fire danger was high. Our analysis indicated that the number of days when surface mulch in the heavy-thinning treatment was less than 10% was significantly greater than that estimated by the standard FFMC (Figure 2.5). The greater exposure of
surface fuels with increased thinning may lead to increased drying rates and a quicker recovery to burnable conditions. Although authors make the generalization that all surface fuels will be comparably dry on high FFMC days, particular levels of thinning might cause fuels that dry out more rapidly and thus stay available for longer periods of time.

We found reasonable agreement between the FFMC and surface moisture in the light-thinning and heavy-thinning treatments, based on the coefficients of determination ($R^2=0.54$ and 0.38, respectively). There is obvious potential for improvement in mulch moisture estimation, as much of the variation in fuel moisture remains unexplained by the FFMC under either treatment level. A similar level agreement was observed by Van Wagner (1987) for comparisons of FFMC versus slash moisture content of approximately the same diameter range ($R^2=0.50$ for 1.0 cm-diameter slash). Whitehead et al. (2006) found strong agreement between FFMC estimates and destructive needle litter samples in all treatments when Fire Danger Class was Low and Moderate, and suggested that the FFMC was robust enough to predict in both studied stands. Differences in moisture content are likely greater between the mulch and deciduous/needle litter in the control for this study, and we know that deciduous litter tends to retain moisture for longer than standard jack pine litter (Wotton and Beverly 2007).

Bigelow and North (2012) suggested that increased water status following thinning likely increases live fuel moisture, and thus increasing the resistance of surface fuels to ignition. Furthermore, additional cover from understory plants change micrometeorology at the fuelbed surface. Weng et al. (2007) found that air temperature in thinned stands returned to pre-thinning status within two to three years due to abundant understory regeneration that moderated air temperature and surface temperature. We might expect similar outcomes to be observed within fuel treatments in western Canada, though the vegetation types that recolonize post-treatment will likely influence surface-level micrometeorology, daily and seasonal fluctuations in moisture content, and have important considerations for potential fire behaviour. Site
maintenance is an important consideration with respect to the efficacy of fuel treatments.

Weng et al. (2007) suggest that it is critical to separate micrometeorology influences that are due to higher-order climatic factors from those actually due to thinning. This could be extended to fuel moisture, and is an important point when considering the applicability of studies from other geographic regions to fuel management in Canada. The Foothills of Alberta receive frequent rainfall, and our observed range of moisture content for surface and deep mulch might not be applicable to other climatic regions within Canada.

2.4.3 Deep mulch moisture

We were unable to find meaningful relationships between the DMC or DC and observed moisture in deep mulch layers under either treatment level. Frequent precipitation received at the site resulted in low ranges of daily DMC and DC, and probably precluded an analysis of how well the moisture codes estimate deep mulch moisture content. Deeper mulch layers were considerably wetter than surface layers throughout the study. Wetness of the season prevented study of the time it takes to dry fuels at these deep levels. These subsurface layers at Carldale were compact, insulated from direct evaporation, and therefore would have slower drying rates than surface fuels of the same size and diameter, similar to results from duff in mature and burned jack pine (Abbott et al. 2007). Van Wagner (1970) found a significant inverse relationship between fuelbed load and drying rate of the fuelbed as a whole; the deeper and more compact the fuelbed the longer the nominal fuel layer response time. Laboratory-based drying experiments on masticated fuels by Kreye et al. (2012) suggest no difference in desorption between fractured vs. intact fuel particles alone, although response times for the entire fuelbed were greater than those of particles at the surface. Particle thickness, packing ratio and bed depth may influence response times in forest fuels (Anderson 1990), and this likely applies to masticated fuelbeds as well. Additionally, mixing with organic material (e.g. vegetation, litter, duff),
mineral soil content and proximity to the mulch-soil interface should contribute to deep mulch moisture retention and influence moisture trends through the masticated fuelbed profile.

An assumption of the mastication approach is that the redistribution of forest fuels into a compact layer on the forest floor ensures that fuels are not available for combustion, whether fire is moisture-limited due to water retention or oxygen-limited due to compaction and minimal aeration, etc. Given the high moisture content observed under both fuel treatments, it is unlikely that these deep layers would be considered available for combustion. This might be useful in considering the likelihood for smoldering to occur after the passage of a flaming front; since we observed continuously wet fuels (>150% MC), smoldering in deep layers may not be likely. Furthermore, as the compacted mulch fuelbed decomposes, these layers may retain greater amounts of moisture (Stocks 1970). However, if significant differences in fuelbed properties were to exist for other treatments and fuel types, the assumed ability for moisture to be retained in deep mulch beds may not hold. Overall, retention of moisture in the deep layers of mulch would be an important consideration in determining the effectiveness of mechanical mastication treatments. Many authors suggest that mastication practices should be combined with subsequent burning to ensure fuel loads are reasonably low (Weatherspoon 1996, Agee and Skinner 2005).

2.4.4 Implications for management

The results of this study suggest that micrometeorology differences between fuel treatments are relatively minor, though this should not be interpreted to mean that under certain high-severity fire weather conditions, fire behaviour would not be exacerbated by potentially windier and more open treatments. Fire severity might be more significantly influenced by the increased surface fuel loads resulting from mastication. Although researchers highlight the careful consideration of trade-offs between reductions in crown fire potential and the possibility of increased surface fire behaviour (Agee and Skinner 2005, Keyes and Varner 2006, Reinhardt et al. 2008),
most agree that the changes in micrometeorology and fuel moisture are outweighed by reductions in aerial fuel loading, though surface fuels may be further treated with prescribed fire following thinning and mastication.

2.5 Conclusions

The results of this experiment suggest that thinning intensity had significant influences on in-stand micrometeorology that potentially alter drying of surface fuels. Moisture differences may not be influenced by micrometeorology alone, but also by various physical properties of these highly-processed fuelbeds that differ from naturally-occurring surface and ground fuels. Masticated surface fuels were driest in the heavy-thinning treatment, where fuels were exposed to greater solar radiation and wind. Moisture in mulch fuelbeds was reasonably correlated with the daily FFMC, though the FFMC tended to over-predict moisture content in the heavy-thinning, and under-predict moisture content in the light-thinning.
3
Modifying the Canadian Fine Fuel Moisture Code for masticated surface fuels

Abstract. Mastication is a relatively novel fuel management technique being applied in western Canada, mostly at the wildland-urban interface, and a better understanding of the moisture dynamics of this processed fuelbed is a necessary component in the prediction of fire behaviour and fire effects. We investigated the applicability of the Fine Fuel Moisture Code (FFMC), a component of the Canadian Fire Weather Index System, in tracking the diurnal and day-to-day changes in surface mulch moisture, and proposed several modifications to the model components to better estimate the fuel-specific parameters of small-diameter (<1 cm) masticated surface fuels (referred to as the MAST model). The MAST model features a fuel temperature relationship with a required solar radiation input, and we contrasted moisture estimates derived from either on-site observations or modelled solar radiation. We also developed calibrations of the hourly FFMC via regression modelling. Model validation was performed using destructive moisture content observations from a mastication treatment in north-central Alberta, Canada. MAST predictions fit well with field observations, and were capable of producing mean error (ME) of 2.9. A calibrated form of the hourly FFMC also performed well (ME=-1.8), and closely resembled previous FWI System calibrations for fast drying surface fuels.
3.1 Introduction

Surface fuel moisture is critical to the ignition, spread and consumption of forest fires (Byram 1963, Rothermel 1972), and is an integral component of many national fire behaviour and danger rating systems (Deeming et al. 1978, Luke and McArthur 1978, Van Wagner 1987). Fuel moisture is an important control on both sustained ignition and fire spread, and because moisture content (particularly that of litter) varies with environmental conditions, there exists a considerable body of literature on fuel moisture modelling; reviews of moisture modelling are provided by Viney (1991) and Matthews (2013). Moisture model development generally involves either empirical or process-based models, with the former tending to use multiple regression of observed environmental variables to predict moisture (Pook and Gill 1993, Marsden-Smedley and Catchpole 2001, Lin 2005, Ruiz-Gonzalez et al. 2009, Sharples et al. 2009, Ray et al. 2010), while the latter employs mathematical equations to describe the physical relationships in moisture dynamics, such as energy and water balance, interception, evaporation and diffusion (Schapp et al. 1997, Nelson 2000, Catchpole et al. 2001, Matthews 2006). Fuel moisture models are useful tools in fire operations, and accurate estimates are essential to decision-making in fire management.

The Canadian Forest Fire Weather Index (FWI) System uses observations of air temperature, relative humidity, wind speed and rainfall to predict fuel moisture in three distinct layers of surface and ground fuels, with the Fine Fuel Moisture Code (FFMC) indicating moisture of dead fine fuels on the forest floor under a closed-canopy pine stand (Van Wagner 1987). In the FFMC model, the atmospheric conditions influence both equilibrium moisture content and rates of wetting/drying, and rainfall alters moisture within the layer. Stand-specific calibrations have been developed from various components of the FWI System to reflect differences in stand characteristics and the fuel layer of interest (Lawson and Dalrymple 1996 1997, Wilmore 2001, Otway 2005, Wotton and Beverly 2007). Wotton (2009) developed a
grass moisture model similar to the structure of the FFMC, with an adjusted response
time for grass fuels and a fuel temperature component that reflects the fact that such
fuels are highly-exposed to solar radiation.

Mastication is a fuel management technique that disrupts the vertical
continuity of forest fuels by mechanical shredding (e.g. chipping, mowing, mulching)
trees and understory vegetation into a highly-compacted surface fuelbed composed of
small-diameter fractured particles (Kane et al. 2009, Battaglia et al. 2010). The
treatment has become increasingly popular among land managers in western Canada,
where it is typically applied around communities and values as a fire protection
measure to reduce potential for ignitions, to decrease the potential for crown fires and
to improve the potential for fire suppression resources to be effective. Although
mastication is becoming increasingly applied as a protection measure in the wildland-
urban interface, it is surprising to find that moisture in masticated surface fuels has
been largely unstudied. Little is known regarding the effects of mastication on fuel
moisture and resulting changes in fire behaviour potential, and thus there is a clear
need to investigate this novel fuel management technique in unstudied Canadian
forest types.

The overall objectives of this study were to: i) modify the standard hourly
FFMC model by estimating parameters that better describe fully-exposed mulched
surface moisture content, hereafter referred to as the MAST model; ii) compare
predictive capability of the MAST model, including the addition of an observed or
modelled solar radiation input, and; iii) contrast MAST model estimates with the
common approach of calibrating the standard MC-FFMC relationship based on field
observations. Model estimates were compared using destructive moisture content
observed at a masticated treatment in north-central Alberta. We hypothesized that: i)
the MAST model would be a more suitable predictor of moisture content than the
current hourly FFMC; ii) the solar radiation component would considerably improve
goodness of fit in the MAST model, and; iii) MAST model would produce more
accurate fuel moisture estimates than calibrated forms of the standard FFMC. A
sensitivity analysis was performed on the MAST model to examine dependence of the model on its parameters.

3.2 Methods

3.2.1 MAST model development

The MAST model is similar to the FFMC in that it employs an iterative bookkeeping method to predict fuel moisture content based on the solution to the diffusion theory differential equation (Byram 1963), and uses equations for the combination of precipitation and drying phases. To account for the differences between a layer of conifer needle-dominated fine fuels assumed by the FFMC, we modified six elements of the basic hourly FFMC formulation to capture important aspects of moisture dynamics in masticated surface fuels: i) maximum moisture content was set at 150%, based on the study at Carldale described in the previous chapter; ii) the fuel layer was assumed to have a higher fuel load and bulk density (3.04 kg m\(^{-2}\) and 152 kg m\(^{-3}\)); iii) fuel temperature was predicted from fuel-specific constants derived from observations collected during the current experiment; iv) fuel relative humidity was dependent on fuel temperature; v) equilibrium moisture content formula was for wood, described by Simard (1968); and vi) response time was scaled to that of wood particles of 12.7 mm diameter (Anderson 1990) following the methods of Wotton (2009). In the MAST model, moisture predictions of the ‘active’ layer pertain to the uppermost 2 cm of mulch.

The MAST model is based upon a method of calculating moisture content for fine fuels (needles, fine twigs, etc.) by Van Wagner (1977). This model of moisture exchange contains two phases: the addition of moisture via precipitation, and an exponential drying process. Exponential drying is described as:

\[
\frac{mc(t) - EMC}{mc(t-\delta) - EMC} = e^{k\delta} \tag{1}
\]
where mc(t) is moisture content at time t, mc(t-δ) is moisture content at time δ prior to t, EMC is the equilibrium moisture content and k is a rate equal to the inverse of the fuel’s time lag. This equation assumes that EMC and k do not vary over the interval of time δ. The book-keeping method employed by this model assumes that rainfall occurs instantaneously at the beginning of the time period, followed by one hour of continuous drying under the constant environmental conditions observed at the beginning of the hour. In our analysis, both the MAST and hourly FFMC models were initiated by converting the daily FFMC from three days prior to an equivalent moisture content (Van Wagner and Pickett 1985), and spinning up the models with hourly weather inputs for two days prior to the start of the desired prediction window.

3.2.2 Precipitation influence

The precipitation phase of the hourly FFMC model requires total rainfall per time step and the estimated moisture content from the end of the previous time step, and is described as follows:

$$MC_r = MC_0 + \frac{\text{rain}}{\rho_{FL}} \cdot 100$$

(2)

where MC_r is the moisture content (%) of the fuel layer after rainfall, MC_0 is the moisture content (%) of the fuel layer before rainfall, rain is amount of precipitation (mm) and \(\rho_{FL}\) is the fuel load. The hourly form of the FFMC precipitation phase also assumes no interception by the canopy (Alexander et al. 1984). This was true in the full-exposure treatment at Horse Creek, however the assumption is likely not valid in treatments with residual standing trees or other vegetation. Another assumption of the formulation in Equation 2 is that 100% of rain that falls is absorbed by the fuel. Average fuel load and bulk density were estimated from destructive sampling of 20 50 cm x 50 cm quadrats at the Horse Creek site. In the MAST model, we assumed a 2 cm thick layer with a corresponding fuel load of 3.04 kg m^{-2}, since we were interested in moisture processes occurring at the surface of the fuelbed. We also assumed that the saturation limit for this fuel was 150% (evidence for this assumption
was corroborated by moisture sampling from Carldale, where surface samples never exceeded 150% moisture content).

3.2.3 Drying phase

**Fuel-level temperature and relative humidity**

Fuel temperature is not directly accounted for in the standard FFMC model but because of the openness of fuel treatments and the consequent increase in solar radiation, fuel temperature was assumed to play a significant role in drying processes and we decided to explicitly include a fuel temperature component within the MAST model. Byram and Jemison (1943) developed fuel temperature relationships for leaf litter from air temperature (at screen-level), solar radiation and wind speed. Using a similar methodology, Van Wagner (1969) developed fuel temperature relationship for a range of common forest fuels, and described the functional form of this relationship as follows:

\[ T_f - T_a = a \cdot I \cdot e^{-kW} \]  \hspace{1cm} (3)

where \( T_a \) is ambient air temperature (°C) measured at screen level, \( W \) is wind speed (km h\(^{-1}\)) measured at screen level, \( I \) is solar radiation (kW m\(^{-2}\)), and \( a \) and \( k \) are two constants specific to the fuel type. We estimated the fuel-specific coefficients of masticated wood based on the log transformation of Van Wagner's model form (Equation 3) via linear regression, using in-situ observations of air temperature, solar radiation, 2-m wind speed and fuel temperature from the fully-exposed treatment at Horse Creek (fuel temperature measurement methodology is described later in this chapter). We used the coefficients for the fully-exposed site for the MAST model.

Fuel-level relative humidity can then be calculated using the estimate of fuel temperature and an approximation for the relationship to saturation vapour pressure based on screen-level observations of air temperature and relative humidity. Saturation vapour pressure is approximated as (Baumgartner et al. 1982):
\[ e_s(T) \approx 6.107 \cdot 100^{\frac{7.5 \cdot T}{237+T}} \]  

(4)

where \( e_s \) is saturation vapour pressure at temperature \( T \) (°C). From this estimate of \( e_s \), actual vapour pressure is calculated as:

\[
RH_f = RH \cdot \frac{e_s(T)}{e_s(T_f)}
\]

(5)

where \( RH_f \) is fuel-level relative humidity (%), \( RH \) is the relative humidity at screen-level (%), \( e_s(T) \) is saturation vapour pressure given screen-level temperature (°C) and \( e_s(T_f) \) is saturation vapour pressure given fuel-level temperature (°C). The values of \( T_f \) and \( RH_f \) provide fuel-specific values for the estimation of equilibrium moisture content and response time for the masticated fuel layer.

**Equilibrium moisture content**

Under constant temperature and relative humidity, a fuel particle eventually equilibrates to the vapour pressure of the surrounding environment, following an approximately negative exponential convergence towards the equilibrium moisture content (EMC) (VineyJ and Hatton 1990). However, many forest fuels tend to never reach EMC in the natural environment as ambient conditions change more rapidly than the fuels are able to respond. Adsorption and desorption processes have slightly different EMC values according to whether the fuel is wetting or drying, and desorption (drying) is typically ~2% moisture content greater than that of adsorption (wetting) under the same environmental conditions (Blackmarr 1972, Van Wagner 1987, Catchpole et al. 2001); this phenomenon is known as the hysteresis effect. The EMC process has been studied extensively for a wide range of forest fuels, and especially forest litter (Nelson 1984, Anderson 1990). Van Wagner also developed EMC models from laboratory studies of pine litter, and is currently used in the Canadian Forest Fire Weather Index.
For the MAST model we chose a functional form of EMC for wood that we deemed to better describe moisture exchange between the atmosphere and wood particles (Simard 1968) in the metric form provided by Viney (1991):

\[
\begin{align*}
\text{EMC} &= 0.03 + 0.2626 \cdot \text{RH} - 0.00104 \cdot \text{RH} \cdot T \\
\text{EMC} &= 1.76 + 0.1601 \cdot \text{RH} - 0.02660 \cdot T \\
\text{EMC} &= 21.06 - 0.4944 \cdot \text{RH} + 0.005565 \cdot \text{RH}^2 - 0.00063 \cdot \text{RH} \cdot T \\
\end{align*}
\]

\[ 50 \leq \text{RH} \]

where EMC is equilibrium moisture content (%) and RH is ambient relative humidity (%). The model by Simard (1968) does not account for hysteresis effect (Figure 3.1).

![Equilibrium moisture content curves](image)

**Figure 3.1.** Equilibrium moisture content curves as a function of relative humidity for wood by Simard (1968) and for conifer needles by Van Wagner and Pickett (1985).

**Response time**

The timelag concept introduced by Byram (1963) describes the time required for a fuel particle to lose or gain 63.2% (1-1/e) of the difference between its initial moisture content and equilibrium moisture content (also known as response time, the time constant, or \( E_{63} \); Viney and Hatton 1990, Viney and Catchpole 1991). Van
Wagner’s (1977) development of the hourly FFMC model included a response time function of the following form:

\[
K = 0.0579 \cdot \ln(10) \cdot e^{0.0365T} \cdot [0.424 \cdot (1-RH^{1.7}) + 0.0694 \cdot W^{0.5} \cdot (1-RH^8)]
\]  

(7)

where \(K\) is the inverse of response time (hours), \(T\) is temperature (°C), \(W\) is wind speed (km h\(^{-1}\)) and \(RH\) is relative humidity (\(RH/100\) for desorption and 1-\(RH/100\) for adsorption). Following methods similar to Wotton (2009), we estimated a response time for masticated surface fuels by scaling Van Wagner’s formulation (Equation 7) to the average of response times for adsorption (10.5 h) and desorption (9.8 h) of 12.7 mm diameter Ponderosa pine dowels (Anderson 1990), resulting in an average response time of 10.15 h. The hourly FFMC model has a response time of 5.72 hours (under ambient conditions of 26.7°C, 20% RH and wind speed of 2 km h\(^{-1}\)). Thus, the new response time was \(0.0579 \cdot \ln(10) \cdot (10.15/5.72)\), and the modified model is as follows:

\[
K_{\text{MAST}} = 0.075 \cdot e^{0.0365T_f} \cdot [0.424 \cdot (1-RH_{f}^{1.7}) + 0.0694 \cdot W^{0.5} \cdot (1-RH_{f}^8)]
\]  

(8)

The final step in the MAST model for masticated fuel moisture is as follows:

\[
MC = EMC + (m_c - EMC) \cdot 10^{-kt}
\]  

(9)

where \(EMC\) is the equilibrium moisture content (%) for the respective time step, \(m_c\) is the moisture content following the precipitation phase (%), \(k\) is the response rate for a masticated fuelbed and \(t\) is time (1 hour in this case).

3.2.4 Model inputs

Hourly observations from the RAWS were used to run both the MAST and hourly FFMC models. To assess the influence of the fuel temperature relationship in the MAST model, we compared moisture estimates between in-situ solar radiation observations (MAST\(_1\)), modelled solar radiation that was adjusted for cloud-cover (MAST\(_2\); described below), modelled solar radiation that was not adjusted (MAST\(_3\)), and no solar radiation input (i.e. \(I=0\), and therefore \(T_f = T_a\); MAST\(_4\)).
We used a solar radiation model presented by Allen et al. (2006) and supplemented by Sellers (1965). As cloud cover reduces solar radiation reaching the earth’s surface, and cloud cover can be correlated with relative humidity, we developed solar radiation reduction factors based on humidity to correct for cloud cover in the modelled solar radiation estimates. We plotted observed solar radiation versus relative humidity, qualitatively assigned relative humidity classes and determined the average value of solar radiation for each class of relative humidity.

A wind power law relationship was used to convert 10-m wind speed from RAWS observations to 2-m wind speed required by the fuel temperature model. The relationship is described as follows (Mell et al. 2007):

\[
u_x = u_r \cdot \left( \frac{z_x}{z_r} \right)^{1/7}
\]

where \(u_x\) is the wind speed at height \(z_x\) (2 m in this study), and \(u_r\) is the known wind speed at a reference height \(z_r\) (10 m in this study).

3.2.5 Hourly FFMC calibrations

We estimated moisture content from the hourly FFMC, converting FFMC values to equivalent moisture content using the FF-scale relationship:

\[
MC_{FF} = 147.2 \cdot \left( \frac{101 - \text{FFMC}}{59.5 + \text{FFMC}} \right)
\]

where MC is moisture content (%) and FFMC is the Fine Fuel Moisture Code.

We tested several approaches to calibrate the hourly FFMC estimates to observations from the field. For the first approach, we converted hourly FFMC estimates to the FX-scale that was proposed by Van Wagner to improve FFMC estimates for fast-drying surface fuels (Lawson et al. 1996), described as follows:
\[ MC_{FX} = 32.87 \cdot \left( \frac{101 - FFMC}{13.28 + FFMC} \right) \]  

(12)

where MC is moisture content (%) and FFMC is the Fine Fuel Moisture Code.

For the second approach, we used non-linear regression to estimate the relationship between observed moisture content and hourly FFMC, similar to the methods described by Abbott et al. (2007). The regression model took the form of the standard FF-scale relationship between moisture content and the FFMC (Van Wagner 1987), modified here to show the empirically derived constants:

\[ MC_{LC} = A \cdot \left( \frac{101 - FFMC}{B + FFMC} \right) \]  

(13)

where A and B are estimated via regression, MC is moisture content (%) and FFMC is the Fine Fuel Moisture Code. We refer to this model hereafter as the Local Calibration or LC-scale.

3.2.6 Field sampling

The Horse Creek Research Site was used for initial model development and testing. The Horse Creek Research Site (54° 01’ 16.08” N, 117° 51’ 3.45” W) is located in the Upper Foothills natural subregion of west-central Alberta, Canada (Beckingham et al. 1996). The forested area is composed of mature lodgepole pine (Pinus contorta var. latifolia Engelm. ex S. Watson) with an understory of black spruce (Picea mariana (Mill.) B.S.P.). Elevation is approximately 1200 m above sea level. All sampling was performed within a 50 m x 100 m plot where all trees and surface fuels had been masticated in June 2012. The terrain within the plot was flat. This treatment left surface fuels fully-exposed to the influences of solar radiation and wind, and controlled for some of the additional micro-site variability in moisture that may be imposed with varying levels of residual stand structure. This plot is part of a
larger set of treatments that make up the Horse Creek Research Site, and more detailed site descriptions can be found elsewhere (Thompson and Schiks, in prep).

For development of the fuel temperature model, an in-situ weather station was installed at plot centre, and consisted of: one multi-channel datalogger (Campbell Scientific CR-1000), one shielded temperature and relative humidity sensor (HC-S3 and 41003-X), one sonic anemometer (Gill 2-D Windsonic sensor) at 2-m height, one solar radiometer (LI200X-20 LI-COR silicon pyranometer) and one T-Type thermocouple (18 gauge) with a junction of the wires attached directly to the top surface of a piece of masticated wood. Observations were recorded at 20-minute intervals from June 17 to August 31, 2012.

We also obtained hourly observations of air temperature (°C), relative humidity (%), 10-m wind speed (km h\(^{-1}\)) and precipitation (mm) from the Horse Creek Remote Automatic Weather Station (RAWS), located <1 km from the site. We used RAWS station observations as inputs for the MAST model and to calculate hourly FFMC.

Destructive sampling for moisture content was carried out at Horse Creek on five days during the 2012 fire season. Three random spot samples of surface mulch were collected every hour in the fully exposed treatment depending on weather, time of day and logistical constraints. Sampling tins were sealed with tape and wet weight obtained within 48 hours of sampling; samples were dried at 95°C to a constant weight and dry weight recorded. Gravimetric moisture content (i.e. by dry mass) was calculated using the standard method; all moisture contents presented in this paper are gravimetric moisture and presented as percentages.

Four 20 m transects were randomly established to determine fuel load and bulk density within the full-exposure treatment. At five equally spaced points along each transect, a 50 cm x 50 cm sampling quadrat was placed in a random orientation. Nails were driven to mineral soil in each of the quadrat corners to determine depth of the mulch layer. All woody debris within the quadrat was collected down to the
Figure 3.2. Map for Horse Creek Research Site with photograph depicting the full-exposure treatment.
duff/mineral soil and bagged. If a piece lay across the edge of the quadrat, it was cut at the intersection, and the inner portion retained. Mulch bulk density (kg m\(^{-3}\)) was calculated by dividing fuel load (kg m\(^{-2}\)) by the average mulch depth (cm) for each quadrat.

3.2.7 Statistical analysis

Observed surface mulch moisture content was plotted over time, along with moisture predictions from the hourly FFMC, the best MAST model and the best calibrated form of the hourly FFMC. All models were compared using the coefficient of determination (R\(^2\)), root mean square error (RMSE) and mean error (ME).

A sensitivity analysis was performed to examine the relative change in the MAST model output based on altering the model parameters. A similar analysis was performed by Matthews (2006) for a process-based model of litter fuel moisture. Relative sensitivity, \(\lambda\), is described as follows (Brylinsky 1972, Esprey et al. 2004):

\[
\lambda_i = \frac{p_i}{Q} \cdot \frac{Q_+ - Q_-}{2\delta_p}
\]  

(14)

where \(Q\) is the output, \(p_0\) is the unperturbed value of the parameter, \(i\), \(Q_+\) is calculated by running the model with \(p_i = p_0 + \delta_p\), and \(Q_-\) with \(p_i = p_0 - \delta_p\). The level of perturbation, \(\delta_p\), was arbitrarily set to 20% of \(p_i\). Relative sensitivity is zero when the output is independent of the parameter, and the positive or negative sign indicates whether an increase in the parameter value produces increasing or decreasing results in the output, respectively (Esprey et al. 2004). Following Matthews (2006), we chose \(Q\) to be the sum of square errors (SSE) of the model output:

\[
Q = \text{SSE} = \sum_{i=1}^{n} (X_i - \hat{X}_i)^2
\]  

(15)

where \(X_i\) is the \(i\)th observed moisture content value and \(\hat{X}_i\) is the predicted moisture content value for \(X_i\). The MAST model was run with Microsoft Excel 2010. All statistical analyses were performed with the R statistical package.
3.3 Results

3.3.1 Field observations

The full-exposure treatment at Horse Creek lacked any residual stand structure following mastication. Mulch cover was 100% continuous over the plot. Vegetation was absent from the plot due to the recentness of the treatment. A summary of fuel characteristics is presented in Table 3.1.

Table 3.1. Surface fuel summary for the study plot.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Std. error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live fuels (kg m(^{-2}))</td>
<td>0.0</td>
<td>(0.0)</td>
</tr>
<tr>
<td>Mulch depth (cm)</td>
<td>10.6</td>
<td>(4.3)</td>
</tr>
<tr>
<td>Mulch fuel load (kg m(^{-2}))</td>
<td>14.4</td>
<td>(5.1)</td>
</tr>
<tr>
<td>Mulch bulk density (kg m(^{-3}))</td>
<td>152.6</td>
<td>(68.8)</td>
</tr>
</tbody>
</table>

In the moisture sampling at Horse Creek, 24 observations of mean moisture content (n=3) were collected over five days. The weather conditions and ranges of moisture sampled are presented in Table 3.2. A significant rainfall occurred before the first sampling period, 8.8 mm in the late evening on July 30; another 5.1 mm rainfall occurred in the early evening on August 7, between the third and fourth day of sampling.

Table 3.2. Summary of observed surface fuel moisture, weather and hourly FFMC for the study periods at Horse Creek.

<table>
<thead>
<tr>
<th></th>
<th>Surface moisture (%)</th>
<th>Temperature (°C)</th>
<th>Relative humidity (%)</th>
<th>Wind speed (km h(^{-1}))</th>
<th>Hourly FFMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>35.6</td>
<td>18.7</td>
<td>73.1</td>
<td>5.3</td>
<td>60.3</td>
</tr>
<tr>
<td>S.D.</td>
<td>28.6</td>
<td>0.6</td>
<td>2.2</td>
<td>0.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Maximum</td>
<td>104.4</td>
<td>31.3</td>
<td>100.0</td>
<td>17.0</td>
<td>89.2</td>
</tr>
<tr>
<td>Minimum</td>
<td>8.6</td>
<td>5.0</td>
<td>32.0</td>
<td>0.0</td>
<td>8.1</td>
</tr>
</tbody>
</table>

Note: Sampling dates were July 31-August 9, 2012; n=5 days. Weather and hourly FFMC from nearby Horse Creek RAWS stations.
3.3.2 Fuel temperature

Equation 3 was transformed to allow estimation of its two coefficients via linear regression, and produced the following model coefficients: \( \ln(\beta_1) = 3.01 \) (s.e.=0.02, p-value<0.0001) and \( \beta_0 = 0.02 \) (s.e.=0.02; p-value=0.252). The insignificant wind term prompted an additional analysis using non-linear regression techniques, resulting in model coefficients of \( \beta_1 = 22.22 \) (s.e.=0.40, p-value<0.0001) and \( \beta_0 = -0.001 \) (s.e.=0.013, p-value=0.928). We decided to remove the wind parameter from the fuel temperature model, since no significant effect of wind could be detected with either analysis. Therefore, the new fuel temperature model form was \( T_f - T_a = a \cdot I \), and we used linear regression to fit the data with a zero intercept. The resulting coefficient for solar radiation was \( \beta_1 = 22.26 \) (s.e.=0.12, p-value<0.0001, \( R^2 = 0.943 \); Figure 3.3).

![Figure 3.3. Relationship of solar radiation and difference between fuel temperature and air temperature (\( T_f - T_a \)) from observations within the full-exposure treatment at Horse Creek Research Site.](image-url)
To create a simple method of assessing radiation attenuation due to cloud cover, we used linear regression of observed solar radiation divided by modelled solar radiation versus relative humidity (Figure 3.4). The analysis produced the following model coefficients: $\beta_1 = -0.01$ (s.e. = 0.00; p-value < 0.0001), $\beta_0 = 0.90$ (s.e. = 0.01; p-value < 0.0001) and $R^2 = 0.59$.

![Figure 3.4. Plot of solar radiation reduction factor (observed solar radiation/modelled solar radiation) versus relative humidity used to assign classes for solar radiation reduction factors.](image)

### 3.3.3 MAST model

The MAST model using an input of on-site solar radiation produced the highest coefficient of determination ($R^2 = 0.93$, p-value < 0.0001; Table 3.3) for the observations at Horse Creek. Replacing on-site measurements with a solar radiation model that was corrected for cloudiness based on observed relative humidity produced the next best coefficient of determination ($R^2 = 0.91$, p-value < 0.0001). MAST model predictions that employed an uncorrected solar radiation model or no solar radiation
resulted in lower coefficients of determination ($R^2=0.89$, p-value<0.0001 and $R^2=0.84$, p-value<0.0001, respectively).

**Table 3.3. Comparison of modelling approaches developed from Horse Creek.**

<table>
<thead>
<tr>
<th></th>
<th>MC$_{hFFMC}$</th>
<th>MC$_{CAL}$</th>
<th>MC$_{FX}$</th>
<th>MC$_{mast1}$</th>
<th>MC$_{mast2}$</th>
<th>MC$_{mast3}$</th>
<th>MC$_{mast4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>All moisture (n=24)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RMSE</td>
<td>54.06</td>
<td>10.50</td>
<td>15.35</td>
<td>11.38</td>
<td>9.15</td>
<td>15.56</td>
<td>26.65</td>
</tr>
<tr>
<td>ME</td>
<td>42.28</td>
<td>-2.65</td>
<td>3.58</td>
<td>4.81</td>
<td>-3.59</td>
<td>-10.22</td>
<td>19.10</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.83</td>
<td>0.88</td>
<td>0.90</td>
<td>0.93</td>
<td>0.91</td>
<td>0.89</td>
<td>0.85</td>
</tr>
<tr>
<td><strong>MC&lt;35% (n=15)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RMSE</td>
<td>39.38</td>
<td>10.11</td>
<td>12.08</td>
<td>8.14</td>
<td>5.95</td>
<td>5.13</td>
<td>21.97</td>
</tr>
<tr>
<td>ME</td>
<td>28.12</td>
<td>-1.80</td>
<td>-0.09</td>
<td>2.90</td>
<td>-2.11</td>
<td>-3.44</td>
<td>13.24</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.51</td>
<td>0.48</td>
<td>0.47</td>
<td>0.54</td>
<td>0.47</td>
<td>0.63</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Note: Each model was significant, with p-value<0.0001. MCCAL is moisture content from the calibrated FFMC model. RMSE is root mean square error; ME is mean error; $R^2$ is the coefficient of determination.

Observed versus predicted moisture content are compared across solar radiation inputs for the MAST model (Figure 3.5). Again, we observe that on-site solar and corrected solar model inputs produce estimates that are close to the 1:1 line of perfect agreement. The uncorrected solar model input appears to under-predict (i.e. estimate drier than observed) moisture content, especially for predictions >50% MC. A Student's t-test indicated that the uncorrected solar model predicted significantly greater solar radiation than observed on-site, with an average difference of 0.061 kW m$^{-2}$ (95% confidence interval of 0.043 to 0.079, p-value<0.0001). This over-prediction in solar radiation influenced the fuel temperature component of the MAST model, resulting in drier estimates for mulched surface fuels than based on the on-site solar or corrected solar model inputs. Removing the influence of solar radiation altogether reduced fuel temperature to that equal with air temperature, and resulted in over-prediction of moisture content (i.e. wetter than observed).

Differences between MAST estimates were influenced by solar radiation through its influence on fuel temperature. For simplicity, only the MAST model using on-site solar radiation was plotted along with the hourly FFMC model estimates and the best calibrated hourly FFMC model (Figure 3.6). Each data point represents
average moisture content (n=3) of the fine surface mulch; bars indicate standard error. As parameterized in the MAST model, moisture content never exceeded 150% moisture.

Figure 3.5. Plots of observed versus predicted moisture content given four inputs for solar radiation: (a) on-site observations, (b) corrected solar radiation model, (c) uncorrected solar radiation model, and (d) no solar radiation.

The difference between predicted and observed moisture content across the range of observed moisture content was modelled with linear regression techniques to assess the significance of increasing error in the model predictions as observed moisture content increases. Linear regression analysis indicated that difference between predicted and observed moisture content increased with predicted moisture
Figure 3.6. Time series plots of observed surface mulch moisture content and estimated moisture content from the $MC_{MAST1}$, $MC_{hFFMC}$ and $MC_{calibrated}$ models for the Horse Creek sampling period. Bars indicate one standard error.
Figure 3.7. Plot of difference between predicted and observed moisture content versus predicted moisture content given the four sets of MAST model inputs.

Moisture content difference versus predicted moisture content from the four MAST models is plotted in Figure 3.7.

Model sensitivity testing was used to compare the difference in outputs (in this case, sum of square errors between observed and predicted moisture) given equal relative adjustments in the parameters of the model (i.e. ±20% of the initial parameter value). The sum of square errors output was most sensitive to the maximum fuel moisture parameter (Equation 2) defined in the precipitation phase ($\lambda_i=-1.9$), and suggested that increasing the maximum fuel moisture parameter resulted in reduced prediction error (SSE). The fuel temperature parameter, $a$ (Equation 3), was marginally sensitive ($\lambda_i=0.2$), and indicated that increasing the parameter value results in marginal increases in prediction error (SSE). Given our dataset, the sensitivity of all other parameters was found to be negligible.
Table 3.4. Results of the sensitivity analysis for select MAST model components.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Relative sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel load</td>
<td>0.0</td>
</tr>
<tr>
<td>Maximum M.C.</td>
<td>-1.9</td>
</tr>
<tr>
<td>a, fuel temperature</td>
<td>0.2</td>
</tr>
<tr>
<td>k, fuel temperature</td>
<td>0.0</td>
</tr>
<tr>
<td>$K_{\text{mast}}$, response rate</td>
<td>0.0</td>
</tr>
</tbody>
</table>

3.3.4 Hourly FFMC and calibrations

The hourly FFMC model had the lowest coefficient of determination given the observations from full-exposure treatment at Horse Creek ($R^2 = 0.83$; Table 3.3). Conversion of hourly FFMC values to the FX-scale produced higher coefficient of determination ($R^2 = 0.90$). Non-linear regression techniques were performed to estimate the calibrated hourly FFMC model:

$$MC_{\text{LC}} = 33.99 \cdot \left( \frac{101 - \text{FFMC}}{21.67 + \text{FFMC}} \right) \quad (16)$$

$A$ and $B$ (Equation 12) were significant (p-value<0.001 and 0.021) and standard errors were 7.96 and 8.59, respectively. The standard FF-scale, FX-scale and LC-scale relationships were plotted in Figure 3.8, along with average moisture content observed at the full-exposure site. Surface mulch moisture was over-predicted by the hourly FFMC. The FX-scale and LC-scale showed very similar relationships for FFMC values greater than ~50; an important difference between the two scales lies in the maximum moisture content (150% for the LC-scale and 250% for the FX-scale). In the LC-scale, the $y$-intercept of approximately 150 was not pre-determined, but rather was the result of regression itself.

Linear regression analysis indicated that difference between predicted and observed moisture content increased with predicted moisture content for the hourly FFMC model (p-value<0.0001); however, this was not the case for the LC- and FX-
scale models (p-value=0.20 and 0.25, respectively). Moisture content difference versus predicted moisture content from the hourly FFMC, LC- and FX-scale models is plotted in Figure 3.9.

![Figure 3.8. Plot of standard FF-scale, FX-scale and LC-scale along with mean observed moisture content from the Horse Creek Research Site. Bars indicate one standard error.](image)

![Figure 3.9. Plot of difference between predicted and observed moisture content versus predicted moisture for the MChFFMC, MCcalibrated and MCfx models.](image)
3.3.5 Model comparisons

The MAST model with on-site solar radiation inputs produced the best estimates of surface mulch moisture according to the coefficient of determination. The MAST model using modelled solar radiation with an RH-based cloud cover reduction factor also produced similar results in terms of the coefficient of determination, and mean error was lower when this solar input was applied (ME=-3.59); the negative sign indicates a tendency towards under-prediction of moisture. The FX-scale also performed well, with only slightly lower coefficient of determination ($R^2=0.90$) and a lower mean error than the best MAST model (ME=3.58). Goodness of fit of the MAST model and FX-scale with the LC-scale should be interpreted with caution, as the LC-scale was trained on the dataset from Horse Creek while the others were not.

3.4 Discussion

3.4.1 Fuel temperature

The influence of solar radiation and wind on fuel moisture has been highlighted by Byram and Jemison (1943) and Van Wagner (1969). Byram and Jemison (1943) used artificial sun apparatus to determine fuel temperature relationships for fuels samples in-situ and in the laboratory. Similarly, Van Wagner (1969) used an artificial sunlight source in the lab, coupled with a fan to introduce wind effects. Both these studies found that radiation increased fuel temperature significantly above that of ambient air, but that this heating could be partially compensated for through a forced convective cooling effect due to wind (i.e. wind forcing air at ambient temperature over the heated fuel elements). Wotton (2009) emphasized the importance of solar radiation on fuel temperature in the development of a grass moisture model, given that these fuel types tend to be open or with low canopy closure, though that work simply used the Van Wagner (1969) formulation for radiation and wind effect.
The fuel heating effect due to solar radiation was observed in the current study, but the potential cooling effect of wind was not detected. Our examination of fuel temperature relationships in masticated surface fuels was not designed to allow the direct comparison of fuel temperature on fuel moisture; this effect remains an assumption with the MAST model. MAST models estimates that used a solar radiation input (MAST₁, MAST₂, MAST₃) did perform better than when solar radiation was excluded (MAST₄). Though mastication treatments tend to retain some overstory stand structure, the underlying fuelbeds become increasingly exposed to solar radiation and wind with treatment intensity, and we would expect increasing fuel temperatures to dry the fuelbeds more rapidly.

3.4.2 Comparison of model estimates

We observed reasonably good estimates of surface fuel moisture from the MAST model. Better estimates of surface fuel moisture content were observed when solar radiation was more accurately estimated. On-site measurements of solar radiation generally produced the best estimates; however, a solar radiation model, corrected for the effect of cloudiness, also performed well. The MAST model with no solar inputs did not perform as well, emphasizing the importance of the fuel temperature component in the MAST model. The MAST model does not explicitly incorporate influences of micrometeorology apart from solar radiation, but rather it takes a similar approach to the standard FFMC in estimating fuel moisture based on empirical relationships given fire weather station inputs.

The hourly FFMC tended to over-predict surface fuel moisture observed in masticated fuelbeds. The LC-scale performed well, and the relationship is quite similar to the FX-scale (Figure 3.8). The most important difference is the maximum moisture content for each scale; however, we did not have the opportunity to observe the maximum moisture that corresponds to extremely low FFMC values. Both scales have very similar relationships to the hourly FFMC, and are almost identical for FFMC values greater than approximately 50. Similarly, Anderson and Anderson
(2009) found reasonable fits for calibrations of the FF and FX-scales at FFMC>50 for elevated dead shrub fuels.

Given the results of the field validation test, our hypothesis that the MAST model would perform better than the hourly FFMC model was confirmed. Furthermore, incorporation of the fuel temperature component provided better estimates of fuel moisture and explained greater variance in observed moisture over a model that did not account for the influence of solar radiation. The MAST model performed slightly better than the local calibration.

FFMC-scale calibrations are common in the literature (Lawson and Dalrymple 1996, Lawson et al. 1997, Wilmore 2001, Abbott et al. 2007, Wotton and Beverly 2007); however, this approach is unable to explain changes in the physical drying process. We have observed masticated fuelbeds that dry out more quickly than the standard FFMC, however we cannot directly determine the cause, though we believe it is due to the increased exposure associated with masticated fuelbeds. Wotton and Beverly (2007) suggested that forest type (encompassing both surface fuels and stand structure) and density influence the relationship between actual moisture content and the FFMC, and we would expect similar effects for fuel treatments that alter stand and surface fuel characteristics.

Some previous studies of moisture modelling restricted their analyses of prediction error to low moisture contents, usually below the fibre saturation point of ~35% (Luke and McArthur 1978). This restriction is justified because: (i) moisture models tend to be developed to predict thresholds in ignition and burning conditions that occur at low fuel moistures; and (ii) there greater variability known to exist at higher moisture contents that generally obscure error statistics. Catchpole et al. (2001) assessed error based on a dataset of moisture observations that were <30%, and reported mean absolute error of 0.008 to 0.025 for predictions that included a calibration based on field dataset. Matthews et al. (2007) assumed <25% MC cut-off to assess prediction errors, and mean error of their model ranged from -0.02 to -0.05.
when the model was calibrated against field observations. Anderson and Anderson (2009) retained all observations in their analysis of predictive error, though the majority of their observations were also approximately <30% MC, and model mean error for their test dataset ranged from 2.77 to 8.36. The error statistics in the current study are more similar to Anderson and Anderson (2009), and might be attributed to assumptions and parameters of the model, the inherent variability of moisture in mulch fuelbeds, and that we did not provide further calibrations of the MAST model based on field data before reporting error statistics.

3.4.3 Model assumptions

Our decision to set maximum moisture content to 150% in the MAST model was based on observations of moisture from a mastication treatment not studied in this chapter (Carldale Site, AB; Chapter 2). The calibrated hourly FFMC regression also produced a y-intercept at approximately 150%, and made us somewhat more confident in this assumption. Surprisingly, our sensitivity analysis suggested that increasing maximum moisture content would reduce error in model estimates, though the moisture observations employed for the sensitivity analysis itself did not exceed 150%.

Kreye et al. (2012) found no difference in the drying rates between intact and fractured surface fuel particles of *Arcostaphylor manzanita* and *Ceanothus velutinus*, two commonly masticated shrub fuels found in California. This provides some confidence that Anderson’s (1990) observations for fuel sticks can be applied to masticated wood, at least for small-diameter fuels. The current study observed moisture in fuel particles with a diameter <1.0 cm, in an attempt to control for the increased variability that would be expected in trying to model moisture relationships for wider ranges of mulch diameters. The fuel-specific parameters may be different for larger size classes of masticated fuels. Van Wagner (1987) developed predictive models of moisture content for medium-sized logging slash, finding that the model’s best predictive ability was observed for slash diameters ranging from 2 to 10 cm.
Other factors that may influence surface moisture relationships in masticated fuels include species, weathering and particle density.

3.4.4 Modelling masticated fuel moisture

In addition to the modifications described in this study, research might further recognize the influence of in-stand meteorology influences on masticated fuelbed moisture. The MAST model estimated moisture content well in a fully-exposed mastication treatment, though estimates for treatments that retain stand structure might exhibit somewhat greater differences in observed versus predicted moisture content.

Moisture dynamics likely differ between surface mulch and those through the fuelbed profile. Masticated fuelbeds likely have a gradient of moisture content because: i) the surface becomes weathered while the deep layers begin to decompose; ii) mineral soil and organic matter may be present and variably mixed with mulch particles; iii) a gradient in bulk density may be present through the profile, especially due to annual snowpack and long-term decomposition; and, (iv) there may be moisture interactions between deep mulch and the underlying soil. While this study did not investigate fuel moisture of the fuelbed profile, observations from the Carldale site (Chapter 2) indicated that moisture was retained in the deeper layers of mulch and drying rates were much slower than for surface mulch. The moisture study from Carldale indicated no relationship between components of the FWI System and mulch moisture within deeper layers (~5-10cm) of the fuelbed, and so simple modifications to current FWI components are not expected to be a viable approach. This perhaps indicates a need for development of other empirical or processed-based modelling of fuel moisture in masticated fuelbeds.

3.5 Conclusions

In this chapter, we proposed modifications to components of the hourly FFMC that we deemed important to better model the moisture dynamics of
masticated surface fuels. We also used the common approach of calibrating the standard FFMC relationship with field observations of moisture, and found similarities with the FX-scale relationship. Results of the MAST model highlighted the importance of a fuel temperature component in estimating surface fuels that lack canopy cover and are exposed to increased solar radiation. Moisture estimation in fuelbeds is critical to understanding fuel availability, and predicting ignition and fire spread. Characterizing the range of physical properties (size class distribution, bulk density, mixing with other constituents) in mulch fuelbeds will be important, as the high variability between treatments has significant consequences for drying processes.
Assessing the probability of sustained flaming in masticated fuelbeds

Abstract. We investigated the influence of fuel moisture content, wind and ignition source size on the probability of sustained flaming of masticated fuelbeds under both laboratory and field conditions. The laboratory component used reconstructed fuelbeds, and provided critical control of predictor variables known to influence sustained flaming in most common forest fuels; the field component used in-situ tests, coupled with simultaneous observations of surface fuel moisture and meteorological conditions. Logistic regression techniques were applied to assess the probability of sustained flaming in both datasets. Models were also developed using estimated moisture from three sets of weather-based models: (i) the Canadian Forest Fire Weather Index (FWI) System components; (ii) the National Fire Danger Rating System (NFDRS) fuel moisture estimates, and; (iii) a masticated fuel moisture model (MAST) developed in the previous chapter. In both the lab and field testing, the likelihood of a successful ignition increased with decreasing moisture content, and increasing wind speed; the effect of firebrand size was only apparent in laboratory testing. Components from the FWI, NFDRS and MAST predictions had somewhat poor discriminative power in predicting probability of sustained flaming based on our field observations, and we attribute this largely to poor accuracy in estimating moisture content in masticated surface fuels.
4.1 Introduction

Mechanical fuel treatments are being increasingly applied within fire-prone landscapes, and the overarching goal(s) of these practices may include moderating fireline intensity, reducing crown fire potential and restoring historical stand structure. Fuel management aims to alter canopy characteristics, disrupt the vertical continuity of fuels and reduce surface fuel loads (Agee and Skinner 2005). Mechanical mastication (e.g. chipping, mulching) is becoming a popular fuel treatment among fire agencies in western Canada, where it is a common means of mitigating fire hazard in the wildland-urban interface. Mastication redistributes aerial and surface fuels into a compacted layer of fractured materials on the forest floor, and is achieved using equipment fitted with rotating drum(s) and cutters (i.e., masticators). The re-structuring and re-distribution of fuels potentially changes the moisture dynamics of the forest floor, and influences its availability for consumption during combustion.

The receptivity of forest fuel to ignition depends on fuel type (encompassing a number of physical characteristics), fuel moisture, ignition source, and micro-site variables (Beverly and Wotton 2007). Kane et al. (2009) found the masticated fuelbeds had different fuel loads by particle size classes and different fuel depths compared to natural and slash fuels. Since the initiation of flaming combustion is strongly supported by the presence of fine fuels, alterations to small-diameter fuel loads via mastication is hypothesized to influence potential for surface fuel ignition and spread. Litter, duff and mineral soil may also mix with mulched fuels during the mastication process. Masticated fuelbeds likely differ in critical ways from natural fuels, potentially changing fire behaviour and effects, and thus warrant scientific investigation.

Anderson (1970) identified three main determinants of a successful fire in its initial phase: ignitability (the ease of ignition), combustibility (rate of burning after ignition), and sustainability (the stability of combustion). One standard technique that
has been used throughout Canada for assessing fine-scale ignition sustainability is the two-minute match drop test (Paul 1969). The approach uses small-scale experimental test fires performed under a range of environmental conditions to assess the likelihood of successful ignition and sustained burning of fuels. The test encompasses not only ignitability of the fuels in question, but also features of combustibility and sustainability, and thus herein we refer to the match drop test as a measure of sustained flaming. Laboratory applications of the test have been used to isolate critical variable(s) in predicting the ignition of fuels while providing control over both fuelbed properties (e.g. packing ratio, bulk density) and environmental conditions (e.g. weather, climate) that would not be possible in the field. However, field applications of the test likely capture more realistic estimates of the range of sustained flaming conditions, as they incorporate complex micro-site variables.

The objective of this study was to determine the influence of moisture content, wind and ignition source on the probability of sustained flaming of masticated fuelbeds. We compared predictive models developed from ignition tests performed in-situ and with reconstructed fuelbeds in the laboratory. We assessed the significance of components of the Canadian Fire Weather Index (FWI) System and National Fire Danger Rating System (NFDRS) in predicting sustained flaming in masticated fuels. We also compared mulch ignition probability relationships against those developed for several common forest fuels found in the literature. Assessing critical explanatory variables of sustained flaming provide a greater understanding of the susceptibility of masticated fuelbeds to fire, and improve our knowledge of the early stages of fire initiation and fire spread.

4.2 Methods

We assessed the probability of sustained flaming in masticated fuelbeds under both laboratory and field conditions. Not only did this approach allow us to compare the controls on sustained flaming that might be observed under each experimental setting, but further permitted more direct comparisons between lab and field
observations. The combination of laboratory and field investigations has been rarely, if ever, used in previous studies of ignition.

4.2.1 Two-minute match drop test

The standard two-minute match drop test, described by Paul (1969), was performed throughout the day to obtain results over ranges in fuel moisture and environmental conditions. Ignition testing was performed by randomly placing a household-sized wooden match on the masticated fuelbed surface, in an area that was considered to be representative of the fuel moisture. We avoided placing the matches on masticated pieces with minimum diameters >1.0 cm. If the match was able to ignite the surface fuel and burn for 120 seconds, the test was considered sustainable and classed as a ‘success’, and the resultant test fire was thoroughly extinguished with a backpack pump and hand tools. If the match was extinguished before igniting the surface fuels, additional attempts were performed; if the surface fuels ignited briefly but flaming could not be sustained, additional attempts were performed to ensure this was not just an outcome influenced by local fuel element size and arrangement. The ignition test was classed as a ‘failure’ if three attempts did not result in a successful ignition. We noted a qualitative assessment of flame vigour, maximum height (cm) and final burn dimensions (cm x cm) after 120 seconds of flaming as further confirmation of success. The test involving up to three attempts was replicated three times to constitute one "round" of sampling, and replications were performed either simultaneously or within quick succession (usually <5 minutes). The same methods were performed with bundles of three matches, wrapped together with a short length of 18 gauge steel wire (all match heads in the same orientation).

4.2.2 Laboratory methods

Ignition testing was performed beneath a 3 m x 3 m exhaust hood in the burn laboratory at the Northern Forestry Centre, Canadian Forest Service (Edmonton,
Alberta, Canada). The standard two-minute match drop test (described above) was applied to each fuelbed.

Surface mulch material was collected within the full-exposure treatment to reconstruct fuelbeds for laboratory testing (previously described in Chapter 3). Fuelbed reconstruction and preparation followed methods similar to Kreye et al. (2011), and we selected fuel diameter size classes I, II and III (<0.5, 0.5-1.0, and 1.0-3.0 cm, respectively; Van Wagner 1968) which corresponded well with the 1-hr (<6.35 mm) and 10-hr (6.36 to 25.4 mm) diameter classes (NFDRS) employed in the previous analysis by Kreye et al. (2011). Due to the fractured nature of masticated particles, diameter was defined as the minimum thickness that spanned >50% of the particle length (similar to Kane et al. 2009). Larger fuel particles were excluded from the reconstructed fuelbeds because they were not expected to contribute during the earliest phases of ignition. Any mineral soil and/or conifer needles were removed. We determined appropriate fuel loads for each size class based on a subset of destructive sampling of fuels from the Horse Creek Research Site (n=5). First, we determined the fuel load proportions for all size classes; because we were only interested in investigating ignition for small-diameter fuel particles, we excluded size classes >3 and re-calculated the proportional contributions from size classes I, II, III, with resulting proportions of 57.8, 14.5 and 27.7%. Bulk density was determined to be 152 kg m$^{-3}$ (n=20), and thus 277, 70 and 132 g of size classes I, II and III, respectively were distributed to each tray. Bulk density was similar to the 138-150 kg m$^{-3}$ observed by Battaglia et al. (2010) for mastication treatments in Colorado conifer stands, and somewhat greater than the 46-115 kg m$^{-3}$ observed by Kane et al. (2009) for mastication treatments in shrub and small-diameter hardwood sites.

To manipulate fuel moisture, the contents of each fuelbed was placed in a permeable poly-woven bag, submersed under pressure (i.e. with weights applied on top) in a water bath for at least 72 hours, removed and drained. Fuelbeds were reconstructed in 30 x 21 x 5 cm aluminum pans. To facilitate mixing of the size classes, the fuelbed pan was covered within another upside down pan and shaken for
~30 seconds. Different moisture contents were achieved by placing fuelbeds under various ambient conditions (e.g. drying ovens at various temperatures) and allowing the fuelbeds to dry; fuelbeds were remixed on a constant basis to allow for more even drying through the fuelbed profile. We recognize that fuelbeds did not necessarily achieve equilibrium moisture content, but rather we wished to observe a wide range of moisture that spanned both completely successful and completely unsuccessful ignition attempts, and required moisture contents above fiber saturation point of ~30% for wood.

Wind treatments used in the laboratory experiment employed a domestic fan mounted to a platform, and produced an angle of -25° from the horizontal. We were satisfied with the relatively consistent wind velocities achieved at each level (0.5 and 1 ± 0.1 m s⁻¹).

Destructive sampling was performed immediately before each test fire. One destructive sample of surface moisture was collected in a metal 500 ml tin, usually near the side of the pan so as not to disturb the fuelbed. The tin was sealed with tape and wet weight obtained within 48 hours of sampling; samples were dried at 95°C to a constant weight and dry weight recorded. Gravimetric moisture content (i.e. by dry mass) was calculated using the standard method; all moisture contents presented in this paper are gravimetric moisture and presented as percentages.

4.2.3 Field methods

Test fires were conducted over five days in July and August 2012 at the Horse Creek Research Site (54° 01’ 16.08” N, 117° 51’ 3.45” W), located in the Upper Foothills natural subregion of west-central Alberta, Canada. The forested area is composed of mature lodgepole pine (Pinus contorta var. latifolia Engelm. ex S. Watson) with an understory of black spruce (Picea mariana (Mill.) B.S.P.). Elevation is approximately 1150 m above sea level. Testing was performed within a 50 m x 100 m plot where all trees and surface fuels had been masticated using a FECON FTX
250 SLGP masticator in June 2012. The terrain within the plot was flat (slope <5%). This plot is part of a larger set of treatments that make up the Horse Creek Research Site, and more detailed site descriptions can be found elsewhere (Thompson and Schiks, in prep). We selected only one treatment level to observe the extreme level of complete overstory removal that left the fuelbed fully exposed to solar radiation and wind. This allowed us to investigate probability of sustained flaming while controlling for additional variability in micrometeorology and fuel moisture that might be imposed by stand structure.

Destructive fuel moisture sampling was performed immediately before each "round" of test fires. Three destructive samples of surface moisture were collected in metal 500 ml tins, adjacent to the test fire location (within ~1 m). Replicates of each match drop test were completed within a short time period (<5 minutes), and one set of weather and moisture observations were used to represent environmental conditions for each such "round" of testing.

An in-situ weather station was installed at the centre of the full exposure treatment, and consisted of: one multi-channel datalogger (Campbell Scientific CR-1000), one shielded temperature and relative humidity sensor (HC-S3 and 41003-X) at 1.5 m height, one sonic anemometer (Gill 2-D Windsonic sensor) at 2 m height. Observations were logged every 30 seconds and recorded as a 20-minute average.

We obtained hourly observations of air temperature (°C), relative humidity (%), 10-m wind speed (km h⁻¹) and precipitation (mm) from a nearby (<1 km) Remote Automatic Weather Station (RAWS). We used this RAWS station’s observations to calculate all components of the Canadian Forest Fire Weather Index System and NFDRS fuel moisture estimates.

Four 20 m transects were randomly established to determine fuel load and bulk density within the full-exposure treatment. At five equally spaced points along each transect, a 50 cm x 50 cm sampling quadrat was placed in a random orientation. Nails were driven to mineral soil in each of the quadrat corners to determine depth of
the mulch layer. All woody debris within the quadrat was collected down to the duff/mineral soil and bagged. If a piece lay across the edge of the quadrat, it was cut at the intersection, and the inner portion retained. Mulch bulk density (kg m\(^{-3}\)) was calculated by dividing fuel load (kg m\(^{-2}\)) by the average mulch depth (cm) for each quadrat. We also quantified particle size class distribution on a random subset of the destructive samples (n=5).

4.2.4 Statistical analysis

The Mann-Whitney non-parametric test was used to evaluate significant differences in observed environmental conditions between success and failure for tests performed in the field. We modelled the probability of sustained flaming via logistic regression, with the outcome of each test fire classified as either a ‘success’ (1) or ‘failure’ (0):

\[
P(sf) = \frac{1}{1 + e^{-(\beta_0 + \beta_1 x_1 + \ldots + \beta_n x_n)}}
\]  

(1)

where P(sf) of the probability of sustained flaming, \(x_1\) to \(x_n\) are predictor variables, and \(\beta_0\) to \(\beta_n\) are coefficients of the regression.

Probability of sustained flaming was modelled as a function of moisture content, wind speed and brand size for both laboratory and field datasets independently. Moisture content was treated as a continuous variable. Wind speed was a continuous variable in the field trials; for the laboratory trials, we tried coding wind as either a continuous variable or as a three-level categorical variable. Brand size was a two-level categorical variable. For field trials we tested other environmental conditions (relative humidity, air temperature, wind speed, vapour pressure deficit) as explanatory variables, as some studies have found these to be significant predictors of ignition success (Schroeder et al. 2006, Beverly and Wotton 2007). We tested for correlation between environmental variables with Spearman's r.
The odds ratio was calculated for each model variable, describing the change in likelihood of sustained flaming given a unit change in the predictor; for categorical variables, the odds ratio represents the change in likelihood when the factor is present.

The FWI System components represent generalizations of fuel moisture and fire susceptibility, and have been found to be applicable across a variety of fuel types. The relationship between ignition of fine fuels and moisture content can be well defined via laboratory investigation, and therefore the FFMC is a logical element to test in the logistic regression framework as it can be an indicator of moisture in fine fuels. We calculated the daily FWI System indices, along with hourly-calculated FFMC, ISI, FWI, and FX-scale conversion of the hourly FFMC to test the significance of these operationally relevant inputs as predictors of sustained flaming. We also tested fuel moisture estimates based on the 1-hr and 10-hr fuel moisture from the NFDRS (Cohen and Deeming 1985) and the MAST model, previously described in Chapter 3.

Model comparison was based on Akaike’s Information Criterion (AIC). The goodness of fit was evaluated with Nagelkerke's pseudo $R^2$ statistic, and discriminative ability was assessed with the C-statistic. The Wald test was used to assess the significance of each predictor variable, and the likelihood ratio was used to test model significance overall. We used a probability of 0.5 as a cut-off to determine model sensitivity, specificity and accuracy; these measures represent the fraction of true positive, fraction of true negative and fraction of correctly classed model predictions, respectively. All analyses were performed with R statistical package, with $\alpha=0.05$ to determine significance.
4.3 Results

4.3.1 Mulch fuelbed characteristics at Horse Creek

Mean values of mulch depth, fuel load and bulk density were 10.4 cm (s.e.=4.3), 15.7 kg m\(^{-2}\) (s.e.=5.1) and 152.6 kg m\(^{-3}\) (s.e.=15.4). We estimated bulk density of the entire mulch layer, and this potentially differs from the bulk density that might be observed for the uppermost portions of masticated fuelbeds. Bulk density estimates from Horse Creek Research Site were somewhat higher, though still within similar ranges observed in other studies that evaluated physical properties of masticated fuelbeds (Hood and Wu 2006, Kane et al. 2009, Battaglia et al. 2010). Mean fuel load estimates by size class are presented in Figure 4.1.

![Figure 4.1](image)

Figure 4.1. Mean fuel load by size class and cumulative proportion (solid line) of total fuel load for destructive samples are Horse Creek Research Site (n=5). Bars show one standard error.

4.3.2 Laboratory testing

A summary of tested model forms are listed in Table 4.1. Multiple logistic regression indicated that moisture content and brand size were significant in lab testing (brand is a binary variable that takes a value of 0 for single brand and 1 for
triple brand). When wind was treated as a categorical variable, there were no significant differences found between the no-wind and ~0.5 m s\(^{-1}\) levels. When these wind levels were pooled and wind was tested as a binary response (i.e. pooled 0 and 0.5 versus 1 m s\(^{-1}\)), there was no significance of the 1 m s\(^{-1}\) wind speed level. Wind speed was a marginally significant predictor when it was alternatively coded as a continuous variable (p-value=0.049). The C-statistic was 0.958 for model 'Lab5' (Table 4.1), indicating high discriminative power, and the AIC value suggested better predictive ability over the model 'Lab2' that used the predictors moisture content and brand size (difference in AIC>2). The odds ratio indicated that employing triple-brands increased the likelihood of successful sustained flaming by 8 times; the presence of wind increased the likelihood by a factor of 6. The relationship for single and triple brands is plotted in Figure 4.2. When the 0 m s\(^{-1}\) wind level was excluded from the model form 'Lab2', the effect of brand size was found to be non-significant (p-value=0.3445).

![Figure 4.2](image)

Figure 4.2. Predicted probability of sustained flaming for (a) single brand and (b) triple brands tested in the laboratory dataset.
Table 4.1. Summary statistics for ignition models developed with the laboratory dataset.

<table>
<thead>
<tr>
<th>Model</th>
<th>Variable</th>
<th>Coefficient</th>
<th>St. Err.</th>
<th>Wald test</th>
<th>Odds ratio</th>
<th>Likelihood χ² test</th>
<th>AIC</th>
<th>C-statistic</th>
<th>Nagelkerke R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab1</td>
<td>Intercept</td>
<td>3.87</td>
<td>0.82</td>
<td>&lt;0.0001</td>
<td>-</td>
<td>96.31 (&lt;0.0001)</td>
<td>83.60</td>
<td>0.94</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>MC</td>
<td>-0.32</td>
<td>0.08</td>
<td>&lt;0.0001</td>
<td>0.72</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lab2</td>
<td>Intercept</td>
<td>3.66</td>
<td>0.86</td>
<td>&lt;0.0001</td>
<td>-</td>
<td>106.08 (&lt;0.0001)</td>
<td>75.80</td>
<td>0.95</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>MC</td>
<td>-0.39</td>
<td>0.09</td>
<td>&lt;0.0001</td>
<td>0.68</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Brand</td>
<td>1.93</td>
<td>0.68</td>
<td>0.00449</td>
<td>6.91</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lab3</td>
<td>Intercept</td>
<td>3.45</td>
<td>0.89</td>
<td>&lt;0.0001</td>
<td>-</td>
<td>110.84 (&lt;0.0001)</td>
<td>75.08</td>
<td>0.96</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>MC</td>
<td>-0.42</td>
<td>0.10</td>
<td>&lt;0.0001</td>
<td>0.65</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Brand</td>
<td>2.12</td>
<td>0.74</td>
<td>0.00395</td>
<td>8.36</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>WS₁</td>
<td>0.52</td>
<td>0.76</td>
<td>0.49757</td>
<td>1.68</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>WS₂</td>
<td>1.83</td>
<td>0.92</td>
<td>0.04792</td>
<td>6.21</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lab4</td>
<td>Intercept</td>
<td>3.51</td>
<td>0.87</td>
<td>&lt;0.0001</td>
<td>-</td>
<td>110.36 (&lt;0.0001)</td>
<td>73.55</td>
<td>0.96</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>MC</td>
<td>-0.41</td>
<td>0.10</td>
<td>&lt;0.0001</td>
<td>0.66</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Brand</td>
<td>2.08</td>
<td>0.73</td>
<td>0.0041</td>
<td>8.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>WS₃</td>
<td>1.64</td>
<td>0.87</td>
<td>0.0603</td>
<td>5.17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lab5</td>
<td>Intercept</td>
<td>3.42</td>
<td>0.89</td>
<td>0.0001</td>
<td>-</td>
<td>110.57 (&lt;0.0001)</td>
<td>73.34</td>
<td>0.96</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>MC</td>
<td>-0.43</td>
<td>0.10</td>
<td>&lt;0.0001</td>
<td>0.65</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Brand</td>
<td>2.13</td>
<td>0.74</td>
<td>0.0038</td>
<td>8.42</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>WS₄</td>
<td>1.69</td>
<td>0.86</td>
<td>0.0489</td>
<td>5.44</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: WS₁ is categorical 0.5 m s⁻¹ wind speed; WS₂ is categorical 1.0 m s⁻¹ wind speed; WS₃ is categorical 1.0 m s⁻¹ wind speed when levels 0 and 0.5 m s⁻¹ were pooled; WS₄ is wind speed classed as a continuous variable; Brand is categorical variable, triple brand. Coef. is coefficient; St. Err. is standard error; AIC is Akaike Informations Criterion; C is C-statistic.
4.3.3 Field testing

A summary of environmental observations during all field testing is presented in Table 4.2. Averages for all conditions were determined to be significantly different between no sustained and sustained flaming according to the Mann-Whitney non-parametric test \( (p<0.05) \). Air temperature and wind speed tended to be higher for successful ignitions; relative humidity and moisture content tended to be lower.

Table 4.2. Summary of environmental observations for test fires conducted in the field.

<table>
<thead>
<tr>
<th>Brand</th>
<th>Variable</th>
<th>No sustained flaming</th>
<th>Sustained flaming</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>mean</td>
<td>s.e.</td>
</tr>
<tr>
<td>Single</td>
<td>Temp</td>
<td>63</td>
<td>20.5(^a)</td>
</tr>
<tr>
<td></td>
<td>RH</td>
<td>63</td>
<td>50.2(^a)</td>
</tr>
<tr>
<td></td>
<td>MC</td>
<td>63</td>
<td>35.8(^a)</td>
</tr>
<tr>
<td></td>
<td>WS</td>
<td>60</td>
<td>1.9(^a)</td>
</tr>
<tr>
<td>Triple</td>
<td>Temp</td>
<td>59</td>
<td>20.2(^a)</td>
</tr>
<tr>
<td></td>
<td>RH</td>
<td>59</td>
<td>51.2(^a)</td>
</tr>
<tr>
<td></td>
<td>MC</td>
<td>59</td>
<td>37.3(^a)</td>
</tr>
<tr>
<td></td>
<td>Wind</td>
<td>56</td>
<td>2.0(^a)</td>
</tr>
</tbody>
</table>

Note: Letters indicate significant differences in means between no sustained and sustained flaming for each fire brand size. Temp is temperature (°C); RH is relative humidity (%); MC is moisture content (%); WS is wind speed (km h\(^{-1}\)).

Summary statistics for field-based models are presented in Table 4.3. Multiple logistic regression suggested that moisture content and wind speed were significant predictors of sustained flaming in the field dataset (Table 4.3, 'Field2'). Brand size was not a significant predictor in addition to moisture content and wind speed (p-value=0.448), nor was it significant in a model employing moisture content and brand size as predictors (p-value=0.631). The C-statistic for model 'Field2' was 0.972, indicating high discriminative power, and AIC value suggested much better predictive ability over the other tested model forms. We did not observe zero-wind conditions during field testing, and this is evident in the plot of model 'Field3' (Figure 4.3). This also makes the odds ratio for the wind predictor difficult to interpret.
Table 4.3. Summary statistics for models developed with the field dataset.

<table>
<thead>
<tr>
<th>Model</th>
<th>Variable</th>
<th>Coef.</th>
<th>St. Err.</th>
<th>Wald test</th>
<th>Odds ratio</th>
<th>Likelihood χ² test</th>
<th>AIC</th>
<th>C</th>
<th>Nagelkerke R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field1</td>
<td>Intercept</td>
<td>3.94</td>
<td>1.01</td>
<td>&lt;0.0001</td>
<td>-</td>
<td>58.71 (&lt;0.0001)</td>
<td>70.46</td>
<td>0.93</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>MC</td>
<td>-0.31</td>
<td>0.07</td>
<td>&lt;0.0001</td>
<td>0.74</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field2</td>
<td>Intercept</td>
<td>0.34</td>
<td>0.06</td>
<td>&lt;0.0001</td>
<td>-</td>
<td>20.14 (&lt;0.0001)</td>
<td>110.94</td>
<td>0.93</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>MC</td>
<td>-0.01</td>
<td>0.00</td>
<td>&lt;0.0001</td>
<td>0.99</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Brand</td>
<td>0.03</td>
<td>0.06</td>
<td>0.631</td>
<td>1.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field3</td>
<td>Intercept</td>
<td>-7.22</td>
<td>3.07</td>
<td>0.019</td>
<td>-</td>
<td>84.00 (&lt;0.0001)</td>
<td>47.18</td>
<td>0.97</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>MC</td>
<td>-0.44</td>
<td>0.15</td>
<td>0.003</td>
<td>0.64</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>WS</td>
<td>10.64</td>
<td>3.70</td>
<td>0.004</td>
<td>41835.48</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field4</td>
<td>Intercept</td>
<td>-7.63</td>
<td>3.18</td>
<td>0.016</td>
<td>-</td>
<td>84.58 (&lt;0.0001)</td>
<td>48.59</td>
<td>0.97</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>MC</td>
<td>-0.45</td>
<td>0.15</td>
<td>0.003</td>
<td>0.64</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>WS</td>
<td>10.80</td>
<td>3.76</td>
<td>0.004</td>
<td>49217.28</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Brand</td>
<td>0.59</td>
<td>0.78</td>
<td>0.448</td>
<td>1.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: WS is wind speed classed as a continuous variable; Brand is categorical variable, triple brand. Coef. is coefficient; St. Err. is standard error; AIC is Akaike Informations Criterion; C is C-statistic.
4.3.4 Meteorology and Fire Weather Indices

We tested for significant influences of temperature, relative humidity, vapour pressure deficit and wind speed for ignitions performed in the field; each was determined to be a significant predictor of sustained flaming (p-value<0.001 for each). Interestingly, wind speed was the best lone predictor of ignition probability within our dataset (AIC=77.291, C-statistic=0.907). Stepwise regression of the four predictor variables yielded a model that included wind speed, air temperature and relative humidity; however we found that all of these variables were highly correlated (Temp-RH=-0.80, p<0.001; Temp-Wind=0.71, p-value<0.001; RH-Wind=-0.71, p-value<0.001). In a model that used temperature as a predictor variable, the addition of relative humidity as a predictor was not significant (p-value=0.203); in a model that used wind speed as a predictor variable, the addition of relative humidity as a predictor was also not significant (p-value=0.335).
Results of logistic regression analysis suggested that all FWI components were significant predictors of in-situ sustained flaming in masticated fuelbeds (p-value>0.001 for each). Firebrand size was also tested as a factor in conjunction with each lone FWI predictor, and was not found to be significant in any model (p-value>0.05). The C-statistics and Nagelkerke $R^2$ for hourly FFMC, FX-scale and MAST models were much lower than for models that used direct meteorological predictors. The 1-hr and 10-hr fuel moisture estimates from the NFDRS were both significant predictors of sustained flaming (p-value>0.001 and p-value=0.01, respectively). The MAST model and 1-hr fuel moisture predictors had similar predictive ability according to AIC values. We plotted observed versus estimated moisture content from the hourly FFMC, FX-scale, 1-hr fuel moisture and the MAST model for observations from Horse Creek (Figure 4.4).

![Figure 4.4. Observed versus predicted moisture content from (a) Hourly-FFMC model, (b) FX-scale, (c) MAST model, and (d) NFDRS 1-hr fuel model. Solid line indicates the line of identity (1:1).](image-url)
Table 4.4. Summary statistics for models developed with the field dataset.

<table>
<thead>
<tr>
<th>Model</th>
<th>Variable</th>
<th>Coef.</th>
<th>St. Err.</th>
<th>Wald test</th>
<th>Odds ratio</th>
<th>Likelihood ( \chi^2 ) test</th>
<th>AIC</th>
<th>C</th>
<th>Nagelkerke R^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field5</td>
<td>Intercept</td>
<td>5.64</td>
<td>1.75</td>
<td>&lt;0.0001</td>
<td>-</td>
<td>29.38 (&lt;0.0001)</td>
<td>99.79</td>
<td>0.83</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>RH</td>
<td>-0.17</td>
<td>0.04</td>
<td>0.0001</td>
<td>0.84</td>
<td>29.70 (&lt;0.0001)</td>
<td>91.23</td>
<td>0.85</td>
<td>0.41</td>
</tr>
<tr>
<td>Field6</td>
<td>Intercept</td>
<td>-5.79</td>
<td>0.99</td>
<td>&lt;0.0001</td>
<td>-</td>
<td>29.70 (&lt;0.0001)</td>
<td>91.23</td>
<td>0.85</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>VPD</td>
<td>0.003</td>
<td>0.000</td>
<td>&lt;0.0001</td>
<td>1.00</td>
<td>29.70 (&lt;0.0001)</td>
<td>91.23</td>
<td>0.85</td>
<td>0.41</td>
</tr>
<tr>
<td>Field7</td>
<td>Intercept</td>
<td>-31.96</td>
<td>9.13</td>
<td>&lt;0.0001</td>
<td>-</td>
<td>68.25 (&lt;0.0001)</td>
<td>64.92</td>
<td>0.94</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>Wind</td>
<td>9.75</td>
<td>2.44</td>
<td>&lt;0.0001</td>
<td>17120.13</td>
<td>68.25 (&lt;0.0001)</td>
<td>64.92</td>
<td>0.94</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>Temp</td>
<td>0.59</td>
<td>0.18</td>
<td>0.001</td>
<td>1.81</td>
<td>68.25 (&lt;0.0001)</td>
<td>64.92</td>
<td>0.94</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>RH</td>
<td>0.17</td>
<td>0.08</td>
<td>0.042</td>
<td>1.19</td>
<td>68.25 (&lt;0.0001)</td>
<td>64.92</td>
<td>0.94</td>
<td>0.66</td>
</tr>
<tr>
<td>Field8</td>
<td>Intercept</td>
<td>0.23</td>
<td>0.45</td>
<td>0.599</td>
<td>-</td>
<td>23.54 (&lt;0.0001)</td>
<td>105.63</td>
<td>0.80</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>MC_FFMC</td>
<td>-0.03</td>
<td>0.01</td>
<td>0.001</td>
<td>0.97</td>
<td>23.54 (&lt;0.0001)</td>
<td>105.63</td>
<td>0.80</td>
<td>0.27</td>
</tr>
<tr>
<td>Field9</td>
<td>Intercept</td>
<td>0.05</td>
<td>0.42</td>
<td>0.909</td>
<td>-</td>
<td>24.47 (&lt;0.0001)</td>
<td>104.70</td>
<td>0.80</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>MC_FX</td>
<td>-0.08</td>
<td>0.03</td>
<td>0.002</td>
<td>0.92</td>
<td>24.47 (&lt;0.0001)</td>
<td>104.70</td>
<td>0.80</td>
<td>0.28</td>
</tr>
<tr>
<td>Field10</td>
<td>Intercept</td>
<td>1.16</td>
<td>0.71</td>
<td>0.102</td>
<td>-</td>
<td>29.05 (&lt;0.0001)</td>
<td>100.13</td>
<td>0.82</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>MC_MAST</td>
<td>-0.12</td>
<td>0.04</td>
<td>0.002</td>
<td>0.89</td>
<td>29.05 (&lt;0.0001)</td>
<td>100.13</td>
<td>0.82</td>
<td>0.32</td>
</tr>
<tr>
<td>Field11</td>
<td>Intercept</td>
<td>9.39</td>
<td>2.98</td>
<td>0.002</td>
<td>-</td>
<td>29.53 (&lt;0.0001)</td>
<td>99.64</td>
<td>0.83</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>1-hr MC</td>
<td>-1.09</td>
<td>0.31</td>
<td>0.001</td>
<td>0.34</td>
<td>29.53 (&lt;0.0001)</td>
<td>99.64</td>
<td>0.83</td>
<td>0.33</td>
</tr>
<tr>
<td>Field12</td>
<td>Intercept</td>
<td>7.05</td>
<td>3.23</td>
<td>0.029</td>
<td>-</td>
<td>13.67 (0.0002)</td>
<td>115.51</td>
<td>0.70</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>10-hr MC</td>
<td>-0.58</td>
<td>0.23</td>
<td>0.010</td>
<td>0.56</td>
<td>13.67 (0.0002)</td>
<td>115.51</td>
<td>0.70</td>
<td>0.16</td>
</tr>
<tr>
<td>Field13</td>
<td>Intercept</td>
<td>0.09</td>
<td>0.42</td>
<td>0.829</td>
<td>-</td>
<td>24.30 (&lt;0.0001)</td>
<td>104.93</td>
<td>0.80</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>MC_LC</td>
<td>-0.08</td>
<td>0.03</td>
<td>0.002</td>
<td>0.92</td>
<td>24.30 (&lt;0.0001)</td>
<td>104.93</td>
<td>0.80</td>
<td>0.27</td>
</tr>
</tbody>
</table>

*Note: Coef. is coefficient; St. Err. is standard error; AIC is Akaike Informations Criterion; C is C-statistic.*
4.3.5 Model comparisons

Classification statistics for select models of sustained flaming are presented in Table 4.5. We also evaluated the ability of the lab-based model of ignition (Lab5) to predict sustained flaming in the field, and the field-based model of ignitions (Field3) to predict sustained flaming under laboratory conditions. We plotted the probability of sustained flaming relationship for masticated fuels at Horse Creek, along with other models of sustained flaming for aspen leaves (Beverly and Wotton 2007) and
for pine litter with slash (Schroeder et al. 2006; Figure 4.6). The probability of sustained flaming was very similar across the three fuel types.

Table 4.5. Classification summaries for select lab and field equations.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Equation</th>
<th>Sensitivity</th>
<th>Specificity</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laboratory</td>
<td>Lab5</td>
<td>0.91</td>
<td>0.89</td>
<td>0.90</td>
</tr>
<tr>
<td>Field3</td>
<td>0.05</td>
<td>1.00</td>
<td>0.58</td>
<td></td>
</tr>
<tr>
<td>Field</td>
<td>Field3</td>
<td>0.78</td>
<td>0.96</td>
<td>0.91</td>
</tr>
<tr>
<td>Lab5</td>
<td>0.90</td>
<td>0.88</td>
<td>0.88</td>
<td></td>
</tr>
<tr>
<td>Field8</td>
<td>0.00</td>
<td>1.00</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td>Field9</td>
<td>0.00</td>
<td>0.82</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td>Field10</td>
<td>0.08</td>
<td>0.96</td>
<td>0.80</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.6. Predicted probability of sustained flaming for in-situ masticated fuelbeds and other common forest fuels (Schroeder et al. 2006, Wotton and Beverly 2007).

4.4 Discussion

4.4.1 Predictors of sustained flaming

Small-scale ignition probability was assessed under lab and field conditions to compare the controls on sustained flaming that might be observed under each of these settings. Our findings suggested that moisture content and wind speed had reproducible influence under both lab and field settings. The effect of firebrand size
was found to be significant under laboratory conditions, where wind speed was more easily controlled; however, the effect of firebrand size in the field was not statistically significant. Other factors that may influence ignition but were not tested in the laboratory study include temperature and relative humidity (Lin 2005).

Fuel moisture is recognized as having the most significant influence on fuel ignitability (Schroeder 1969, Blackmarr 1972, Nelson 2001), and fuel moisture was used as a primary predictor in the current analysis. During pre-ignition, heat is required to: (i) raise the fuel temperature to ignition temperature; and, (ii) liberate moisture and volatiles from the fuel (Plucinski 2003). Heat required in this pre-ignition stage is dependent on the moisture content of the fuel. Moisture content was likely to be more uniform across replicates in laboratory testing. Moisture varies spatially in the field, as the degree of shading, exposure to wind and structural variability in the fuel complex influence the rates of fuel drying (Fernandes et al. 2008). Moisture gradients exist through the fuelbed profile (as observed in Chapters 2), with greater variation at higher moisture contents. Stand structure can influence moisture content and thus the likelihood of ignition (Tanskanen et al. 2005); however our preliminary field investigation in masticated fuelbeds was able to control for the influence of stand structure.

Wind may play an influential role in sustained flaming, as it alters the heat transfer to adjacent fuels (Plucinski 2003). The current experiment observed ranges of wind speed in the field, and multiple levels of wind speed recreated in the laboratory, expanding upon the common method of testing significant effect of the presence of wind. Previous studies have indicated mixed results for the effect of wind speed, with some authors reporting positive effects (Zhou et al. 2005, Plucinski and Anderson 2008) while others reported no such effects (Plucinski and Catchpole 2001, Anderson and Anderson 2010, Marino et al. 2012). Countryman (1980) suggested there might be optimum wind speeds for different firebrand types, as increasing wind speed provides more oxygen for combustion, but also may result in greater heat loss.
Considering the range of ignition sources employed in previous studies, it is not surprising that results have been mixed.

Schroeder (1969) suggested that larger ignition sources are more likely to raise fuel temperature to the heat of pre-ignition than smaller sources. Various ignition methods beyond matches have been employed in studies of ignition, including cotton balls soaked in methylated spirits (Plucinski and Anderson 2008), drip torches (Fernandes et al. 2008, Dimitrakopoulos et al. 2010) and wooden cubes that were ignited against a radiant heater (Marino et al. 2012). Lin (2005) found that larger firebrands increased ignition probability in a study of ignition that excluded wind. Similarly, Plucinski and Anderson (2008) found that increasing the volume of spirits applied to cotton balls significantly increased the probability of ignition in litter. The current study found a significant effect of firebrand size in laboratory testing, however this effect becomes unclear when wind is introduced; furthermore, the results of field testing indicated that firebrand size was not significant.

Moisture content is overwhelmingly the best predictor of sustained ignition, and therefore ensuring the best estimates of moisture should improve model predictions. We observed varying results in model fit across FWI, MAST model and NFDRS predictors. Since strong discriminative power could be derived from direct moisture estimates alone, this suggests that the moisture estimates from the FWI and NFDRS did not accurately reflect the moisture content observed in-situ.

Relative humidity as a surrogate of moisture content was a significant predictor, but the results of our field data set are likely limited due to the short duration of testing. It was surprising that air temperature was suggested to be a better predictor than relative humidity for our field tests. Other authors have suggested relative humidity as a significant predictor of ignition success in the field (Schroeder et al. 2006).

The physical parameters of masticated fuelbeds were not manipulated in the current study. The lab experiment controlled for bulk density and attempted to
maintain a similar size class distribution across trays to avoid introducing further variability to the data. The cross-sectional shape of individual fuel particle may deviate within one size class (Kane et al. 2009), so other fuel particle characteristics may also vary across trays, and we attempted to randomize this potentially confounding component of the experiment. Surface area to volume (SAV) ratio of fuel particles can influence combustion due to rates of heat transfer, with higher SAV transferring heat more quickly (Kreye et al. 2011). Surface area also affects fuel drying and production of volatiles during pyrolysis (Zhou et al. 2005). Size class distribution plays a role in sustained flaming, and fuelbeds with increased load or proportions of fine fuels dry more rapidly and require less heat input for successful ignition.

Direct comparison of ignition models is sometimes confounded by the manner in which success or failure of ignition is quantified, as this would alter the results of logistic regression models. The current study only considers ignition sustainability from a point source during the initial stages of ignition and propagation. Other studies evaluated the success of ignitions based on a minimum duration for combustion or successful spread (Dimitrakopoulos et al. 2010, Davies and Legg 2011). In addition, multiple drops within a round of testing influence the interpretation of probability of successful ignition, as was performed for the test fire database (Beverly and Wotton 2007) and other studies (de Groot et al. 2005).

4.4.2 Laboratory versus field investigations

Investigations of sustained flaming generally follow a methodology of applying an ignition source to fuels under varying ranges of influential variables; however, these assessments of ignition are performed under either laboratory or field environments. The laboratory environment allows for greater control and manipulation of single or multiple variables relevant to the assessment of sustained flaming, though the simulation of such environmental variables, particularly wind, might only approximate more complex wind characteristics observed in the field (e.g.
more turbulent wind). Field experiments likely capture a larger range of variability, as fuelbed properties can be heterogeneous even within close proximity. The current study suggests that several significant predictors of sustained flaming can be observed under both laboratory and field conditions, though this was not the case for brand size.

The combination of laboratory and field trials has rarely, if ever, been used in previous studies of ignition. Authors suggest that translation of laboratory results to field conditions is problematic (White and Zipperer 2010), and that laboratory testing cannot directly predict various aspects of in-situ fire behaviour (Ganteaume et al. 2013). Van Wagner (1971) discusses the "two solitudes" that are laboratory and field approaches in forest fire research, suggesting that each be used to complement our understanding of fire behaviour; full disclosure of the limitations of each approach must be discussed.

4.5 Conclusions

We performed ignition testing under laboratory and field conditions to assess the probability of sustained flaming in masticated fuelbeds. The relationship between probability of sustained flaming and moisture content was similar between mulch and other surface fuels; however, the inability of various operational models to accurately estimate moisture of masticated surface fuels presents significant challenges for predicting the likelihood of sustained flaming meteorological predictors obtained in the field (i.e. weather station observations and forecasts). Field testing introduces increasing variability in assessing sustained flaming; however, it is necessary to validate laboratory work through such means, and ultimately provides a more complete assessment of an important measure of fire behaviour in masticated fuelbeds.
5 Conclusions

5.1 Intent of research

The objectives of this research were to evaluate the effects of mastication on mulch fuel moisture and probability of sustained flaming. We recognize the time and resource limitations of this research project; however our aim through much of this research was to provide an initial exploration of masticated fuelbeds in a Canadian context.

5.2 In-stand micrometeorology and moisture content differences

The results of our first experiment suggested that thinning intensity (achieved via mastication) had significant influences on in-stand micrometeorology that potentially alter drying in surface fuels. Masticated surface fuels were driest in the heavy-thinning treatment, where fuels were exposed to increased solar radiation and wind. We were able to compare masticated fuel moisture with deciduous-needle litter from an adjacent, untreated forest stand. In addition, we compared mulch moisture content with moisture estimates from the FWI System, and investigated the applicability of the various moisture codes and calibrations.

The influence of fuel management and silvicultural treatments on in-stand micrometeorology has been previously studied. Several authors have also investigated the influence of fuel treatments on moisture more directly using observations of moisture content in standard forest fuels and fuel sticks. Moisture differences may not be influenced by micrometeorology alone, but also by various physical properties of these highly processed fuelbeds that differ from naturally-occurring surface and ground fuels. We observed a range of relationships to the moisture estimates of the Fine Fuel Moisture Code, and post-treatment stand
characteristics likely play a significant role: moisture content in a light-thinning treatment (Chapter 2) resulted in relationships that were wetter than the hourly FFMC; conversely, heavy-thinning (Chapter 2) and full-exposure (Chapter 3) treatments resulted in relationships that were significantly drier than the hourly FFMC. Future research might compare in-stand micrometeorology and fuel moisture across Canadian forest types. Perhaps more importantly, these studies should identify the critical structural characteristics of stands to determine what is driving potential micrometeorology and moisture differences, as understanding of these characteristics might further inform fuel management prescriptions.

5.3 Modifying the Canadian Fine Fuel Moisture Code for masticated surface fuels

The second experiment proposed modifications to components of the hourly FFMC that we deemed important to better describe the drying processes of masticated surface fuels. We also performed a calibration of the standard FFMC relationship with field observations of moisture, a common approach to characterizing fuel moisture relationships with components of the FWI System. We compared MAST model moisture estimates with hourly FFMC estimates, as well as estimates produced by applying the FX-scale conversion. Results of the MAST model highlighted the importance of a fuel temperature component in estimating surface fuels that lack canopy cover and are exposed to increased solar radiation. Our local calibration of the FFMC was very similar to the FX-scale relationship.

Moisture estimation in fuelbeds is critical to understanding fuel availability. Surface moisture significantly controls the initial phases of ignition and fire spread; moisture of deep layers is important to understanding fuel consumption, fire severity and fire effects. As discussed in Chapter 3, researchers have been successful in modelling moisture of various forest fuels. We did not investigate variations in moisture of deeper mulch layers; however, observations from the Carldale Site (Chapter 2) indicate that greater moisture was retained in deeper mulch layers. Future
research might employ empirical or physical modelling of the entire mulch fuelbed. Characterizing the range of physical properties (size class distribution, bulk density, mixing with other constituents) in mulch fuelbeds will be important, as the high variability between treatments has significant consequences for drying processes.

5.4 Probability of sustained flaming in masticated fuelbeds

The third experiment assessed predictors of sustained flaming in masticated surface fuels under both laboratory and field settings. The relationship between probability of sustained flaming and moisture content was similar between mulch and other surface fuels; however, the inability of various models to accurately estimate moisture of masticated surface fuels presents significant challenges for predicting the likelihood of sustained flaming meteorological predictors obtained in the field (i.e. weather station observations and forecasts). Our experimental approach emphasized the differences in predictors of ignition between laboratory and field investigations.

Probability of sustained flaming is an important initial fire behaviour measure that we investigated in this study. Further experimental work might consider the manipulation of physical properties of mulch fuelbeds in the laboratory to understand their effects on ignition and other fire behaviour parameters (e.g. intensity, flame residence time, heat flux and energy balance). Field investigations should compare fire behaviour observations against modelled fire behaviour predictions (e.g. Canadian Forest Fire Behaviour Prediction System, National Fire Danger Rating System, etc.). Though field testing may introduce increased variability, it is necessary to validate laboratory work through such means, and ultimately provides a more complete characterization of the consequences of mastication.
6 References


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