The effect of strip-harvesting on fuel moisture and loading in lodgepole pine stands

By

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Abstract

Fire and insect outbreaks are the two leading natural disturbance factors affecting Canadian forests. Over the last 20 years Mountain Pine Beetle (*Dendroctonous ponderosae* Hopkins) has killed more than 50 percent of western Canada's merchantable lodgepole pine (*Pinus contorta*) forests and spread beyond its historical range. The outbreak has affected forests and communities throughout British Columbia and Alberta and has prompted investigation into forest harvesting and modification management strategies to reduce likelihood of outbreak and impact of infestations. For these treatments to be successful they must not only account for effect on insects, but fire as well.

This study examined how progressive strip cut harvesting affected fuel moisture and loading. Stands were treated with alternating parallel clear cut five-meter-wide machine corridors and fifteen-meter-wide thinned retention strips. Fuel moisture content and fuel load was sampled from both treatment types and compared against unaltered control sites. Fine fuel moisture content was significantly different between each treatment, though interestingly the thinned treatment sites were drier than the cleared sites. Duff moisture content was not significantly different from control in either of the altered sites, though again thinned site moisture content was significantly lower than in the clear treatment. Fine fuel load was not significantly different from control in either of the altered sites, though the cleared treatment had significantly higher fuel load than the thinned treatment. Total site fuel load was not significantly different between the control and thin but was considerably lower in the clear treatment. These findings suggest that thinning affects fuel moisture content in a manner not accounted for in standard fuel moisture models. Increases in fine fuel moisture content leads to increased flammability, however the dramatic overall reduction in fuel load and duff moisture content indicate a reduction in difficulty of control.

Dedication

Dedicated to my parents, Wanda Angelomatis and Fred Wallace, and my partner Katharine Melnik.

Acknowledgments

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Introduction

Mountain Pine Beetle and Fire

Pine forests in western Canada have experienced significant large scale mountain pine beetle (*Dendroctonous ponderosae* Hopkins) epidemics in the last 20 years, killing in excess of 18 million ha and 700 million m^3 of BC's and Alberta's pine forests (Nealis & Cooke, 2014a). While the mountain pine beetle is native to western Canada's pine forests, changes to land management and climate since recording began has led to more suitable conditions for pine beetle outbreak. (Alfaro et al., 2010; Allen et al., 2005; Jenkins et al., 2014; Meddens et al., 2012; USFS, 2010).

Preferring lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) as a primary host, mountain pine beetle has also demonstrated a capacity to attack, kill, and frequently reproduce in a wide variety of other novel host species (Berryman, 1988; Cullingham et al., 2011; Furniss & Carolin, 1977; Logan & Powell, 2001; Rosenberger et al., 2017; L. Safranyik et al., 2010). Notable among the long list of pines susceptible to mountain pine beetle attack is hybridized lodgepole-jack pine and pure jack pine (*Pinus banksiana*), a common financially and ecologically valuable tree species with a native range from Alberta through to Nova Scotia (Berryman, 1988; Cullingham et al., 2011; Lusebrink et al., 2013; Nealis & Cooke, 2014a). There is also strong evidence to suggest that while mountain pine beetle range was previously temperature limited by elevation and winter temperatures, warmer climate has facilitated beetle range expansion which will continue north and east as long as suitable temperature and host species persist. (Logan & Bentz, 1999; Logan & Powell, 2001; Nealis & Cooke, 2014a; Robertson et al., 2009)

Under normal conditions mountain pine beetle populations exist at low levels throughout western Canada usually only colonizing diseased, damaged, or old trees incapable of mounting sufficient defence against attack (Alfaro et al., 2010; Cullingham et al., 2011). Under suitable conditions such as warmer than average years however, greater numbers of mountain pine beetles survive and mature to emerge simultaneously to swarm and overwhelm trees normally capable of resisting low population levels of attack. The first stage of attack is initiated by females who bore into the tree's outer bark and release trans-verbenol, an aggregation pheromone derived from α-pinene in the tree's phloem. This aggregation pheromone signals males to join and a swarm attack begins, strengthened by additional production of trans-verbenol as well as reactive host volatiles which indicate tree stress. Attack is observable as pitch tubes signalling boring activity by females who proceed to burrow vertical galleries along which they lay their eggs, as well as introduce blue stain fungus (*Ophiostoma montium* and *Grosmannia clavigera*). These eggs hatch and burrow laterally, mechanically ringing the tree and disrupting sap flow. Blue stain fungus introduced by attacking beetles simultaneously colonizes the xylem, impeding water transport and tree defensive responses, weakening the tree. (Logan & Powell, 2004; Raffa & Berryman, 1987; Rosenberger et al., 2017; Les Safranyik & Carroll, 2006; Tabacaru, 2015).

As a poikilothermic species mountain pine beetle's activity is regulated by the temperature of their environment, affecting rate of maturation and degree of mortality (Logan & Bentz, 1999; Zaslavski, 1988). In regions with suitable yearly temperature profiles mountain pine beetle is univoltine, growing from an egg to mature adult in one year, while in regions of marginal suitability it may take up to two years to mature. Rapid and coordinated maturation is important as the beetle relies heavily on synchronous emergence to overwhelm host trees (Logan & Powell, 2004; Raffa & Berryman, 1987). While beetles may mature under less ideal conditions they may begin to exhibit fractional voltinism or semivoltinism, which risks uncoordinated emergence or longer exposure to environmental threats, reducing reproductive success (Amman, 1972; Les Safranyik, 1978). In addition to affecting rate of maturation, temperature may also directly affect pine beetle mortality as extremely cold temperatures, or cold periods during less cold tolerant life stages may result in significant beetle mortality rates (Logan & Bentz, 1999; Logan & Powell, 2001). Increases in beetle populations to epidemic levels may be caused by a shift to weather conditions more suitable to beetle maturation and survival, or conditions reducing host vigour and resistance to attack (Raffa & Berryman, 1987).

Given the influence of temperature on pine beetle life cycle, reproductive success, and mortality, climate change along with subsequent shifts in habitable areas is of concern and may result in more frequent outbreaks or expansion into new regions and host species. While mountain pine beetle epidemics are a natural and integral part of ecosystem function, changes to seasonal conditions may result in greater stress on host trees and expansion of suitable range north and east, and increases in elevation in which beetles may mature within a single year, reducing mortality and increasing capacity for massed simultaneous attack on host trees. Historical fire suppression resulting in a landscape of more uniform old age stands also alters conditions to be conducive to outbreak and spread (Bentz et al., 2010; Logan & Powell, 2004).

Mountain pine beetle attack follows a series of defined stages, named after the appearance of the stand during each period. The first stage of beetle attack is known as the green attack stage and may span up to 12 months from initial infestation (Jenkins et al., 2014; Les Safranyik & Wilson, 2006;

Schoennagel et al., 2012). It is during this period that attacks on trees have begun and signs such as pitch tubes or boring dust may be found on stems or around the bases of targeted trees. In the green attack stage trees may not yet have succumbed to attack, or may have only recently succumbed and foliage may be green or beginning to show signs of stress such as yellowing chlorotic vegetation as attack progresses (Franklin et al., 2013; Hubbard et al., 2013). Transition to red attack stage follows within 6-12 months of initial attack, span up to 12 months, and indicates successful infestation and death of the target tree, with the characteristic transition to bright rust red needles caused by chlorophyll degradation (Franklin et al., 2013; Jenkins et al., 2014; Schoennagel et al., 2012). Grey attack stage occurs within 12-24 months of the attack and is caused by shedding of foliage from deceased trees, exposing faded bark or bare stems (Jenkins et al., 2014; Schoennagel et al., 2012). Successfully attacked trees will usually fully reach grey attack stage within 30 months (Les Safranyik & Wilson, 2006).

As beetle attack develops, stands undergo changes to foliage moisture and chemical composition as well as structure, ultimately affecting fire behaviour. The first distinct effect of attack is in the changes to chemical composition and moisture content. Upon sensing attack, target trees will release a broad range of terpenes and phenolics to repel the attack. Composition and concentration of these chemicals also changes, with the most beetle-toxic compounds increasing the most in volume and concentration. This resin release is both a toxic and a physical impediment to the beetles, in some cases halting or slowing the attack and even interfering with or smothering aggregation pheromones (Jenkins et al., 2014; Raffa & Berryman, 1987). If attack progresses and the tree is killed, further chemical changes occur, resulting in decreases of crude fats, sugars, and starches in the foliage from the yellow attack phase onwards. Reduction in these reduces flammability, but this is offset by a simultaneous decrease in moisture content (Page et al., 2012).

Moisture content in fuels is also affected by attack. While physical girdling by larvae boring horizontally causes some disruption of water and photosynthate transport, most of the limitation to fluid transfer is caused by the introduction and spread of the blue stain fungus through the xylem by the mountain pine beetle (Alfaro et al., 2010; Hubbard et al., 2013; Raffa & Berryman, 1987; Les Safranyik, 1978). Blue stain fungus actively blocks fluid transfer and aids the pine beetle in colonization, reducing resistance far more rapidly than mechanical damage by beetle attack would otherwise achieve (Hubbard et al., 2013). While foliar moisture may decline during green attack, it is after tree death during the yellow and red attack phases that moisture content drops to 10-12% or less, significantly increasing flammability (Jolly et al., 2012; Page et al., 2012; Perrakis et al., 2014; Schoennagel et al., 2012). Due to a cessation of sap flow and evaporative moisture loss, foliage volume decreases, leading to increased sensitivity to drying and wetting events. This increased surface area to volume ratio in desiccated foliage increases sensitivity to heating and combustion (Page et al., 2012). Following changes to chemical composition and moisture content, fuel load and structure begin to change.

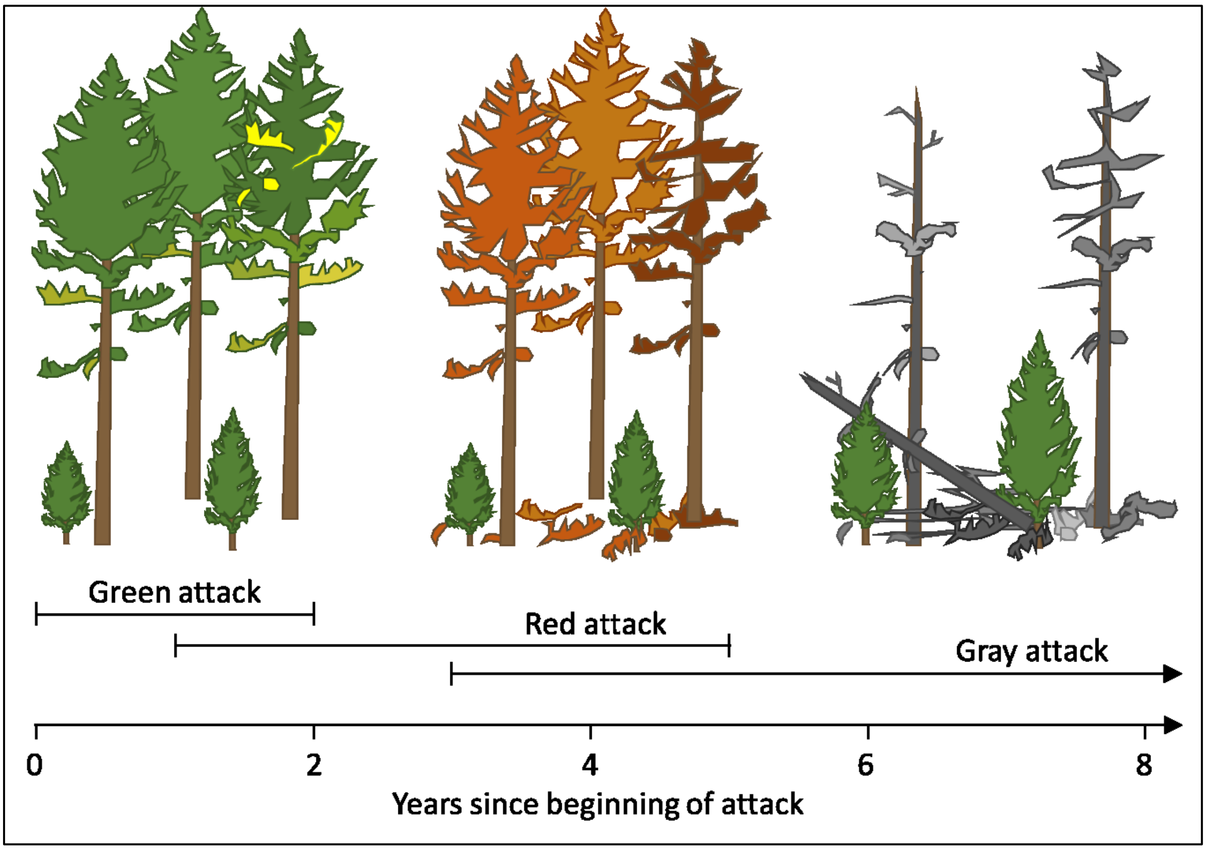

Figure 1. Three main stages of mountain pine beetle attack modified from original source (Simard et al., 2011) with additional information from Jenkins et al., 2014; Safranyik & Wilson, 2006; Schoennagel et al., 2012.

Fuel load and structure changes are especially pronounced in the late red stages and grey stages as needle fall begins, followed over time by fine branches and bark (Jenkins et al., 2014). While fine fuels decay rapidly, variation in individual tree mortality at a stand level results in longer periods of increased litter loading than would otherwise be expected given individual tree attack stage times (Jenkins et al., 2014; Page et al., 2012). As the overstory declines and foliage and branches are shed, canopy fuel load declines and understory species are released, increasing ladder fuels and horizontal continuity. Significant coarse fuel loading may occur for up to 20 years following attack as large branches and stems fall, resulting in a complex and changing fuel environment well after the actual attack has passed (Jenkins et al., 2014; Schoennagel et al., 2012).

The net result of these changes to fuels is a change in potential fire behaviour. While there is some variation between studies in exact observed effects, most studies confirm some manner of increase in some aspect of fire behaviour including ignitability, sustainability, or intensity, with significant effects on fire behaviour following transition to yellow attack stage. Page et al (2012) observed decreased time and temperature required for ignition, as well as higher heat yield resulting in increased likelihood of sustained ignition in yellow and red attack stage fuels when compared to equivalent green fuels. Changes to chemical composition of fine fuels noted earlier has also been observed in fallen fine fuels, increasing surface fuel ignition potential and contributing to increase surface fire intensity (Jenkins et al., 2014; Schoennagel et al., 2012). Increase in surface fire intensity was also observed by Harvey et al(2014), though only under extreme conditions in the grey attack stage. Likelihood of crown fire is also affected by these fuel changes, occurring at lower wind speeds and under less extreme weather conditions, likely resulting in underprediction of active crown fire (Schoennagel et al., 2012). This finding is corroborated by Perrakis et al (2014) who found fire behaviour in red and early grey attack stands frequently exceeded predictions with unified active crown fire dominating observed behaviour when models predicted surface or intermittent crown fire. Furthermore, observed fires exceeded predicted rate of spread by an order of two or three times that of un-attacked stands. Case studies of wildfires in red and grey stage MPB stands in Colorado and Wyoming found fire activity exceeded expectations with increased short distance rate of spread, intensity, spotting, active and crowning with or without normally required ladder fuels, all under moderate weather and fuel moisture conditions (Hoffman et al., 2015; Moriarty et al., 2019). Even as canopy fuels are lost there is evidence that MPB attack stands retain capacity for increased rate of spread, intensity, and crown fire behaviour over that of a normal lodgepole pine stand (Hoffman et al., 2015; Moriarty et al., 2019).

The time span during which MPB attacked stands may exhibit increased fire behaviour is also greater than previously expected. As has been noted regarding fine fuel loading, while individual trees may experience increased ignitability and capacity for sustained ignition for up to five years as part of the transition from green to early grey attack, stand flammability due to red attack stage effects may significantly exceed that due to variation in attack and individual tree death (Hoffman et al., 2015; Moriarty et al., 2019; Page et al., 2012). Following transition to grey attack stage and the corresponding loss of the dry canopy fuels most commonly considered in MPB attack stands, deviations from predicted fire behaviour have been observed 16 years after attack with increased likelihood of ignition and spread, and increased intensity (Lynch et al., 2006; Moriarty et al., 2019). Intensity and success of beetle attack also plays a major role in dictating both the potential fire behaviour and duration of effects (Hoffman et al., 2015). In this light MPB affected stands behave in a manner dissimilar to unaffected pine stands and require research on treatments that may assist in reducing fuel flammability through increasing fuel moisture content and reducing intensity through increased fuel moisture content and reduced fuel load.

Fuels

Forest fire occurrence and intensity are dependent on three primary drivers: weather, topography, and fuels (Agee, 1996). Each of these drivers plays a unique role in influencing fire, and each also interacts with the others to create unique conditions. While topography is an important part of the fire triangle, it does not change over most time scales involved in fire research, and so is considered as fixed for a particular area (Schroeder & Buck, 1970). Weather by comparison, may change frequently and in many ways drives fire behaviour through creation or removal of conditions facilitating ignition and spread. However, as weather is not controllable, fire managers must work with fuels to affect change in fire occurrence and intensity. While some fuel treatments have been found to reduce tree mortality and regime shifts of particularly intense fires in fire adapted forests there remains much work to be done (Waltz et al., 2014).

Fuel in respect to wildfire is defined as any organic flammable materials present in the forest that may be consumed during a fire. These flammable materials may be specifically classified in relation to their size (size classes ranging from smallest to largest) or position and orientation (surface fuels, canopy fuels) to examine specific effects fuel-fire relationships or as groups to examine effects as a whole. The availability and behaviour of these fuels depends on fuel load, structure, and moisture content.

Fuel moisture content is one of the primary factors controlling flammability and availability of fuels. It affects the energy required to raise a fuel to combustion temperature through conduction and evaporative cooling as well as displacing oxygen away from fuel necessitating higher intensity longer duration flame contact to initiate combustion and spread. High fuel moisture may be observed to directly impact fire behaviour by reducing spread, flame height and intensity, as well as increasing smouldering combustion (Kane & Prat-Guitart, 2019). It is partially for this reason that fires more commonly occur and spread in hot dry conditions, while cold and damp conditions generally do not lead to active fire behaviour. Fuel moisture is driven by weather and diurnal cycles so may shift relatively quickly and often, resulting in fuels becoming available or ceasing to be available for combustion repeatedly during the course of a single fire.

Dead woody debris such as twigs, branches and logs all gain and lose moisture from drying and wetting, however do so at differing rates due to differences in the ratio between their surface area and volume. As increased surface area relative to volume results in increased transfer of moisture, dead fuels with high proportions of surface area to volume such as fine fuels react quickly to drying or wetting, while coarse fuels with lower surface area to volume are slower to react to external influences. Similarly, exposed near surface fuels are most affected by wetting and drying, while deeper more sheltered layers are slower to respond to wetting and drying trends. Because of this, different soil horizons and size classes of fuel are seen to behave similarly and are often linked, as fine fuels and surface fuels are the most exposed, with the greatest exposure and surface area to gain and lose moisture, while larger diameter fuels and deep duff fuels are less exposed and have proportionately less surface area to transfer moisture in relation to their internal volume. These associations between woody debris and organic soil layers are discussed later in respect to their roles in the Canadian Fire Weather Index System (Van Wagner 1987).

Woody debris and forest floor fuels are categorized into size classes from 1-6 and relate to fuel diameter increasing from 0cm to >7.0cm. Most fuels consumed on flame front passage and those that primarily contribute to fire intensity are those <1.0cm (size classes 1,2) in diameter (Stocks et al., 2004). The ratio of fine and coarse fuels (<1.0cm>) also affects flame residency time, with higher percentages of fine fuels resulting in faster moving fires and higher percentages of coarse fuels resulting in increased likelihood of longer flame residency time and smouldering combustion (Graham et al., 2004; Wotton et al., 2012). For this reason, fine and coarse fuels are often examined separately as well as together.

In addition to being categorized in relation to size, fuels are also considered in terms of position. When classed in relation to position, fuels may be identified as duff fuels, surface fuels, and canopy fuels. Duff fuels include organic soils and other compacted organic materials (Graham et al., 2004), with surface layers reacting quickly to changes in weather and deeper layers reacting more slowly to drying and wetting influences. For the purposes of our research, we consider the top 2cm of organic soil to be a litter layer, while the remaining organic component is considered the duff layer. Because of this variable response to drying and wetting, lightning caused ignitions are strongly related to moisture content of the deeper duff layers due to the ability of lightning to penetrate deeply into still-dry duff layers following passage of weather events that may have also brought precipitation and made surface fuels less flammable (Wotton, 2009). This ability to reach deep, dry, protected duff layers is a feature of lightning caused ignitions that also allows lightning ignitions to “hold over” and smoulder below the surface until surface conditions are suitable, resulting in fires breaking out and spreading long after the initial ignition occurred. By contrast, human caused ignitions are often caused by low intensity, low duration events such as sparks or hot embers and frequently occur in the fine fuel surface layers where fuels dry rapidly and are receptive to these low intensity short duration ignition sources. The majority of duff fuel consumption occurs after the flame front passage as smouldering combustion, and may occur for extended periods of time from hours up to weeks (Graham et al., 2004).

The surface fuel group starts at the top layer of the organic fuel horizon and includes litter, dead and down woody material of all sizes, ground covering plants and shrubs. During flame front passage surface fuels contribute significantly to fire intensity, with most fuels consumed being <1.0cm diameter. Surface fires are a key part of fire spread and are important to supporting crown fire transition and spread (Graham et al., 2004).

Crown fuels are those fuels that reach into or are overstory canopy. These include tall shrubs, small trees, and all fuels (bark, branches, foliage, mosses/lichens) present within the overstory canopy. Where fuels span the gap between the surface fuels and the overstory canopy, they are called ladder fuels as they facilitate flame transfer from ground fires to canopy fires (Graham et al., 2004). Ladder fuels are integral to crown fires, as they reduce the gap between the crown and surface fuels, reducing the intensity of the surface fire needed to transform a surface fire into a crown fire (Van Wagner, 1977). Additionally, horizontal spacing between crowns also affects crown fires as higher density in the form of canopy bulk density (kg m^{-3}) decreasing energy required to move between fuels and increasing possibility of continuous crown fire.

To assess the quantity of fuel present in any of these fuel types or classes, fuel load (kg m^{-2}) is used to determine how much total potential energy is present in a stand in the form of combustible material. As we have already seen that fuels may be categorized by size class or position, fuel load allows a quantifiable method of determining total fuel present of a given type as well as possible effects on fire behaviour. For example, a high percentage of fine fuels (<1.0cm diameter) will predispose the area towards higher likelihood of ignition and fast burning, fast moving fires, while an area with high levels of coarse fuels (>7cm) may be less likely to ignite but burn more intensely for longer duration if ignition were to occur. This difference in rate of burning and ignition is due to surface area, as fine diameter fuels have greater surface area compared to coarse fuels (Davis & Byram, 1959).

While fuel load determines total potential energy present in a stand, fuel availability for consumption is controlled by both fuel moisture and fuel structure and orientation. Fuel structure and orientation affects the ability of flame to transfer to new fuels. With increased horizontal and vertical distance between fuels, greater energy output is required to increase temperature to ignition and fire spread rates and intensity may decline or halt. This is especially evident in ground fires when a fire may pass through a stand on the forest floor but lack sufficient energy to transition to the crown (Van Wagner, 1977). In these conditions, ladder fuels that aid transition from surface to canopy such as tall shrubs, saplings, understory trees and overstory trees with low crown base heights and hanging or dead branches and flammable bark on the stems are especially important as they reduce the physical spacing between fuels and energy required for flame transfer to the canopy. Horizontal spacing is similarly important, as natural breaks such as bare rocky ground, sparse/reduced fuels, or water, or man-made fuel breaks such as roads, green fire resistant fields, or cleared trails may affect a fire's spread by limiting the availability of fuel and requiring significantly greater energy to transfer fire over the greater distance between susceptible fuels (Cheney & Sullivan, 2008; Pearce & Anderson, 2008). In addition to creating or bridging gaps for fire spread, fuel structure also plays a role in influencing moisture content of fuels through altering shading and sheltering of fuels from drying or wetting events.

Fuel's role in fire is factored for in equations such as Byram's fireline intensity equation (Figure 1) which utilizes fuel as a factor in calculating fireline intensity, the primary metric by which fire energy output is quantified. Fireline intensity shown in Equation 1 and expressed in kilowatts per meter (kW m^{-1}) is governed by three inputs. H is the net low heat of combustion expressed as kJ kg^{-1}, and frequently used as a constant due to low variability between fuels. W is the amount of fuel consumed or available per unit area of active flame front (kg m^{-2}), and r is linear rate of spread (m s^{-1}). As w represents either fuel consumed or available fuel, changes to fuel availability has a direct and established effect on flame front energy output (Alexander & Cruz, 2012, 2019; Davis & Byram, 1959). Though this paper does not go so far as to predict variation in fireline intensity from differing fuel availability between treatments, understanding the effect of changes to fuel availability is necessary in understanding the effect of otherwise apparently unimportant changes to fuel moisture content and loading.

$$I = H \times w \times r \tag{1}$$

Under natural conditions both fuel load and structure are relatively stable in that they do not usually change significantly over the short periods of time (days to weeks) that fire occurrence and intensity forecasts are able to be accurately predicted. Moreover, many forests exhibit natural tendencies towards specific fuel load ranges, structure, and moisture trends. Changes to the structure of these forests, either by natural disturbances such as intense widespread insect attack, or human disturbances such as thinning results in deviation away from standard fuel load, structure and moisture trends and therefore affect the accuracy of predicted fire behaviour. Variations in fuel load, structure, and moisture content may result in dramatically different probability of ignition and fire behaviour. Because of this forest managers seek to modify fuels to affect change in some aspect of fire behaviour (Graham et al., 2004).

Fuel Treatments

Since fuels are the only portion of the fire triangle that may be directly altered to influence fire behaviour it is a natural progression to consider fuel treatments to manage fire (Hoffman et al., 2018). Ignition probability and fire intensity are strongly dependent upon fuel load and composition. By altering fuel load and composition managers may alter a forest in such a way to promote less frequent fires, or less intense fires. Fire resistant forests are those that contain surface fuels that limit fireline intensity, fire tolerant trees (species, size, structure), and have low probability of crown fire initiation and spread (Agee, 1996). Targeting of understory and ladder species may be effective at limiting likelihood of ignition and intensity (Allen et al., 2005). Given that forests vary considerably in their characteristics, regional weather, and seasonal conditions no single treatment type is suitable for every forest and each treatment must be considered in regard to the desired outcomes (Graham et al., 1999, 2004). In this study a modified progressive strip cut harvesting technique was used to balance outcomes to reduce susceptibility to pine beetle attack while minimizing likelihood of fire occurrence and fuel load. Thinning has been previously used as a method to reduce fuel load and alter spacing of fuels (Agee et al., 2000; Finney, 2001, 2007; Graham et al., 1999, 2004; Hoffman et al., 2018; Ma et al., 2010), however strip cut harvesting is novel in that it also creates continuous clear-cut strips throughout the stand without requiring complete modification of the stand.

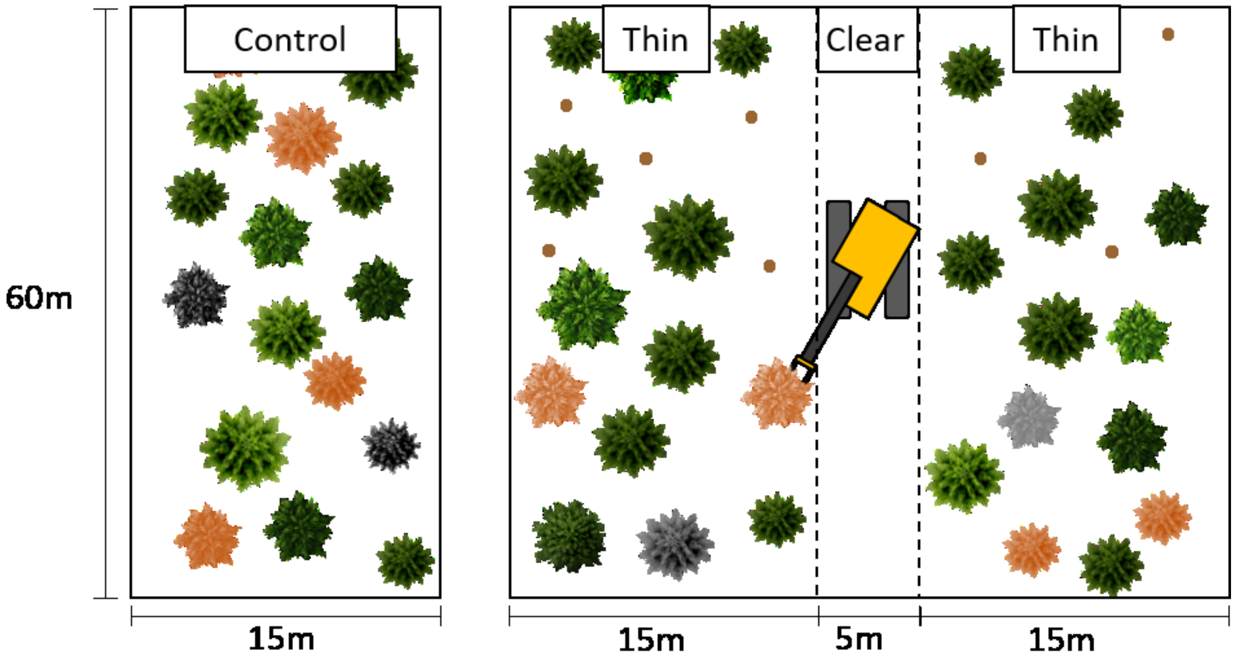

Figure 2. Control, Thin, and Clear fuel treatments. Control sites were unaltered, leaving grey and red stage standing trees, while thin treatments removed attacked, dead, or vulnerable trees. Clear treatments were harvested entirely.

Project treatments alternated 5 m wide clear-cut machine access corridors (referred to as clear treatments) with 15 m wide thinned retention strips (thin treatments) as shown in Figure 2. Treatments were laid out in a North-South orientation perpendicular to prevailing winds with cleared treatments established on the downwind side of each thinned treatment to reduce windthrow and fuel loading. Stand harvest occurred in the winter of 2014-2015 to minimize forest floor disturbance by utilizing frozen ground and snow cushioning. Equipment was also required to reverse out of stands to lessen area disturbed from turning and churning up soil. Cut trees were removed whole from the stand and processed at landing sites to minimize slash load and facilitate debris removal. The cleared treatment involved total removal of all trees within the treatment area, while thinning removed visibly attacked or vulnerable trees. Width of thinning treatments allowed equipment to reach in from adjacent cleared treatments to remove target trees without disturbing the understory or surrounding trees within the thinned treatments. All three plots were located within larger areas of similar treatments with a minimum of 25 m buffer from any change in fuels such as roads or treatment edges.

While only the first harvest was conducted at this site for our research, progressive strip cut harvesting is novel in that it allows for repeated fuels modification over time to maintain the effect of the fuel treatment on the stand. Repeated treatments are performed on a time-based rotation that divides stand rotation age by the number of repetitions to be performed before the entire stand has been harvested. Following treatments are performed on the established time-based rotation in which a new clear strip is cut into the previous thin treatment, upwind and adjacent to the previous clear strip. Following repetitions advance further through the previous thin treatments until the entire stand has been harvested and the original cleared treatment has reached a full rotation, at which time the entire process repeats from the beginning (Department of Natural Resources, 2005; Ministry of Forests, 2003). This treatment has the intended benefit of both reducing overall stand susceptibility to pine beetle outbreak as well as reducing potential for ignition and fuel load (Agee et al., 2000; Hoffman et al., 2018; Jenkins et al., 2014; Les Safranyik et al., 1974).

Fire Weather Index

Canada and many other countries utilize decision support tools to predict and quantify fire occurrence, behaviour, and difficulty of control. The prediction system used in Canada is known as the Canadian Forest Fire Danger Rating System (CFFDRS) and is composed of Fire Weather Index (FWI) and the Fire Behaviour Prediction (FBP) Subsystems. It is the Fire Weather Index System that we utilize in this paper.

The Fire Weather Index is a weather driven empirical model that predicts fire behaviour based on calculated fuel availability and wind. Four main weather inputs (temperature, relative humidity, wind, and precipitation) are used to track the increase or decrease of fuel availability to fire, as well as predicted rate of spread, and difficulty of control (de Groot, 1987; Stocks et al., 1989). Though physically sampled fuel moisture would provide the most accurate data for fuel availability in an area, it is not practical or possible to quickly acquire current and future predictions at the landscape level that Fire Weather Index predictions are usually used.

As mentioned in the fuels section, fuels in the FWI include any dead organic substance that could be present in a forest, including organic soils and woody material of any size. As moisture gain and loss is affected by surface area to volume, small diameter woody material and surface organic layers react quickly to influencing weather factors, while larger or deeper fuels react more slowly. Because of this the FWI System classes the fuels being acted on by weather into three distinct moisture codes that relate to increasing size and depth (the Fine Fuel Moisture code – FFMC; the Duff Moisture Code – DMC; and the Drought Code – DC). These codes respond to different weather factors according to their properties and are represented by unitless numeric ratings for fuel availability.

When further examined these codes may be used to assess potential effects on rate of fire spread, availability of fuel, intensity, and difficulty of control.

Fuel moisture and fuel moisture codes are relevant to our work as they are the portion of the Fire Weather Index and Canadian Forest Fire Danger Rating Index that we are best able to make comparisons to following fuel modifications. While fuels themselves will not change their rates of absorption and desorption due to the fuel treatments, changes to the sites through fuel treatments will alter fuel exposure to drying and wetting weather factors. Direct measurement through destructive sampling of organic fuels will show actual moisture content of targeted fuels and differences between treatments under identical weather conditions. As the Fire Weather Index fuel moisture codes are standardized, effect of fuel treatments would normally be expressed in the Fire Behaviour Prediction System as a new Fuel Type, however for the purpose of this study we have elected to compare differences in moisture content of fuels, and differences in moisture code for the Duff Moisture Content fuel code since treatment effects can be seen in different moisture content between treatments.

Research Questions and Hypothesis

As fuel modification has been identified as a potentially effective tool in managing both Mountain Pine Beetle and fire in lodgepole pine stands this study seeks to identify some of the effects of treatment on fuels in relation to fire, specifically:

1) Does the progressive strip cut harvesting method employed in this study affect fine and total fuel load in treated areas?
2) Does the progressive strip cut harvesting method employed in this study affect fuel moisture content in litter and duff layer fuels?

To assess these questions fine and coarse fuels (litter, duff, dead and down woody debris, and standing trees) will be measured for their contributions to fuel load. Likewise, fuel moisture samples of litter and duff organic soil layers will be destructively tested to determine moisture content.

Harvesting treatments are hypothesized to increase fine fuel loading of litter and fine woody debris as level of disturbance increases due to susceptibility of fine fuels to breakage during harvesting, resulting in increased forest floor fine fuel loading. It is believed that foliage fuel load will not be affected in thinned plots as treatments target dead or dying trees with already reduced foliage and only a small proportion of live trees meeting the harvesting criteria. Treatments requiring complete clearance and removal of trees will result in complete foliage reduction, however this reduction will be captured in total fine fuel load results. Total fine fuel load is predicted to increase with level of disturbance.

Coarse fuel loading including all classes of woody debris and duff fuel load is not anticipated to be affected by treatments as larger fuels are more manageable in machine harvesting operations and likely to be minimized by the prescribed harvesting methods. Standing trees are expected to decline in thinned treatments while the clear treatments will see a complete removal which will be captured in total treatment fuel load results. Total treatment fuel load is predicted to decline with treatment owing to removal of coarse woody fuels from the treatment areas as part of the harvesting prescription.

Fuel moisture is predicted to decline for both litter and duff fuel layers as disturbance increased due to increased wind and light penetration into the harvested areas, raising temperatures and reducing relative humidity resulting in increased drying. While the reduction in canopy interception will result in increased precipitation reaching ground fuels it is believed this will not counteract the drying influences, especially if summer conditions follow the trend of long periods of hot and dry periods with only intermittent precipitation.

Materials and Methods

Site Description

Research was conducted in the Silver Valley, Saddle Hills County of North Western Alberta (56°15'04.0"N 119°05'20.3"W), 700 m elevation. As part of the Boreal Forest Natural Region and Dry Mixedwood Natural Subregion Peace River unit, this forest type composes 12.8% (85,321 km^2) of Alberta’s surface area. It is characterized by flat topography, lodgepole pine-aspen-white spruce forests, and the warmest seasonal conditions of the boreal Natural Regions (Natural Regions Committee, 2006). The research site was stocked at 2038 ± 197 stems per hectare (control 1925 ± 247 stems per hectare, thin 2150 ±71 stems per hectare) and composed of a lodgepole pine (83%) and trembling aspen (13%) overstory with intermittent white spruce (2%) and paper birch (2%). Lodgepole pine was 47 ± 11 years, 18.2 ± 2.8 m height, and 15.6 ± 4.0 cm diameter at breast height. Trembling aspen was 53 ± 13 years, 21.2 ± 2.7 m height, and 20.5 ± 5.2 cm diameter at breast height.

Stands were attacked during the 2007-2011 Alberta outbreak and experienced low to moderate levels of infestation (Cooke & Carroll, 2017; Nealis & Cooke, 2014b). During the 2015 sampling some green attack pines with fresh pitch tubes and larvae visible in galleries under the bark were observed in control sites, however by 2016 these trees were deceased and no further active attack was observed.

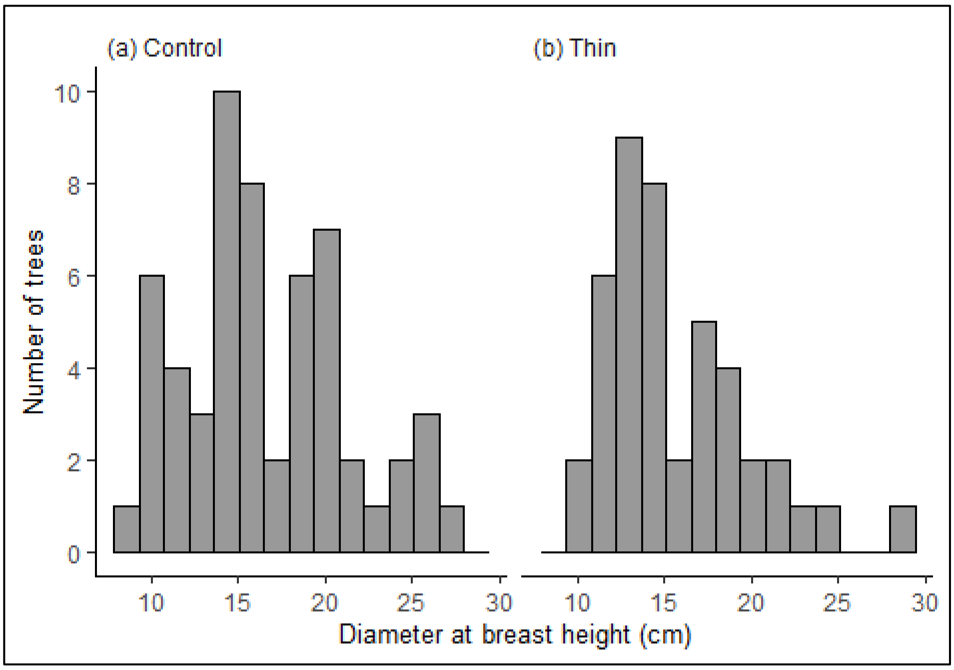

Figure 3. Number of trees at given diameter at breast height (DBH). Thinning methods skewed stand DBH downwards.

2016 site weather data was gathered from Alberta Agriculture and Forestry Savanna AGCM weather station while historical climate normal weather data for Dry Mixedwood Natural Subregion (1961-1990) was gathered from the Natural Regions and Subregions of Alberta report by the Government of Alberta (2006). A comparison between observed site data and climate normal data is found in Table 1. Comparison of site actual weather conditions and Alberta Dry Mixedwood Natural Subregion Climate Normals (Natural Regions Committee, 2006).

Table 1. Comparison of site actual weather conditions and Alberta Dry Mixedwood Natural Subregion Climate Normals (Natural Regions Committee, 2006).

Month	Site Temperature (°C, mean ± SD)	Dry Mixedwood Temperature (°C, mean ± SD)	Site Total Precipitation (mm)	Dry Mixedwood Total Precipitation (mm, mean ± SD)
May	10.4 ± 6.4	10 ± 0.5	58.1	41.9 ± 6.7
June	15.1 ± 4.7	14 ± 0.5	67.6	74.9 ± 13.6
July	16.2 ± 4.3	15.9 ± 0.5	84.8	80.4 ± 14.2
August	15.3 ± 4.7	14.7 ± 0.4	72.6	63.7 ± 6.8
September	9.8 ± 4.9	9.4 ± 0.4	47.3	42.8 ± 6.4
October	-1.3 ± 2.5	3.8 ± 0.9	60.4	23.1 ± 4.4

Following selection the overall project area was divided into control and treatment blocks with site development was performed in the winter of 2014-2015 (Figure 2, Figure 4). Control blocks were left unmodified representing natural fuels while treatment blocks were laid out in a modified progressive strip cut harvesting pattern with the block divided into alternating parallel north-south oriented 15 m and 5 m wide strips (Figure 2). The 5 m wide strips were completely cleared of standing trees to allow equipment access into the stands. The 15 m wide strips were selectively thinned by feller bunchers reaching in from the cleared corridors to remove visibly attacked trees. Treatment was performed during winter months and required equipment to reverse rather than turn in the stand as well as removing the whole tree to be processed at a landing site outside of the stand. Winter harvest reduced impact to the stand by using the cushioning effect of snow and tougher frozen ground to limit damage to forest floor plants and soils. Controlling harvesting practices by requiring equipment to reverse out of harvest corridors rather than turn around and removal of whole trees for processing at landing sites rather than in-stand further decreased unintended stand modification, as they limited ground disturbance and reduced slash deposition in the stands. The narrow machine access corridors and wide retention strips reduced risk of wind penetration and windthrow in stands. Stand layout was also oriented perpendicular to prevailing winds to further aid in reduction of windthrow. As the retention strips are three times wider than the machine corridors, this allows for a progressive strip cut method of harvesting wherein the stand may be repeatedly harvested to maintain fuel breaks and treatments without altering the entire stand simultaneously. Disturbance to the thinned stands is minimized as harvesting equipment may reach up to half the width of the retention strip from an access corridor to cut and remove targeted trees. In commercial operations harvest interval is determined by dividing stand rotation age by number of cleared strips to be taken, with cuts progressing into the prevailing winds to reduce potential wind throw (Department of Natural Resources, 2005; Ministry of Forests, 2003).

The project's research sites were selected to include two thinned retention strips (15 m x 60 m), two cleared machine corridors (5 m x 60 m) and two control areas of natural forest with no treatments (15 m x 60 m). To account for edge effect thinned and clear treatments were bordered by a minimum 25 m buffer on all sides of alternating retention strips and machine corridors, while the control had a buffer of at least 25 m of similar untreated fuels. Specific site locations were chosen based on the site prescription of dominant lodgepole pine overstory, north-south corridor alignment, 15 m – 5 m strip spacing, and suitable buffer strips.

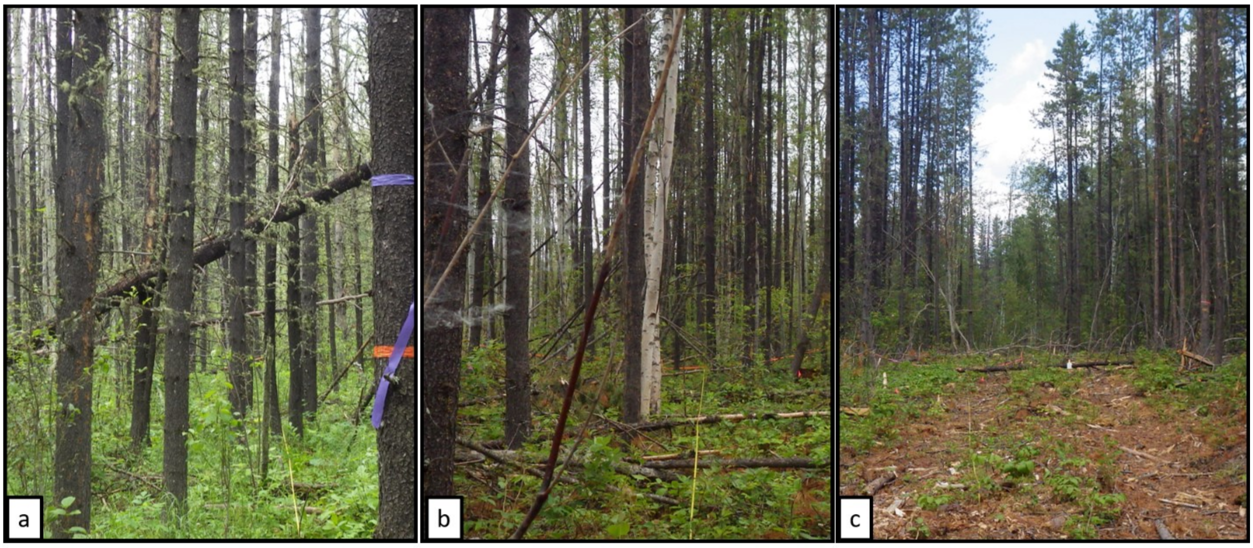

Figure 4. Control (a), Thin (b), and Clear (c) treatments demonstrating effect of harvesting on fuel load and spacing.

Fire Weather Index

A method of translating effect of fuel treatments to likelihood of ignition and intensity is to utilize the Canadian Forest Fire Danger Rating System (CFFDRS) and it's subsystems, the Fire Weather Index (FWI) and Fire Behaviour Prediction System (FBP). While the system as a whole is used to determine risk of fire and anticipated behaviour, the Fire Weather Index is most relevant to our work as it predicts fuel moisture content and availability from weather inputs in the form of fuel moisture codes, while our work assesses the impact of fuel treatments on fuel moisture content (Merrill & Alexander, 2003; Stocks et al., 1989; Van Wagner et al., 1992).

At the heart of the FWI are the fuel moisture codes, numeric unitless indicators of potential fire behaviour in their respective class of fuel, driven by wind, temperature, precipitation and relative humidity (Van Wagner et al., 1992). The moisture codes are integral to the FWI and larger CFFDRS because while fuels may be physically present in a forest they may not be available to fire due to moisture content exceeding the fire's ability to dry and ignite the fuel. The FWI tracks fuel availability and some of the effects of this varying availability on fire behaviour including flammability of related size classes and depths of fuel, likelihood of specific behaviour and indicators of period specific or seasonal trends (de Groot, 1987; Van Wagner, 1987; Van Wagner et al., 1992).

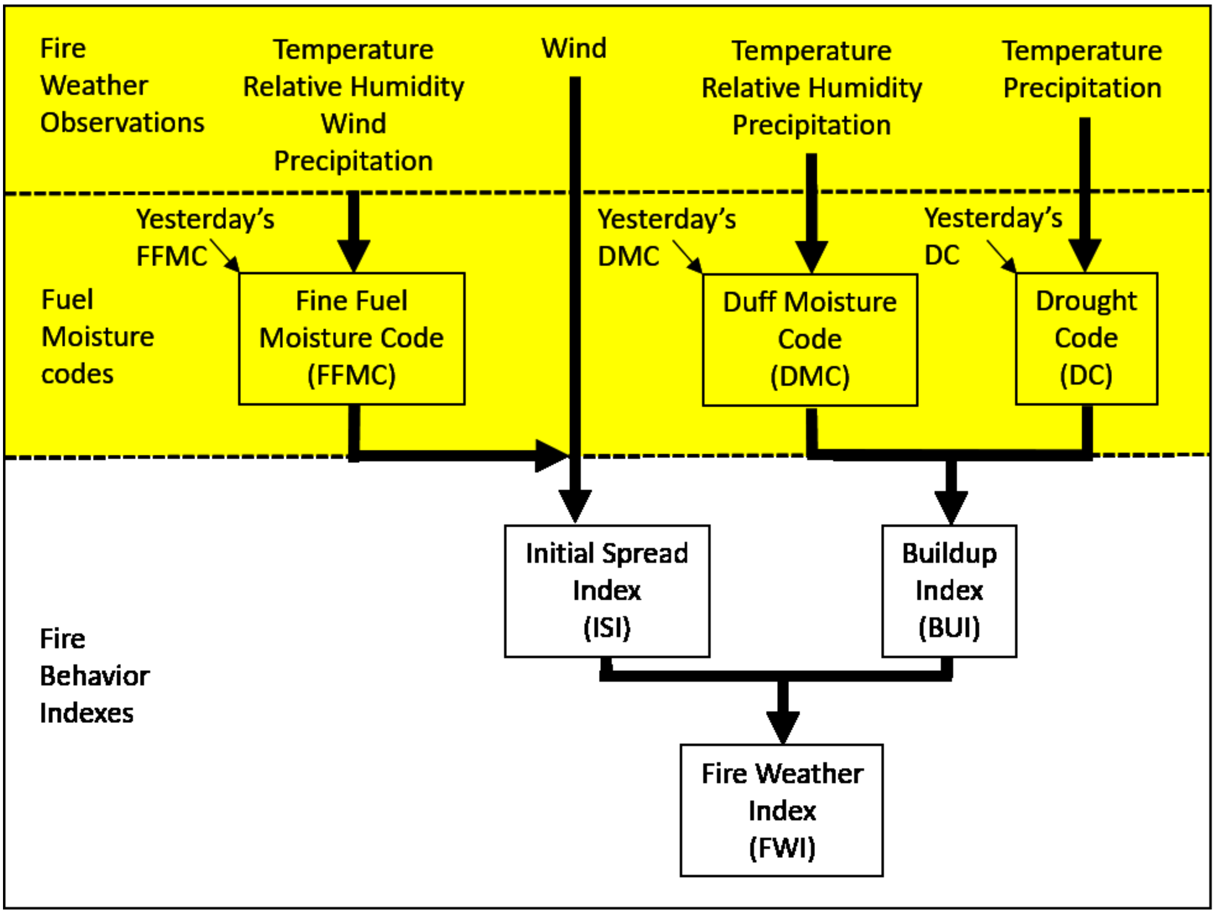

Figure 5. The Fire Weather Index inputs, structure, and outputs. Weather observations combined with an areas previous code value are used to calculate current values for an area. Yellow highlighted area is primary focus of fuel moisture related work. Adapted from Lawson and Armitage (2008).

As previously mentioned the FWI has three moisture codes corresponding to three classes of fuels, the Fine Fuel Moisture Code FFMC), Duff Moisture Code (DMC), and Drought Code (DC) (Figure 5).

The Fine Fuel Moisture Code is usually the first moisture code discussed in the FWI system and represents fine woody fuels <1.0 cm in diameter and fine organic surface soils such as needle litter to depth of 2 cm. Precipitation, temperature, relative humidity and wind speed all contribute to increase or decrease the FFMC numeric moisture content. Representative of both an exposed surface layer and fuels with high surface area to volume ratios less than 1.0 cm diameter, the FFMC responds quickly to wetting and drying, taking 2/3 of a day to lose 2/3 of its moisture content, a process known as timelag. In a standard pine forest fuel type a typical fuel load is approximately 0.25-0.5 kg m^{-2}. The FFMC represents flammability of fine fuels, likelihood of ignition, and possibility of fast flashy fires in light fuels (de Groot, 1987; Lawson & Armitage, 2008). Fine fuel moisture content was not converted to FFMC in this paper as our sampling method wasn't suited to conversion to FFMC.

The Duff Moisture Code is the second fuel encountered in the FWI system and is composed of organic soil approximately 2 - 10 cm in depth and moderately sized surface fuels 1.0 - 7.0 cm. It is composed of semi-decomposed organics and may be used to predict medium-sized woody debris flammability. Due to its nature as a sheltered sub-surface and moderate sized fuel the DMC does not react to wind, however is still affected by precipitation, temperature and relative humidity. Being somewhat sheltered the DMC has a timelag of 12 days to respond to changes in weather conditions. The DMC has a weight of approximately 5kg m^{-2}. Owing to the sheltered characteristics of the DMC, it indicates the likelihood of moderate intensity fires consuming both moderate duff layers and medium downed woody debris. This same sheltering characteristic also plays a role in ignition from lightning strikes where the high intensity penetrating strike may reach sheltered fuel inside tree stems or underground and cause it to ignite even when surface fuels are not receptive due to precipitation accompanying the storm. In some cases, these ignitions may hold over for days to weeks following the strike and only appear once surface conditions have dried sufficiently to allow spread. A DMC greater than 20 is considered the lower threshold for successful lightning ignitions in DMC associated fuels (de Groot, 1987; Wotton et al., 2005). Duff fuel moisture was converted to DMC in this paper.

The Drought Code is the last and deepest of the fuels encountered in the FWI system. Consisting of decomposed homogenous organic soil, it extends from the base of the DMC layer to mineral soil approximately 10 – 20 cm and also represents coarse woody debris >7.0 cm. Some shallow fuels may not have a representative DC layer. As a deep organic layer, the DC reacts slowly to changes with a timelag of 52 days and is only influenced by precipitation, relative humidity, and temperature. The DC comprises the bulk of the fuel load in the standardized pine fuel model with a weight of 25-44 kg

m^{-2}. Deep-burning difficult to control fires and high levels of fuel consumption are associated with high DC scores (de Groot, 1987; Government of Alberta, 2016; Lawson & Armitage, 2008; Stocks et al., 1989; Van Wagner et al., 1992).

FWI fuel moisture codes are based on data from a "standard" fuel type most closely resembling a lodgepole pine or jack pine stand. Because of this FWI moisture codes are not meant to represent exact fuel availability or behaviour in a specific location for every forest type but rather a standardized and comparable prediction system across large areas of dissimilar fuels (de Groot, 1987; Van Wagner, 1987). This results in discrepancies between true fuel availability and FWI predicted fuel availability. Because the Fire Weather Index does not provide fuel specific availability predictions, the Fire Behaviour Prediction system, the second subsystem within the Canadian Forest Fire Danger Rating system, must account for fuel specific variations to predict specific quantifiable and observable fire behaviours for a specific fuel type (such as rate of spread, fuel consumption, head fire intensity, fire type, spread rates, speeds, area/growth, length-breadth ratio). This results in some a somewhat difficult challenge, as the Fuel Moisture Codes within the Fire Weather Index are used to represent fuel moisture for a given fuel diameter class in a specific area but are not responsive to different forest type specific variations in wetting and drying which in reality do affect them. Instead, the Fire Behaviour Prediction System fuel types account for those fuel specific differences in moisture content in their outputs, though without explicitly acknowledging doing so. Because of this and the limited scope of this paper, there must be an understanding that while the effects of treatments on fuel moisture content here are shown and discussed in relation to fuel moisture content and Fuel Moisture Codes for clarity and simplicity, under the full Canadian Forest Fire Danger Rating System effects of treatments would not directly affect the moisture codes but would instead be expressed within the Fire Behaviour Prediction system as a new or modified Fuel Type.

Soil Moisture Sampling

Soil moisture sampling was performed from May through September 2016. Each plot contained ten sampling points established using stratified randomization, and five of these points were sampled at random on each sampling day.

Samples were gathered daily between 1 and 5 pm to minimize variation in site conditions between samples and concentrate sampling during peak burning conditions (Lawson & Armitage, 2008; Van

Wagner et al., 1992; Whitehead et al., 2008). There were 21 sampling days in 2016 with nineteen of the twenty-one sampling days occurring in June, July, and August. The sampling methodology was based on a modified version of Lawson and Dalrymple's (1996) ground truthing system. A tubular soil coring tool was used to cut a core down to mineral soil at a suitable spot within 0.5 m of the marked sampling point. The core was then quickly separated into the litter and duff layers corresponding closely to the FFMC and DMC layers and placed into heavy duty resealable plastic bags, sealed, and transported back to the field house for weighing. This sampling process was repeated daily for each replicate for up to 8 days at a time before returning to Edmonton. Once back at the lab the samples were transferred to tins and dried in the oven for 24 hours at 100 °C. After the drying cycle was complete samples were removed in small batches and weighed to obtain dry weight.

Classifying characteristics for each soil layer were established to ensure repeated accurate separation of the soil samples at their correct point. As shown in Figure 6, Litter was defined as forest floor surface fuels excluding live plants and fuels less than 1 cm diameter to a maximum depth of 2 cm (de Groot, 1987). Additionally, litter was defined as "freshly cast or slightly decomposed organic materials" (Merrill & Alexander, 2003) and so in areas with thinner litter layers was still distinguishable from the more homogenous heavily decomposed duff. In areas with a moss layer present, the litter-duff separation zone was defined by the commonly found transition between green live or uncompacted moss and the easily identified and separated wafer-like layer of dead moss defined by Merrill and Alexander (2003) and the Alberta Wildlands Fuels Inventory Program Field Sampling Manual (Government of Alberta, 2016) as the beginning of the duff layer. Duff was defined as the remaining organic soil below the litter layer extending to but not including mineral soil. The duff layer fell completely within the Duff Moisture Code range for depth (2-10 cm) (de Groot, 1987) and was seldom more than 7 cm thick. It was ultimately found that the methodology for determining the litter layer resulted in excessively large samples for the litter layer and was not able to be converted to FFMC.

Figure 6. A standard site soil core. Litter layer with fine litter and loose surface moss (left), Duff layer with characteristic wafer-like semi-decomposed organic transition on top and dark completely decomposed organic on bottom (middle), and Mineral layer (right).

Fuel Load and Structure

Fuel load, structure and composition was assessed mid-summer of 2015 and 2016. Fuel load was assessed using the Alberta Wildland Fuels Inventory Program Field Sampling Manual protocols (Government of Alberta, 2016) with the assistance of Agriculture and Forestry sampling crews. The only variation in sampling methods from the manual was elimination of two perpendicular transects due to the treatment plots being too narrow to accommodate the 50 m perpendicular transects. The inventory included soil sampling and classification, dead and down woody materials fuel load assessments, shrub inventory, ground cover inventory, and small and large tree sampling.

Calculations and Data Analysis

Data manipulation and analysis was performed using the R project for statistical computing (R Core Team, 2013). Weather data was acquired from Alberta Climate information Services, Savanna AGCM Station for 2016 (Government of Alberta Climate Information Service, 2019). Predicted DMC fire weather indices were calculated from Savanna AGCM Weather Station readings using the CFFDRS R package (Wang et al., 2017). For the purpose of calculating fire weather indices, if a whole day of data or more was missing, the gaps in the data were filled by interpolating the most recent preceding and following data inversely weighted by time. Start-up value for DMC FWI calculations were set based on Turner and Lawson (1978), where calculations began on the third snow-free day of the year based on satellite imagery. Starting value for DMC was 6.

Moisture content from soil moisture cores was calculated in Equation 2.

$$mc = \frac{m_w - m_d}{m_d} \times 100 \tag{2}$$

Where m_w is wet mass and m_d is dry mass. Mass is in grams.

To determine the difference in effective duff moisture between treatments, DMC was calculated both from weather station data as per the FWI System as well as from duff moisture samples taken on the site. The standard transformation from measured duff moisture to DMC was used.

$$DMC = \mathrm{Ln}(mc - 20) \times -43.43 + 244.72 \tag{3}$$

Where mc is gravimetric duff moisture content as derived from Equation 2 soil moisture cores (Lawson et al., 1997; Wotton & Beverly, 2007; Wotton et al., 2005).

Litter and duff loading was calculated using Alberta Wildland Fuel Sampling Manual (2015) calculations where bulk density was calculated by dividing oven dry weight by average transect volume, and fuel load was calculated by multiplying bulk density by average soil depth per plot.

Dead and down woody debris calculations for fine (Equation 5) and coarse (Equation 6) woody debris were also drawn from the Alberta Wildland Fuel Sampling Manual, with additional multiplier coefficients drawn from Nalder et al (1999) for woody debris classes 1-5 and Bessie and Johnson (1995) for sound and rotten woody debris class 6 (Table 2. Multiplier coefficients for fine and coarse woody).

Fine woody debris fuel load was calculated in Equation 5 for fine woody debris size classes 1-5. Each size class was calculated separately and later combined.

$$W_{FWD} = \frac{(n * c)}{L} * \left[\left(S_1 * M_{Spp1}\right) + \left(S_2 * M_{Spp2}\right)\right] \tag{4}$$

Where W is fuel load (kg m^{-2}), n is intercepts of targeted size class over length of transect, c is a correction factor for slope, L is transect length (m), S is percent species composition of site, and M is the species specific multiplier coefficient drawn from Table 2. Multiplier coefficients for fine and coarse woody .

In addition to being calculated as part of total fuel load, fine fuels (size class 1,2; 0 - 1.0 cm) were assessed independently from total fuel load, as the majority of fuels consumed in the flame front are those <1 cm (Stocks et al., 2004). These fuels include forest floor litter, fine woody debris, bark, twigs, and needles (de Groot et al., 2004) and make up the majority of fuels consumed in front passage (Stocks, 1987, 1989; Stocks et al., 2004).

Coarse woody debris fuel load was calculated in Equation 6 for size class 6. Coarse woody debris was categorized as sound or rotten, and separate calculations were performed for each. Within their decay type, debris was further grouped by species to apply the appropriate multiplier coefficient.

$$W_{CWD} = \frac{c}{L} * [(\sum diameter.sp1^2 \ * M_{SPP1}) + (\sum diameter.sp2^2 * M_{SPP2}) + \cdots] \qquad (5)$$

Where *W* is fuel load (kg m^{-2}), *c* is a correction factor for slope, *L* is transect length (m), *diameter.sp* is grouped by species diameters of downed debris, and *M* is the species specific multiplier coefficient drawn from Table 2. Multiplier coefficients for fine and coarse woody .

Table 2. Multiplier coefficients for fine and coarse woody debris.

Fuel Type	Species	Multiplier Value for Size Class							Source
		I	II	III	IV	V	VI Sound	VI Rotten	
Fine woody debris	*Pinus contorta*	0.073	0.319	1.98	9.48	19.5	NA	NA	(Nalder et al., 1999)
Fine woody debris	*Populus tremuloides*	0.06	0.32	1.63	7.51	16.4	NA	NA	(Nalder et al., 1999)
Fine woody debris	*Betula papyrifera**	0.06	0.32	1.63	7.51	16.4	NA	NA	(Nalder et al., 1999)
Coarse woody debris	*Pinus contorta*	NA	NA	NA	NA	NA	0.5552	0.3824†	(Bessie & Johnson, 1995)
Coarse woody debris	*Populus tremuloides*	NA	NA	NA	NA	NA	0.5305	0.3824†	(Bessie & Johnson, 1995)

Coarse woody debris	*Betula papyrifera*	NA	NA	NA	NA	NA	0.5256	0.3824†	(Bessie & Johnson, 1995)
Coarse woody debris	*Salix* spp	NA	NA	NA	NA	NA	0.5305 ‡	0.3824†	(Bessie & Johnson, 1995)

*No multipliers available for *Betula papyrifera* fine woody debris so *Populus tremuloides* multipliers were used. There was only one instance of *Betula papyrifera* so the effect is limited.

† Class VI Rotten for all species uses an “Other” category composed of the mean of pine, spruce, fir, and aspen were used as recommended by Bessie and Johnson (1995).

‡ Class VI Sound for Willow is the mean of *Salix spp., Shepherdia canadensis, Potentilla fructicosa, Rosa spp., and Alnus tenuifolia.*

Large tree fuel load data was calculated using Alberta Wildland Fuels Sampling Manual (2015) calculations (Equation 7) in addition to fuel specific allometric equations (Bond-Lamberty et al., 2002; Lambert et al., 2005).

$$Y_{wood} = \beta_{wood1} D^{\beta wood2} H^{\beta wood3} + e_{wood}$$

$$Y_{bark} = \beta_{bark1} D^{\beta bark2} H^{\beta bark3} + e_{bark}$$

$$Y_{stem} = \hat{\mathrm{Y}}_{wood} + \hat{\mathrm{Y}}_{bark} + \mathrm{e}_{stem}$$

$$Y_{foliage} = \beta_{foliage1} D^{\beta foliage2} H^{\beta foliage3} + e_{foliage} \tag{6}$$

$$Y_{branches} = \beta_{branches1} D^{\beta branches2} H^{\beta branches3} + e_{branches}$$

$$Y_{crown} = \hat{\mathrm{Y}}_{foliage} + \hat{\mathrm{Y}}_{branches} + \mathrm{e}_{crown}$$

$$Y_{total} = \hat{\mathrm{Y}}_{wood} + \hat{\mathrm{Y}}_{bark} + \hat{\mathrm{Y}}_{foliage} + \hat{\mathrm{Y}}_{branches} + \mathrm{e}_{total}$$

Allometric equations were performed for each sampled tree and are dependent on species, status (live/dead), dbh, and height. In Equation 7, Y_i is the calculated dry mass of the relevant portion (*i)* of a single tree. β_{jk} is a model parameter in which *j* is a coefficient estimate for wood, bark, foliage or branches, and *k* is coefficient estimate 1, 2, or 3. *D* is diameter at breast height (centimetres); *H* is height (meters); and e_i is the error term. $\hat{Y}$ is the resulting calculated value for Y_i. Stem mass is determined by combining wood, bark, branch mass, and the error term while crown mass is determined by combining branch mass, foliage mass, and the error term. Total mass is the addition of all component (Ŷ) masses.

Table 3. Multiplier values for allometric fuel load calculations (Lambert et al., 2005).

Species	**Parameter**	**Estimate**	**Parameter**	**Estimate**	**Parameter**	**Estimate**
Lodgepole Pine	b_{wood1}	0.0202	b_{wood2}	1.7179	b_{wood3}	1.2078
	b_{bark1}	0.0099	b_{bark2}	1.6049	b_{bark3}	0.7456
	$b_{\mathrm{branches1}}$	0.044	$b_{\mathrm{branches2}}$	3.719	$b_{\mathrm{branches3}}$	2.0399
	b_{foliage1}	0.0785	b_{foliage2}	2.5377	b_{foliage3}	1.1213
Trembling Aspen	b_{wood1}	0.0142	b_{wood2}	1.9389	b_{wood3}	1.0572
	b_{bark1}	0.0063	b_{bark2}	2.0819	b_{bark3}	0.6617
	$b_{\mathrm{branches1}}$	0.0137	$b_{\mathrm{branches2}}$	2.927	$b_{\mathrm{branches3}}$	0.6221
	b_{foliage1}	0.027	b_{foliage2}	1.6183	b_{foliage3}	-
Paper Birch	b_{wood1}	0.0338	b_{wood2}	2.0702	b_{wood3}	0.6876
	b_{bark1}	0.008	b_{bark2}	1.9754	b_{bark3}	0.6659
	$b_{\mathrm{branches1}}$	0.0257	$b_{\mathrm{branches2}}$	3.1754	$b_{\mathrm{branches3}}$	0.9417
	b_{foliage1}	0.1415	b_{foliage2}	2.3074	b_{foliage3}	1.1189
White Spruce	b_{wood1}	0.0265	b_{wood2}	1.7952	b_{wood3}	0.9733
	b_{bark1}	0.0124	b_{bark2}	1.6962	b_{bark3}	0.6489
	$b_{\mathrm{branches1}}$	0.0325	$b_{\mathrm{branches2}}$	2.8573	$b_{\mathrm{branches3}}$	-0.9127
	b_{foliage1}	0.202	b_{foliage2}	2.3802	b_{foliage3}	-1.1103

Total fine fuel load was a combination of fuel loads from litter, dead and down woody debris classes 1 and 2, and foliage. This was calculated to assess total fuel available and likely to burn during flaming front passage.

To assess the effect of the three treatments on DMC, one-way analysis of Variance (ANOVA), blocked by day was performed followed by post-hoc tests. Fuel load was examined in a similar manner however was not blocked by day. Prior to running ANOVAs data were examined for normality visually and using the Shapiro-Wilk test, as well as for homogeneity of variances visually and with Bartlett's test. For normally distributed data, a regular one-way ANOVA was performed followed by Tukey's HSD test to determine how treatments differed from each other. Duff fuel load data were normally distributed but had unequal variances, so they were log-transformed to attain equal variances. Since the litter fuel load data were not normal or homoscedastic, they were log-transformed to achieve normality, and Welch's ANOVA was used to deal with inequality of variances. As the Welch's ANOVA found significant difference, multiple comparisons were performed using Holm–Bonferroni method. Crown fuel load was absent in the clear treatment due complete harvesting, and therefore was only compared between control and thin treatments using a Student's t-test, after the data were found to be normal with equal variances.

Results

Fine Fuel Load

Fine fuels (<1.0 cm diameter) comprise most of the fuels consumed in flame front passage and contribute significantly to fire intensity. Because of this, fine fuel loading was examined independently (Figure 7) before being included in total biomass (Figure 8). Figure 7a to c show the effect of treatment on the constituent in-stand fine fuel components, while Figure 7d shows the effect on the total of these components.

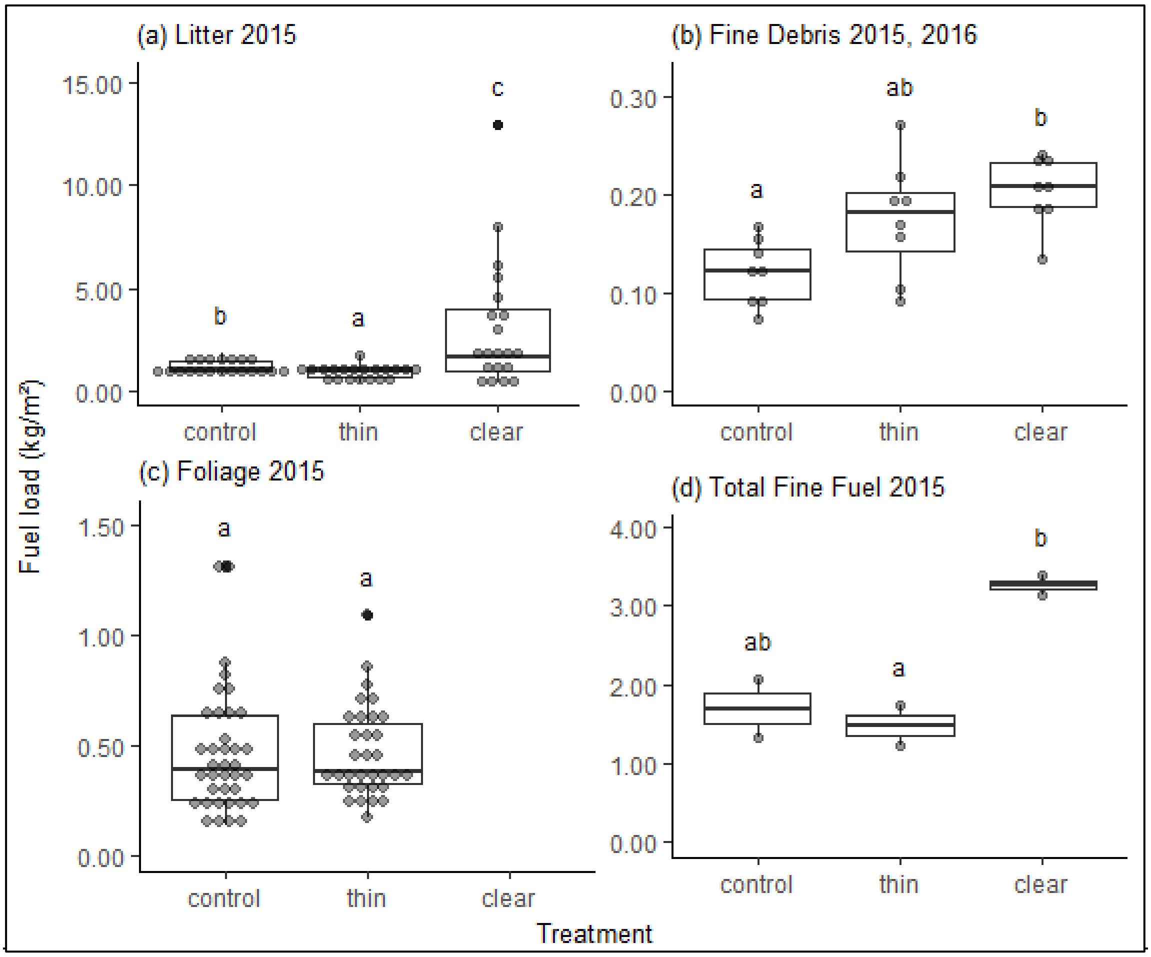

Figure 7. Fine fuel load representing fuels available during flame front passage: organic surface layer fuel load 2015 (a), fine woody debris size classes 1 and 2 (0-1.0 cm diameter) 2015 and 2016 (b), standing tree foliage 2015 (c), and total site fine fuel load 2015 (d) composed of combined site litter, fine woody debris size classes 1 and 2, and foliage from the 2015 sampling period. Fine woody debris was sampled for 2015 and 2016, with no significant effect of year on fuel load, and only data from 2015 was used to create total fine fuel load for 2015. Grey dots represent individual samples. Note that y-axis scales vary between graphs.

Litter fuel load was significantly affected by treatment (p=0.003, Figure 7a). Fuel load was found to be highest in the clear treatment (3.059 ± 0.180 kg m^{-2}), lower in the control treatment (1.180 ± 0.368 kg m^{-2}), and lowest in the thin treatment (0.887 ± 0.351 kg m^{-2}). This is partially consistent with our hypothesis that disturbance would increase fuel loading, as the clear treatment has a mean fuel load roughly three times that of the control and thin treatments, as well as dramatically wider error bars indicating disturbance related heterogeneity that can be expected from harvesting operations. There is also some conflict with our hypothesis as the partially harvested, limited disturbance treatment demonstrated lower fuel loading than the undisturbed control site.

Fine woody debris class 1 and 2 (0-1.0 cm) fuel load was also affected by treatment (p=0.003, Figure 7b). Fine woody debris was measured in both 2015 and 2016 from all treatments so comparison by year was also performed, however was not found to have an effect. While increasing level of disturbance did have an effect on fuel loading, with clear (0.204 ± 0.036 kg m^{-2}) and control treatments (0.120 ± 0.033 kg m^{-2}) being significantly different from each other, the thinned treatment (0.175 ± 0.060 kg m^{-2}) occupied the middle ground and was not significantly different from either treatment.

Foliage fuel load (Figure 7c) was not significantly different between the two remaining treed treatments (control 0.406 ± 0.192 kg m^{-2}, thin 0.461 ± 0.075 kg m^{-2}), though there was somewhat more variation in the control treatment than the thin.

Total fine fuel load, composed of organic surface fuels, fine woody debris <1.0 cm, and standing tree foliage, was found to be significantly affected by treatment (p=0.032, Figure 7d). Interestingly, while the clear treatment had the highest fuel load (3.268 ± 0.169 kg m^{-2}), it was not significantly different from the control treatment which had the second highest fuel load (1.698 ± 0.517 kg m^{-2}). The only significant difference in fuel load between the treatments was between the clear treatment and the thin treatment (1.488 ± 0.365 kg m^{-2}), which had the lowest overall fuel load of the three treatments. This runs counter to our hypothesis that increased level of harvesting would result in a significantly increased overall fine fuel load across the treatments. Due to the differences in sampling methods between different fuel types the smallest common experimental unit present across all sampling methods was the treatment plot, so only two samples are available per treatment.

Total Site Fuel Load

Total site fuel load was significantly affected by treatment (p=0.013, Figure 8). Clear treatment had significantly lower fuel load (13.073 ± 3.826) than both control (31.097 ± 1.611 kg m^{-2}) and thin (30.126 ± 2.672 kg m^{-2}) treatments with the latter two not significantly different from each other. Total site fuel load is composed of all measured fuel load sub-categories including litter and duff organic soil layers, woody debris size classes 1-6 (0 to 7.0+ cm), and all standing tree fuel loads composed of stem, bark, branches, and foliage. Dead and down woody debris size classes 1-6 (0 to 7.0+ cm) were not discussed separately as they were sampled in both 2015 and 2016 and no effect was found on fuel load from either year or treatment (control 2.172 ± 0.836 kg m^{-2}, thin 2.995 ± 0.841 kg m^{-2}, clear 2.572 ± 0.914 kg m^{-2}). Duff fuel load was also not discussed separately as it was not significantly affected by treatment (control 6.986 ± 3.480 kg m^{-2}, thin 4.576 ± 3.526 kg m^{-2}, clear 7.184 ± 5.372 kg m^{-2}), as was standing tree fuel load (control 20.735 ± 0.674 kg m^{-2}, thin 21.650 ± 1.279 kg m^{-2}).

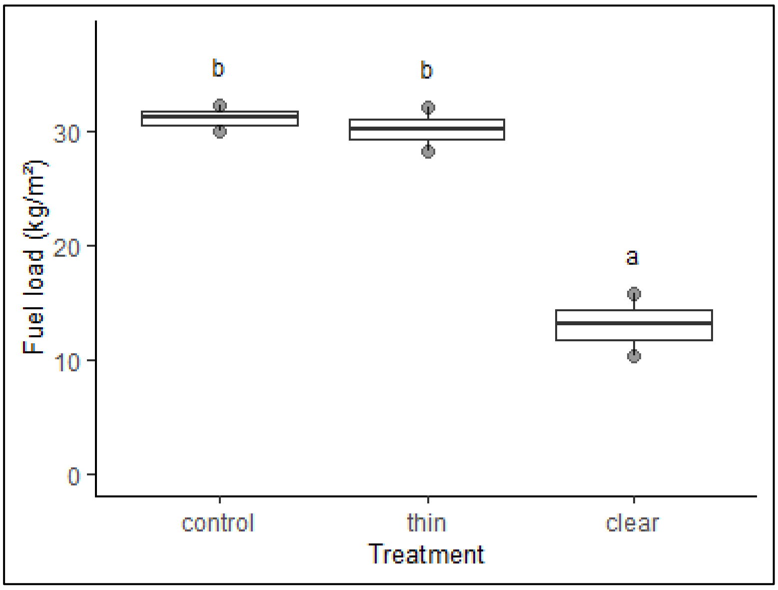

Figure 8. Total site Biomass 2015. Total site fuel load includes organic soils, dead and down woody debris size classes 1-6, and standing tree fuels. Grey dots represent individual samples.

Upper Forest Floor Moisture

Upper forest floor and fine fuel moisture was found to be significantly affected by treatment ($p < 0.001$, Figure 9). While it was expected that the control treatment (182 ± 34%) would have the highest moisture content and that there would be significant differences in moisture contents between each treatment, it was believed that moisture would decrease with increasing degree of disturbance and exposure to weather events. Instead it was found that the thin treatment (111 ± 21%) had the lowest moisture content while the clear treatment (149 ± 28%) held the middle ground, with each treatment being significantly different from the others.

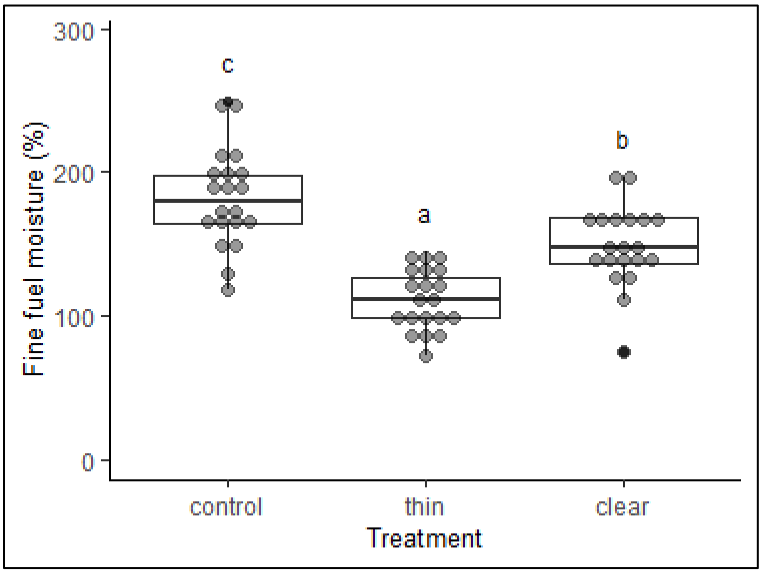

Figure 9. The effect of treatment on fine fuel moisture in 2016. Grey dots represent individual samples.

Duff Fuel Moisture and Duff Moisture Code

Duff moisture content was significantly affected by treatment (p < 0.001, Figure 10a). As blocking by day was utilized, the analysis is more sensitive to relative differences between treatments on any given day, with the effect of day accounted for separately and therefore removed from the error term. Interestingly the thin treatment (189 ± 39) again exhibited the lowest moisture content of all treatments. The control treatment (213 ± 52) was significantly wetter than thin as well as significantly drier than the clear treatment (243 ± 35).

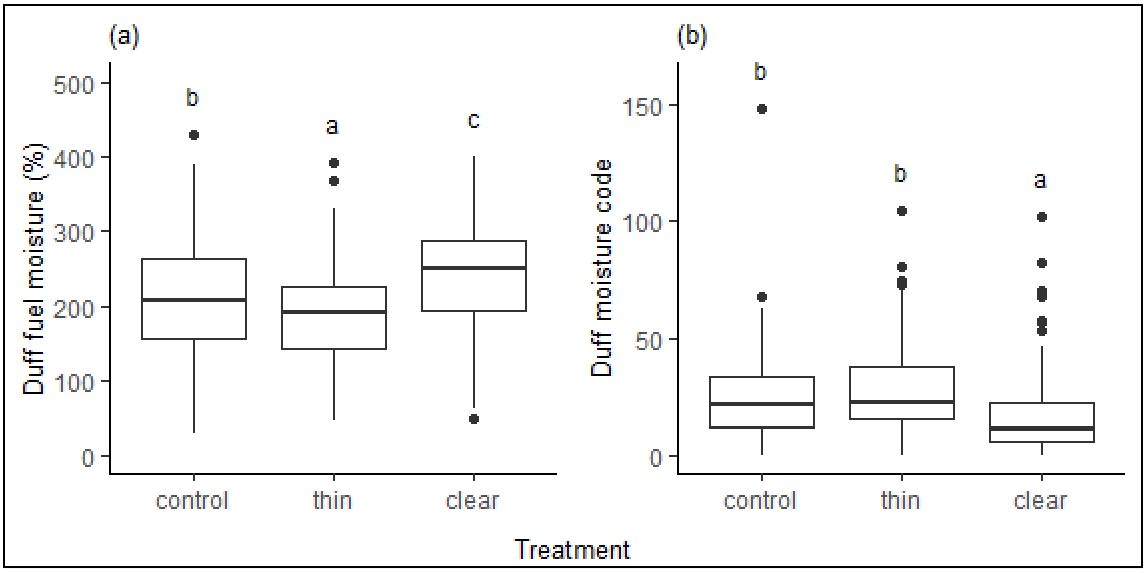

Figure 10. Duff fuel moisture (a) and duff moisture code (b) 2016, blocked by day. Individual samples not shown due to their large number.

Conversion from fuel moisture content to duff moisture code resulted in slightly changed relationships between treatments due to the non-linear nature of the transformation. Duff moisture code indices continued to be affected by treatment (p < 0.001, Figure 10b), however the clear treatment (12 ± 9) was now the only significantly different treatment, being significantly lower than both the control treatment (20 ± 12) and thin treatment (26 ± 12) which were not significantly different from each other.

Discussion

Fuel load

Litter Fuel Load

Our findings that litter fuel load (Figure 7a) was different between each treatment partially supported our hypothesis, but with some unexpected results. The initial hypothesis that harvesting would increase surface organic litter depth because of disturbance and deposition is in part borne out by significantly higher litter loading in cleared treatments. However, since litter load in thinned treatments was consistently and significantly lower than both the control and cleared treatments does cause some conflict with this hypothesis. It is suspected that the harvesting method employed in this project may have had the unforeseen effect of avoiding detectable litter loading in the thinned sites as harvesting equipment reached into thinned stands from the cleared corridors and removed targeted trees fully intact with the objective of minimizing disturbance of surface and aerial fuels. While this discrepancy between our hypothesis and findings was unexpected it also demonstrates that it is possible to perform efficient real-world mechanical harvesting operations without causing significant fuel loading.

Increased fuel loading in the clear treatment (2.6x the load of control and 3.4x thin) may be due to predicted increased disturbance from harvesting. Removal of trees from the clear treatment as well as targeted stems from the thin treatments to either side likely dislodged at least some foliage and fine branches regardless of the level of care taken to reduce in-stand fuel loading. Dislodged fuels in the clear treatments are also subject to compaction by harvesting equipment as it moved along the treatment, forcing fallen fuels into a denser mass more resembling organic surface litter layer than suspended fine woody debris layer. Given that fine fuels decompose more rapidly than larger fuels and that compression and layering may speed this decomposition, it is expected and appropriate to identify these fuels as a litter layer.

When compared to similar undisturbed forest types in other studies (Table 4) control and thin treatment litter fuel load are within normal ranges for undisturbed jack pine stands, though decidedly at the higher end (control 1.180 ± 0.368 kg m^{-2} and thin 0.887 ± 0.351 kg m^{-2} as compared to 71 year old lodgepole – spruce mix 1.31 ± 0.4 kg m^{-2} and 108 year old lodgepole – spruce mix 0.72

± .54 kg m^{-2}) (Lavoie et al., 2010). The clear treatment was far higher than other pine stands, however as a disturbed harvested site this is expected.

With Litter load comprising 60% (thin treatment) to 94% (clear treatment) of total fine fuel loading any harvesting method that can minimize increase or even decrease litter loading will have a significant effect on potential for ignition and intensity. As fine fuels <1.0 cm make up the majority of fuel consumed during flame front passage and Byram’s fireline intensity equation uses fuel as one of three factors affecting heat energy release in the fire front, any increases or decreases in litter loading is likely to show direct effects on fireline intensity (Davis & Byram, 1959; Stocks et al., 2004). That said, while fuels must be present in a stand in order to burn as quantified by fuel load measurements, fuels may not be available to burn due to position or moisture content. Because of this, any speculation on effect of treatments on fire behaviour must also involve fine fuel moisture, discussed below.

Table 4. Comparison of fuel loading between different Jack Pine and Lodgepole Pine stands in Alberta and Northwest Territories. Hirsch et al.’s data did not provide standing tree fuel load required to calculate total site fuel load, so standing tree fuel load was calculated using Hirsch et al.’s height, dbh, stem, stem density, and species data and multiplier coefficients from Lambert et al.

	(Lavoie et al., 2010)		(Hirsch et al., 1999)		Current Study		
Fuel categories	Untreated Jack Pine	Untreated Jack Pine	Untreated Lodgepole Pine	Treated Lodgepole Pine	Control	Thin	Clear
DBH (cm)	9.6	16.1	14.5	19.8	16.6	15.6	-
					2050	1675	-
Height (m)	11.6	13.8	14.2	14.3	18.3	18.7	-
Age	71	108	-	-	48	57	-
Stems per ha	6635	2 973	2825	650	1925± 247	2150 ±71	-
Litter (kg m^{-2})	1.3	0.7	0.5	0.3	1.2	0.9	3.1
Duff (kg m^{-2})	8.1	9.2	8.7	7.5	7.0	4.6	7.2
Woody debris <1.0cm (kg m^{-2})	0.1	0.1	-	-	0.1	0.2	0.2

Total woody debris (0-7cm+) (kg m^{-2})	1.7	1.0	2.2	0.4	2.2	3.0	2.6
Foliage (kg m^{-2})	-	-	1.7	0.5	0.4	0.5	-
Total site fine fuels, <3cm (kg m^{-2})	-	-	6.0	2.3	-	-	-
Total site fine fuels <1.0cm (kg m^{-2})	3.7	4.6	-	-	1.7	1.5	3.3
Total site fuel load (kg m^{-2})	28.8	39.4	29.0	15.6	31.1	30.1	13.1

Woody Debris: Dead and Down Fine Fuel

Increased fuel loading of fine woody debris in conjunction with increased level of harvesting disturbance matches our initial hypothesis that there would be an effect of harvesting on fuel loading. However as this consistent increase in loading was only observable in fine woody debris rather than in all fine fuels and in total spanned 0.08 kg m^{-2} between 0.12 kg m^{-2} and 0.20 kg m^{-2} from the lowest to highest mean loads with the thin treatment occupying the middle ground without significant difference from either the control or clear treatment, it suggests that harvesting methods were successful in controlling overall fine woody debris fuel loading.

Increased loading with increased disturbance is understandable as mechanized harvesting is expected to cause some degree of fine fuel loading. As the point-intercept method records every contact along the length of the transect it is ideally suited for detecting consistent changes in density of horizontally distributed debris, while changes to vertically piled debris may be missed even if loosely spaced, as the method registers only the highest piece of debris encountered. The rest of the vertically piled debris is accounted for as part of litter sampling, so while there may be some disagreement on where fuels would be better categorized they are at least accounted for.

By examining fine woody debris loading in conjunction with litter loading, we can see that the clear treatment experienced a consistent increase in horizontal and vertically distributed fuels (a deep, even fuel bed) while the thin treatment experienced a consistent, but limited increase in fine fuels (a shallow, but consistent horizontal fuel bed). This matches the harvesting treatment which would have dislodged or damaged fine fuels to fall in the thin treatment but would concentrate far more fuels in the cleared treatments as stems were laid down and pulled along narrow and defined access paths.

Fine woody debris fuel loading exceeded comparable findings in Lavoie et al. (2010) (by 0.05 kg m^{-2} to 0.13 kg m^{-2}).

Foliage Fuel Load

Foliage was not significantly different between treatment but the tighter error bars in the thin treatment may indicate that thinning removed the less vigorous trees without significantly altering foliage fuel load. This runs somewhat counter to our hypothesis that increased thinning would decrease foliage load.

Foliage fuel load for both control and thin treatments were similar or lower than fuel loads found in other research (Table 4). Given that foliage fuel load is known to decline following pine beetle attack (Jenkins et al., 2012), there are natural variations in foliage loading among similar species and characteristic stands especially when geographically distant, and that the compared stands from other studies were not post epidemic stands, it is not considered especially problematic that foliage fuel loading was dissimilar to other research findings.

Total Fine Fuel Load

Fine fuels are the primary fuel consumed during fire front passage and directly affect fire intensity so merit careful examination (Davis & Byram, 1959). Total fine fuel load (including woody debris <1.0 cm, surface litter, and overstory tree foliage) was not significantly different from control in either treatment. Based on this metric the harvesting treatment removing targeted standing trees without increasing total fuel loading may be considered successful, as harvesting without increasing fine fuel load was a primary objective of the research. The observation that there was no significant difference of either treatment from the control must be taken with a certain degree of caution however. At the risk of implying significance where none was found control and clear treatments were “almost” significantly different ($p=0.0508$), and mean fuel load in clear (3.268±0.169) was 1.9 times higher than the control (1.698 ± 0.517 kg m^{-2}).

When compared to measured total fine fuel loads in other studies (Table 4), each of this paper’s treatments were less than those measured elsewhere. Lavoie et al (2010) found total fine fuel loads in Jack-pine dominant-black spruce forests (defined as ladder and crown fuels <1.0 cm, Dead and down fuels <1.0 cm, and litter <2.0 cm depth) to be 3.72 kg m^{-2} on average in 71 year old stands and 4.63 kg m^{-2} in 108 year old stands. Hirsch and Pengelly (1999) found fine fuel load (defined as foliage and twigs <1.0 cm, dead and down <3.0 cm, and litter) to be 6.03 kg m^{-2} on average in untreated lodgepole pine stands and 2.28 kg m^{-2} in hand thinned treated stands in Banff National Park in trees of similar dbh and height, with their hand treatment a slow and labour intensive process yielding roughly equivalent fuel loading as our mechanical clearing, though resulting in a different structure.

Accepting that the differences in methodology included in Hirsch et al’s study would increase fuel load values to some degree (namely inclusion of woody debris <3.0 cm and branch fuels <1.0 cm), our project’s total fine fuel load remained dramatically below other studies on undisturbed natural jack pine sites with only the cleared treatment (3.268 ± 0.169 kg m^{-2}) approaching other sites total fine fuel loads. As our study calculated branch fuel load to include all size classes and was therefore unusable as part of our fine fuel calculations, we may somewhat under-represent total fine fuel load across the control and thin treatments, though our total branch fuel load, calculated and included in total standing tree fuel load, amounted to only ~1.0-1.1 kg m^{-2} (inclusive of branch size classes exceeding 1 cm) so it is unlikely that our results are far off an accurate assessment.

Interestingly while Lavoie et al’s (2010) total fine fuel load methodology closely matches our own, the bulk of their fine fuel load comes from ladder and crown fuels (71 years: 2.3 kg m^{-2} of a total 3.72 kg m^{-2} constituting 62% of total fine fuels; 108 years: 3.73 kg m^{-2} of a total 4.63 kg m^{-2} constituting 81% of fine fuels, with an average of 72% of fuel loading attributable to ladder and crown fuels) while the majority of our fine fuel load comes from litter (Control: 1.18 kg m^{-2} of a total 1.70 kg m^{-2} constituting 69%; Thin: 0.89 kg m^{-2} of a total 1.49 kg m^{-2} constituting 60%; Clear: 3.06 kg m^{-2} of a total 3.27 kg m^{-2} constituting 94%, with an average of 74% of fuel loading attributable to litter).

As discussed in relation to litter fuel load, fine fuels are the primary fuel contributing to firefront intensity. Total fine fuel in both treatments was not significantly different from control, with the proviso that the clear treatment was 1.9 times greater than control. While this increase does seem to be great enough that some effect should be observed it must also account for fuel moisture content. Additionally, it appears that even with the increased fuel loading the stands remain at or below normal fine fuel loads for other comparative stands.

Duff Fuel Load

While not significantly affected by treatment duff fuel load merits discussion. Harvesting techniques employed in this project sought to minimize ground disturbance by limiting vehicle travel within the sites and harvesting during the winter to make use of frozen ground and a cushion of snow between the equipment tires and organic soils. This matched our hypothesis that duff would not be significantly impacted by harvesting as site impact was minimized by reduction in machine activity, and harvest occurring in winter months when frozen ground and a cushion of now would reduce disturbance. Removal of selected trees to a landing site for processing was hoped to reduce fuel loading in the stands, as in stand processing would ultimately result in surface layering, compaction, and an increased duff and litter layer over time. Interestingly, while it is accepted that there was no significant difference in fuel loads, the extremes of duff fuel loading came from the clear and thin treatments, with the highest duff loading in the clear treatment (7.18 kg m^{-2}) and the lowest loading in the thin treatment(4.58 kg m^{-2}), with the control treatment (6.99 kg m^{-2}) occupying the middle ground, though considerably closer to the clear treatment than the thin treatment.

Because the thin treatment did not experience any organic soil disturbance site heterogeneity is likely the cause of the significantly lower duff fuel load, suggesting that disturbance in the adjacent thin treatments may have resulted more duff loading than would otherwise be visible when compared to the further removed control treatment. There may also be an effect of mechanical disturbance in which equipment scraped and mounded organic layers, leaving some sampling locations bare and unusable, while the soils removed from that point created artificially deep layers elsewhere for sampling. If this is the case then the overall site duff fuel load would remain the same, but sampling methods requiring organic soil to be present in order to sample would have artificially inflated the duff fuel load results. As the increase was not significantly different from the thin treatment or the control, the effect is not believed to be overly problematic.

Across treatments, study duff fuel load fell well below comparable duff fuel loads found in other research (Table 4), though with moderately more variation between treatments than in other studies. This is likely due to the fact that one study examined undisturbed stands at different ages, while the other performed manual thinning, which would cause significantly less soil disturbance.

Total Woody Debris

Our hypothesis that harvesting with a focus on minimized slash loading would result in no change to coarse woody debris fuel loading was borne out by the results showing non-significant variation between treatments. As standard harvesting techniques often cause considerable coarse woody fuel loading, the modified harvesting method in which trees were cut and removed whole from the stand to be processed at landing sites and disturbance of remaining trees was minimized is attributed with minimizing coarse woody debris fuel loading (Anderson, 1982). Non-significant variation between sites may be due to limited debris deposition in machine harvested stands and fallen debris post-harvest.

Coarse woody debris fuel load for all sites (control 2.2 kg m^{-2}; Thin 3.0 kg m^{-2}; Clear 2.6 kg m^{-2}) exceeded that of Lavoie et al (2010) in Table 4 (1.65 kg m^{-2} and 0.95 kg m^{-2}), however was similar to Hirsch and Pengelly (1999) (2.19 kg m^{-2}). Given that slash may reach 4.8 kg m^{-2} in harvested stands, the increased loading of 0.4 to 0.83 kg m^{-2} over control to a maximum of 3.0 kg m^{-2} was substantially lower than could be expected in a machine harvested stand and was in line with other findings in other beetle attacked fuels (Collins et al., 2012). Based on this it is considered that harvesting methods to mitigate effects of harvesting on fuel load were successful.

As this study period only spans two years post-harvest and less than 10 years post attack, some mention must be made of delayed fuel loading in beetle attacked stands. Studies of untreated beetle attack stands in lodgepole pine and Engelman Spruce have found significant coarse woody debris fuel loading over a span of 20 to 100 years post attack, with coarse fuel load peaking 20 to 50 years following attack. As harvesting removed those trees most likely to contribute to coarse fuel loading (vulnerable, visibly attacked, or standing dead trees) it is believed that this will minimize coarse woody debris fuel loading due to grey stage trees falling (Jenkins et al., 2008, 2012; Schoennagel et al., 2012).

Windthrow post-harvest may also affect coarse fuel loading, however as harvesting was performed with narrow cleared breaks and the harvest layout was perpendicular to prevailing winds, this is thought to mitigate windthrow effects as it will not significantly expose any individual trees or sections of the stand to excessive direct winds (Department of Natural Resources, 2005; Ministry of Forests, 2003).

Total Fuel Load

Total fuel load was significantly lower in the clear treatment when compared to the control and thin treatments due to the total removal of standing trees from the clear site. This removal resulted in a 58% reduction in overall fuel load when compared to control and thin treatments. As the difference in total fuel load between the clear treatment and others is roughly equivalent to sampled standing tree fuel load in control (20.74 kg m^{-2}) and thin (21.65 kg m^{-2}), this makes sense given a moderate degree of additional litter, duff, and woody debris fuel loading in the clear treatment. It also confirms our hypothesis that harvesting with intent to reduce overall fuel load is possible in a manner that does not leave heavy slash loading that would counteract the benefits of treatment. Comparison of control and thin treatments with the findings in Table 4 found similar total fuel loading in unmodified stands (28.81 kg m^{-2}, 39.41 kg m^{-2} (Lavoie et al., 2010) and 29.0 kg m^{-2} (Hirsch & Pengelly, 1999)) while clear treatment fuel loading was 45%-33% that of other studies' untreated fuels and 84% of Hirsch & Pengelly's (1999) hand treatment.

As there was no significant change in overall fuel load in the thin treatment due to harvesting, and a significant decrease in overall fuel load in the clear treatment from harvesting, it is believed that total fuel consumption in the event of a fire would decrease due to reduction in total fuel across the two treatments. Fire suppression effectiveness may also increase as the clear treatments form continuous breaks through the standing fuels, both reducing the capacity of a fire to spread as a continuous crown fire and increasing ease of access and fire break development by suppression crews during the period the clear treatment remains open. Anecdotally the clear treatments were observed to be colonized in the second year by herbaceous understory plants, and the clear treatments were found to be significantly more humid than their adjacent thinned treatments which had a predominantly moss and woody plant understory. It is also accepted that these treatments will likely transition over time as larger shrubs and young trees colonize the clear treatments in high density, likely resulting in an increase in ladder fuels. Now that we have observed the effect of strip cut harvesting on fuel loading at one level of retention, future work should be especially focussed on varying the degree of thinning within thin treatments, with attention to maintaining a low level of fuel loading across size classes.

Upper Forest Floor Moisture Content

While our hypothesis was somewhat incorrect in that fuel moisture did not consistently decrease as level of harvest increased, our results are consistent with other work that has determined a more complex relationship between fuel moisture and thinning. Since the Fire Weather Index's Fine Fuel Moisture Code is driven exclusively by weather inputs of temperature, relative humidity, wind, and rain (Lawson & Armitage, 2008; Stocks et al., 1989) the logical conclusion is that as stand density and canopy closure decrease, solar radiation and wind penetration increase. Increases in solar radiation and wind penetration should cause decreased relative humidity and precipitation interception and increasing temperature and drying winds. Denser stands by comparison were believed to shelter fuels, with greater shading and protection from wind maintaining higher relative humidity and lower air and fuel temperatures (Graham et al., 2004; Whitehead et al., 2008). This appears however to be an overly simplistic explanation as research by van der Kamp (2017) found that while open stands experience higher day time temperatures and wind speeds and decreased relative humidity, these effects were overwhelmed by increased overnight radiative cooling in open stands, resulting in all fuels but those <0.635 cm having consistently higher moisture content than their closed stand counterparts across a 24-hour period. These effects were found to be especially evident in cool, moist conditions with low wind speeds, and least evident in extreme dry conditions. As 2016 was characterized by consistent relatively cool and wet periods at the site it is likely that our results are representative of the extreme fuel moisture variations described as occurring in the period following precipitation (van der Kamp, 2017; Whitehead et al., 2008). Additionally, since our fine fuel categories follow the Fire Weather Index definitions of <1.0 cm rather than the American National Fire-Danger Rating System's 1-hour <0.635 cm fuels, our fine fuels may behave in a more similarly to the larger fuels in van der Kamp's (2017) study, rather than his fine fuels, despite the similarity in name. Transpiration may also play a greater role than previously considered by drawing moisture from surface litter layers from below. Thinning has been shown to increase potential for transpiration and soil moisture content in White Spruce (*Picea glauca*), with transpiration increasing by as much as three times due to increased wind speed, net radiation, and vapor pressure deficit, while duff moisture has been shown to significantly alter fine fuel moisture content to a greater degree than predicted by the Fire Weather Index (Bladon et al., 2006; Pook & Gill, 1993; Whitehead et al., 2008; Wotton & Beverly, 2007). Both studies found that individual tree transpiration increased dramatically with thinning due to increased vapor pressure deficit, however overall transpiration was reduced due to overall reduction in stem density. Since our thinning treatment did not significantly reduce stem density, but was flanked closely by clear treatments creating conditions analogous to extreme thinning, it is likely that the thin treatments experienced the effect of neighbouring open clear treatments and the associated vapor pressure deficits without the overall reduction in stem density experienced by the other studies, thus increasing individual tree transpiration without reducing the overall area transpiration through tree removal for the thin treatment.

These papers and our own findings confirm the seldom discussed fact that while the Fire Weather Index uses specific weather inputs to predict fuel moisture codes and indicate regional fuel moisture trends, these weather inputs represent far more complex interactions that may not behave as expected if disturbed. Underestimating the influence that these interactions play on fuel moisture content leads to error predicting the effects of fuel modifications on fuel moisture content.

Despite our findings running counter to the original hypothesis that increased level of harvest would decrease fuel moisture content, they are consistent with previously quoted research. Our results are especially understandable as our harvesting method alternating thinned and cleared treatments would likely have created conditions in which the thinned stands would experience stronger influence of wind speed, net radiation and vapor pressure deficit than would otherwise occur across large thinned blocks due to the presence of cleared treatments to either side, while the cleared treatments would no longer experience soil moisture loss from transpiration, and would be partially but not completely temperature sheltered by their neighbouring thinned treatments. Based on this the results are more understandable.

With low levels of thinning it is likely that there will be an increase in transpiration without significantly increasing overnight cooling and relative humidity. As thinning continues towards total removal of standing trees however, a threshold is crossed and transpiration effect on soil moisture drops off and overnight cooling and relative humidity take effect and fuel moisture begins to increase. Dubé and others similarly found that soil moisture increased the most in post-harvest in areas with previously low moisture levels (i.e. wet sites stayed wet, dry sites became significantly wetter), due to reduced evapotranspiration, reduced canopy interception, and increased overnight relative humidity (Dubé et al., 1995; van der Kamp, 2017). As effects of thinning on both transpiration and daily variations in relative humidity are most pronounced under normal conditions without drought and 2016 was a season with consistent levels of precipitation it is likely that we are seeing the more extreme examples of these effects (Barg & Edmonds, 2011; Pook & Gill, 1993; van der Kamp, 2017; Whitehead et al., 2008).

Another factor that had potential to influence litter layer moisture content in the clear treatment was compaction of forest floor fuels from mechanical harvesting. While compaction has been shown to effect ignition potential and heat release (Cramer, 1974; Ganteaume et al., 2014), with limited compaction leading to increased potential for ignition, spread and intensity to a point, after which compaction results in oxygen limitation, decreased drying rates, and decreases in the same potential fire behaviour (Cramer, 1974), examination of bulk density samples found no effect of treatment on litter bulk density (p=0.08774). While it is usually assumed equipment harvesting will cause significant soil disturbance and compaction, this study's prescription of using frozen ground, a cushion of snow, large surface area soft tires, and reduced travel in stand appears to have been successful in mitigating harvest effects on soil compaction. Though significantly increased compaction would likely reduce flammability through excessive density and reduced drying rates, this level of disturbance is not believed to be suitable to meet other objectives of the wider project.

The lower fuel moisture content in both of the harvested treatments suggest that compared to the control they will experience more days at levels likely to support an ignition or days at levels where fire control would become difficult. When considered in conjunction with fine fuel loading we can see that while the clear treatment had significantly higher fine fuel loading than the thin treatment it also had a significantly higher fine fuel moisture content than the clear treatment, suggesting some degree of reduced fuel availability in the clear treatment which may offset the increased fine fuel load. This offset would likely have a direct effect on fireline intensity, reducing what would be suggested to be a high potential fireline intensity if only fuel load were considered. The thin treatment with similar fuel loading to the control but the lowest fuel moisture may result in higher than anticipated intensity. As the control group had the highest fine fuel moisture content and was not significantly different from either treatment in regard to fine fuel load, it is suggested that it would have the lowest fuel availability. When considering fine fuel load and moisture content together, it is believed that the thin and clear treatments will increase likelihood of ignition over the short term under "regular" conditions by decreasing fuel moisture in treated stands but that this increased likelihood of ignition will be at least somewhat offset by reduction in intensity from reduced fuel load (Davis & Byram, 1959; Keeley, 2009).

Duff Fuel Moisture Content and Duff Moisture Code

As with Fine Fuel moisture, treatment had a significant but unexpected effect on duff moisture and moisture code results. Duff moisture content for both thin and clear treatments was not significantly different from the control group though the clear treatment was significantly wetter than the thin treatment. As the hypothesis was that increased thinning would result in increased duff drying, no significant difference between the control and harvested stands forces us to conclude that some other event is occurring in the treatment area that is not accounted for. Once converted to Duff Moisture Code the thin and clear treatments were no longer significantly different due to the non-linear duff moisture code conversion while the clear treatment remained significantly wetter.

As the duff moisture code represents medium depth duff and fuels and is strongly related to likelihood of ignition from lightning strikes and difficulty of control, a decrease in duff moisture code is of interest as it suggests that likelihood of lightning caused fire and overall fuel consumption from a fire may be reduced or at minimum remain the same as in untreated stands. As with the litter layers, duff bulk density was not found to be significantly affected by treatment ($p=0.0666$). Based on this it appears that mechanical harvesting did not influence the actual drying and wetting rates of the clear treatment duff layer or its potential fire behaviour, so other mechanisms are likely at play.

Given that each treatment was exposed to the same weather inputs yet shows different fuel moisture contents, it is likely that the same additional factors affect duff as affect fine fuel moisture content: night time radiative cooling and transpiration. Van der Kamp's (2017) overnight radiative cooling was most evident in fuels >0.635 cm, as fuels below this size may respond to some daytime changes in relative humidity while larger fuels are less responsive to daytime drying, resulting in net moisture gain for fuels exceeding 0.635 cm diameter. It is believed that these effects also affect duff layers, as they ultimately behave in a similar manner to medium sized woody debris and react to changes in relative humidity and reduced canopy interception. Increased transpiration, with its direct removal of moisture from the soil is also likely to play a role in reducing moisture content as shown in other studies (Bladon et al., 2006; Pook & Gill, 1993). This is especially likely as our treatments dramatically increased vapor pressure deficit adjacent to thinned stands without significantly reducing stem density, increasing individual tree transpiration without significantly reducing the number of trees in the site. This is further supported by research which found that transpiration accounts for up to 31% of duff moisture loss in natural Jack Pine-Aspen stands (Thompson et al., 2015). Barg and Edmonds' study (2011) also found similar relationships with moisture content increasing with degree of thinning, though the effect was not significant and moisture content was taken from mineral soil samples. In addition to reduced transpiration in the cleared stands, increased exposure of the forest floor to increased solar radiation and daytime air temperature along with decreased daytime RH may have somewhat counterintuitively acted to slow moisture loss, as Ma et al (2010) found that dry surface layers may act as a cap or barrier to further moisture loss from deeper layers.

Given that the Duff Moisture Code is representative of both moderate duff layers and moderately sized woody fuels, it is worth mentioning that there may be a decoupling effect between soil moisture and above ground woody fuels moisture in treated stand, as transpiration especially would not have a direct effect on woody fuels. Decreased canopy interception may also play a significant role in increasing duff moisture content in the clear plot, as canopy interception can account for up to 0.5 mm of precipitation per day that would not otherwise reach the ground (de Groot, 1987; Whitehead et al., 2006). While the Fire Weather Index does not seek to predict exact moisture content for every fuel type and location, but rather a broad scale trend, harvesting treatments will likely change the relationship between organic fuel layers and woody debris.

Following conversion from fuel moisture content to duff moisture code there was a change in significance between treatments with the control and thin treatments remaining similar, but the clear treatment becoming significantly wetter from the others. As this change in significance is a mechanism of the non-linear fuel moisture conversion this must be taken with some degree of caution, however since the moisture codes represent fuel relationship to flammability the difference is still important. Throughout 2016, a somewhat wet year, control and thin treatments were approaching dry conditions (DMC>30) while the clear treatment was significantly lower when assessed over the entire season. During individual sampling periods the thin and control treatments periodically exceeded a DMC of 30 while the clear treatment did not. A lower DMC will result in reduced medium fuel and duff consumption in the event of a fire, which will in turn reduce total fuel consumption as well as smouldering combustion, a significant factor in smoke pollution and particulate generation from fire (Chakrabarty et al., 2010; Garlough & Keyes, 2011; Mckenzie et al., 1995; Otway et al., 2007). Reduced fuel loading combined with increased medium fuel moisture content should reduce impact of a burn occurring in cleared treatments, while not significantly increasing impact in the thin treatment in comparison to the control.

While the Fire Behaviour Prediction System and its Fuel Types are outside of the scope of this study, any research into the effects of thinning treatments on fire behaviour should be expanded to include the FBP system. Since the Fuel Types currently available in the FBP system are “natural” except for C6 Conifer Plantation and S1 to S3 Slash fuel types they are likely not representative of the extensively modified fuels in our study, so will not account for treatment related variations in fuel moisture content and fuel load. Investigation into the actual effects on the primary and secondary FBP system outputs would be very useful if this treatment is used on a wider scale or further studied.

Conclusion

This paper set out to establish the effect of progressive strip cut harvesting on fuel load and moisture. Fine fuel load was not significantly different in either treatment from the control treatment, despite the clear treatment being 1.9 times higher than the control. Compared to other studies in similar fuels (Table 4), fine fuel loading was not exceptional, suggesting the treatment would not lead to excessive fire behaviour due to fine fuel loading. Total fuel loading was found to be significantly reduced in the clear treatment, while the thin treatment was not different from the control. This was almost entirely due to removal of standing tree fuel load from the clear treatment. While large diameter fuels do not significantly contribute to flame front passage, they remain a significant portion of total fuel load and may affect potential fire behaviour as well as support considerable smouldering combustion if they reach the fuel bed. Within total fuel load it was also observed that harvesting treatments did not result in significant changes to dead and down fuels. This suggests that the harvesting techniques employed in the research, namely focussing on minimizing disturbance and slash loading was at least in part effective. As harvesting may lead to dead and down debris loading up to 2m deep, no significant difference between a control and machine harvested treatments is a notable result (Van Wagner et al., 1992).

Fuel moisture was significantly affected by treatment for both forest floor and duff layers. It did not however follow our prediction of declining as level of disturbance increased. Instead while forest floor moisture content was lower in both treatments when compared to the control, it was the thin treatment that was the driest, while the clear was closer to the control in terms of moisture content. As there were no significant periods of drought throughout the sampling period it is thought the lack of canopy interception as well as overnight evaporative cooling resulted in cumulative moisture gain in the clear treatments due to their exposure, rather than in spite of it. Duff moisture content was likewise not as predicted, with the thin treatment again being the driest, but the clear treatment being the wettest. When converted to Duff Moisture Code the control and thin treatment were no longer significantly different while the clear treatment remained significantly wetter. It is believed that the same drivers that affected the forest floor fuels affect the duff layers, with the addition of increased transpiration from remaining trees driven by increased vapor pressure deficit from adjacent clear treatments. While treatments clearly affect both fuel load and fuel moisture, the factors driving fuel moisture changes merit further research. Additionally, research is required to examine the interaction between progressive strip cut harvesting altered fuel loading, structure, and moisture content in relation to likelihood of ignition, intensity, and rate of spread.

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