Predicting duff moisture in a boreal forest ecosystem at various retention levels

By

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Abstract

The Canadian Fire Weather Index (FWI) system is used across Canada and worldwide to provide numerical ratings of fuel moisture based on the fine fuel moisture code (FFMC), duff moisture code (DMC) and drought code (DC). DMC is related to dryness of the duff layer. While DMC has been widely calibrated and validated in different stand types, it has not yet been calibrated for retention harvesting sites in the boreal mixedwood landscape of north-central Alberta.

The objective of this research was to explore whether duff characteristics (duff load) and stand parameters (leaf area index, basal area) could be used in predicting duff moisture and whether the standard-DMC estimated by the FWI system matches with field-DMC. This study was conducted in conifer-dominated mixedwood stands that had received a range of variable retention harvesting in 1998/1999 (clear-cut, 20%, 50% , 75% -retentions and control) as part of the EMEND research project near Peace River, Alberta. Duff moisture, duff characteristics and vegetation parameters were measured in the field and DMCs were estimated for June, July and August in 2014 across retention levels. A trenching experiment was conducted to see if transpiration losses were related to duff moisture across retention levels. The results indicated that duff characteristics were influenced by litter deposition during harvesting and addition of fresh leaf litter from regenerated aspen. Duff moisture was influenced by slope and elevation more than species composition. Among the duff variables, duff load was a better predictor of duff moisture (R^2= 0.60). A three-way ANOVA revealed that standard DMC-MC relationships underestimate both field and sensor DMC in June and July.

Keywords:

Duff moisture, duff characteristics, duff depth, duff bulk density, duff load, retention harvesting, leaf area index, duff moisture code

Dedication

my parents, my siblings and my family

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List of Acronyms used

Terms

%DM	Duff moisture measured in %
20%,50%,75% -R	20%, 50%, 75% Retention
BA	Basal Area Index
BD	Bulk density
CC	Clear-cut
CFS	Canada Forest Service
DD	Duff depth
DMC	Duff Moisture Code
EMEND	Ecosystem Management Emulating Natural Disturbances
Eq.	Equation
FI	Fire Intensity
Field-DMC	DMC measured in the field
FS	Fire Severity
FWI	Fire weather index
LAI	Leaf Area Index
MmDM	Duff moisture measured in the mm scale
Sensor-DMC	DMC measured using sensors
Standard-%DM	Duff moisture (%) measured using standard DMC-MC equation
Standard-DMC	DMC measured by FWI system

Chapter 1.

Introduction

Fire is a dominant force in shaping ecosystems in Canada (Ryan, 2002) and has been the major natural disturbance in the boreal landscape since the last Ice Age around 10,000 years ago (Bergeron et al., 2001; Long, 2009; Stocks et al., 2002). The annual area burned in Canada fluctuated between ~0.3 million ha in 1978 and 7.5 million ha in 1995. Area burned in the 1990s increased significantly compared to those fires documented for 1920-1950 period (Stocks et al., 2002) with an average of ~2.7 million ha. More recently ~7,319 forest fires was reported in 2011 across Canada equaling the average fire number during 2000-2009 period, however area burned was ~86% higher than this period (NRC, 2011). Only 2% to 3% of all fires are more than 200 ha, defined as 'large fire' by Stocks et al. (2002) which combinedly contributes approximately 98% of the total area burned. Of the remaining ~97% of the fires are less than 200 ha, some are suppressed. Over 80% of the area burned in large fires in northern Canada are initiated by lightning (Stocks et al., 2002). One-third of the wildfires across Canada are caused by lightning which are responsible for about 90% of the total area burned (Kourtz and Todd, 1992). Lightning-induced ignition also varies temporally every year in Canada, for example 5,438 fires occurred in 2000 whereas 12,000 fires in 1989.

Whether human-caused or lightning-caused, fire affects infrastructure and causes loss of harvestable forests during extreme fire years (Terrier et al., 2013). Fire disrupts daily life and may cause loss of human life and property. For example, a large fire occurred in the eastern boreal Canada in 2011 forcing a state of emergency and the evacuation of communities. Another fire in the same year that occurred in the western boreal Canada (Slave Lake, Alberta) caused the evacuation of over 15,000 residents and resulted in losses totaling over $700 million (Terrier et al., 2013).

Nevertheless, fire is an essential and natural element in the boreal forest as it plays crucial role in forest renewal. Post-fire vegetation succession depends on many factors such as pre-fire vegetation species and their state of development, the season of the burn, fire behavior, fire intensity (heat output), fire severity (effects on the ecosystem), fire size, physical site characteristics and post-fire environmental conditions (Beck et al., 2005). Based on the adaptation exhibited by major forest trees in the Canadian boreal forest Weber et al. (1998) indicate that fire must have been an integral component of vegetation dynamics since the Miocene (30 million years BP) or early Pliocene (12 million years BP) and that boreal forest ecosystems originated from propagules initiated from the south of the ice sheet or from unglaciated refugia. In the boreal forest - consisting of jack pine (*Pinus banksiana* Lamb.), black spruce (*Picea mariana* (P. Mill.) B.S.P), white spruce (*Picea glauca* (Moench) Voss), paper birch (*Betula papyrifera* Marsh.) and aspen (*Populus tremuloides* Michx.), post-fire regeneration occurs immediately by the same species (Johnstone et al., 2004). This somehow resembles the direct regeneration hypothesis (DRH) stated by Yih et al. (1991) based on their research in Nicaraguan tropical rain forests after hurricanes where they observed that regeneration was dominated by seedlings of primary forests species rather than secondary pioneers. However, some researchers (Chen et al., 2009; Ilisson et al., 2009) argue that this regeneration hypothesis is only partially true in boreal forests in Canada. Ilisson et al. (2009) concluded that DRH can be applicable to conifers with serotinous cones, but may not be relevant to non-serotinous conifers. They also indicated that all disturbances such as fire, clearcutting and windthrow favored broadleaf trees regardless of regeneration strategy. Chen et al. (2009) found in their study conducted at 94 upland boreal forest stands between 5 and 18 years after fire in Ontario, Canada that fire significantly increased post-fire regeneration densities (stems/ha) for jack pine, aspen, black spruce, paper birch but not white spruce and balsam fir (*Abies balsamea* (L.) P. Mill.), and post-fire regeneration density was correlated with pre-fire basal area. Based on this study they also suggest that the boreal landscape will be more dominated by hardwood and mixture of conifers and hardwoods if fire occurrences increase with global climate change.

Fire size and severity influence distance to seed sources and consequently influence possibilities for colonization (Bergeron et al., 2014). In the western boreal forests of Canada, species such as aspen and balsam poplar (*Populus balsamifera* L.) that have the ability of vegetative reproduction regenerate earlier than conifers following a wildfire (Frey et al., 2003). These shade-intolerant broadleaf species may be eventually replaced by shade-tolerant conifers such as white spruce, black spruce if no major disturbance takes place. Serotinous species such as black spruce, lodgepole pine (*Pinus contorta* Dougl. ex loud var. latifolia Engelm.), and jack pine are well adapted to fire because their cones remain closed on the tree and provide a seed bank. Following fire these serotinous cones open up when sufficient heat is generated in a wildfire (Johnson and Gutsell, 1993). Meanwhile, non-serotinous white spruce depends on the seed released following fire on the forest floor. Dispersal from surviving seeds sources is also critical for white spruce regeneration in a burned site. As white spruce seeds every two to six years (masting), Peters et al. (2005) studied whether time of mast years relative to fire significantly effect on the density and timing of regeneration. They found that regeneration after fire was higher if fire occurred in mast years than the regeneration after fires occurred 1-3 years before a mast year. As such, masting is an important process that interacts with fire to influence stand composition in boreal mixedwood forests (Peters et al., 2005). Over time the shade tolerant conifers, particularly spruce (black or white), become dominant and the mixed stands changes into a conifer dominated stand (Bergeron et al., 2014).

Fire interval plays an important role in determining successional trajectories in conifer-dominated boreal forests in northwestern Canada. For example, in a study conducted in the Yukon and British Columbia, Johnstone and Chapin III (2006) found that when stands over 75 years old were burnt, recruitment density of conifers was significantly correlated with the pre-fire species basal area. In contrast, when the stand age was less than 25 years, the post-fire regeneration showed reduced conifer recruitment (black spruce, white spruce, lodgepole pine) due to a lack of local seed supply. On the other hand, deciduous species such as aspen, balsam poplar and paper birch can recruit and increase in abundance due to root suckering following fire. These species can also regenerate on a burned site by means of dispersal of seeds from nearby unburnt site.

As well as its important role in boreal forest succession, fires serve two other major functions to promote successful regeneration. Firstly, it creates mineral seedbed prerequisite for germination and, secondly, it eliminates overstory shade and other competition thus promoting the growth of shade-intolerant species. Fires also affect ecosystem nutrient cycling through nutrient redistribution during and after fire (MacLean et al., 1983). Based on post-fire comparisons of burned sites and adjacent unburned sites, it was found that nitrogen losses during intense fire range between 500-800 kg/ha in the temperate region (Grier, 1975) and up to 1000 kg/ha in tundra and forest-tundra (Weber, 1975). In general, changes due to fires include possible increased leaching into the soil profile, overland flow or erosional transfer of nutrients, increased soil pH, lowered albedo from the fire-darkened surface, increased active layer depth, and warmer soil profiles which affect microorganisms and decomposition process (MacLean et al., 1983). Fires also affect soil biota which in turn affects the development of organic matter. Fires may cause organic carbon losses up to 50% in the forest (Fernandez and Carballas, 1997) however it may increase inorganic carbon in the soil which suggests a substantial incorporation of forest necromass (Rashid, 1987). The heat generated in fires turns the soil to coarser textured by forming stable aggregates from clay and silt fractions (González-Pérez et al., 2004).

Fire releases large amounts of CO_2 to the atmosphere. Van Bellen et al. (2010) reviewed Net Ecosystem Exchange and carbon fluxes in several ecosystem in Canada and globally and noted that fire releases more carbon than the annual ecosystem carbon sequestration in the absence of fire in the boreal forest. The carbon emission rate varies among forest types. For example, carbon emission rates due to wildfire in Alaskan black spruce forest ranged between 0.56 and 5.67 kg/m^2 (Kasischke and Johnstone, 2005), North American boreal peatland ranged between 2.1 to 7.57 kg/m^2 (Zoltai et al., 1998) and Canadian boreal forest ranged between 0.29 to 2.43 kg/m^2 (de Groot et al., 2009). The estimated mean annual direct carbon emissions in Canada due to wildfire for the period of 1959-1999 was 27±6 Tg C per year (ranged from 3 to 115 Tg C per year) which represent about 18% of the total CO_2 emission from Canadian energy sector including transportation (Amiro et al., 2001). During the 1990-2008 period, this emission rate was also similar (23±16 Tg C per year) (Stinson et al., 2011). However, when all natural disturbances including fires were combined, the total carbon emission rate was estimated to be more than twice that of fire alone (~52±16 Tg C per year) (Stinson et al., 2011). In fact, the Canadian boreal forest had been identified as a source of carbon emission since 2002 and remained in this state through 2022 in a modeling study based on carbon budget model of Canadian forest sector (CBM-CFS3) (Kurz et al., 2008). They related insect outbreak as the major reason for transition from sink to source of Canadian forest. Furthermore, the concomitant changes in weather conditions and increase in area burned was also projected to contribute in increased carbon emissions in Canadian boreal forests (Kurz et al., 2013).

Understanding fire characteristics and behavior is crucial for wildfire management. In the discipline of forest fire science, some key terms are used in describing fire characteristics. The term fire regime is one such term and refers to spatial and temporal fire pattern and describes fire effects at the ecosystem and landscape level. Brown (1995) referred to fire regime as the 'nature of fires occurring over an extended period of time'. Fire regime is also defined as "the kind of fire activity or pattern of fires that generally characterize a given area" (Merrill and Alexander, 1987). It is described by severity (depth of burn or impact), frequency, intensity (energy output in kW/m of fireline), seasonality (timing of the fire), fire type (ground, surface or crown) and strategies (e.g. serotinous cones, suckering, sprouting, thick bark etc.). Fire frequency refers to the average number of fires that occur at a given point (CIFFC, 2003). Fire return interval or fire interval is the average number of years between the occurrences of two successive fires at a given point. The number of years required to burn over an area equal to the entire area of interest is called fire cycle (CIFFC, 2003). No generally accepted fire regime classification exists to date due to local and regional differences in vegetation and climate (Sommers et al., 2011).

Many researchers classified fire regimes in great detail (Agee, 1993; Falk et al., 2007; Heinselman, 1973). Agee (1996b) provided a simplified classification of fire regime into three categories based on fire severity and the fire adaptation of vegetation: low, mixed or moderate and high. Low-severity fire regime refers to low intensity, frequent fires (often <20 years) on which the dominant vegetation in an ecosystem is well adapted to survive fire. In a mixed or moderate severity fire regime, fire is of intermediate frequency (25-100 years) with low to high intensity and with vegetation that has a wide range of adaptations. A high severity fire regime is usually infrequent (> 100 years) but with a high intensity leading to death of most of the vegetation. More recently, Rogeau (2006) reviewed the US Fire Regime Condition Class developed by Barrett et al. (2010) and developed two fire regime classes based on fire cycle and mean fire return interval applicable to Alberta. The proposed Alberta fire regime classes (based on fire cycle) has five fire regime categories: 0-50 years (low-mixed severity), 51-100 years (mixed severity), 101-150 years (high severity), 151-200 years (mixed to high severity) and 250+ years (high severity).The proposed fire regime classes based on mean fire return interval are: 0-35 years, 36-75 years, 76-150 years, 151-200 years, and 250+ years.

Two other important terms i.e. fire intensity (FI) and fire severity (FS) are widely confused in the literature. Commonly used in Physics, 'intensity' refers to the time-averaged energy flux or the energy per unit (W/m^2) volume multiplied by the velocity of the energy (Keeley, 2009). FI describes the physical combustion process of energy release from organic matter (Keeley, 2009). However, other researchers link FI to the description of fire behavior quantified by the temperature (Neary et al., 1999; Whelan, 1995) and heat release by the flaming front of a fire (Keeley, 2009). No single metric, to date, exists bridging all aspects of fire energy. Byram (1959) used fireline intensity (kW/m) to relate FI and defined fireline intensity as the energy output from a strip of the actively combusting area, 1m in length, that extends from the leading edge of the fire front to the rear of the flaming zone. However, Rothermel (1972) described FI as the heat release rate per unit area (kW/m^2), which is widely known as fire reaction intensity. Some other metrics are temperature, residence time, radiant energy etc. (Keeley, 2009).

In contrast, FS refers to the overall effects of fire on an ecosystem (Feller, 1996) and the magnitude of ecological change due to the fire (Heward et al., 2013). Many authors including Keeley (2009), Lentile et al. (2006) and Neary et al. (1999) related fire severity to the loss of organic matter both aboveground and belowground. Concisely, measurement of the degree of loss is fire severity. FS metrics are objectively linked up with the degree of environmental changes caused by fire and currently there is no operationally useful metrics of fire severity (Keeley, 2009). Typically, FS indices have been expressed in terms of mortality (Ryan and

Noste, 1985), crown volume scorch (Heward et al., 2013), ash characteristics (Neary et al., 1999), changes in soil structure (Neary et al., 1999), increased hydrophobicity (Keeley, 2009). Contrasting opinions exist whether or not these indices are related to FS. For example, Wade (1993) claimed that mortality could not be used as a FS indicator since it is more related to FI. Remote sensing applications assess burned areas using burn severity indexes such as differenced Normalized Burn Ration (dNBR) or Burned Area Reflectance Classification (Keeley, 2009).

During a moving fire, several phases of combustion may take place. In the first phase, the flame front results in preheating, drying, and partial distillation of fuels (Byram, 1959). Further heating initiates pyrolysis at about 400 °F (204 °C) which results in the chemical breakdown of solid fuel under the influence of heat and usually in an oxygen-deficient environment (Miller, 2001). Combustible gasses and vapors produced in the pyrolysis rise above the fuels and mix with oxygen. Flaming combustion may occur at this point if combustible gasses are heated to the ignition point of 800 to 900 °F (427 to 482 ℃) (Miller, 2001). Heat produced from flaming combustion accelerates the rate of pyrolysis which releases greater amounts of combustible gasses and concomitantly increases flaming combustion. If incomplete combustion occurs, unburnt combustible gasses are condensed to form smoke which takes on a whitish appearance when mixed with water vapor (Byram, 1959). When enough heat is generated in a fire, elemental carbon is produced and forms into tiny particles that absorb light and appear in the sky as black smoke while inefficient and cooler combustion produce less pure forms of carbonized particles which tend to reflect light easier and make the smoke look white. After most of the volatiles are consumed in flaming combustion, the remaining carbon in the fuel may experience surface oxidation, referred to as smoldering or glowing combustion (Pyne et al., 1996). Glowing is different from smoldering combustion only in that thermal decomposition of fuel does not occur nor is required (Pyne et al., 1996). Unlike flaming combustion, smoldering combustion in a fire lasts longer (Wotton et al., 2005b) and can cause more ecological damage (Watts and Kobziar, 2013).

Fire behavior is influenced by three important interacting components: fuel, weather, and topography. Fuel is the only controllable factor and is profoundly related to structure (Agee, 1996a; Pyne et al., 1996) and forest type (Agee, 1997; Podur and Martell, 2009). Fuel properties vary with spatial scale (Keane et al., 2012) and are so highly variable that they are often unrelated to vegetation characteristics, topographic variables or climate parameters (Cary et al., 2006). Fuel properties may include fuel loading (amount of live and dead fuel expressed in weight per unit area), fuel size classes <1/4-inch in diameter (1-hour fuel), ¼ to 1-inch (10-hour fuel), >1 inch in diameter, 100-hour fuels], surface area to volume ratio, fuel bed depth, packing ratio (measure of the compactness of the fuel bed, expressed in percentage of the fuel bed which is composed of fuel, the remainder being air space between the fuel particles), bulk density (actual fuel weight per unit of fuel bed depth) and fuel continuity (Beck et al., 2005). Surface fuels consist of litter, duff, twigs, logs and cones. Ground fuels consist of herbs and shrubs, whereas aerial fuel (live/dead) can be at the tree level (crown) or at the stand level (canopy) (Mitsopoulos and Dimitrakopoulos, 2007). Some important canopy fuel characteristics such as canopy fuel load, canopy bulk density and canopy base height are important factors affecting crown-fire occurrence and behavior (Reinhardt et al., 2006).

Weather and topography also influence fire behavior but are beyond human control. These two factors vary in both space and time; however weather is the most unpredictable one. Topography relates to elevation, slope, aspect and terrain. Elevation influences climatic regimes in relation to annual precipitation, snow, snow melt rates, type of vegetation, vegetation green-up and curing dates. Therefore, elevation is directly linked to fuel complex and length of the fire season. The amount of solar energy a site receives depends largely on aspect which ultimately influences the vegetation type and fuel complex (Beck et al., 2005). For example, north-facing and toe–slope forests are cooler, wetter and have deeper organic layers and deeper permafrost due to receiving less insolation compared to southerly slopes (Kane et al., 2007). This phenomenon also influences surface fuel consumption. In a wildfire in interior Alaska, Kane et al. (2007) found that north facing slopes experience less consumption (62%) compared to south-facing slope (77%). On steeper slopes adjacent unburnt fuel can be preheated as the fire moves upslope since radiation and convection simultaneously impact on the fuel lying just above it (Beck et al., 2005).

Fire weather includes relative humidity, vapor pressure deficit, temperature, wind speed and its direction and precipitation. Low relative humidity causes fuel to dry faster. Higher temperature means less energy is required to raise unburned fuels to their ignition points. Wind makes more oxygen available for combustion, moves heat and fire as well as promotes evaporation rates. Also, wind is the primary determinant of the direction of fire spread, rate of spread, fire size and fire shape if fuel and topography remain constant (Beck et al., 2005). Wind can also create extreme fire weather, for example, autumn foehn winds such as the Santa Annas in coastal California are very destructive as they typically follow 6 months or more drought and, once ignited, fire is virtually unstoppable until the weather changes (Keeley, 2008). Many researchers have linked forest fire incidence with vapor pressure deficit (VPD) which explained more variance in area burned than did precipitation, drought indices, temperature and wind. Seager et al. (2015) described VPD as a measure of the ability of the atmosphere to extract moisture from the surface vegetation which influences variation in the moisture content and flammability of forests better than relative humidity and that it accounts for the combination of low RH and high temperature which create the most fire-prone conditions. VPD is more effective than temperature or relative humidity as a descriptor of fire weather since it reflects the non-linear dependence of saturated vapor pressure on temperature and measures the actual moisture content of the air (Seager et al., 2015). Recently, Williams et al., (2015) found that annual burned area in the southwest United States during 1984-2013 was strongly correlated with spring-summer VPD ($r = 0.74$) since VPD is related to atmospheric moisture demand. Based on fires during the 2002-2011 period in the Alaskan Intermontane Boreal Interior, Sedano and Randerson (2014) revealed that VPD influenced average area burned of both individual fires ($r = 0.03$ to 0.77) and the region ($r = 0.28$ to 0.71). They also found significant positive correlations between the sum of positive VPD anomalies during the fire season and annual area burnt ($R^2 = 0.841$). Moreover, Anderson (1936) strongly suggested using VPD in biological research instead of relative humidity since: (i) VPD is more sensitive to water vapor condition of atmosphere than RH and undergoes greater variation for temperature changes than does RH; (ii) Two different areas having the same RH does not imply similar water vapor condition of the atmosphere unless temperatures are also identical. On the other hand, areas with the same VPD do influence evaporation rates in the same way regardless of temperature reading; (iii) RH does not give any indication of evaporation rate.

Understanding the influence of fuels and weather is critical to predicting fire behavior and planning for effective fuel management. Several contrasting studies exist on the relative importance of weather and fuel in determining fire behavior (Cumming, 2001; Podur and Martell, 2009) which resulted in the origination of the weather hypothesis and the fuel hypothesis. The weather hypothesis implies that fires are primarily determined by weather (Cumming, 2001). According to Agee (1997), "large severe fires are driven by extreme weather events and burn intensely through forests regardless of the condition of their fuels". On the other hand, the fuel hypothesis advocates that fire behavior is principally influenced by spatial variation of fuels or forest types (Cumming, 2001). According to Bessie and Johnson (1995), weather is the most important factor for fire occurrence based on their studies conducted in forty-seven stands (upland sup-alpine conifer forests mainly consisting of *Pinus contorta* Dougl., *Picea engelmannii* Parry, *Abies lasiocarpa* Hook and occasionally *Populous tremuloides*) located in the Kananaskis Valley of southwest Alberta (44 stands) and Vermillion Pass area of Banff and Kootenay National Parks. Their conclusion was attributed to larger variation explained by the weather variables than the fuel variables. For example, over the course of hours and days, fine fuel moisture variation ranged between 5 and 100 %, and wind speed ranged between 0 and 100 km/h. In contrast, the fine and medium size fuels varied only from 0.5 to 4 kg/m^2 and were found to be stable over long periods of time. Gillett et al., (2004) found that temperature was highly correlated with total area burned ($r = 0.77$) and that it explained 59% of the variance of the observed area burned in Canada for 1920 - 1999. A similar result was found by Hély et al. (2001) in their study in eastern Canada, however, they emphasized differences in fire behavior among stand types.

Flannigan and Harrington (1988) also indicated that weather could be the most important factor in Canadian boreal mixedwood forest when fire frequency is low. Meanwhile, vegetation composition may be the critical factor when fire frequency is high within a forest mosaic with heterogeneous composition such as found on the boreal forest (Hély et al., 2001). In a modeling study, Hély et al. (2000) found that fires in deciduous stands in Canada's boreal mixedwood forest were less intense and spread more slowly than fires in coniferous stands. They also found that intensity of fires in spring was higher than that of summer fires and that seasonal differences increase with the increase of deciduous basal area.

Recently, climate change has been a major concern to fire managers and fire scientists in Canada and globally due to the shifts in temperature and precipitation patterns at high latitudes (Solomon et al., 2007). In Canada, temperature has increased at a rate of 1.7 ℃ per century since 1890 (Gullet and Skinner, 1992). An increase in mean annual temperature of at least 2 ℃ is expected in Canada over 2000-2050 period (Price et al., 2013). They also predicted that the annual mean temperature across the Canadian boreal zone could be warmer by 4-5 ℃ in 2100 compared to the base year (2013). Increased temperature can potentially increase the frequency of severe fire weather, extend the fire season or increase the number of fire ignitions (Weber and Stocks, 1998). Wotton and Flannigan (1993) predicted that the fire season length in Canada could increase by an average of 22% or 30 days under the Canadian GCM $2\times CO_2$ scenario. There was a 46% increase in seasonal fire severity rating along with an increase in area burned by 44% under the $2\times CO_2$ scenario for Canada (Flannigan and Van Wagner, 1991). Bergeron and Flannigan (1995) studied these phenomena in detail using empirical daily data from the Canadian Atmospheric Environment Services' General Circulation Model for $1\times CO_2$ and $2\times CO_2$ scenarios and calculated components of Canadian FWI system. They showed that effects of climate change on fire regime could not be generalized for the entire country due to that fact that the effects varied from region to region. For example, the average FWI decreased over most of the eastern Canada and increased over western Canada. Paradoxically, there has been a decrease in fire frequency in Canada since the end of the little ice age in 1850 which Flannigan et al. (1998) related to fire suppression activities. Recently, Flannigan et al. (2005) studied weather, FWI system components and potential area burned in Canada for different ecozones. They suggested that area burned will increase by between 74 to 118% in all ecozones by the end of this century in a $3\times CO_2$ scenario. Most recent studies by Yue et al. (2015) with 13 different climate models under the A1B scenario [a future world of very rapid economic growth, rapid introduction of new and more efficient technologies with a balance of fossil-intensive and nonfossil energy sources as described in Solomon et al. (2007)] had predicted more severe area burned in Canada and Alaska for the 2046-2065 period. According to them, almost all models predicted increase up to 150-390% of which varied with ecoregions. They backed up their prediction with two important causes which together created favorable conditions for wildfire spread: firstly increased surface temperature and secondly 500 hPa geopotential heights relative to the present day. Lowering of water tables due to climate change is also predicted to increase vulnerability of Canada's boreal peatlands to fire (Roulet et al., 1992).

In addition, several modelling studies have revealed that climate change could increase both human-caused and lightning-caused fire ignitions. Wotton et al. (2003) estimated that human-caused fire might increase by 18% by 2020 and 50% by 2100 in Ontario. Their study was based on daily projections of fire weather and fuel moisture from two GCMs (CCC GCM2 and HAdCM2). Increases in human-caused fire activity were also predicted for Alberta (36%), Saskatchewan (38%) and Manitoba (25%) (Wotton, 2001). In another study Wotton et al. (2005a) projected a 24% increase in lightning fire by 2040 and 80% by 2100 in Ontario due to climate change.

Changes in fire regimes due to climate change are expected to cause changes in vegetation composition in the boreal landscape. According to Flannigan et al. (1998) increased fire frequency over the southern boreal forest in central Canada could accelerate vegetation change from the present mixed-wood forest of aspen, poplar, birch, spruce and pine to an increase in the aspen/grassland mosaic presently bordering this forest. In contrast, if fire frequency decreases, shade-tolerant balsam fir might increase in abundance over the boreal forest of Eastern Canada. Assuming changes in fire regime and fire management strategies in a changing climate, de Groot et al. (2002) simulated the long-term impacts of fire suppression and prescribed burning on boreal forest of western Canada for the 2080-2100 period. They predicted that a longer fire cycle would favor late successional species such as white spruce, black spruce, and balsam fir whereas shorter fire cycles could favor early successional/pioneer species such as jack pine, and aspen at the expenses of white spruce. In addition, the projected increase in fire regime and area burned would escalate carbon emission rates and may exacerbate air quality. For example, forest fire emission had been predicted to increase mean surface ozone levels by 1 ppbv in western US, 3 ppbv in Canada and 5 ppbv for Alaska (Yue et al., 2015).

A wildfire might consume up to 25% of the pre-burn aboveground fuel load (de Groot et al., 2007) and up to 100% of the forest floor fuel load (Kasischke and Johnstone, 2005). For the period of 1959-1999 in Canada Amiro et al. (2001) estimated that the overall mean crown fuel consumption and surface fuel consumption were 0.37 kg/m^2 and 2.1 kg/m^2 respectively. Their results suggest that surface and ground fire may result in more carbon emission than crown fire. A surface fire is one that burns in the surface fuel layer while a crown fire advances through the crown fuel layer usually in conjunction with the surface fire. An intermittent crown fire (also known as a passive crown fire) is one in which trees discontinuously torch, but the rate of spread is controlled by the surface fire. In an active crown fire, fire advances with a well-defined wall of flame extending from the ground surface to above the crown fuel layer. The third category of crown fire is termed an independent crown fire which advances in the crown fuel layer only (CIFFC, 2003). An active crown fire can occur if three conditions are fulfilled – ground fuel permits development of surface fire, the crown base is moderately high above the ground and the crown layer is continuous with moderate to high bulk density as well as low to normal foliar moisture content (Van Wagner, 1977).

Ground fires occur in the duff layer and it spread very slowly without any visible flame. Duff layer, defined as the organic matter on the forest floor in fermentation (F) layers by Canada Soil Survey Committee (1978), is derived from decomposing litter such as leaves and twigs from the trees, shrubs, and herbaceous plants as well as from mosses (Miyanishi and Johnson, 2002). The degree of duff decomposition gradually increases with depth making duff a very heterogeneous material vertically. Spatial variability in duff is also influenced by canopy type and tree proximity (Raaflaub, 2011). It often constitutes the largest single fuel fraction in the natural stands and is the most uniform of all components of the surface and ground fuels.

Chemically, duff is largely composed of cellulose, hemicellulose and lignin (Mason, 1976). The amount of cellulose, hemicellulose and lignin varies between the F layer and the underlying humus (H) layer. Since cellulose and hemicellulose decompose faster than lignin, duff contains relatively higher amounts of lignin. The deeper the duff depth the lower the cellulose and hemicellulose content in the duff. Likewise, lignin content is higher in the H layer than in the F layer. The F and H layers also differ in physical characteristics such as bulk density (Miyanishi, 2001). These differences in chemical composition affect duff smoldering and duff consumption.

Although it is a common phenomenon in duff, smoldering combustion may also occur in woody fuels and peat (Watts and Kobziar, 2013). In a wildfire, the duff layer is mostly consumed by smoldering combustion. A thin layer from the upper duff can be consumed by flaming combustion; however deeper layers of more decomposed and compacted duff are unlikely to undergo self-sustaining flaming combustion due to the presence of higher lignin in deeper layers which is not readily volatilized and which produces higher char than cellulose when heated (Rothermel, 1976; Shafizadeh and DeGroot, 1976; Shafizadeh and Sekiguchi, 1984). Also, the latent heat of vaporization required to drive off the moisture in the duff may act as a large heat sink which slows down the rate of its heating by the flaming front. Furthermore, the rate of heat release from a spreading fire depends on the packing ratio (fraction of fuel array volume occupied by fuel or ratio of fuel array bulk density to fuel particle density) of the duff layer. The rate of heat release decreases when packing ratio approaches 10% (Rothermel, 1972) and since duff has packing ratios greater than 10% (Frandsen, 1991), the rate of heat generation by its oxidation is generally insufficient to sustain flaming combustion.

The duration of duff smoldering is longer when duff moisture is lower and vice versa as had been depicted by Varner (2005) in both experimental and observed burns in long-unburned longleaf pine forests at Eglin Air Force Base in Florida Panhandle, USA. The heterogeneity of duff consumption occurs due to the spatial pattern of duff on the forest floor (Kreye et al., 2014). Severe and deep burning duff results in smoke production and impaired vegetation re-growth (Otway et al., 2006). In boreal mixed forests, longer duration smoldering combustion may cause long-duration heating to stems and organic and underlying mineral soil which can damage or kill roots of aspen and other species (Swezy and Agee, 1991). However, duff consumption is very critical in boreal forest landscape since it helps seeds come in contact of soil for germination and growth. Severe duff consumption may lead to burning of seeds, therefore, may influence post-fire density and species composition of trees, shrubs and herbs (Miyanishi, 2001). Furthermore, duff consumption is the largest contributor of smoke production and has a large impact on soil nutrient cycling (Neary et al., 1999).

Physical characteristics of duff such as depth, bulk density, mineral content, and moisture content influence the ignition and spread of smoldering fires more than does weather (Kreye et al., 2014; Miyanishi and Johnson, 2002). Duff depth is a function of litter input and decomposition and varies both between and within stands (Miyanishi and Johnson, 2002). Stocks (1970) found that as drying continues duff in lower depths exhibits higher moisture content. He also concluded that duff dries out from the top downward, which means that "the moisture content of all layers decreases with increasing time after rain, but the moisture content of each layer decreases more than that of the layer directly below it". He related this inversion characteristic of duff moisture at different duff layers to physical or chemical properties of the humus layer. He postulated that duff in the humus layer was incapable of holding more water than the layers above it. Otway et al. (2007) also described inversion characteristics of duff moisture in the duff and mineral soil layers at Elk Island National Park which they assumed could have been caused by a residual forest soil moisture deficit initiated during 2002 and maintained through the 2003 fire season. This indicates that duff depth can be one of the important determinants of duff moisture at a particular point of time and that a thicker duff layer may be associated with higher duff moisture. Miyanishi and Johnson (2002) found a positive relationship between duff depth, moisture content and smoldering propagation. In the event of low moisture contents smoldering can be propagated in even very thin duff, whereas a thicker duff depth is necessary to propagate smoldering when duff moisture is high (Miyanishi and Johnson, 2002). Duff depth influences the proportion of heat generated by char oxidation that is lost through convection in smoldering propagation and it also positively related to duff moisture (Miyanishi and Johnson, 2002). Hille and Stephens (2005) found that duff depth was larger closer to trees than between trees, primarily due to increased litter fall directly beneath canopies. Duff inorganic materials also influence duff consumption. For example, inorganic material within the peat moss restricts duff consumption since it absorbs heat that could otherwise contribute to the vaporization of water (Frandsen, 1987). Duff bulk density is also an important factor in heat transfer in the smoldering process and influences the rate of drying in the absence of precipitation. In addition, fuel loading influences fire behaviour. For example, increased fuel loading was observed to increase flame length (49-90 cm) and fireline intensity (183-773 kJ/m/s) in an experimental burning at masticates sites in pine flatwoods forests in northern Florida (Kreye et al., 2013). They also found that higher fuel loading results in higher soil temperature. Similar results were also found by Graham and McCarthy (2006). Fuel loading has also been highly correlated with fuel consumption in experimental ($r = 0.798$) and wild fires ($r = 0.476$) in eastern Canada (de Groot et al., 2009).

Of these factors (duff depth, mineral content, bulk density and moisture content), moisture content is the most variable and influences duff consumption strongly during a fire. According to Kittredge (1948) absorbance of moisture in F- and H- layers together reach up to 600% of their dry weight of water. Duff moisture determines the amount of heat required to vaporize the water and raise the temperature of the fuel to ignition temperature (Frandsen, 1987). Meteorological conditions that influence duff moisture content include relative humidity, precipitation (including fog and dew), solar radiation, air temperature, and canopy interception (Nelson Jr., 2001).

Conspicuous duff moisture variability may occur temporarily and spatially in a forest type (Raaflaub and Valeo, 2008; Stocks, 1970). According to Raaflaub (2011), the factors that cause spatial variation of duff moisture are not well understood. The mixed nature of the boreal forest, interspersed by areas of wetland-upland mosaic (muskeg and vast bogs), generates its own type of spatial variability (Raaflaub, 2011). Spatial variation in duff moisture can be influenced by precipitation throughfall, which is related to overstory canopy structure and understory vegetation (Hille and Stephens, 2005). For example, dense canopies in lodgepole pine and white spruce stands resulted in high interception and lead to fine-scale variation in duff moisture (Raaflaub and Valeo, 2008), which is not the case in trembling aspen forest (Matthews, 2014). Many other researchers report that within stand variation in interception results in drier duff under conifer tree crowns than at the edge of a tree crown or in a gap (Chrosciewicz, 1989a; Miyanishi and Johnson, 2002). Canopy interception of precipitation has also been found to influence duff moisture content on pine hillslopes with thinner duff at the Marmot Basin Research Watershed located in the Kananaskis Valley, Alberta (Johnson et al., 2013; Keith et al., 2010). They also reported that lateral redistribution of moisture during periods of high precipitation was more important at spruce hillslopes with thicker duff layers although canopy interception and evaporation were still important factors. Basically, horizontal movement of water through soils is controlled by capillary forces. High porosity in duff produces weak capillary forces, and results in poor horizontal movement of water (Tiktak and Bouten, 1992). However, lateral movement of water occurs downslope due to gravitational forces and collection of water in depressions making downslope areas wetter than the top slope (Potts et al., 1983). Generally, duff at the base of hillslopes has higher MC than the duff located upslope (Miyanishi and Johnson, 2002). In addition, moisture content of soil directly below duff may influence duff moisture. However, studies on this interaction between duff moisture and soil moisture have been very limited (Raaflaub and Valeo, 2009).

Spatial variation in duff moisture can also occur differently in the litter, cones and woody fuels found in the same stand. In their study in Jeffrey pine-white fir forests of the Lake Tahoe Basin, USA, Banwell et al. (2013) found that duff moisture varied spatially within stands whereas moisture in the litter, cones and woody fuels did not vary spatially. Aspect also significantly affects duff moisture. For example, Otway et al. (2007) and Keith et al. (2010) reported that south-facing sites consisting of both aspen and lodgepole pine dominated stands were comparatively drier than north-facing sites. At larger scales (such as hillslope scale), atmospheric processes are responsible for duff moisture variability (Keith et al., 2010). Seasonal variation in duff moisture commonly occurs as a result of seasonal patterns of temperature and precipitation. For example, duff moisture was lower in summer than in the spring and fall in a trembling aspen stand in Elk National Park, Alberta (Otway et al., 2007).

The emerging response to wildfire is manifested by a clear shift in the forest management paradigms from an extensive clear-cut harvesting to retention and emulation of natural disturbance (END) in Alberta (EMEND, 2014) , British Columbia (Andison and Peter, 1999; Nitschke, 2005), Ontario (Kramkowski, 2012), and the USA (Aubry et al., 2009; Long, 2009). Conceptually, emulation silviculture is related to silvicultural techniques that try to imitate natural disturbances (McRae et al., 2001) through retaining forest structure that typically remains following the fire. Forest policies in Ontario and British Columbia has been revisited in support of END, and Alberta supports retention systems including aspen overstory harvest with understory white spruce protection (Thorpe and Thomas, 2007) and retention of live tree patches. The central objective of END approaches is to find a way to maintain and restore biodiversity and other ecosystem functions at pre-disturbance levels (Work et al., 2010) while allowing for harvesting (Nitschke, 2005), biodiversity conservation (Thorpe and Thomas, 2007), and maintaining spatial and structural integrity (McRae et al., 2001) In addition, fuel treatments and other silvicultural practices have been extensively used as a means to limit the size and intensity of surface and crown fire (Agee and Skinner, 2005; Keyes, 2002; Peterson et al., 2001; Stephens and Moghaddas, 2005). While there are many positive responses of END to achieving these objectives, we have no scientific information on how retention sites may respond to future fire events.

Various levels of retention harvesting have been tested in North America. For example, the Demonstration of Ecosystem Management Options (DEMO) study in the Pacific Northwest region of USA tested effects of 75% aggregated, 40% aggregated, 40% dispersed, 15% aggregated, and 15% dispersed retention levels (Aubry et al., 2009). In Ontario, the suggested percentage of internal and peninsular patch residual varies by forest type in the range of 2-8% and 8-28% respectively (OMNR, 2001). Alberta’s landmark END research project, Ecosystem Management Emulating Natural Disturbance (EMEND), has been testing the effectiveness of END at 0-2%, 10%, 20%, 50%, 75% and 100% (uncut) retention levels (EMEND, 2014).

Retention harvesting alters forest structure at the stand-level and age class diversity at the landscape level (Long, 2009). This eventually can result in a homogenous landscape at stand level and heterogeneous landscape at the landscape level. This spatial variability will result in variability in fuel loading, not only within the heterogeneous structure but also in homogenous structure (Clark et al., 2014). Apart from changes in canopy base height (CBH), canopy bulk density (CBD), and canopy depth (CD), harvesting will result in changes in leaf area index (LAI) which influences canopy interception and throughfall (Park and Cameron, 2008) and eventually variation in duff moisture. Transpiration rates of beech stands with similar LAI was found to be correlated in Hesse, France (Granier et al., 2000). According to Brown et al. (2014) canopy structure, and especially LAI, affects environmental factors such as radiation penetration, wind, atmospheric humidity (or VPD), and soil moisture. Due to these changes in composition and canopy characteristics, significant changes in duff physical characteristics are likely to occur on retention sites.

These stand structural changes may also influence processes such as evaporation and transpiration. Bladon et al. (2006) observed that potential evapotranspiration increased significantly at a retention site in a boreal mixedwood forest compared to a partially harvested stand and an unharvested control stand. This indicates faster drying rates and higher transpiration following harvesting, which can influence ignition and fire spread. While the Bladon et al. (2006) study provides a general understanding of evapotranspiration in retention sites, it does not quantify the effects of different levels of retention. Increased opening of the canopy due to a lower level of retention (e.g. 20% compared to 50% retention) can increase throughfall resulting in more duff moisture while also increasing wind circulation and radiation loading at the duff surface which will cause faster drying rates. Also, lower levels of retention may favor regeneration of aspen and other shrubs which may result in higher transpiration and also higher shading and interception. Since opening and vegetation regrowth will influence evaporation and transpiration in the retention sites, they are also expected to influence the quantity of duff moisture. To date END research has not explored the behaviour of retention sites to fire events. This information is critical to harmonize the objectives of END and fire management with the overarching goal of fire resilient sustainable forest management.

The Canadian Forest Fire Danger Rating System (CFFDRS) provides a system of evaluating and integrating individual factors that define the elements of fire danger in Canada. The CFFDRS includes two major components used throughout Canada during the fire season:

the Canadian Forest Fire Weather Index (FWI) System and the Canadian Forest Fire Behavior Prediction System (FBP) system (Figure 1-1).

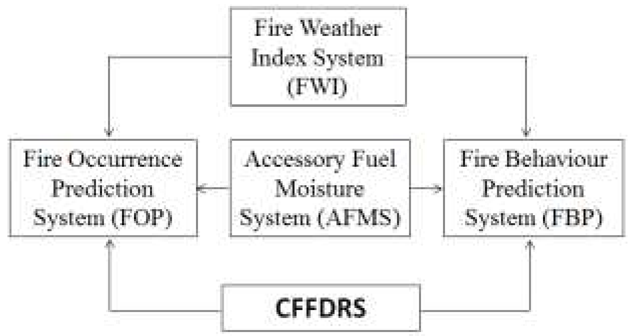

Figure 1-1: The basic structure of the Canadian Forest Fire Danger Rating System
(Forestry Canada Fire Danger Group, 1992)

The FWI System (Van Wagner, 1987) is a means of evaluating the severity of fire weather conditions in different forest types and provides for numerical ratings of fuel moisture in important fuel layers and several relative indices of fire behavior (Wotton, 2009). The FWI System output is used in the FBP System to provide a quantitative assessment of fire behavior in 16 major fuel types across Canada (Wotton, 2009). The FWI system is based on four climatological variables e.g. temperature, humidity, wind speed and direction, and rainfall. It consists of three fuel moisture codes (unitless) in order to track moisture content in different forest floor layers: duff moisture code (DMC), fine fuel moisture code (FFMC) and drought code (DC) (Figure 1-2).

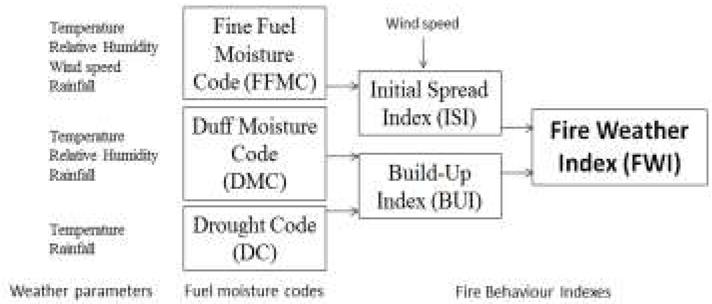

Figure 1-2: The structure of the Canadian Forest Fire Weather Index System (after Van Wagner, 1987)

The FWI system is designed to apply these three moisture codes in calculating three fire behavior indexes. The Initial Spread Index (ISI) provides for an estimate of spread rate and the Buildup Index (BUI) estimates fuel consumption. The final index, FWI, is a measure of fire intensity as energy output rate per unit length of fire front indicating fire danger. The FFMC corresponds to the moisture content of the litter and other cured fine fuels up to 1.2 cm depth with a fuel dry weight of 0.25 kg/m^2. Its value increases with increasing dryness and ranges from zero (0) at saturation (250% moisture content) to 101 (completely dry). FFMC determines the sustainability and vigor of surface fire spread (Forestry Canada Fire Danger Group, 1992). A simple exponential model of moisture exchange is the key to converting moisture values to code values. Calculation of FFMC for a particular day accounts for previous days FFMC which is converted back to moisture content (MC) via an standard equation below (Van Wagner, 1987).

$$MC = 147.2 * \frac{101 - FFMC}{59.5 + FFMC} \qquad (1)$$

Meanwhile, the DMC describes the moisture content of the forest floor organic matter in the top 7 cm of the forest floor in a mature jack or lodgepole pine stand with a fuel load of 5 kg/m^2 (Van Wagner 1987). It refers to the level of dryness of loosely compacted forest floor organic matter and depth of burn and it is important to the sustainability of smoldering and fuel consumption in the forest floor (Van Wagner, 1987). Like FFMC, moisture in this layer increases from a code value of 0 (saturation moisture content of 300%). While DMC values can reach up to 200 at equilibrium moisture content (20%), values over 150 are rarely seen (Wotton, 2009). Duff moisture content can be derived from the standard DMC equation below (Van Wagner, 1987).

$$MC = 20 + \ln\left(\frac{DMC - 244.73}{-43.43}\right) \tag{2}$$

In the FWI System, the DC (drought code) indicates extreme dryness and drought conditions which have the potential to make fire suppression more difficult and time-consuming. The atmosphere does not influence this layer directly but provides input through only rainfall. The DC tracks moisture in an 18 cm thick organic layer with a fuel load of 25 kg/m^2 as well as large down and dead woody debris on the forest floor. Similar to the DMC and FFMC, the moisture content of the layer modelled by the DC is converted to a code value where increasing values indicate increasing levels of dryness. A DC value of 0 corresponds to a saturation moisture content of 400% (Van Wagner, 1987). The maximum DC value is open, however values over 1,000 are extremely rare (Wotton, 2009). The DC value is often converted to moisture content (MC) using the following equation (Van Wagner, 1987).

$$MC = 400 * e^{\frac{-DC}{400}} \tag{3}$$

The equilibrium moisture content (EMC) and timelag are important moisture response characteristics of fine forest fuels which establish the moisture content at any time depending on the environmental conditions (Anderson et al., 1978). The time-lag is defined as the amount of time required for the fuel to lose $1 - e^{-1}$ (about 2/3) of the free moisture above equilibrium on a standard day (noon temperature of 21.1 ^{0}C , relative humidity of 45 %, 13 km/h wind, during the month of July) (Merrill and Alexander, 1987), where 'e' is the base of natural logarithms. On the contrary, EMC is defined as the moisture content fuel finally attains uniformly when exposed to an atmosphere of fixed temperature and humidity (Anderson et al., 1978). The slope of the exponential curve of moisture content over time, defined as log drying rate by Van Wagner (1987), can also be used to measure drying speed of fuel. In FWI systems, a simple moisture exchange model is used to calculate the three moisture codes (Wotton, 2009). Table 1-1 below summarized key properties of three fuel moisture codes including timelag at a noon temperature of 21.1 ^{0}C and relative humidity of 45% in July.

Table 1-1: Summary of properties of the FWI system's fuel moisture codes. Adapted from Van Wagner (1987)

Codes	Soil horizon	Timelag (days)	Water capacity (mm)	Rainfall thresholds (mm)	Nominal fuel depth (cm)	Nominal fuel load (kg/m^2)	Bulk density (kg/m^3)
FFMC	L	2/3	0.6	0.6	1.2	0.5	20.8
DMC	F	12	15	1.5	7	5	71.4
DC	H	52	100	2.9	18	25	140

Moisture code values for a specific day are calculated from the day's observed weather and the previous day's fuel moisture code values. Calculation of these codes does not consider mechanisms controlling the water budget (Johnson et al., 2013), instead, it accounts for weather variables such as temperature, relative humidity, precipitation and wind. Related to the focus of this study, duff moisture, DMC is of special importance. The DMC is defined for loosely compacted, decomposing organic matter with a nominal depth of ~7 cm (F layer) and bulk density of 71 kg/m^3 (Johnson et al., 2013). It was developed for red pine (*Pinus resinosa* Aiton), white pine (*Pinus strobes* Linn.), jack pine (Van Wagner, 1987) and aspen stands without regard to differences in duff depth and bulk density among other forest types.

In essence, duff characteristics such as duff depth and duff bulk density are crucial elements influencing variability in duff moisture between and within sites. In managed ecosystems such as those at EMEND, duff characteristics may differ due to changes in stand composition and canopy characteristics and lead to variability in duff moisture between retention levels. Changes in stand composition and canopy characteristics may also affect leaf area index (LAI) and rainfall interception. Various levels of retention may also influence the amount of fuel loading on the forest floor. According to Van Wagner (1970) an increase in fuel loading results in reduced drying rate of the fuelbed as a whole. In addition, increased opening due to retention harvesting may increase evaporation and drying. These and other factors may result in variable duff moisture regimes in retention landscape (Figure 1-3). Accurate predication of duff moisture is crucial to predicting fire danger and fire behavior as well as overall fire management.

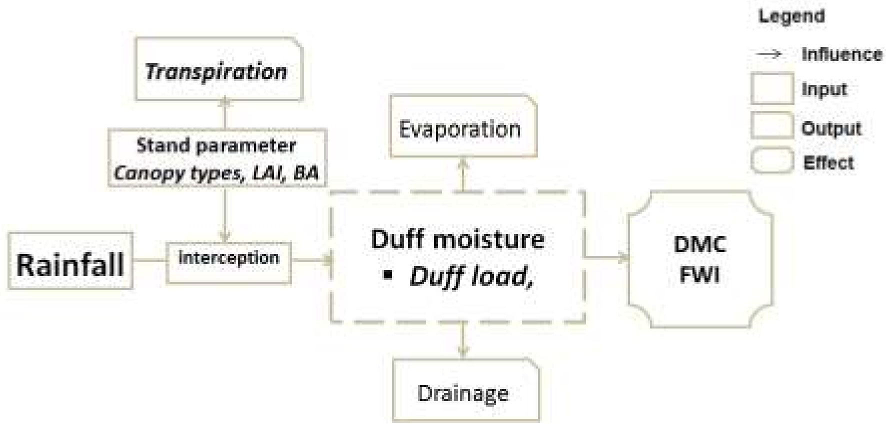

Figure 1-3: Conceptual diagram showing different component of the research objectives

1.1. Objectives

The overarching objective of this research was to explore the effect of retention harvesting on duff moisture dynamics and to calibrate the FWI system's DMC equation (Van Wagner, 1987) for conifer-dominated mixed forest with various levels of retention harvesting.

Objective 1: To examine the effects of retention levels on duff moisture.

Hypothesis 1.1: Duff moisture increases with decreasing levels of retention (i.e. 20% sites will have higher moisture content than that of 50% and 75% retention levels).

Hypothesis 1.2: Control plots might have lower duff moisture than other plots due to higher canopy interception and transpiration.

Objective 2: To explore whether duff characteristics such as duff load, duff depth and bulk density are related to duff moisture and whether these characteristics can be used to predict duff moisture.

Hypothesis 2.1: Increasing retention levels will decrease duff depth, density and load.

Objective 3: To explore whether stand characteristics such as LAI and basal area are related to duff moisture.

Hypothesis 3.1: Increasing LAI and BA with increasing retention level result in lower duff moisture.

Objective 4: To explore the effect of retention levels on transpiration loss and whether duff characteristics could be used to predict transpiration loss.

Hypothesis 4.1: Decreasing level of retention will reduce transpiration loss.

Objective 5: To explore whether observed duff moisture code (field-measured) is related to sensor-estimated DMC (sensor-DMC) and standard DMC (estimated by Eq. 2).

Hypothesis 5.1: There is no difference in DMC measured by these three methods.

1.2. Significance of the study

Duff moisture is function of many factors such as stand type, duff characteristics, weather variables, topography. To date, spatial and temporal variability of duff moisture in Canadian boreal forest have been studied fairly well but no study explored duff moisture dynamics in retention harvesting sites. Variable retention harvesting alters stand structure and influences stand characteristics such as LAI, duff characteristic such as depth, load, density and weather variables such as rainfall interception, evaporation, and radiation. Therefore, it is assumed that duff moisture may vary on retention sites compared to uncut (control) and clear-cut stands. This information will be useful to model fire behaviour, duff consumption and post-fire ecosystem dynamics in retention harvesting sites.

The standard DMC-MC equation (standard DMC-MC) (Eq. 2) used in the FWI system is suitable for predicting duff moisture status and assist in predicting fire danger along with other codes for most of the forest types including peatlands (Waddington et al., 2012) in Canada. However, local variation may exist due to variation in duff characteristics such as depth, bulk density and load, and stand composition. The DMC does not consider stand-specific characteristics such as LAI and duff characteristics in its calculation; rather it takes in to account duff moisture as the weather input. Variation in duff moisture can be attributed to the water holding capacity of duff which depends on the physical properties of duff. Duff depth varies from stand type to stand type. If the observed duff depth, load, and bulk density are larger than the duff depth (7cm), load (5 kg/m^2) and density (71.4 kg/m^3) assumed in the FWI system, the observed duff moisture might not match with that of standard MC (derived from FWI's standard-DMC equation). Even if duff depth, load and density are within the range of assumed values in FWI system, underestimation or overestimation of real duff moisture may occur due to differences in forest type. For example, standard DMC-equation derived duff moisture was underestimated in lodgepole pine forest when duff was drying and overestimated in Engelmann spruce forest during and after precipitation in the study conducted by (Johnson et al., 2013) in the Kananaskis Valley, Alberta.

As such, research has been conducted to calibrate Van Wagner's (1987) national DMC-MC equation for several forest floor types. For example, Chrosciewicz (1989a, 1989b) calibrated it for the prediction of forest-floor moisture content in jack pine cutovers and under jack pine canopy with Schreber's moss (*Pleurozium schreberi*) respectively in Saskatchewan and Hondo, Alberta. Lawson et al. (1997) showed that standard-DMC underestimated duff moisture when DMC values were below 40-55 for several stand type in British Columbia and Southern Yukon (pine/white spruce with feathermoss, pine-white spruce with reindeer lichen etc.) and provided overestimates when DMC values exceeded 55. In another experiment conducted in a mature jack pine stand in northern Ontario, Wotton et al. (2005b) showed that forest floor moisture content near the boles of dominant trees was overestimated by the standard DMC-MC model. They suggest that this anomaly resulted from tree canopies affecting throughfall. Based on their research, they developed a new DMC-MC relationship for extremely sheltered locations (within

0.5 m of the boles). Similarly, Wilmore (2001) also found that field measured duff moisture values did not fully match with those provided by the standard DMC-MC model in Alaska's black spruce feather moss due to hydraulic properties of the bulk density of feather moss.

Currently, we do not know if duff moisture estimated using the standard DMC-MC equation matches with actual duff moisture in boreal retention harvesting sites. By measuring duff characteristics e.g. duff depth, load and bulk density along with LAI and basal area, this research will address whether these parameters are related and whether they are useful in predicting duff moisture. This research will also explore whether various levels of retention harvesting influence duff moisture.

Chapter 2. Materials and Methods

2.1. Description of EMEND study area

This study was conducted at the Ecosystem Management Emulating Natural Disturbance (EMEND) experiment station located near Peace River, Alberta (Figure 2-1). EMEND is located in the Clear Hills Upland Ecoregion within the Boreal Plains Ecozone in Alberta, approximately 90 km North-West of Peace River. The site is approximately 24 km^2 and the elevation ranges from 677 to 880 m above sea level (Work et al., 2010). This area corresponds to the Lower Foothills Natural Subregion of Alberta. The area extends from approximately 56º44'N to 56º51'N and from 118º19'W to 118º27'W (Kishchuk, 2004). The climate in this ecoregion is characterized by cool, short summers and cold winters with severe temperatures moderated by frequent chinooks. While the mean annual temperature can be as low as ~ -0.5 ℃, the mean summer and winter temperature is ~13 ℃ and ~ -17.5 ℃, respectively. Mean annual precipitation ranges between 400 and 600 mm and permafrost is limited to isolated patches along the northern boundary of the ecoregion (Ecological Stratification Working Group, 1995).

Developed on fine-textured glacial till or glaciolacustrine deposits containing few coarse fragments, the soils of EMEND sites were classified primarily as Luvisolic, with the limited occurrence of Brunisolic, Gleysolic, and Solonetzic soils (Kishchuk, 2004). The soils were generally well drained and were relatively consistent across the entire 1000-ha experimental area (Kishchuk, 2004).

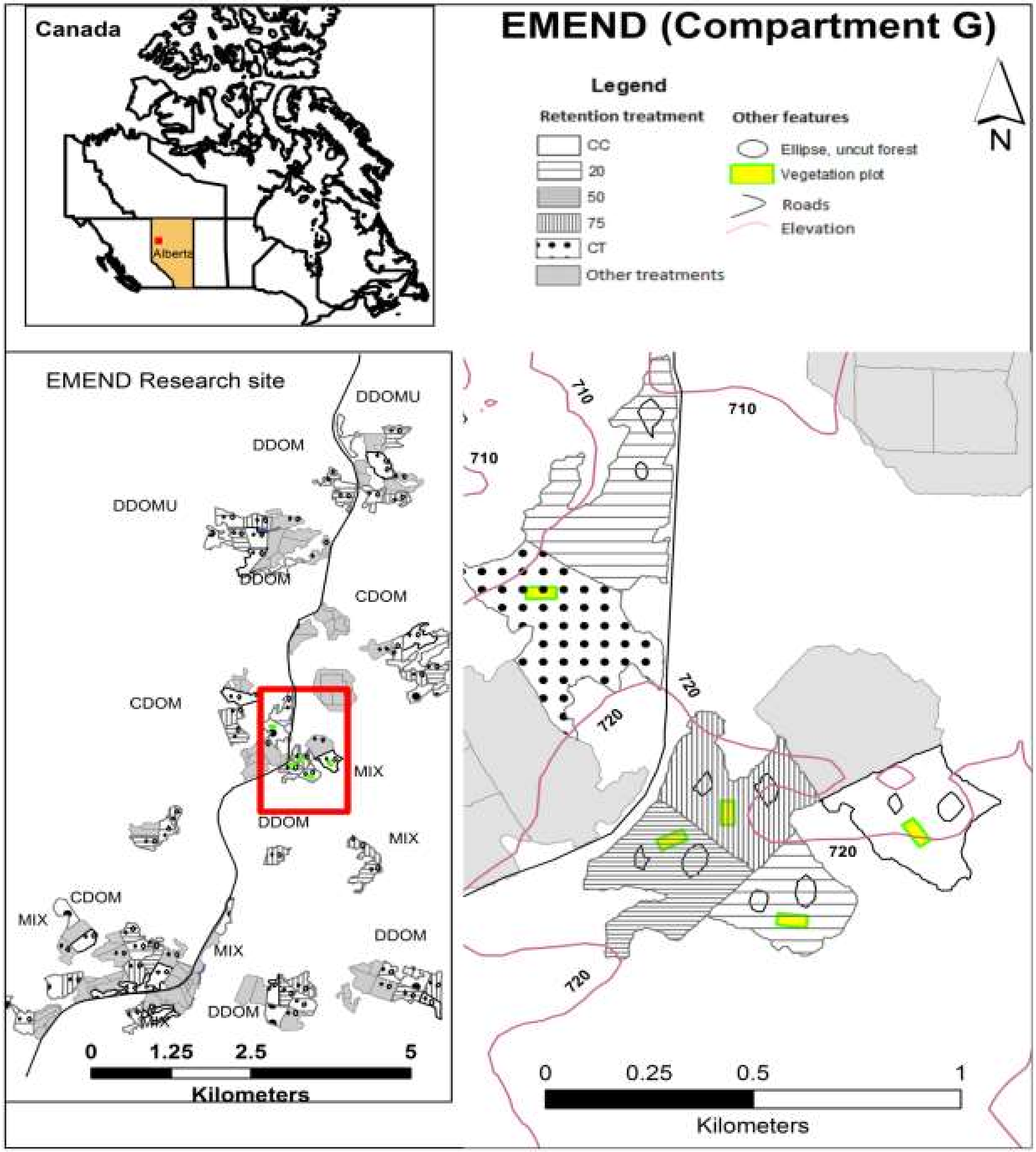

Figure 2-1: EMEND experimental station, near Peace River, Alberta illustrating cover types – CDOM (conifer dominated), DDOM (Deciduous dominated), DDOMU (Deciduous canopy dominated, developing conifer understory) and Mixed (Deciduous and coniferous canopy). Projection: NAD 1927 UTM Zone 11 North. (Source: base map was provided by Daishowa-Marubeni International Limited, one of the partners of EMEND project)

The EMEND project has been a joint effort among scientists at the University of Alberta, Northern Forestry Centre, Forest Engineering Research Institute of Canada, Alberta Research Council, representatives of the Alberta Lands and Forest Service, and foresters working for Canadian Forest Products Ltd. and Daishowa-Marubeni International Ltd. Alberta Vegetation Inventory maps were used to select composite forest polygons in 1997 within the Forest Management Agreement area granted to Daishowa–Marubeni International.

The overarching objective of EMEND experiment was to test the interaction among stand cover types, forest harvesting, and prescribed wildfire through stand-level manipulations of standing green-tree retention. There were two main variables: forest cover types (4 cover types) and amount of living residual retained after harvest (5 harvest treatments) (Spence et al., 1999). In addition, there were two fire treatments (prescribed burns on unharvested stands and 10% harvest with slash burn) and one 100% green-tree retention (uncut control). These variables formed a 4x8 factorial experimental design with three replications applied to each stand type in compartments of approximately 10 ha. Four cover types representing the major successional stages of the boreal mixedwood forest in this area (Lieffers et al., 1996) include (i) Early successional deciduous-dominated stand types (DDOM) having 70-95% deciduous trees in the canopy. Dominant deciduous tree species are aspen (*Populus tremuloides* Michx,) and balsam poplar (*Populus balsamifera* L.,) with minor elements of paper birch (*Betula papyrifera* Marshall); (ii) Late-successional coniferous-dominated cover class (CDOM) consisted of stands with 70-95% coniferous trees (*Picea glauca)* in the canopy; (iii) Stands with a deciduous canopy and a developing conifer understory (DDOMU) dominated by white spruce (*Picea glauca* (Moench) Voss), with minor elements of black spruce (*Picea mariana* (P. Mill.) B.S.P.), balsam fir (*Abies balsamea* (L.) P. Mill.), and lodgepole pine (*Pinus contorta* Dougl.) with at least 50% of canopy height representing the early–mid-succession stand types; (iv) Mixedwood stand with 35-65% each white spruce and aspen. The second variable, level of retention, was designed for experimental manipulation as follows: (a) 0%, clear-cut; (b) 10%; (c) 20%; (d) 50%; and (e) 75%. All harvested treatments above contained two ellipses of un-cut forest, one ~0.25 ha and the other ~0.5 ha to provide internal controls for each compartment while serving to test their utility in retention of biodiversity (Spence et al., 1999).

All harvesting treatments were applied consistently as per prescription in the winter of 1998–1999 using feller-buncher harvesting machines. These machines operated in a north–south direction so that leave strips were oriented perpendicular to the prevailing winds (Figure 2-2). Simply cutting the machine corridors created a 75% retention treatment (Work et al., 2004). The other retention treatments were created by removing an additional number of stems (>5 cm DBH) from the vegetation corridors at the following ratios (cut : left): (a) 1:2 for 50% retention, (b) 3:1 for 20% retention, and (c) 7:1 for 10% retention (Work et al., 2010).

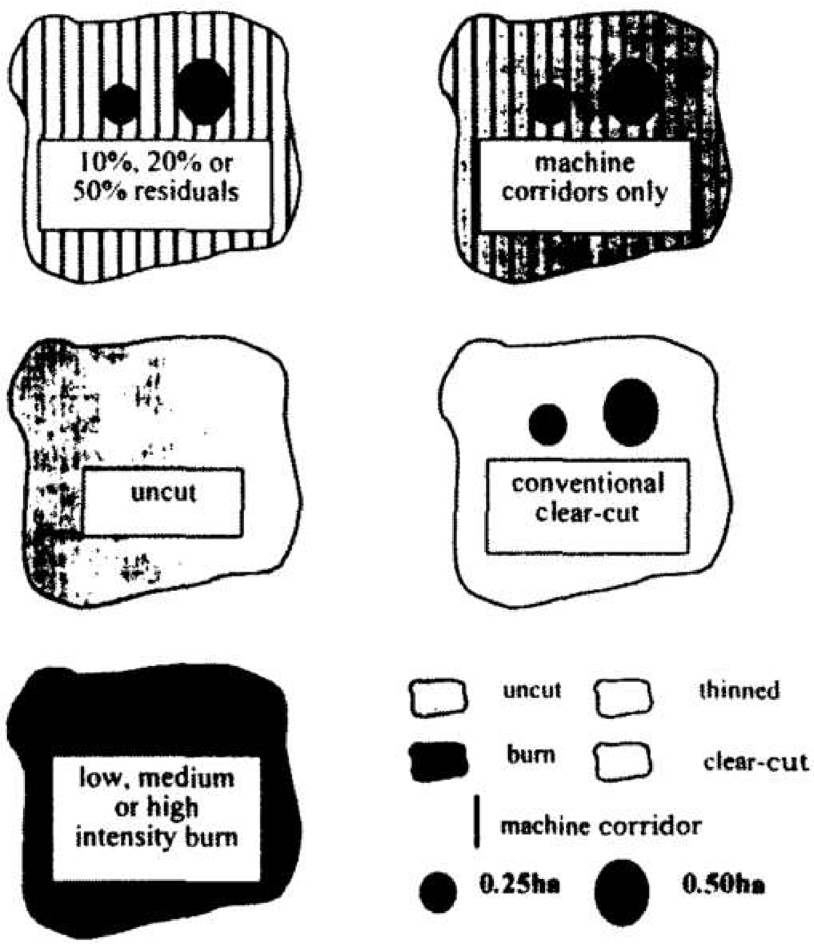

Figure 2-2: EMEND harvesting treatment; source (Spence et al., 1999)

Fire occurrence and area burned varied spatially within and between Natural Regions in Alberta (Tymstra et al., 2005). Most of the fires occurred in Boreal Forest Natural Region (62%).

The Foothills Natural Region in which EMEND site is located had the second highest (~ 31%) fire occurrences for this period followed by the Rocky Mountain (6%) and Canadian Shield (~2%), Grassland (0.06%) and Parkland (0.21%) Natural Regions. The average wildfire size in the EMEND study area (Lower Foothill Subregions) was 76.65 ha per year. On the other hand, the highest wildfire size (average) was found in Athabasca Plain (over 2400 ha). Basic fire characteristic of Alberta and Lower Foot Hill region areas are summarized in Table 2-1.

Table 2-1: Basic wildfire regime for the EMEND site representing Lower Foothills Subregion and Alberta for 1961-2002 period, based on (from Tymstra et al., 2005)

	Alberta	Lower Foothills
Average wildfires/year	843	176
Average area burned/year	142,793 ha	13,516 ha
Average 'Class E' fire/year	17	2
Human caused fire,	48.3 %	53.2 %
Lightning caused fire	49.3 %	44.3%
Peak fire season	May-August	April-August
Average wildfire/10^6 ha/year	21.47	27.5
Average wildfire size, ha	171 ha	77 ha
Annual are burn rate, %	0.37%	0.21 %
Fire cycle, years	273 years	475 years
Fire regime	Boreal NR: Frequent, large, high-intensity fire East slopes: Infrequent, large, low to medium intensity fire	Frequent medium sized wildfire

2.2. Field sampling

2.2.1. Duff sampling protocol

Duff sampling was carried out in June, July and August 2014 in order to explore relationships between duff moisture with duff characteristics (depth, load, bulk density) and stand characteristics across four levels of retention in a conifer-dominated (70% white spruce) stand. The four levels of retention sampled were: 20% (compartment # 910), 50% (compartment

911), 75% - retention (compartment # 912), clear cut (compartment #914) and, uncut (control, compartment # 918). Each treatment block was approximately 300m×300m with a machine corridor of variable size separating blocks from each other. Duff samples were collected at 5 m intervals along three 40 m transects established in each retention block and oriented perpendicular to machine corridors. Existing EMEND transects were used as a reference point to set up transects for this study. Three EMEND transects were randomly chosen from every compartment (Table 2.2). Duff transects were laid 20m south of the EMEND transect and in parallel to the chosen EMEND transect in order to avoid disturbance to the EMEND research (Figure 3). In this way, a total of 15 transects were established including 910P8, 910P4, 910P9, 911P4, 911P8, 911P5, 912P1, 912P3, 912P5, 914P4, 914P7, 914P8, 918P1, 918P3, and 918P8. When any transect came within 10m from the 'no cut patch' or another nearby EMEND-transect, it was moved to the northern side. To avoid edge effects, transects were established at least 40m inward from the edge of treatment blocks (Cape et al., 1991).

Table 2-2: Choosing PSP's through random numbers

Retention level	Existing PSP (assigned random number)	Chosen PSP
20%	P3 (1), P4(2), P7(3), P8(4), P9(5)	P4(2), P8(4), P9 (5)
50%	P3(1), P4(2), P5(3), P6(4), P7(5), P8(6)	P8(6), P4(2), P5(3)
75%	P2(1),P3(2), P4(3), P5(4), P6(5), P7(6)	P3(2), P2(1), P5(4)
Uncut (Control)	P1(1), P2(2), P3(3), P4(4), P5(5)	P2(2), P1(1), P4(4),
Clear cut	P3(1), P4(2), P5(3), P7(4), P8(5), P9(6)	P7(4), P8(5), P3(1)

2.2.2. Transpiration loss sampling protocol

In order to study the effects of retention levels on transpiration loss, trenched plots with trenches 50cm long × 50cm wide × 30cm deep were established at points located every 5 m along each transect on the left side of the transect start point, within 1m from the transect line unless otherwise obstructed by fallen trees (Appendix C). This provided 9 trenched plots per transect, 27 trenched plots in a compartment and 135 for the study (Figure 2-3). Tree roots were cut to a depth of 30 cm and litter from the trench was removed.

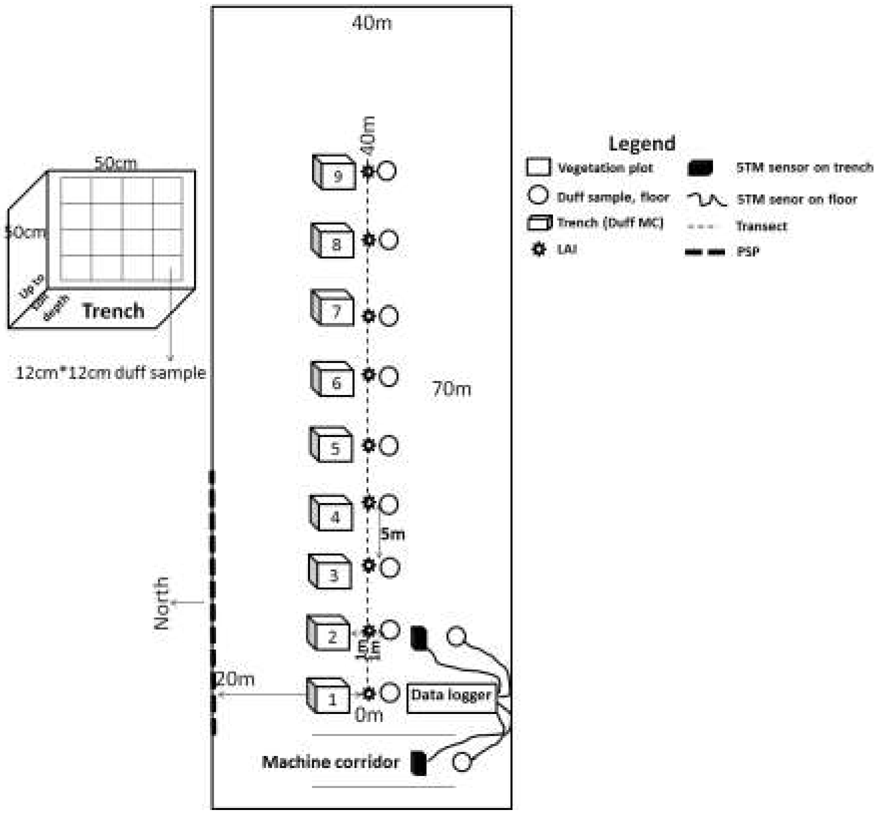

Figure 2-3: Detailed sampling layout depicting a transect, vegetation plot, trenches, duff sampling points and sensors position. Transect was used to record duff characteristics and moisture at nine points along its length. Trench was used to record duff characteristics and moisture and to calculate transpiration loss. Vegetation plot was used for vegetation sampling. Sensor was used to estimate duff moisture.

5TM Soil Moisture and Temperature sensors (Decagon Devices, 2012a) were used to measure field duff moisture. Four sensors, connected to Em50 data loggers (Decagon Devices, 2012b), were installed in one randomly selected compartment in each retention level. Two of the four sensors were installed under forest canopy (one in the trench and one in the floor) and the remaining two sensors were installed in the retention corridor (one in the trench and one in the floor). The purpose of placing sensors under the canopy and in the corridor was to document differences in duff moisture. All sensors were installed horizontally, in the middle of the duff layer. For example, if the duff depth were 6cm, the sensor was installed 3 cm from the top. Precaution was taken to insert the sensor prong fully into the duff. The data logger recorded readings every 10 minutes for the entire duration of the study period.

The 5TM sensor uses an oscillator running at 70 MHz oscillating wave to the sensor prongs that charge according to the dielectric of the material. The stored charge is proportional to soil dielectric and soil volumetric water content (Decagon Devices, 2012a). A properly installed 5TM sensor in a normal mineral soil provides estimates with an error of ±3% VWC (Decagon Devices, 2012a). The recorded VWC is multiplied by 100 to convert it to percentage moisture content.

2.2.3. Vegetation sampling

With the objective to understand effects of species composition, five rectangular (70m×30m) vegetation plots (one in each retention compartment) were established. These plots were established in such a way that previously established duff transects were located in the middle of the plot. Each vegetation plot was established in the following way (Figure 2-4).

- Plot establishment started from the transect start point from where a straight line of 15m was taken towards the south at an angle of 90° with respect to transect line.
- A second straight line was taken at 45° angles (S-W) and a distance of 21.21 m was measured and marked with a ranging rod which served the first corner of the plot.
- For the second corner, another 21.21 m distance was measured and marked at angle of 45° in N-W direction.
- The other two corners were established from transect end point with the same procedure above.
- All four corners were marked with ranging rods.

In order to record locations (x and y-coordinates) of every tree, 14 grids of equal size (10m×15m) were established. The survey started from S-W corner (corner 1) and moved towards N-E corner (corner 2) in the order of grid 1, grid 2, and grid 3 and so on. In every grid, 10 1m×15m horizontal swath lines were established. During sampling, a ribbon was always placed along the swath lines and was marked at 50 cm intervals for the entire 15 m distance to facilitate recording X coordinates. A measuring tape was placed along the Y-axis to facilitate recording Y-coordinates of individual trees. Actual tree measurement was undertaken in this rectangle

(1m×15m). First, trees within this rectangle were marked with a ribbon affixed around the bole and given a unique identification number. Two crews were involved in the survey. Crew 1 always stayed around starting point (0 at X-coordinate) corner. Crew 2 always moved from one tree to another and called out the X- and Y-coordinate to crew 1 who record in the writing book. A diameter tape was used to measure DBH over-bark at 1.35 m for all trees 10cm or larger in diameter. A Suunto clinometer was used to measure height (using percent scale) of the trees with the methodology described in SUUNTO user manual (SUUNTO, 2014). A Suunto field compass was used to take bearings for the corners and swath. A 30 m measuring tape was used to measure the horizontal distance.

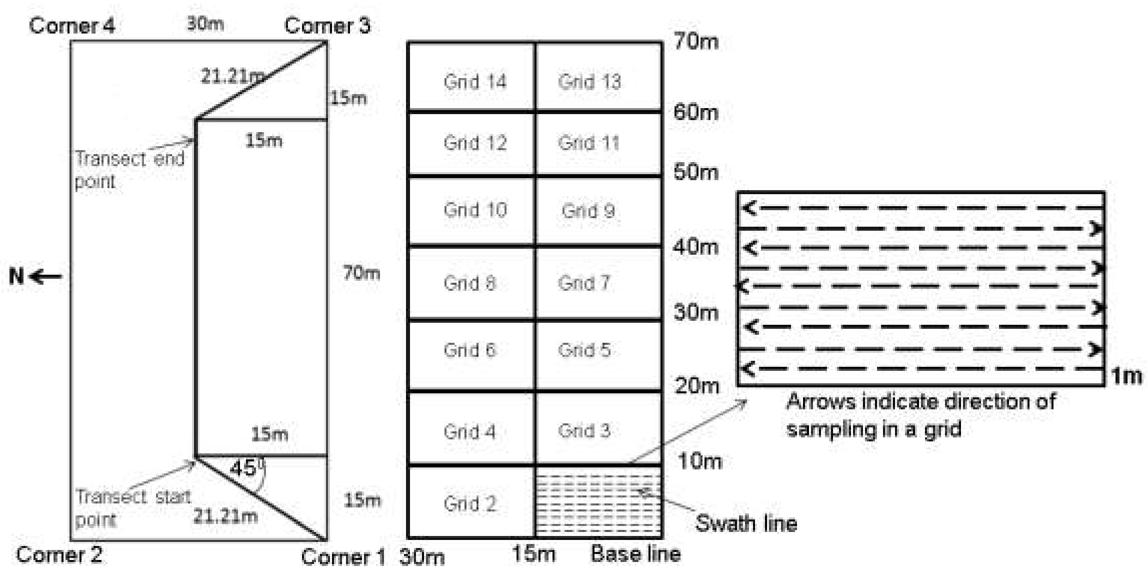

Figure 2-4: Vegetation sampling layout

2.2.4. Leaf Area Index

Leaf Area Index (LA) is the total one-sided area of leaf tissue per unit ground surface area (Bréda, 2003; LICOR, 2009). LAI was measured in August using an LAI-2200 Plant Canopy Analyzer (LICOR, 2009) at every duff sampling point along each transect on a cloudy day. Below canopy readings were taken at every point in each of four cardinal directions at 0.8 m height above the ground. The above canopy reading was taken in a clearing that was large enough for an unrestricted view of the sky. If the clearing is greater than 3 times the height of the tallest surrounding vegetation, the clearing is of acceptable size (Law et al., 2008). No view restricting cap was used. Measurements were taken ~80 cm above the ground with appropriate precaution so that grasses or shrubs do not restrict the view. Since the distance between two successive LAI in the same transects was 5 m, there were chances of overlapping of measured LAI. In order to rule out overlapping of the area covered FV2200 v1 software was used to recompute LAI using only mask 1 (first ring, 70°-90°).

2.2.5. Canopy overstory density

A spherical Densiometer (concave) was used for estimating forest overstory canopy density. This pocket-type instrument has a spherical mirror that views a large overhead area (Lemon, 1956).

Readings were taken at every duff sample point (5 m interval) along transect in the study area. The densiometer has 24 quarter-inch squares and the users need to imagine four equally spaced dots in each square (Lemon, 1956). The unoccupied dots observed in the field were multiplied by 1.04 to obtain the percent of overhead area not occupied by the canopy. This figure, when deducted from 100 provides the overstory density (crown closure). Overstory density measured in plots was averaged to give overstory density of a compartment.

2.3. Measurements and estimation of variables

2.3.1. Duff moisture measurement

At each sample point, duff depth was measured with a ruler to two decimal places. Duff samples (12cm×12cm×up to mineral soil) were collected from both trench (herein trench duff) and forest floor (herein floor duff). Transect lines served as the reference for duff collection. Floor duff was collected from the right of transect line and trench duff was collected from the left. Samples were usually collected within 1m from the transect line. In my study, litter and moss layers were excluded from the measurement of duff depth.

The Canadian fire weather index (FWI) system calculates its four parameters e.g. standardized weather reading of dry-bulb temperature, relatively humidity (measured at 1.4 m above the ground in a radiation shielded screen), wind speed in the open at 10m height, and 24-hr accumulated precipitation at noon Local Standard Time (or 13:00 hour for day light saving time) from April to October to measure fire danger for the afternoon (until 16:00 hour) (Van Wagner, 1977). As such duff sampling was carried out between 12:00 and 16:00 hours. The sampling hour was extended for an additional hour up to 17:00 hour since Alberta has longer sun hours in summer. The sequence of duff sampling was determined using a random table to make sure that all transects had equal chances of being sampled at different hours throughout sampling duration. In addition, the FWI system considers the first 1.5 mm of precipitation to be intercepted by the forest canopy or evaporate from the forest floor before reaching the duff layer (Wotton et al., 2005b). Consequently, duff samples were collected when rainfall did not exceed 1.5 mm for the day and when there was no rainfall. Duff sampling was resumed on the second day following a rainy day (over 1.5 mm). Collected duff samples were weighed onsite (wet weight) using electronic balance and stored in ziploc plastic bag and, later dried in the oven at 105 ℃ for 24 hours before reweighing. Moisture content was calculated as follows:

$$Duff\ moisture\ (\%) = \left\{\frac{Wet\ weight - dry\ weight}{dry\ weight}\right\} (\theta_d) \times 100 \tag{4}$$

$$Duff\ moisture\ (mm) = \theta_d \times \frac{duff\ bulk\ density\ (kg.m^{-3})}{water\ density\ (kg.m^{-3})} \times duff\ depth\ (m) \times 1000 \tag{5}$$

In addition, bulk density and duff load was calculated as follows:

$$Bulk\ density\ (kg.m^{-3}) = \frac{dry\ sample\ weight\ (kg)}{Sample\ volume (m^3)} \tag{6}$$

$$duff\ load\ (kg.m^{-2}) = bulk\ density\ (kg.m^{-3}) \times duff\ depth (m) \tag{7}$$

2.3.1.1. Calibration of sensor data

Custom calibration is required to use the 5TM sensor in a porous medium such as duff (Decagon Devices, 2012a) which could be time-consuming. Instead, the 5TM sensor reading (percentage moisture content) recorded at a specific time in a specific day was calibrated against real duff moisture observed for the same time and the day. The duff sample collected for calibration was taken within 1 m from the sensor to ensure representativeness of both data. Simple regression analysis was conducted to calibrate sensor recorded duff moisture against the real field moisture content (Figure 2-5). The sensor moisture content explained approximately 73% of the variation in the field measured duff moisture (Table 2-3). Data were normal according to the Durbin-Watson test. Breusch-Pagan test confirmed that there was no violation of homoscedasticity. The regression equation derived from this calibration was used to convert sensor readings into duff moisture content.

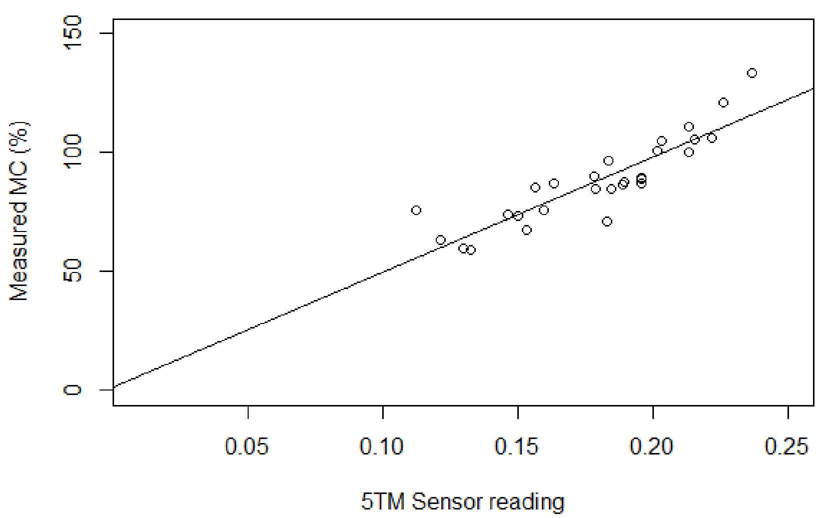

Figure 2-5: Calibration of the 5TM sensor reading against field measured duff moisture content. The line represents simple linear regression equation in Table 2-3.

Table 2-3: Simple linear regression statistics of sensor reading with field duff moisture

Intercept	Coefficient	R^2	Adjusted R^2	D-W test	BP test
1.56	482.52	.0783	0.775	DW = 2.2, p = 0.78, n = 28	BP=0.06, p = 0.8

2.3.2. Estimation of duff moisture code (DMC)

The Canadian national standard DMC equation was produced based on the field moisture content of duff observed mainly in red pine and jack pine stands at Petawawa, Ontario. In order to obtain moisture content data, Van Wagner (1987) placed large samples of duff including all material from the surface to mineral soil in a wire mesh container and inserted it in the ground with containers weighed daily from May through October. Calculation of DMC is based on the wetting and drying of the duff sample over a range of weather conditions (Van Wagner 1970) and was developed to track moisture exchange in the forest floor *of a closed canopy conifer stand away from the* very strong sheltering effects of the canopy of individual overstory trees. The assumption of the moisture exchange model for drying is as follows (Van Wagner, 1970):

1. Day to day drying in constant weather is exponential.
2. The duff layer has for all practical purposes, a constant equilibrium (hygroscopic) moisture content of 20 percent.
3. The logarithmic (log) drying rate is proportional to temperature, becoming negligible at about –1 ℃.
4. The logarithmic drying rate is proportional to the deficit in relative humidity.
5. The day length, varying with season, has an effect roughly proportional to 3 less than the number of hours between sunrise and sunset.

And the equation of exponential drying is (Van Wagner, 1970):

$$\log(M_0 - E) - \log(M - E) = kt \quad (8)$$

Where, M_0 , M, E, t, *and* k respectively refers to initial moisture content (%), final moisture content (%), equilibrium moisture content, time in days, and log drying rate in units of *log M* per day. In this equation, duff depth was kept constant (7cm). After the exponential drying rate was calculated, there is no need to consider the actual moisture content for given day. Equation 1 above finally takes the form:

$$wk = d(T - T_0) \times (100 - H) \times (L - L_0) \quad (9)$$

Where, *w, d, T, H, L,* T_0, L_0 respectively referred to oven-dry duff weight (lb/ft^2), regression constant, noon temperature, relative humidity (%), day length in hours (sunrise to sunset), constant representing periods of negligible drying at each end of the day.

wk in equation 9 is graphed successively against temperature, relative humidity deficit (100-H) and day length L, each time adjusting to the average value of the other variables using straight-line relationships obtained from the graphs (Van Wagner, 1970). After all adjustments, the final equation for the daily log drying rate of 1 lb/ft^2 duff layer was:

$$k = 0.1052\ (T - 30)(100 - H)\ L_e \times 10^{-6} \quad (10)$$

The assumption of the moisture exchange model for wetting is as follows (Van Wagner, 1970):

1. Increases in moisture content for a given rainfall are inversely proportional to the weight of the duff layer.
2. The increase in moisture content per inch of rain is inversely proportional to the amount of the rain.
3. The wetting efficiency of a rainfall decreases with increasing initial moisture content.

The DMC works as a simple bookkeeping system that adds points to the code value on drying days and subtracts them on wetting days. A DMC value is equated to moisture content (MC) with the following empirical equation developed from the pine duff fuels at Petawawa, Ontario (Van Wagner, 1987):

$$MC = \ln\left[\frac{DMC - 244.7}{-43.4}\right] + 20 \quad (11)$$

Where, the constant *20* is the theoretical equilibrium moisture content of the F-horizon.

In this research, the field measured moisture content was converted to DMC using national DMC equation applicable to white spruce / feather moss dominated stands (Hrobak, 2004; Lawson et al., 1997) as follows:

$$\mathrm{DMC} = \{(\ln(\mathrm{MC}) * (-20.9))\} + 149.6 \tag{12}$$

This equation has been used in the western interior Alaska and Whitehorse, Yukon. The stand type at EMEND is similar to those in these areas.

The standard DMC data used in this research was provided by Alberta Agriculture and Forestry (Brett Moore, Wildfire Modeling Technologist) based on measurements provided by an EM50 weather station installed in ~2 km (the latitude of 56° 48' 21.6", longitude of -118° 21' 36") from the study site. The equation 11 (also mentioned in Eq. 2) was used to convert these standard DMC to standard duff moisture (%) values.

2.3.3. Rainfall data

The rainfall data from the above mentioned weather station was used in this study.

2.4. Statistical methods

Multiple regression analysis (backward regression) was used to determine the best model for predicting duff moisture from several independent variables including duff depth, bulk density and LAI at various retention levels using the 'R' statistical software (R Core Team, 2014). Preliminary analysis indicated that basal area was not correlated to duff moisture at any level of retention, so it was not included in the multiple regression models. Multiple regressions were conducted in three ways: at the plot level, at stand level and from an individual variable in which retention levels are treated as a dummy variable.

To determine the best-fitted model at the plot and stand levels, RMSE, VIF, and adjusted R^2 was used.

The dummy variable (or additional sums of squares) test was used to evaluate whether models differed between retention levels. This was done using the following F-test as described in Zar (1984):

$$F = \frac{\frac{SS_t - SS_p}{(m+1)(k-1)}}{\frac{SS_p}{DF_p}} \tag{13}$$

Where, SS_t, SS_p, m, k, DF_p refers respectively to the total residual sum of squares, pooled residual sum of squares (sum of all k residual sum of square), the number of independent variables, the number of replications (retention levels), and pooled residual degrees of freedom. Here, $(m+1)(k-1)$ and DF_p are the degrees of freedom. The total residual sum of square was found when all data from all replications containing the same variable are combined to fit one regression model. Whereas, the pooled residual sum of square simply the sum of all k residual sum of squares (Zar, 1984)

The slopes of multiple regression lines were tested with the null hypothesis that they are parallel. They will be parallel if they all have the same $\beta_1, \beta_2, \beta_3 \ldots\ldots \beta_k$. The F-test was given by (Zar, 1984):

$$F == \frac{\frac{SS_c - SS_p}{(k-1)}}{\frac{SS_p}{DF_p}} \tag{14}$$

Where, SS_c is combined residual sum of square. In order to calculate SS_c ,each element in a corrected sum of squares and the sum of cross-products matrix is formed by summing all those elements from the k regression (Zar, 1984).

Test of no difference of the intercepts / elevations ($\beta_{0d1} = \beta_{0d2} = \beta_{0d3} \ldots\ldots = \beta_{0dk}$) was conducted as follows:

$$F = \frac{\frac{SS_t - SS_c}{(k-1)}}{\frac{SS_c}{DF_c}} \quad (15)$$

Duff moisture outliers up to 300% were treated as normal since duff moisture code (DMC) in FWI System accounts for duff moisture up to 300% (Wotton, 2009). The normality test (Durbin-Watson) and homoscedasticity test were conducted using 'lmtest' package in R (Hothorn et al., 2015). The models were evaluated and selected based on 'adjusted R^2', standard error of estimates (B), unstandardized error (β) and residual mean standard error (RMSE) from all possible models (appendix 3). Multicollinearity was tested using the 'fmsb' package in R (Nakazawa, 2015). The squared partial regression coefficient was calculated to detect the relative contribution of different variables in overall regression coefficient following Abdi (2003).

In order to compare DMC calculated through field sampling, sensors and the CFS-DMC (obtained from CFS), a 3-way ANOVA was conducted using the R statistical package. In order to predict sensor DMC from CFS-DMC, a linear mixed model was tested considering retention levels and months (June, July and August) as random effects, and including repeated measurements of DMC using package 'lme4' in R statistical software (Bates et al., 2015)

Chapter 3. Results

3.1. Vegetation attributes of the retention levels

Aspen (*Populus tremuloides* Michx.) was the dominant species in clear-cut, 20% and 50% retention plots. White spruce (*Picea glauca* (Moench) Voss) was the dominant tree species in control plots. The percentage of white spruce (44%) and aspen in 75% plots (47%) were nearly same. Aspen was present in all retention plots; however its percentage composition varied by retention levels (Figure 3-1). Aspen composition declined with increasing retention levels whereas white spruce composition increased with increasing retention. In addition to aspen and white spruce, there were a few black spruce (*Picea mariana* (P. Mill.) B.S.P), lodgepole pine (*Pinus contorta* Dougl. var. latifolia) and birch (*Betula papyrifera* Marsh.) recorded. In terms of density (trees/ha), aspen was most abundant of all other species in all retention plots except control where white spruce was most abundant (Figure 3-1b).

Initially designated as conifer-dominated stands, retention harvesting in this stand transformed it to more of a mixed type due to very rapid aspen regeneration, particularly in the 50% and 75% retention treatments which had nearly equal proportions of aspen and conifers. The 20% and clear-cut treatments were dominated by aspen to such an extent that they resemble the monospecific aspen compartment (Table 3-1 and Figure 3-2). Other vegetation characteristics such as lowest branch height and DBH are shown in Table 3-1.

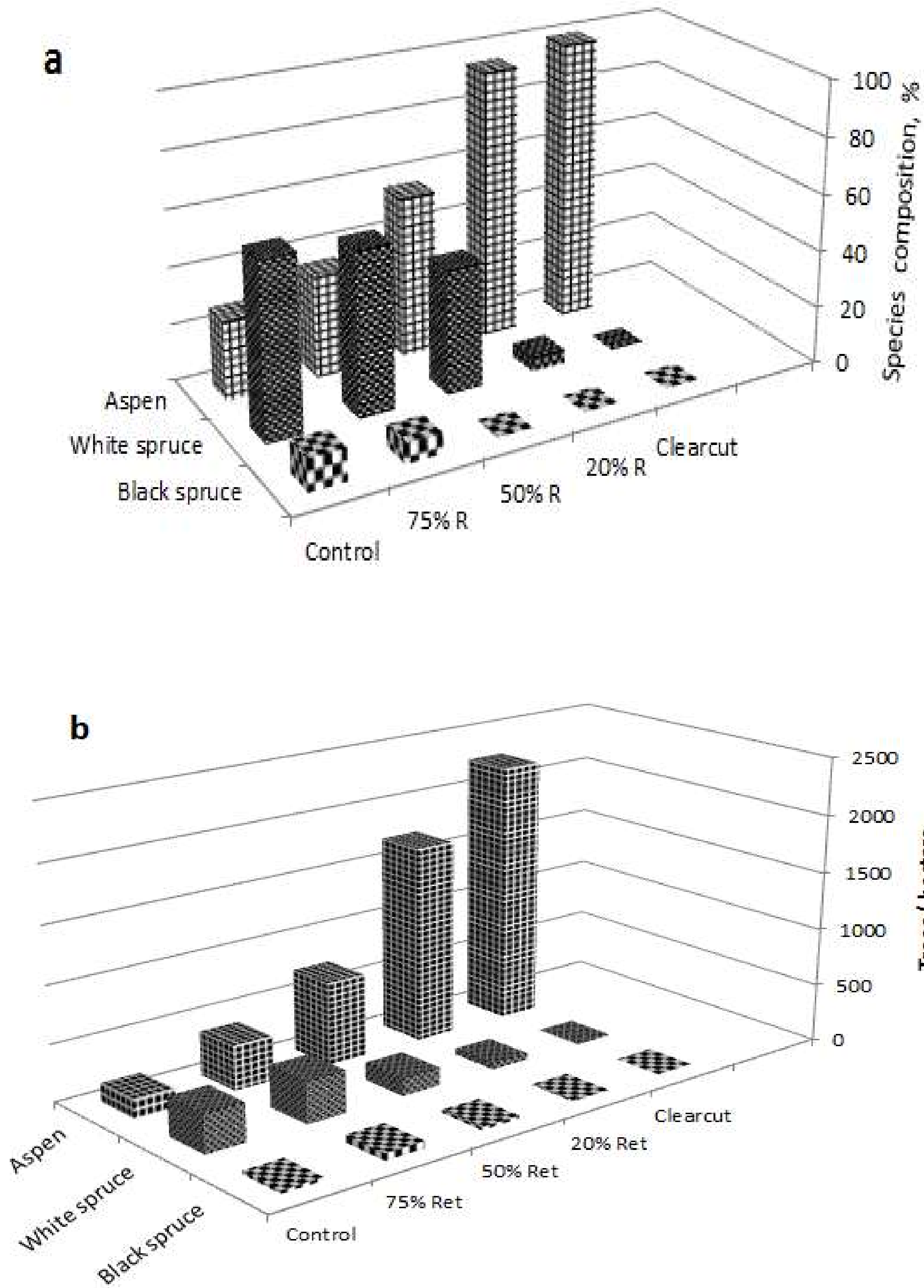

Figure 3-1: Species composition (a) and density (trees/ha) (b) in the study area (n= 639, 499, 258, 233 and 149 respectively for Clear-cut (CC), 20%-50%- 75%- retention and control respectively)

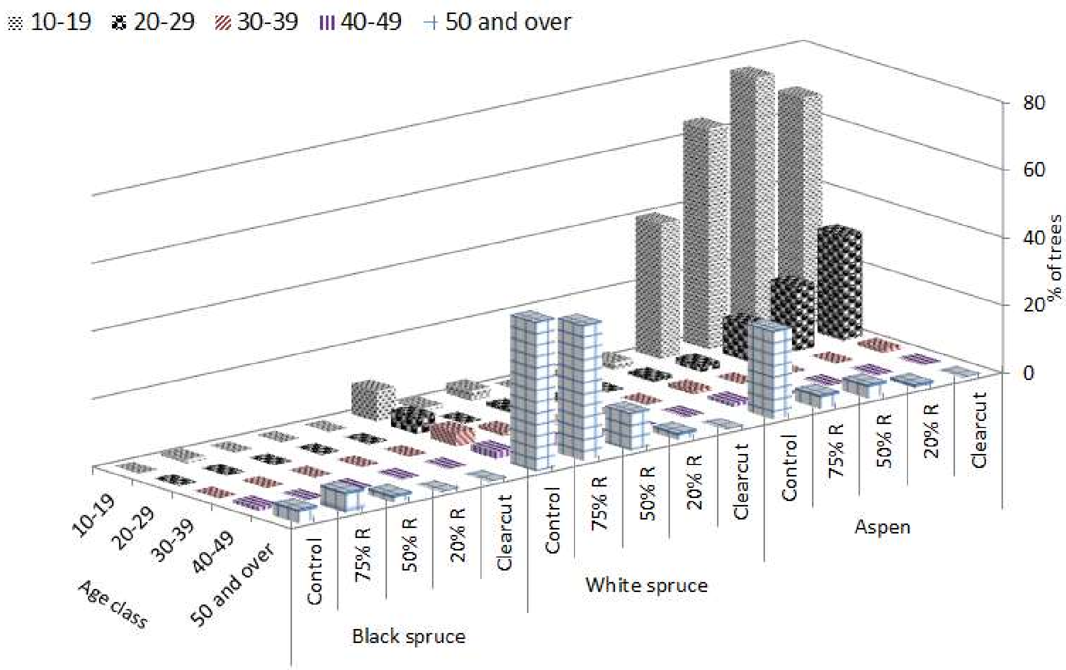

Figure 3-2: Species composition by age-class

Table 3-1: Vegetation attributes of the study site (R = retention level, WS = white spruce, BS = Black spruce, JP = Jack pine, LP = Lodgepole pine, LB= Lowest branch height, NF = Not found, trace = less than 5 individual trees)

Level		Aspen	WS	BS	Birch	JP	LP	Overall
20% R (910)	Composition (%)	479 (96%)	15 (3%)	2 (<1%)	2 (<1%)	NF	NF	498
	DBH	16.84±0.54	67.53±11.24	74±24	16±6	-	-	18.6±0.74
	Height	7.23±0.11	11.89±2.34	17.15±2.7	6.65±1.45	-	-	7.41±0.13
	LB	2.86±0.07	5.02±1.27	6.45±0	0.45±0.15	-	-	2.92±0.081
50% R (911)	Composition (%)	202 (78%)	44 (17%)	7 (3%)	5 (2%)	NF	NF	258
	DBH	19.76±1.39	63.67±5.0	83±12.64	15±3.37	-	-	28.87±1.84
	Height	8.99±0.29	22.01±2.9	22.59±3.1	6.46±0.78	-	-	11.53±0.64
	LB	3.55±0.23	7.24±0.88	7.82±1.85	0.91±0.21	-	-	4.24±0.26
75% R (912)	Composition (%)	109 (47%)	103 (44%)	18 (8%)	-	3 (1%)	NF	233
	DBH	20.29±2.3	75.51±2.41	73±8.51	-	114.67±6.22	-	4.99±2.47
	Height	6.74±0.53	17.09±0.66	15.82±2.87	-	26.05±0.9	-	12.27±0.54
	LB	2.76±0.38	6.76±0.37	5.37±1.71		14.91±0.93	-	4.89±0.29
Clear Cut (914)	Composition (%)	633 (99%)	NF	NF	1 (<1%)	1 (<1%)	3 (<1%)	638
	DBH	17.48±0.2	-	-	trace	trace	trace	17.44±0.2
	Height	7.83±.06	-	-	-	-	-	7.8±0.06
	LB	3.28±0.04	-	-	-	-	-	3.26±0.03
Control (918)	Composition (%)	46 (31%)	95 (64%)	8 (5%)	NF	NF	NF	149
	DBH	94.56±5.90	70.04±4.04	69.12±6.58	-	-	-	77.56±3.30
	Height	23.11±1.14	18.04±0.91	23.4±1.20	-	-	-	19.89±0.71
	LB	14.52±0.94	8.0±0.54	11.05±2.01	-	-	-	10.18±0.52

The mean height of regenerated aspen trees ranged between 6.74±0.53 m (75% retention) and 8.99±0.29 m (50% retention). However, the mean height of mature aspen was 16.84 ± 0.54 m. In contrast, the mean height of white spruce was between 11.89±2.34 m (20% retention) and 22.01±2.9 m (50% retention) (Table 3-1). Basal area showed an increasing trend from clear-cut to control due to control plots having larger trees (Figure 3-3).

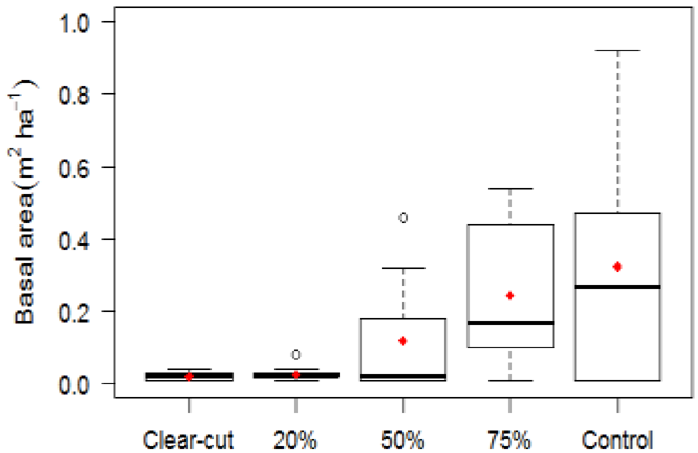

Figure 3-3: Boxplot elucidating basal area across retention levels (n= 639, 499, 258, 233 and 149 respectively for Clear-cut (CC), 20%-50%- 75%- retention and control respectively). Red dot represents mean basal area.

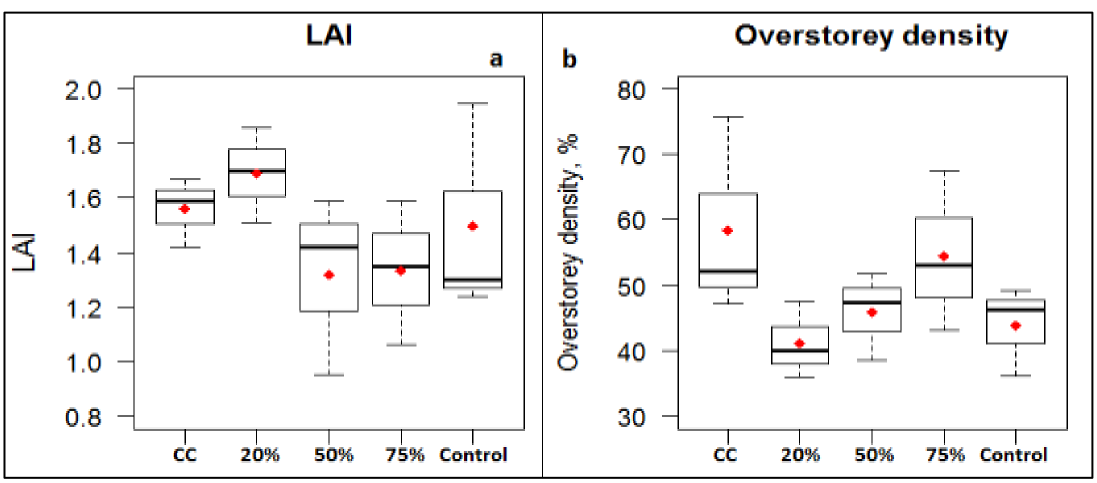

Figure 3-4: Boxplot showing LAI (panel a) and overstorey density (panel b) in the study area (n = 27 for each compartment). CC= clear-cut, 20%-50%-75% = 20%, 50%, 75% retention plots). Red dot represents mean values.

Leaf area index (LAI) increased from 50% to 75% to control. Clear-cut had higher LAI than these three compartments and maximum LAI was found in the 20% retention compartment (Figure 3-4a). The highest overstory density (%) was recorded in the clear-cut and the lowest in the 20% (Figure 3-4b). Results indicated an increasing trend in overstory density for the 20%, 50% and 75% retention (Figure 3-4b).

The 50% and 75% plots had the lowest mean slope (3.33%) and the 20% plots had the highest mean slope (6%). Meanwhile, control and clear-cut had a mean slope of 4.66% and 4.33%, respectively (Table 3-2).

Table 3-2: Site characteristics

Retention	**Clear cut**			**20%**			**50%**			**75%**			**Control**		
Block	P4	P7	P8	P8	P4	P9	P4	P8	P5	P1	P3	P5	P1	P3	P4
Slope (%)	7	4	2	1	7	10	2	7	1	0	1	9	3	5	6
Aspect (degree)	255	70	85	251	86	257	256	256	250	249	44	67	245	248	339

3.2. Physical properties of duff in retention levels

Duff depth (cm) was similar across all retention levels. Due to a lack of replication, it was not possible to make statistical comparisons between retention levels. However, results indicated that the clear-cut had the highest duff depth (5.02±0.12) and the 75% (4.42±0.12) retention had the lowest duff depth of all retention levels. The duff depth of 20% (4.49±0.11), 50% (4.42±0.12), 75% (4.42±0.12) and control (4.53±0.12) were very close to each other (Figure 3-5).

The lowest and the highest duff bulk densities (kg/m^3) were found in the control (109.31±3.02) and 50% (143.71±5.94) retention plots, respectively. The clear-cut, which had the highest duff depth, did not have the highest bulk density (Figure 3-5 and Figure 3-6).

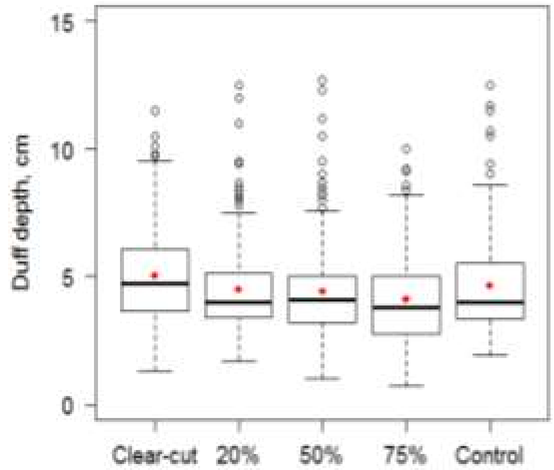

Figure 3-5: Boxplot showing duff depth (cm) in the forest floor at various retention levels (n=243, 225, 234, 234, 234 respectively for clear-cut, 20%, 50%, 75%, control). Red dot represent mean value.

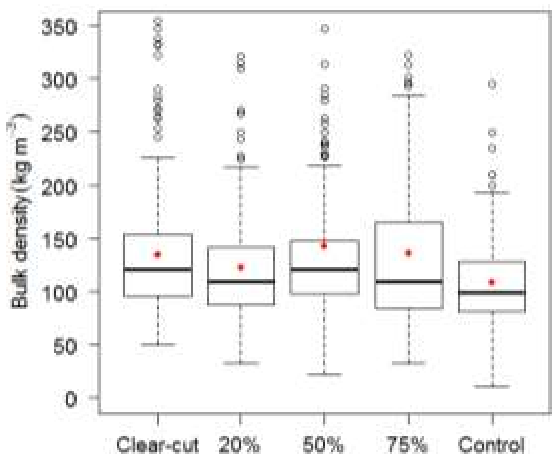

Figure 3-6: Boxplot showing bulk density (kg/m^3) in the forest floor at various retention levels (n=243, 225, 234, 234, 234 respectively for clear-cut, 20%, 50%, 75%, control). Red dot represent mean value

The trend of mean duff load was similar to the mean bulk density across retention levels (Figure 3-5 and Figure 3-6). Clear-cut plots showed the highest duff load (kg/m^2) (6.55± 0.22) compared to all followed by 50% (5.92±0.2), 75% (5.49±0.25), and 20% (5.37±0.19). The control recorded the lowest duff load (5.07±0.21). Several outliers found towards the upper extreme for all retention treatments indicate high within plot variation in duff load (Figure 3-7).

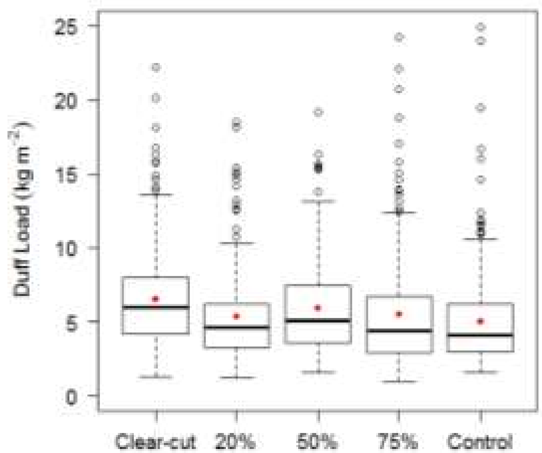

Figure 3-7: Boxplot showing duff load (kg/m^2) in the forest floor at various retention levels (n=243, 225, 234, 234, 234 respectively for clear-cut, 20%, 50%, 75%, control). Red dot represent mean value.

Correlations between these duff variables varied in magnitude and strength with both retention levels and variables. Duff depth was significantly correlated with duff load (kg/m^2) but the direction of correlation was both positive and negative at various levels of retention. Duff depth (cm) and bulk density (kg/m^3) was negatively correlated in all retention levels (Table 3-3). Only duff load and bulk density showed positive and strong correlation at every retention levels (Table 3-3).

Table 3-3: Correlation among duff depth, bulk density and load across retention levels (R= retention level)

Independent variables	Clear-cut (df=241)	20% R (df=223)	50% R (df=236)	75% R (df=235)	Control (df=236)	Overall (df=1179)
Duff depth (cm) and bulk density (kg/m^3)	-0.22*	-0.078	-0.026	-0.09	-0.0063	-0.133*
Duff depth (cm) and load (kg/m^2)	0.53*	0.623*	0.465*	0.661*	-0.444*	-0.362*
Load (kg/m^2) and bulk density (kg/m^3)	0.646*	0.664*	0.583*	0.574*	0.688*	0.762*

3.3. Duff moisture and duff moisture code (DMC)

3.3.1. Descriptive statistics of duff moisture and DMC

The field measured mean percent duff moisture (%DM) was similar across all retention levels (Figure 3-8a) and was almost identical in the 20% (107.78±0.29) and clear-cut (106.48±0.33). Control showed the highest moisture content (126.7±0.27) of all retention levels. Meanwhile, the lowest %DM was observed in 50% retention level (97.7± 0.36) (Table 3-4). The maximum %DM (~312%) was recorded at 20% retention level. Sensors measured mean %DM was also similar across retention levels (Figure 3-8b). However, the field measured overall mean %DM (pooled data) (110.52±1.45) was comparatively higher than that of sensor measured (99.84±2.2). This was due to the presence of outliers in the field measured %DM (Figure 3-8). A one-way ANOVA revealed that the differences of overall mean %DM between these two methods was only marginally non-significant [$F (1, 338) = 3.40$, $p = 0.066$] at 5% significance level.

Table 3-4: Field measured mean percent duff moisture and mm of duff moisture at various retention levels over June, July and August across retention levels

	Clear-cut	20%	50%	75%	Control	Overall
Percent duff moisture						
June	114.78±2.92	118.0±10.47	98.35±2.70	122.58±3.5	135.7±1.9	124.87±3.34
July	108.48±3.18	115.78±7.82	93.63±1.33	117.35±2.74	122.91±2.63	112.43±3.37
August	103.55±3.23	103.01±9.32	92.14±1.56	112.9±2.71	119.04±3.6	106.53±2.74
Overall	106.48±0.33	107.78±0.29	97.70±0.36	119.04±1.76	126.7.9±0.27	114.96±1.62
mm of duff moisture						
June	12.7±0.76	12.48±0.56	12.74±0.87	13.24±0.92	11.32±0.69	12.7±0.76
July	9.51±0.64	8.97±0.64	8.72±0.63	9.1±0.82	7.88±0.49	9.51±0.64
August	3.89±0.16	3.35±0.14	2.68±0.12	3.36±0.19	3.93±0.16	3.89±0.16
Overall	7.10±0.34	6.63±0.32	6.26±0.37	6.83±0.39	6.45±0.28	6.65±0.15

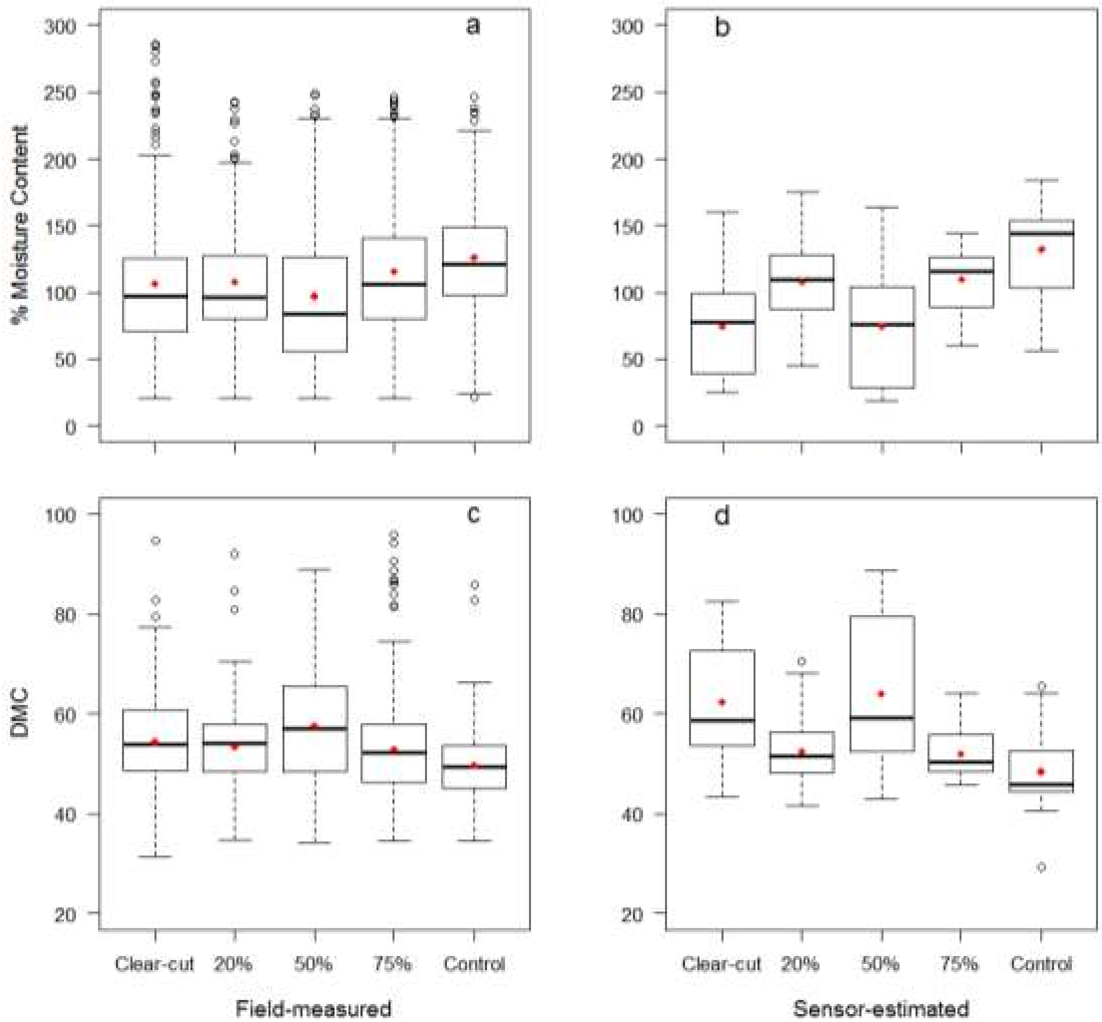

Figure 3-8: Boxplot showing percent duff moisture (panel a and b) and DMC (panel c and d) across retention plots; panels a and c represent field measured values (n=243, 225, 234, 234, 234 respectively for clear-cut, 20%, 50%, 75%, control); Panels b and d represent TDR estimated values (n=69 for all retentions); red dot represents mean value; CC = Clear-cut, 20%, 50% and 75% = 20%, 50% and 75% retention levels.

The control and 50% retention level had the lowest and highest field measured DMC (field-DMC), respectively, across retention levels for the entire study period (Figure 3-8c). The overall mean sensor measured DMC (sensor-DMC) (55.79±0.61) was slightly higher than that of field-DMC (53.59±0.3). As per retention level, clear-cut had the highest mm of duff moisture (mmDM) of all (Table 3-4).

3.3.2. Seasonal trend of percent duff moisture and DMC

There was monthly variation in %DM across retention levels (Table 3-4). The %DM decreased from June to August steadily across retention levels although there were fluctuations observed due to differential amounts of rainfall on different days (Figure 3-9a). Over the 69 day sampling period, there were 24 days with rainfall. These days with rainfall were distributed into 7 clusters consisting of 2-5 rainy days along with a few single rainy days. %DM increased following rain (Figure 3-9a). The 24-hour accumulated rainfall was moderately correlated with daily %DM ($r = 0.49$) derived from the standard-DMC equation. However, four-day accumulated rainfall was better correlated with standard-DMC ($r = 0.66$, $R^2 = 0.44$, MC = 2.81*4-days accumulated Rain + 138.28) than 2-days ($r = 0.60$), 3-days ($r = 0.60$) and 5-days ($r = 0.62$). For sensor measured duff moisture, 6-days accumulated rainfall correlated best ($r = 0.51$). On the other hand, for the field-measured duff moisture, 4-days accumulated rainfall correlated best ($r = 0.39$) with %DM.

The control plots were the wettest among all plots over June, July and August. A one-way ANOVA revealed that the %DM in these three months were statistically significantly different [$F (2, 1212) = 252.71$, $p<0.001$] at a 5% significance level. A Tukey post-hoc test revealed that duff moisture did not differ between June and July, but did differ between June and August and between July and August.

DMC and duff moisture showed different trends for all three DMC measurement methods (Figure 3-9a&b) over three months. Standard DMC was always lower than sensor DMC and field measured DMC except for a few days in the middle of August and duff moisture was always higher when estimated using the standard equation than obtained from either sensors or field measurements. Overall, standard DMC underestimated field measured values. For example, standard DMC was approximately 48% lower in June and July compared to both field and sensor DMC. In August, it was lower by 17% compared to sensor DMC and 1% compared to field DMC (Table 3-5). However, standard DMC and sensor DMC showed similar increasing trends until the middle of August when standard DMC reached to peak and then dropped sharply towards the end of month.

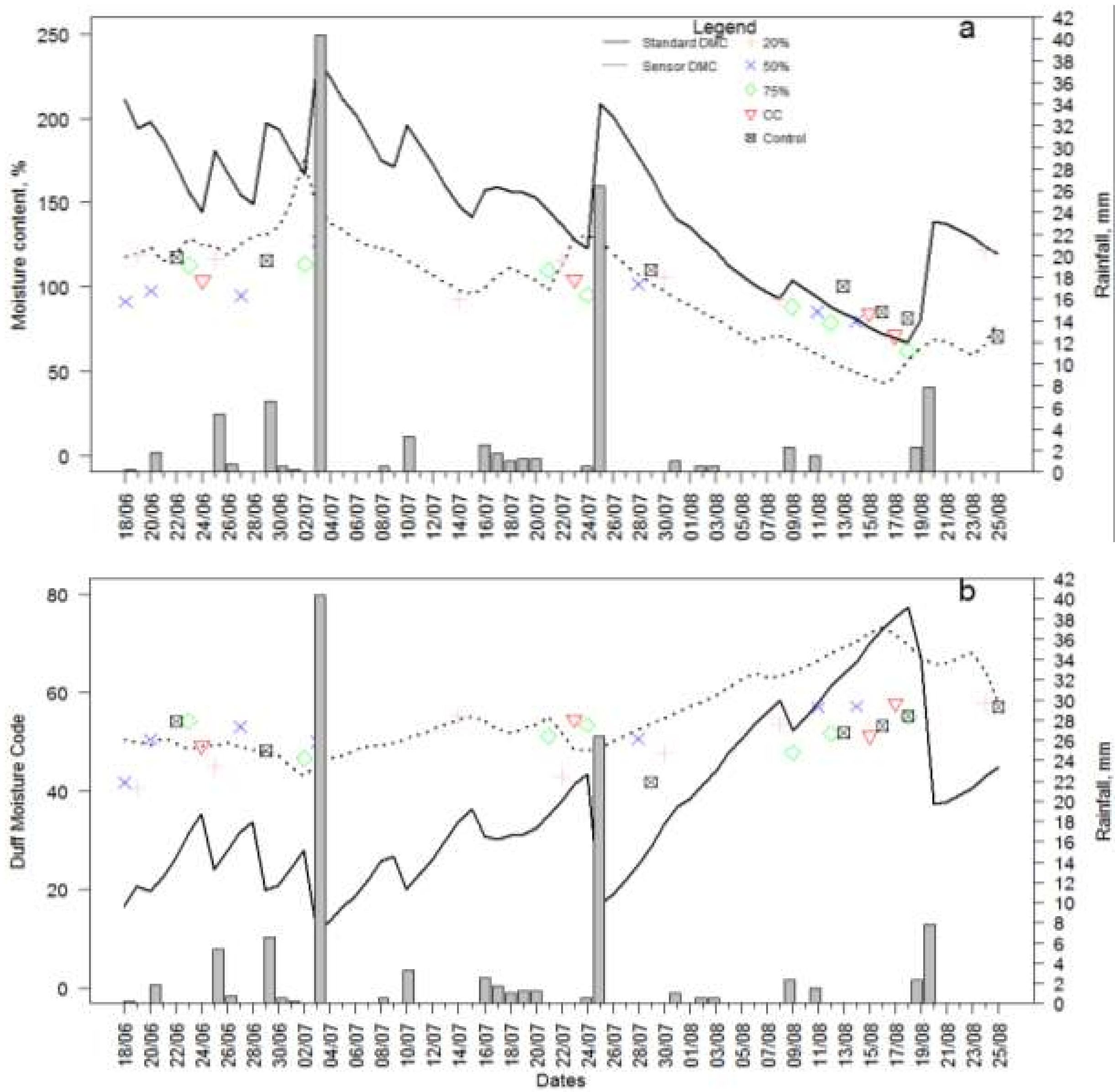

Figure 3-9: Trends of averaged daily duff moisture (panel a) and DMC (panel b) over sampling periods for the study period

Table 3-5: Mean DMC over June, July and August (percentage figure in the bracket refer to the increase of DMC compared to standard DMC); SE = standard error

	Duff Moisture Code					
	Standard		Sensor		Field	
	Mean	SE	Mean	SE	Mean	SE
June	25.41	1.68	49.15 (48.3%)	0.28	48.56 (48%)	1.73
July	27.49	1.43	50.88 (46%)	0.6	48.76 (48%)	1.46
August	54.1	2.53	65.47 (17%)	0.89	54.37 (1%)	0.86

A one-way ANOVA revealed that the DMC values derived from the three methods were significantly different [$F(2, 93) = 48.31$, $p < 0.001$]. Post-hoc comparisons using the Tukey HSD test indicated that the overall mean difference between field-DMC and sensor-DMC ($M_{diff} = -6.77$, SE = 2.93, p = 0.6) was not significant. However, the mean differences of standard-DMC with both field-DMC ($M_{diff} = 22.83$, SE = 2.93, p<0.001) and sensor-DMC ($M_{diff} = 29.6$, SE = 2.93, p<0.001) were statistically significant. This demonstrates that the field-DMC and sensor-DMC produced a consistent result.

3.3.3. Relationship between percent duff moisture and duff moisture code

The DMC and %DM were negatively and very strongly correlated over June ($r_{28} = -0.96$, $p < .001$), July ($r_{28} = -0.961$, $p < .001$) and August ($r_{73} = -0.96$, $p < .001$). The scatter plots revealed exponential curves for all months which matched with standard DMC-MC relationship. The Durbin-Watson test revealed that there was no autocorrelation for field data for June (DW = 1.772, p = 0.26), July (DW = 1.66, p = 0.16) and August (DW = 1.83, p = 0.23). Similar results were obtained for sensor data for June (DW = 2.07, p = 0.47) and July (DW = 1.67, p = 0.13) but not for August (DW = 1.772, p = 0.002). When field data were pooled, the Durbin-Watson test revealed that there were slightly positive autocorrelation (DW = 1.67, p = 0.0012). Pooled sensor data also did not show any autocorrelation (DW = 2.03, p = 0.62).

Separate regression models were developed for each of the three months and for all months pooled. All models explained over 90% variation in %DM. Models fit to sensor data explained comparatively higher variation in %DM than models fit to field measurement data (Table 3-6).

Table 3-6: Summary of DMC-MC model built for June, July, and August and for all months (pooled data) together (* significant at p<0.001).

	Month	Models	R^2	Adj. R^2	RMSE	n	F	Eq.
Field	June	$MC = 20 + 1593.1 * e^{-0.054*DMC}$	0.921	0.918	0.057	30	327.6	(16)
	July	$MC = 20 + 1805.6 * e^{-0.056*DMC}$	0.894	0.890	0.070	30	237.6	(17)
	August	$MC = 20 + 2579.0 * e^{-0.063*DMC}$	0.924	0.923	0.071	75	898.9	(18)
	Pooled	$MC = 20 + 2196.8 * e^{-0.06*DMC}$	0.915	0.914	0.070	135	1430	(19)
Sensor	June	$MC = 20 + 1666.2 * e^{-0.056*DMC}$	0.996	0.996	0.003	13	3230	(20)
	July	$MC = 20 + 1492.3 * e^{-0.054*DMC}$	0.993	0.993	0.014	31	4736	(21)
	August	$MC = 20 + 2638.1 * e^{-0.063*DMC}$	0.924	0.920	0.081	25	280.1	(22)
	Pooled	$MC = 20 + 1591.5 * e^{-0.055*DMC}$	0.986	0.986	0.053	69	4281	(23)

Figure 3-10 shows differences in predictions of duff moisture provided by the standard DMC model and models fit to field data (Table 3-6) for each month. The standard model underestimated the predicted %DM until a DMC value of ~50 in June (panel a), ~46 in July (panel b) and ~44 in August (panel c) beyond which overestimation occurred (Figure 3-10). For most measurements, the standard model overestimates duff moisture.

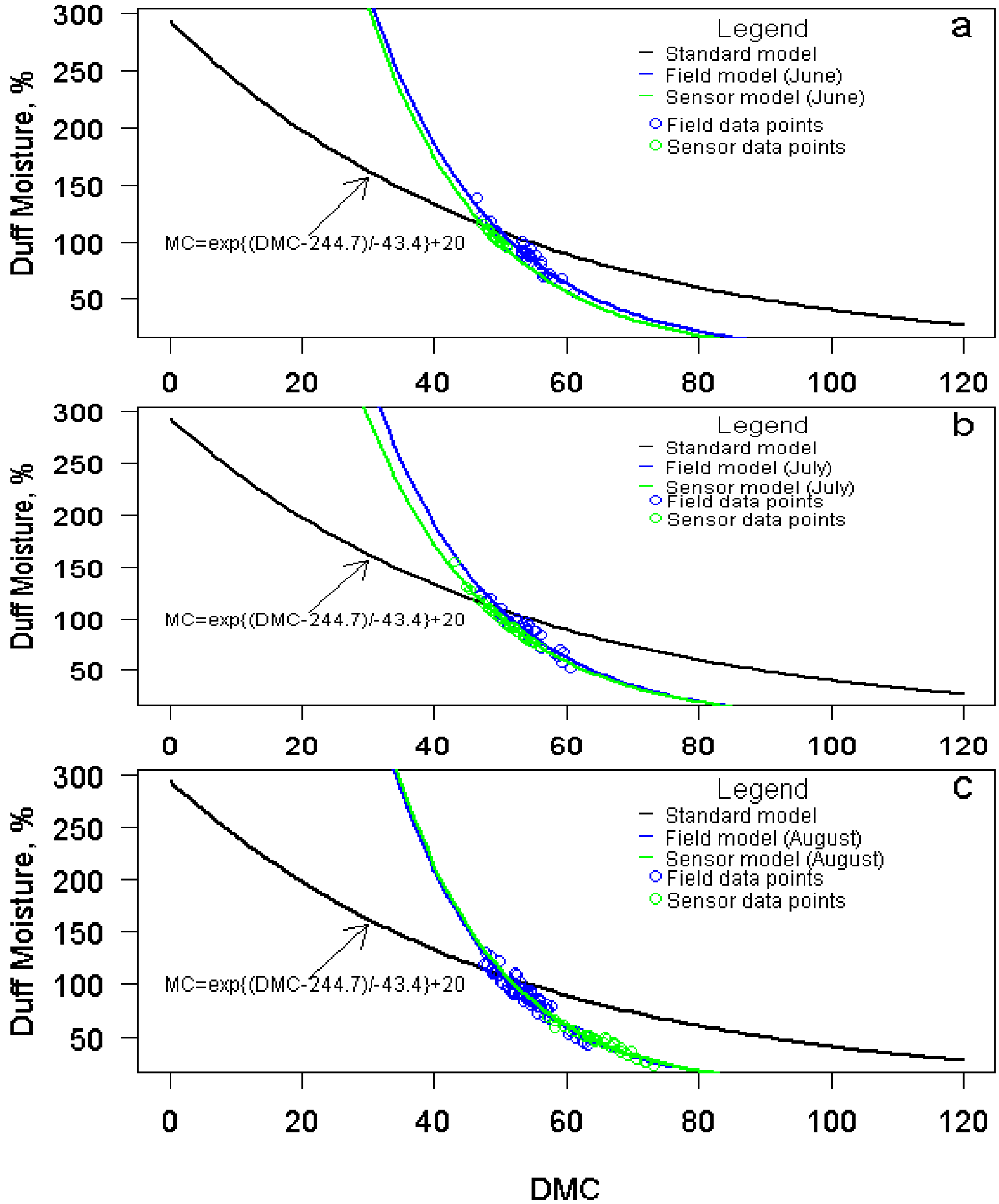

Figure 3-10: Comparing predicted duff moisture from field and sensor data for June (panel a), July (panel b), and August (panel c) with that of standard duff moisture. Standard model line (solid black color) represents national standard DMC equation (2). Field model lines (blue colored) in panel a, b and c represents equation - 16, 17, and 18 in Table 3-6. Sensor model lines (green colored) in panel a, b and c represents equation - 20, 21 and 22 respectively in Table 3-6.

The pooled regression models (i.e. for all months combined) (Figure 3-11) show similar results to those obtained for models fit to individual months. The differences of %DM predicted by the field and sensor models were wider at DMC values between 30 and 50 after which the differences culminates steadily. The standard model underestimated the predicted %DM until a DMC value ~46 beyond which the standard model overestimates %DM. For most measurements, the standard model overestimates duff moisture.

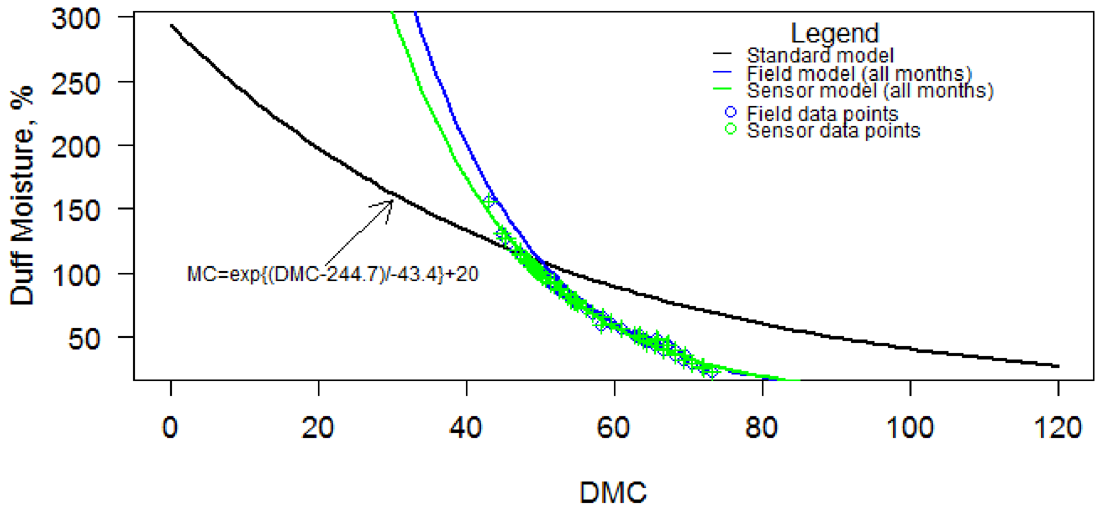

Figure 3-11: Comparing predicted duff moisture from field and sensor data for all months (pooled data) with standard duff moisture estimated from equation (2). The blue line represents pooled field model (equation 19) and green line represent pooled sensor model (equation 23).

3.3.4. Prediction of field-DMC from standard-DMC

It had been previously seen that DMC-MC relationship obtained via all three methods showed similar trends (Figure 3-9 and Figure 3-10) and that standard-DMC provided significantly different estimates than provided by sensor-DMC and field-DMC models (difference between field-DMC and sensor-DMC was not significant). Moreover, a strong correlation (r_{69} = 0.88, $p<0.001$) was found between field-DMC and sensor-DMC across retention levels over all three months (Figure 3-12). Residual plot and Normal Q-Q plot revealed homoscedasticity (Appendix 2a), which was confirmed by the Breusch-Pagan test (BP = 32.1, p = 0.001) (Appendix A1). A simple linear regression between sensor-DMC and standard-DMC (sensor-DMC = 44.72 + 0.46 * Standard-DMC) was tested. The standard-DMC explained over 78% of the variation on sensor-DMC [F (1, 68) = 245.7, p < 0.001].

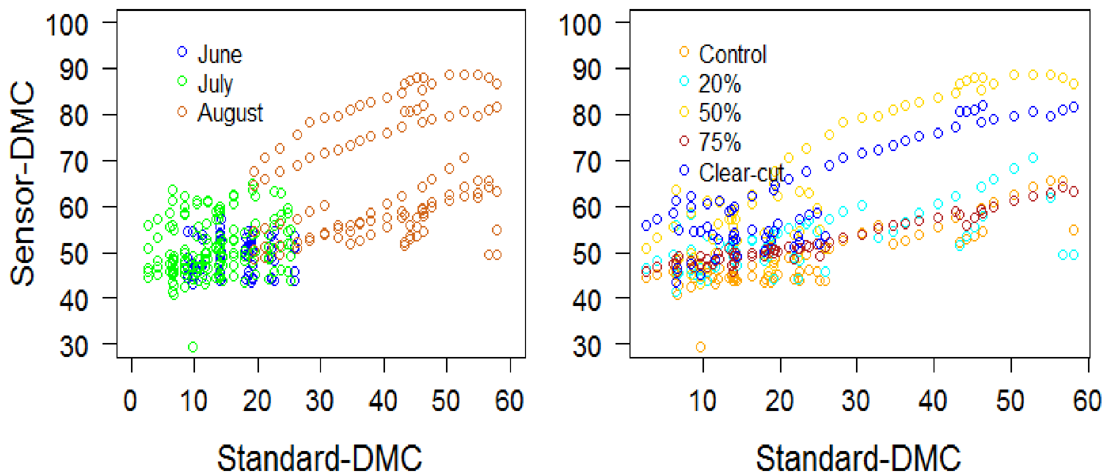

Figure 3-12: Scatter plot showing increasing trend of sensor-DMC against standard-DMC over months (left panel) and across retention levels (right panel) at 1 pm.

Since DMC varied by month and retention level, dummy regression was used to test for effects of month and retention level. Standard DMC explained ~87% variation in sensor-DMC for June, July and August across retention levels (Table 3-7). The slopes and intercepts of all retention levels were significantly different from control (reference variable) except the slopes of 75% retention level. For months, the slopes for June and July did not differ significantly.

Table 3-7: Regression coefficients and statistics of dummy variable regression analysis (*significant at p < 0.01) to predict sensor-DMC from standard-DMC; R = Retention level, stDMC = Standard-DMC.

Model	R^2	Adj. R^2	F-test	Eq.
$\text{sensor} - \text{DMC}^{*} = 43.78 + 6.72 \cdot 20\%R + 3.80 \cdot 50\%R + 4.99 \cdot 75\%R + 7.45 \cdot CC - 0.08 \cdot stDMC - 0.11 \cdot stDMC \cdot 20\%R + 0.52 \cdot stDMC \cdot 50\%R - 0.06 \cdot stDMC \cdot 75\%R + 0.27 \cdot stDMC \cdot CC - 0.54 \cdot July + 3.4 \cdot August + 0.18 \cdot July \cdot stDMC + 0.31 \cdot August \cdot stDMC$	0.88	0.87	(13,321)= 183.8	(24)

3.4. Prediction of duff moisture from duff and stand characteristics

3.4.1. Correlation between duff moisture and explanatory variables

Pearson's product-moment correlation revealed that among five variables (i.e. duff load, duff depth, LAI, bulk density and basal area) tested only duff load and depth were significantly correlated with both %DM and mmDM within each retention level (Table 3-8). The correlation between duff load and mmDM was stronger than all other variables. The magnitude of correlation was very strong in the control [$r_{238} = 0.83, p < .01$] followed by 75% retention [$r_{236} = 0.82, p < .0001$], clear-cut ($r_{242} = 0.77, p < .001$), 20% retention ($r_{224} = 0.73, p < .001$), 50% retention ($r_{237} = 0.72, p < .001$). However, duff load did show significant correlation with %DM in the 50% retention compartment.

Duff depth was positively and linearly correlated with %DM across all retention levels (Table 3-8). The magnitude of correlation was low (e.g. clear-cut [$r_{242} = 0.354, p < .0001$], 50% retention [$r_{237} = 0.39, p < .001$], 75% retention [$r_{236} = 0.373, p < .001$]) and poor in 20% retention ($r_{224} = 0.22, p < .0001$) and control ($r_{238} = 0.371, p < .001$). The magnitude of correlation between duff depth and mmDM was moderate.

Bulk density showed negative and poor correlation with %DM (clear-cut [$r_{242} = -0.02, p < .001$] and control [$r_{238} = -0.23, p < .001$]), while it showed positive and moderate correlation with mmDM (Table 3-8).

LAI was positively correlated with percent duff moisture in 20% retention [$r_{224} = .123, p < .05$] and negatively correlated in control [$r_{238} = -0.153, p < .01$] while being positively correlated in all retention levels overall [$r_{1179} = 0.084, p < .01$]. Basal area was not correlated with duff moisture in any retention level (Table 3-8).

Table 3-8: Pearson correlation coefficient between percent duff moisture and mm duff moisture with all explanatory variables (* = significant at 0.05 level, df = degrees of freedom)

Independent variables	Clear-cut (df=238)	20% retention (df=224)	50% retention (df=237)	75% retention (df=236)	Control	all retention levels (df=1179)
Duff moisture in percent scale						
Duff load, kg/m^2	0.07	0.08	0.19*	0.14	0.05	0.06*
Duff depth, cm	0.354*	0.222*	0.390*	0.373*	0.185*	0.29*
Bulk density, kg/m^3	-0.02*	0.38	0.023	-0.015	-.23*	-0.08*
LAI	0.01	0.123*	0.073	0.007	-.153*	.084*
Basal area, m^2/ ha	-0.026	0.046	-0.019	-0.090	-0.051	-0.05
Duff moisture in mm scale						
Duff load, kg/m^2	0.77*	0.73*	0.72*	0.82*	0.83*	0.77*
Duff depth, cm	0.33*	0.58*	0.55*	0.67*	0.51*	0.56*
Bulk density, kg/m^3	0.33*	0.43*	0.34*	0.41*	0.52*	0.38*
LAI	-0.023	-0.0096	-0.067	0.06	-0.082	-0.035
Basal area, m^2/ ha	-0.31	0.024	0.017	-0.017	0.06	0.051

3.4.2. Prediction of percent duff moisture from duff characteristics

The backward regression step revealed statistically significant regression models for predicting %DM from duff load, depth and bulk density, however these models all had low R^2 values indicating that they may have limited value in explaining %DM. The pooled model explained very little variation (0.091) in %DM. Duff load and depth were significant but explained very little variation, (5.7% and 13.8% respectively) in %DM. Bulk density also explained very little variation (4.6%) in %DM.

3.4.3. Prediction of percent duff moisture from Leaf Area Index

Although the correlation between LAI and %DM was low, further analysis was conducted to explore its ability to predict duff moisture since LAI can easily be estimated for remote areas using GIS and remote sensing. Since LAI varied by retention levels, separate regression models were built for each retention level. The Durban-Watson normality test (=0.754, $p < 0.01$) showed that data were not normal and transformations were not effective for producing normality. Visual inspection of residuals and the Normal Q-Q plot showed homoscedasticity (Appendix A2), which was confirmed by the Breusch-Pagan test (BP = 26.1, p = 0.001).

A pooled model, across all retention levels was then fit. The adjusted R^2 showed that LAI explained only 3.7% variation in %DM in the dummy variable regression model.

The intercept was highest in the control followed by 75%, clear-cut, 20% and 50% retentions levels (Eq. 25, Figure 3-13). All regression lines were statistically significant. The slope of control decreased with increasing LAI and increased in others. The slopes were not significant in the 75% and clear-cut. Overall, the slope and intercept of the model was statistically significant [$F(0.05, 4, 1169) = 4.13 >$ critical $F = 2.38$; $F(0.05, 4, 1175) = 4.95 >$ critical $F = 2.38$].

Additional dummy regression models were constructed to see if models were significant when control had been dropped from the analysis. The reduced model showed that the intercept for the 20% retention compartment was the only one that differed significantly from other retention levels and no slopes were significant (Table 3-9). The same result was obtained when clear-cut was removed in the third model (Table 3-9).

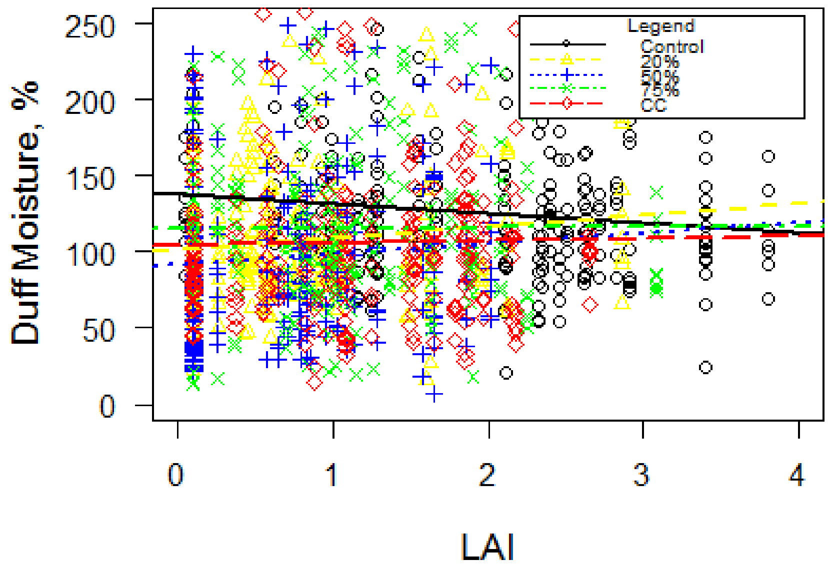

Figure 3-13: Predicted duff moisture as a function of LAI in across retention levels. Lines illustrate the linear regression model for each retention level described in Eq. 25 in Table 3-9

Table 3-9: Regression coefficients and statistics of dummy variable regression analysis (*significant at p < 0.01) to predict percent duff moisture from LAI; R = Retention level, L= load, mmDM = mm of duff moisture, CC= Clear-cut

Model	R^2	Adj. R^2	F-test	Eq.
$mmDM^* = 138.42 - 36.89 \cdot 20\%R - 47.04 \cdot 50\%R - 23.87 \cdot 75\%R - 33.44 \cdot CC - 6.42 \cdot LAI + 14.1 \cdot LAI \cdot 20\%R + 13.36 \cdot LAI \cdot 50\%R + 6.94 \cdot LAI \cdot 75\%R + 7.68 \cdot LAI \cdot CC$	0.037	0.028	(9,1171) = 6.054	(25)
$mmDM^* = 101.53 - 10.14 \cdot 50\%R + 13.02 \cdot 75\%R + 3.45 \cdot CC + 7.68 \cdot LAI - 0.75 \cdot LAI \cdot 50\%R - 7.17 \cdot LAI \cdot 75\%R - 6.42 \cdot LAI \cdot CC$	0.02	0.012	(7,935) = 2.75	(26)
$mmDM^* = 101.53 - 10.14 \cdot 50\%R + 13.02 \cdot 75\%R + 7.68 \cdot LAI - 0.75 \cdot LAI \cdot 50\%R - 7.17 \cdot LAI \cdot 75\%R$	0.027	0.020	(5,694) = 3.91	(27)

3.4.4. Prediction of mm duff moisture from duff and vegetation characteristics (pooled data)

The backward regression analysis revealed that all possible regression models (eq. 28-35) except LAI (Eq. 33) were statistically significant (Table 3-10). In the first model (Eq. 28), the slope of LAI was not significant. Reduced models representing Eq. 29 and 30 had the same R^2 value but the slope of bulk density was not significant in Eq. 29. First three models (Eq. 28-30) explained ~62% variation in mmDM. The intercepts of models representing Eq. 31-32, were not statistically significant. Based on this, Eq. 30 was better than remaining multivariate or bivariate models and also it had second lowest RMSE. There was no multicollinearity detected in Eq. 30.

Among the univariate models, duff load (Eq. 32) was better predictor than others. The bivariate model (Eq. 30) explained ~4% more variation in mmDM than that of univariate model (Eq. 32).

Table 3-10: Summary of backward regression analysis for predicting mmDM from duff and vegetation variables. (Ld = Load, DD=Duff depth, BD= bulk density, LAI=Leaf Area Index; * = significant at p< 0.05)

Models	R^2	Adj. R^2	RMSE	F-test	VIF	Eq.
$mmDM^* = -4.17 + 0.72 \cdot Ld + 0.012 \cdot BD + 1.11 \cdot DD - 0.06 \cdot LAI$	0.624	0.622	0.11	(4, 967) = 401.7	Load = 5.47, DD = 3.66, BD=3.85, LAI = 1.00	(28)
$mmDM^* = -2.18 + 0.95 \cdot Ld + 0.004 \cdot BD + 0.65 \cdot DD$	0.622	0.621	0.094	(3, 1211) = 665.3	Load = 4.2, DD = 2.7, BD=3.09	(29)
$mmDM^* = -1.72 + 1.03 \cdot Ld + 0.56 \cdot DD$	0.621	0.620	0.094	(2, 1212) = 994.8	Load = 1.39, DD = 1.39	(30)
$mmDM^* = 0.35 + 1.33 \cdot Ld - 0.009 \cdot BD$	0.600	0.6	0.097	(1, 1212) = 907.2	Load = 1.26; BD = 1.26	(31)
$mmDM^* = -0.19 + 1.21 \cdot Ld$	0.588	0.588	0.098	(1, 1213) = 1735	-	(32)
$mmDM = 6.97 - 0.27 \cdot LAI$	0.0012	0.0001	0.03	(1, 970) = 1.194	-	(33)
$mmDM^* = 2.99 - 0.03 \cdot BD$	0.148	0.147	0.140	(1, 1213) = 210.9	-	(34)
$mmDM^* = 0.014 + 1.46 \cdot DD$	0.313	0.313	0.127	(1, 1213) = 554.2	-	(35)

3.4.5. Prediction of mm of duff moisture from duff load across retention levels

Due to very strong correlation between duff load and mmDM (Table 3-8) and the ability of duff load to explain high variation in duff moisture (Eq. 32 in Table 3-10), duff load was further used for the prediction of mmDM at various retention levels. Multiple regression analysis was conducted to predict mmDM from duff load using retention levels as dummy variables. The mmDM data was not normal (Shapiro-Wilk normality test =1.03, $p<2.2e-16$) due to some data having very high duff moisture (>15 mm). Square root transformation did not improve normality (Shapiro-Wilk normality test = 0.88, $p<2.2e-16$). Residual plots, Normal Q-Q plots (Appendix A3) and the Breusch-Pagan test confirmed that there was violation of the assumption of homoscedasticity (BP = 184.93, $p < 2.2e-16$). The variation in duff moisture (adjusted R^2) explained by duff load in the dummy variable regression model (89%) was higher by only 1% points than that of a pooled model (88%).

Duff load had significant effects on mmDM across all retention levels. Duff moisture regression lines for all retention levels represented different populations as confirmed by the F-test [F (0.05, 8, 1220) = 4.04 > critical F = 2.38]. The intercept of the control was the highest, followed by 20%, 75%, clear-cut and 50% retention. All intercepts were significantly different when control was considered as the reference in the dummy regression. Also, all slopes were significantly different from control except for 20% retention and clear-cut. On the other hand, the highest slope was observed in 75% treatment and the lowest was found in control. The slopes of 20% and clear-cut were not significant (Figure 3-14 and Table 3-11).

Additional dummy regression models were constructed to see if the treatments differed significantly when control and clear-cut had been dropped from the analysis. When control was dropped, all intercepts were significant except for the 20% compartment. The same result was found when clear-cut was dropped. The results of these two reduced model reflect the result of full model.

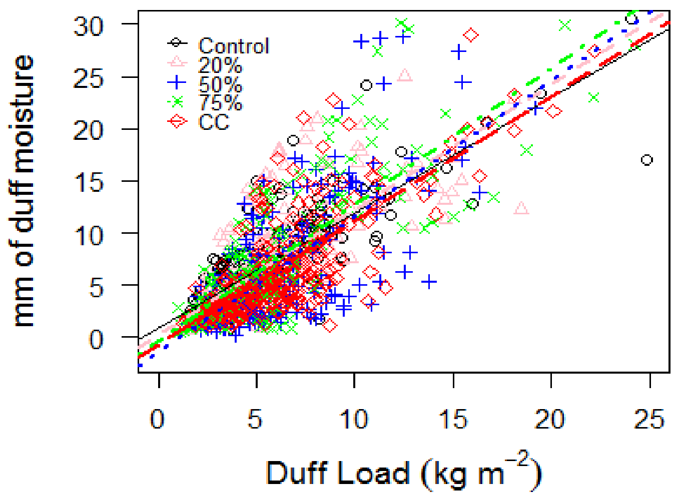

Figure 3-14: Predicted mm of duff moisture as a function of duff load across all retention levels. Lines depict simple linear regression models described in equation 36 in Table 3-11

Table 3-11: Regression coefficients and statistics of dummy variable regression analysis (*significant at p < 0.01) to predict mm of duff moisture from duff load (kg/m^2); R = Retention level, L= load, mmDM = mm of duff moisture, CC= Clear-cut

Model	R^2	Adj. R^2	RMSE	F-test	Eq.
$mmDM^* = 0.82 - 0.62 \cdot 20\%R - 2.26 \cdot 50\%R - 1.17 \cdot 75\%R - 1.53 \cdot CC + 1.11 \cdot L + 0.09 \cdot L \cdot 20\%R + 0.19 \cdot L \cdot 50\%R + 0.2 \cdot L \cdot 75\%R + 0.08 \cdot L \cdot CC$	0.60	0.59	0.09	(9,1171) = 201.6	(36)

3.5. Transpiration loss in various retention levels

Trenching treatments remove effects of plant transpiration on duff moisture. The differences in duff moisture between the trench and non-trench (floor) provided an estimate of transpiration loss. Lateral and vertical movement of water in the duff and evaporation were not taken into account. Mean transpiration loss was similar across retention levels but was the highest in the control and lowest in the 20% retention level (Figure 3-15).

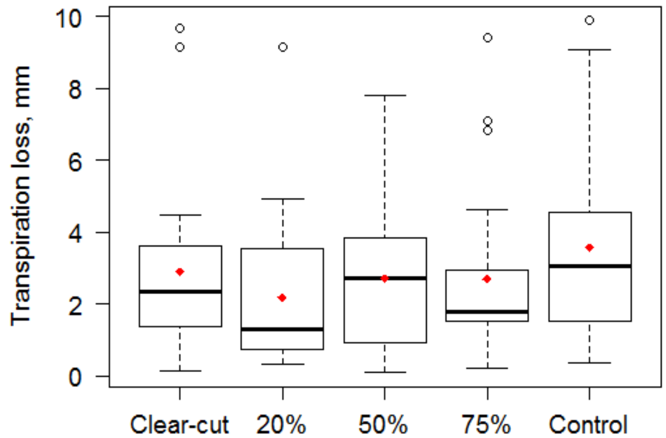

Figure 3-15: Boxplot showing mm of transpiration loss measured through duff sample collected from the forest floor. Red dot represents mean transpiration loss (n = 156, 153, 92, 106, 118 respectively for clear-cut, 20%, 50%, 75% and control)

Transpiration loss was not correlated with duff load [$r_{238} = 0.13, p = 0.16$], bulk density [$r_{238} = -0.07, p = 0.44$], or LAI [$r_{238}$) $= 0.41, p = 0.25$]. Only duff depth was statistically significantly correlated with mm of transpiration loss [$r_{238} = 0.344, p < .001$]. The multiple regression model was also not statistically significant [F (0.05, 8, 1220) = 2.41, p = 0.02).

Chapter 4. Discussion

4.1. Vegetation characteristics

Aspen (*Populus tremuloides* Michx.) regeneration was very prominent across retention plots due to the gaps created by retention harvesting. With the decreasing levels of retention, aspen composition (%) and density (trees/ha) increased sharply. For example, aspen accounted for ~47%, ~78% and ~96% of all trees (≥10cm DBH) within the 75%, 50% and 20% retention levels, respectively. Aspen composition in these retention plots were higher than those observed in the control (31%). Aspen tree density were nearly doubled in the 50% retention (721 trees/ha) compared to the 75% retention (389 trees/ha). Similarly, the 20% retention compartment (1711 trees/ha) had more than four times the aspen density than found in the retention compartment. Seedling and sapling less than 10cm DBH were not included in this study.

In addition to influencing stand composition, retention harvesting also influenced stand structure. Initially, the forest stand was composed of dominant white spruce (*Picea glauca* (Moench) Voss) along with black spruce (*Picea mariana* (P. Mill.) B.S.P) and aspen trees. The dominant conifer (white spruce and black spruce) and broadleaf trees (aspen) occupied the top storey (15.82±2.87 – 23.4±1.20 m in height), and young to near-mature conifer trees constituted middle storey (11.89±2.34 – 15.82±2.87 m). During the sampling period, the lower-middle storey, composed of ongoing recruitment mainly by broadleaf (aspen) and to a lesser extent by conifer species (white spruce, black spruce), were between 6.74±0.53 m and 8.99±0.29 m in height. Few birch (*Betula papyrifera* Marsh.), lodgepole pine (*Pinus contorta* Dougl. var. latifolia) or jack pine (*Pinus banksiana* Lamb.) seedlings were found. Approximately 15 years after retention harvesting, the stand resembles a multi-aged mixedwood forest common in boreal mixedwood forests in western Canada (Bergeron et al., 2014).

Regeneration of aspen had a strong influence on leaf area index (LAI) across retention levels. The clear-cut and 20% retention plots, which had the highest density of aspen regeneration also had wider crown spreads than (5.2±0.35m) that of mature white spruce (3.1±0.1m) in the study site. As such comparatively higher LAI was found in clear-cut (1.56±0.07) and 20% retention plot (1.69±0.1) compared to the control (1.5±0.23) compartment. In their study Chen et al. (1997) recorded similar LAI for highly productive intermediate aspen (2.04±0.22) at the BOREAS study site in Prince Albert and Candle Lake, Saskatchewan. They also report a LAI value of ~1.23 ± 0.19 for a mature mixed stand consisting of aspen, white spruce, black spruce, and jack pine. Brown et al. (2014) found an LAI value of 1.45 in aspen stands located at Utikuma Region, Alberta. Pinno et al. (2001) measured LAI in twenty-six aspen-dominated stands in Slave Lake, Drayton Valley and Grand Prairie (Alberta) and found that younger aspen stands had LAI values of up to 4 at age 9 with LAI declining after age 25. Soil compaction, shade from retained trees and patches and site factors may have contributed to lower LAI values in the blocks used in my study (Frey et al., 2003).

The mean overstory canopy density in the control was also lower than that in the clear-cut. This is likely due to the fact that the control plots were dominated by large white spruce with narrow crowns relative to their size and lower tree densities compared to the young aspen dominated clear-cut. These factors would result in higher gap fractions in the conifer stands. Mean overstory canopy density increased with increasing retention, from 20% to 50% to 75% retentions which could be associated with increasing basal area.

4.2. Physical characteristics of duff

Duff depth (cm) differed little between 20% (4.49±0.11), 50% (4.42±0.12), 75% (4.42±0.12) retention, control (4.53±0.12) and clear-cut (5.02±0.12). This could be related to the similar but variable composition of tree cover consisting of white spruce, black spruce and aspen, as well as the short period since the creation of these treatments. Analysis of variance (ANOVA) was not used to determine whether duff depth differed statistically significantly among retention levels since this study did not include necessary replication. In the boreal forests of Canada, duff depths under trembling aspen are usually less than under conifer forest types, due to rapid decomposition of aspen leaves and their comminution into the mineral soil (Otway et al., 2007). However, visual observation of mean duff depth (Figure 3-5) revealed that the clear-cut which was dominated by young aspen had deeper duff than the control which was dominated by large white spruce intermingled with large aspen. This anomaly could be due to the large additions of litter during logging and accumulation of grass and aspen litter after harvesting in the clear-cut plots. This result was consistent with what Raaflaub and Valeo (2008) found in aspen and mixed stands at Kananaskis Valley region of Alberta. Raaflaub (2011) also found similar results in another study conducted in the Kanaskis in stands dominated by lodgepole pine, white spruce, balsam poplar, and trembling aspen. He found statistically significant differences between trembling aspen and pine/spruce plots where trembling aspen stands had, on average, deeper duff layers than pine/spruce plots, with an average depth of 11 cm and 9 cm, respectively. However, Hély et al. (2000) did not find significant differences in duff depth among stand types in their study of 48 mature stands in the boreal mixed-wood forest (consisting of balsam fir, black spruce, white spruce, aspen, paper birch) near Lake Duparquet, Quebec although there were noticeable differences in mean duff depth such as deciduous (5.9±0.3 cm), mixed deciduous (6.8±0.5), mixed coniferous (7.4±0.9) and coniferous (6.6±0.6). The reported duff depths in this study were similar to the values (2.7 to 5.3; mean 4.18) reported in a previous study at EMEND research site, but in a different block, 10 years earlier (Almuedo, 2003).

Bulk density was higher in aspen dominated retention plots than in conifer dominated control plots. This could be attributed to faster decomposition rate of aspen leaf litter than conifer needles. Very weak and negative correlations were observed between duff depth and bulk density in all compartments except clear-cut at which duff depth was significantly but poorly correlated with bulk density. In their study conducted at Elk Island National Park, bulk density increased with increasing duff depth in aspen-dominated stands (Otway et al., 2007). In long-unburned *Pinus palustris* forests in northern Florida, USA, Kreye et al. (2014) also found a positive relationship between duff depth and bulk density. My results contrast with these results due to variability in duff conditions prior to the harvest and variability in ground disturbance and slash deposition at the time of harvesting. According to OMNR (2001) forest harvesting may increase depth of duff through addition of litter or reduce duff depth through compaction. Logging is also associated with removal of organic matter from the top layer, and can expose mineral soil if duff is shallow (Jurgensen et al., 1997). Furthermore, my duff sample was collected along transects without regard to the position of tree bole which effects duff depth. Duff depth near to the bole is deeper due to the deposition of litter just below it (Raaflaub and Valeo, 2009). Supporting root networks and diminished snow pack near tree boles result in comparably less long term compaction and lower bulk density (Raaflaub, 2011).

Like duff depth and bulk density, duff load was also comparatively higher in aspen dominated stands than the conifer dominated control plots. Addition of litter during logging, species composition and and an abundance of young aspen may have contributed to higher duff load than found in conifer dominated plots. Both duff depth and bulk density was statistically significantly correlated with duff load across all retention plots. In particular, the overall correlation between duff load and bulk density was very strong ($r = 0.76$). The mean duff load in my aspen dominated clear-cut was 6.55±0.22 kg/m^2 which was comparable to values reported by Letang and Groot (2012) for the boreal plain (8.8±7.5) in Canada. While white spruce sites in Canada's boreal plain show a wide range of duff load (13.7±11.7) (Letang and de Groot, 2012), duff load estimates documented here are lower and have a lower range (5.07±0.21).

4.3. Duff moisture

While observations indicated that duff moisture varied with retention levels, the differences could not be compared statistically due to a lack of replication. The 50% retention plots had the lowest duff moisture. This block was located close to a road, exposing the plots to higher wind velocity which might contribute to quicker drying and increased evapotranspiration.

The studied plots in the 50% retention also had a South-West aspect which would have been warmer than other aspects.

Aspen duff layers contain relatively high inorganic content especially within the upper 2cm (Otway et al., 2007). This might reduce porosity and consequently lower water holding capacity. As such, aspen dominated clear-cut and 20% retention compartments had lower duff moisture than that of 75% and control. In addition, clear-cut, 20% and 75% retention compartments were located at higher elevations (720 msl; Figure 2-1) than the control (710 msl) which could result in faster drainage in the clear-cut, 20%, 50% and 75% retention. The slope of the clear-cut (4.33%) and the 20% retention (6%) plots were also comparatively higher providing for increases in run-off and drainage.

Differences in species composition and structure of the overstory tree canopy and understory vegetation layers between the retention treatments could influence duff moisture through their effects on the amount of precipitation reaching the ground through effects on both interception and transpiration. Interception loss is usually higher in conifer (20-40%) than broadleaf dominated forests (10-20%) (Zinke, 1967 in Xiao et al., 2000). In their study Brown et al. (2014) observed that aspen intercept as much as 25% of incoming precipitation, for events greater than 5 mm rainfall and up to 15% on an annual basis. Raaflaub (2011) found that pine/spruce canopies intercept on average ~28% of the rainfall, which increases up to ~62% within 0.7m from a tree. The control compartment was dominated by needle leaf trees (white spruce and black spruce) which usually causes higher interception than broadleaf species and was expected to result in lower duff moisture (Komatsu et al., 2011; Raaflaub and Valeo, 2008). For this reason Raaflaub (2011) found that aspen stands had wetter duff (e.g. lower DMC) than pine / spruce stands. This is in contrast to what I found for the conifer-dominated control compartment.

Water use efficiency of young aspen was observed to increase over time in an experiment conducted by Robinson et al. (2001). Young aspen stands have higher below canopy evapotranspiration and above canopy evapotranspiration than a developed canopy (Brown et al., 2014). Based on soil tension and moisture data within the rooting zone Brown et al. (2014) suggested that in addition to capillary recharge from below at night, some form of hydraulic redistribution occur in aspen. This redistribution results in transportation of soil moisture from wetter areas to meet the demands of the transpiring aspen canopy. Mid-day transpiration rates per unit leaf area (Q1) were two-times greater in variable retention sites compared with control for white spruce trees. However, its Q1 was lower than that of paper birch (Bladon et al., 2006). They also found that variable retention sites utilize ~3.2 times more water per day than control sites. Based on this, aspen dominated retention harvesting sites should have had lower duff moisture than that in the control.

The presence of feather moss in the control could be an important factor since mosses have the ability to withdraw moisture from the mineral soil and slow evaporation from duff layers (Wilmore, 2001) which could help retain moisture in the duff layers. In essence, presence of feather moss and comparatively flatter slope might have contributed to higher duff moisture in the conifer dominated control compartment. On the other hand, despite having higher broadleaf composition (%), steeper slope might have contributed to lower duff moisture in aspen dominated stands. My results suggest that while stand composition influences duff characteristics between aspen dominated retention and conifer dominated control plots, it has little effect on duff moisture. More rigorous studies are needed to differentiate the effects of slope and stand characteristics on duff moisture.

Transpiration loss was not related to duff moisture. For example, control had higher transpiration loss and should have resulted in lower duff moisture, while in reality the control plot showed the highest duff moisture. My trenching experimental design in this study possibly was not appropriate to study transpiration loss. In particular, all calculated transpiration loss value should have had trench and floor duff moisture measured from under canopy to catch the effect of trenching on transpiration loss. In my design, I measured floor and trench duff moisture sample along transects without regard to their position with canopy, thus the calculated transpiration values did not represent true situation. Many floor duff moisture values which were measured in gaps had their corresponding trench duff moisture values measured below canopy resulting in many negative transpiration loss values as duff moisture in gaps are usually higher than under canopy. There were more negative values noted than positive values and those negative values were not used in the analysis. A better experimental design may consider measuring trench and floor moisture under canopy to include the effect of trenching (removing tree roots) from floor under the same microenvironment e.g. below canopy. More detailed measurement of precipitation, canopy interception, throughfall, transpiration, evaporation and drainage would contribute to a better understanding of how tree canopies and retention levels influence duff moisture and transpiration loss.

4.4. Seasonal trends in duff moisture and DMC

Duff moisture was correlated with rainfall. During high rainfall, duff moisture increased and vice versa. Wetting and drying conditions directly affected the duff moisture content and duff moisture code. In this study, wetting and drying of duff were not monitored, however, correlations between rainfall and duff moisture revealed that 4-days accumulated rainfall was better correlated ($r = 0.66$) with standard DMC equation derived duff moisture than values for longer or shorter periods. For the sensor-estimated and field-measured duff moisture it was 6-days ($r = 0.51$) and 4-days ($r = 0.39$) accumulated rainfall that provided better correlation than other durations. The correlation value dropped beyond 4-days (sensor) and 6-days (standard-DMC and field DMC) accumulated rain. This provided an indication that duff moisture memory diminishes after 6 days at the EMEND site while Van Wagner (1987) suggests that it might continue for up to 12 days. The correlation reported in this study for standard equation derived duff moisture (standard-%DM) and rainfall was similar to that of Abbott et al. (2007) (0.64-0.77) who predicted forest floor moisture for burned and unburned jack pine forests in the Canadian northwest territories.

Mean duff moisture showed seasonal variation over the study period. It was higher in June, followed by July and August. A one-way ANOVA revealed that duff moisture differed significantly between June and August as well between July and August but was not significantly different between June and July. This is likely a result of differences in rainfall frequency and amount in June (17 days, 55.56 mm), July (12 days, 80.24) and August (9 days, 14.96mm), as well as differences in air temperatures.

The effect of variable rainfall and duff moisture was also apparent in DMC. DMC decreased continuously until the 3rd of July after which it increased steadily until 23rd of July and then dropped due to a 26 mm rainfall. DMC increased sharply from July 25th reaching a zenith point on August 17th with the highest value of 78. Amiro et al. (2004) found that fires over 2 km^2 occurring during 1959-1999 in different ecozones in Canada had a DMC ranging from 38 to 78. The mean field-DMC in July was 48.76±1.46 which increased to 54.37±0.86 in August. The mean standard DMC was nearly same (54.1±2.53) as field DMC in August. Based on this result, August might be more prone to fire ignition depending on other important factors such as source of ignition.

4.5. Predicted duff moisture

Van Wagner (1987) used exponential drying rates in the development of DMCs and the best fitting regression between the codes and corresponding moisture content were exponential. The DMC-MC relationship derived in this study through field sampling and sensors conformed to this expectation. The sensor derived DMC-MC regression model (pooled) was better than that of field sampling as it explained ~7% more variation than the latter one (~91%). In both cases, when regression models were built separately for June, July and August, their R^2 values increased by a meagre amount (~1%) compared to their respective pooled models. The DMC-MC relationship based on field sampling had a larger sample size (1215) taken from 15 transects in each of five retention blocks representing a heterogeneous mix of conditions which slightly reduced R^2 value. On the contrary, sensor DMC-MC relationship was built using data from five fixed locations where sensors were placed for the entire study period.

The R^2 value of DMC-MC regression models derived in this study (sensor pooled model R^2 = 0.986 and field pooled model R^2 = 0.914) was higher than that of Otway et al. (2007) derived for trembling aspen stands in Elk Island National Park (spring R^2 = 0.16, Summer R^2 = 0.65 and Fall R^2 = 0.68). Chrosciewicz (1989a, 1989b) calibrated DMC-MC equation under jack pine canopy conditions and jack pine cut over sites. Under jack pine canopy at F+H layers he recorded an R^2 value of 0.60 and at L+F+H layer the value increased to 0.73. Meanwhile, in jack pine cutovers the R^2 value was lower (F+H under slash cover = 0.49 and F+H in slash opening = 0.53) than that of under canopy conditions.

The standard DMC-MC relationship underestimated DMC-MC derived in this study until a DMC value between 44 and 50 beyond which overestimation occurred (Figure 3-10). The underestimation could be attributed to overestimation of duff moisture (Figure 3-9) due to differences in duff characteristics such as duff bulk density, depth and load between field site and Petawawa study site based on which standard DMC-MC relationship were built. The standard DMC-MC relationship was built based on pine stands which represented an average bulk density of 71 kg/m^3 and load of 5 kg/m^2 which are lower than that in my field sites (bulk density, 130.38±2.13 and load, 5.68±0.1). It could also be related to higher water holding capacity and poor drainage at my study sites.

4.6. Prediction of field DMC from standard DMC

Although standard DMC were lower than field and sensor estimated DMC, they showed similar trends over the study period. The differences between sensor and field DMC was not statistically significant whereas standard DMC statistically differed from both field and sensor DMC. A scatter plot portrayed that sensor DMC and standard DMC were linearly and positively related. Therefore a simple regression model was built (R^2 = 0.78) that could be used to convert standard-DMC to sensor-DMC value representative of field-DMC in situations where resources are limited to monitor field condition in remote and inaccessible areas.

4.7. Relationship of duff moisture and DMC with other duff characteristics

Duff characteristics contribute to variability in duff moisture within and between forest types. For example, Raaflaub and Valeo (2008) reported that thicker duff was correlated with higher duff moisture in lodgepole pine / white spruce stands in the Kananaskis Valley, Alberta. Otway et al. (2007) found that duff moisture was not related with bulk density in their study conducted at Elk Island National Park for 2003 but was negatively related in 2004. They also found that duff moisture increased as bulk density decreased which as found in my study. Although correlations between duff moisture and other duff characteristics were explored previously, there was no regression model built to explore the ability of duff characteristics to predict duff moisture. In this study, since bulk density and duff depth was poorly correlated with %DM and mmDM, no regression model was built. In contrast, duff load was highly correlated with mmDM which could be due to the fact that the calculation of both mmDM and duff load included bulk density and depth providing a three-dimensional assessment of duff moisture. As such, in the model duff load explained ~58% variation in mmDM. This finding can be very important in fire ecology and science as it indicates the ability of duff load in modelling duff moisture and duff consumption at different stand types. Further studies can be conducted to verify if the relationship between duff load and duff moisture is significant at other stand types.

Significant correlation between LAI and %DM was retention specific such as 20% and control plots where they were significant. It was also positively correlated in the entire stand when data were pooled. The LAI dummy variable regression model explained only 3.7% variation in %DM. The intercept and slopes of duff moisture regression line was significant except for the slope of 75% and clear-cut. However, when a reduced model (control plot was dropped) was tested, the slopes and intercept of remaining retention levels were not significant indicating that the differences in the main model was attributed to control plot and that slopes and intercepts of remaining retention plots were same. LAI was not correlated to mmDM in any retention levels.

Although LAI explained less variation in duff moisture than did duff depth, it showed encouraging and promising results to some extent to consider for more research. In fact, if LAI along with rainfall, wetting and drying cycle, and duff load were parametrized to estimate duff moisture for different forest types, it could be very convenient to predict fire danger for remote and inaccessible forest. Importantly, estimation of LAI had been made easier than ever using remote sensing (e.g. MODIS) and LIDAR technologies (Gong et al., 2003; Zheng and Moskal, 2009). Although many studies related duff moisture with interception, to date, no research had been conducted to directly relate LAI and duff moisture. This would likely be useful, since interception is a major factor influencing duff moisture within and between stand (Miyanishi and Johnson, 2002; Raaflaub and Valeo, 2008) and interception is highly affected by LAI (Brown et al., 2014; Park and Cameron, 2008).

Chapter 5. Conclusion

Duff moisture influences smoldering combustion, fire danger and fire behavior. Post-fire regeneration depends on the degree of burn which depends on fuel type and fire weather including duff moisture. Accurate prediction of duff moisture is fundamental to a reliable fire danger rating system. I attempted to ascertain duff moisture dynamics in a variable retention experimental station near Peace River in Alberta. Variable retention harvesting emulates natural disturbance through retaining forest structure that typically remains following fire and helps achieve many ecological, environmental and conservation goals. It is unclear how the changes in forest structure may bring about changes in fire environment in variable retention sites. As such, I choose to develop and evaluate empirical models for predicting duff moisture using duff and vegetation characteristics as well as calibrate standard DMC-MC relationship for variable retention sites which are not carried out to date.

Several studies have examined effects of canopy types on interception loss and a few studies indicate higher leaf area index (LAI) results in higher rainfall interception loss. But to date there is no empirical model built to predict duff moisture from LAI in various stand types. Likewise, several researchers related duff characteristics such as duff depth, bulk density to duff moisture, but no empirical relationship is built with duff moisture.

In this study I attempted to build empirical models for predicting duff moisture from LAI and other duff variables. I found that duff load was better correlated with mmDM than other duff variables while no duff variable was strongly correlated with %DM. Duff load was related to duff moisture in all retention levels, both plot (300m x 300m) and stand scale. LAI was correlated with duff moisture at 20% retention and across all retention levels. Basal area was not related to duff moisture in any retention site.

I tested multiple regression models to predict duff moisture from all these four variables. I found that duff load was a strong predictor of mmDM, however degree of variation explained by duff load varied by retention level. LAI showed potential in predicting duff moisture, but again these variables explain less than 5% variation in duff moisture.

There was variability of duff moisture over the study period due to the sampling protocol followed in this study. The data were collected when there was no rain or less than 1.5 mm rain before sampling started at 12pm. If rainfall exceeds 1.5mm, data collection was resumed on the second day following a rainy day. So duff moisture varied by how many days after rain data were collected. For example, data collected on the second day had higher moisture than data collected on the third or fourth days in absence of rain. This variability might have reduced the variation of duff moisture explained by predictor variables. Secondly, I did not separate duff moisture data recorded from near the tree bole and away from the tree bole which were found statistically different by (Wotton et al., 2005b) who developed a DMC code for sheltered duff to improve FWI system.

Previous studies have shown that estimated %DM from standard DMC-MC relationship resulted in inaccuracy at locally specific stand types. As such, several attempts have been made to validate and calibrate DMC equations in the boreal forest of Canada (Chrosciewicz, 1989a, 1989b; Wilmore, 2001). I compared field-DMC with that of sensor-DMC and standard-DMC. Since measured DMCs (field-DMC and sensor-DMC) did not differ statistically but measured DMCs were different from standard-DMC, it can be concluded that the measured DMCs are consistent and the difference between measured DMC (field and sensor) and standard-DMC are reliable. Future research aimed at developing stand specific models for estimating duff moisture and DMC might consider duff load and other duff characteristics, together with information on vegetation and stand characteristics that may be effective in estimating water balance within the duff layer.

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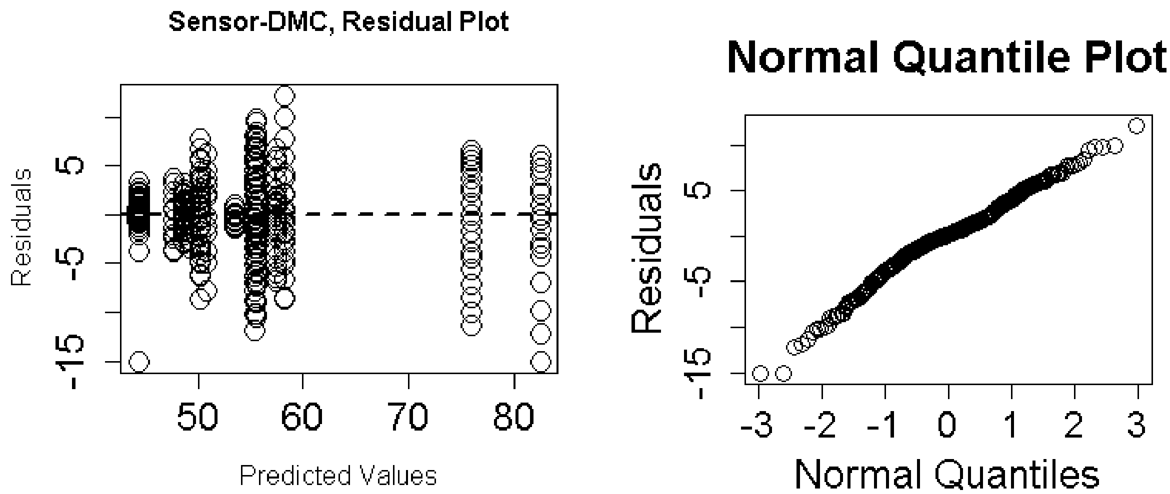
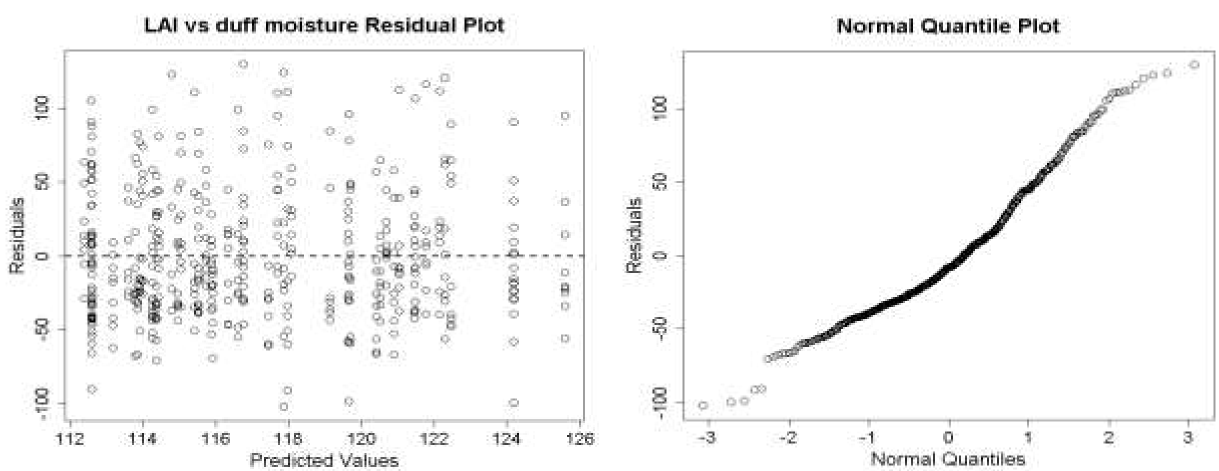
Appendix A

Residual Analysis

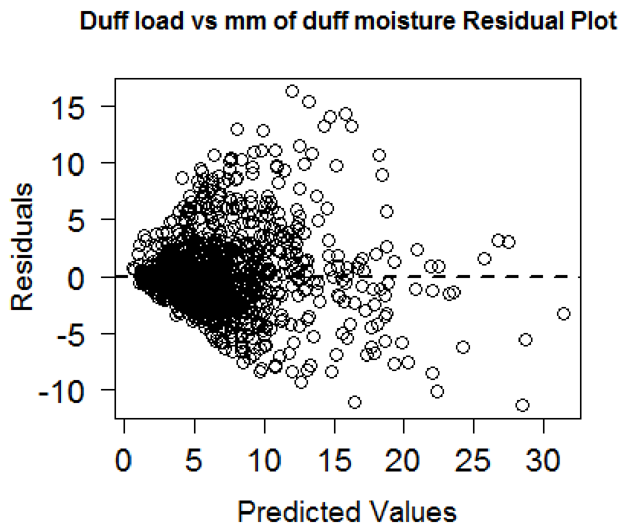
Appendix A1: Studentized residual and Normal Q-Q plots for predicting sensor-DMC/field-DMC from standard-DMC

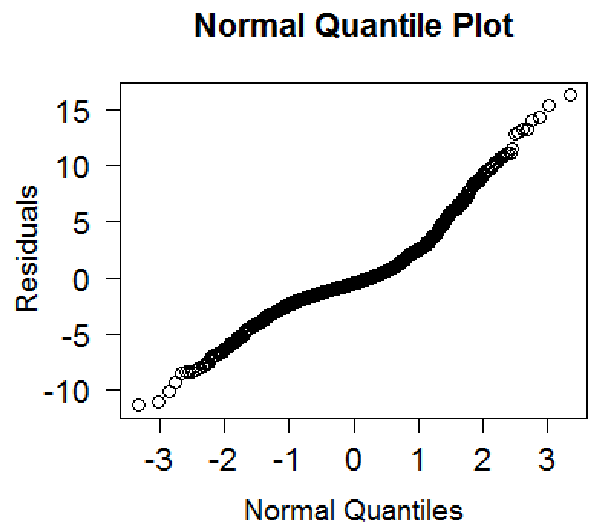


Appendix A2: Studentized residual and Normal Q-Q plots for model predicting duff moisture from LAI in all retention levels.



Appendix A3: Studentized residual and Normal Q-Q plots for model predicting duff moisture from duff load in all retention levels.





Appendix B

Data

Appendix B1: DMC and rainfall data

Date	Standard DMC	Field DMC	Sensor DMC	Rainfall
6/18/2014	16.6	41.64	50.27	0.25
6/19/2014	20.7	40.59	49.93	-
6/20/2014	19.7	50.51	49.39	1.78
6/21/2014	22.4	-	50.76	
6/22/2014	26.4	54.16	49.67	-
6/23/2014	31.4	54.46	48.39	-
6/24/2014	35.2	49.27	49.02	-
6/25/2014	24.1	45.06	49.1	5.34
6/26/2014	27.8	-	50	0.76
6/27/2014	31.7	53.14	48.9	-
6/28/2014	33.6	-	48.2	-
6/29/2014	19.9	48.17	47.98	6.59
6/30/2014	20.8	-	47.28	0.5
07-01-14	24.4	-	44.83	0.25
07-02-14	28	46.67	42.95	-
07-03-14	11.5	49.97	45.37	40.37
07-04-14	13.6	-	46.72	-
07-05-14	16.5	-	47.36	-
07-06-14	18.7	-	48.28	-
07-07-14	21.9	-	49.05	-
07-08-14	25.7	-	49.28	0.51
07-09-14	26.8	-	49.79	-
07-10-14	20.1	-	50.63	3.29
07-11-14	23.1	-	51.5	-
07-12-14	26.2	-	52.51	-
7/13/2014	30.1	-	53.63	-
7/14/2014	33.6	-	54.62	-
7/15/2014	36.3	-	55.06	-
7/16/2014	30.9	-	54.08	2.54
7/17/2014	30.3	-	52.52	1.77
7/18/2014	31.1	-	51.84	1.02
7/19/2014	31.3	-	52.67	1.27
7/20/2014	32.5	-	53.62	1.27
7/21/2014	35	51.11919	54.90107	-

7/22/2014	38	43	51.92174	-
7/23/2014	41.3	54.64	48.30599	-
7/24/2014	43.5	53.42	48.1858	0.51
7/25/2014	17.1	-	48.73881	26.42
7/26/2014	19	-	50.09132	-
7/27/2014	21.9	-	51.40156	-
7/28/2014	25.2	50.55	52.60065	-
7/29/2014	28.7	41.78464	53.77603	-
7/30/2014	33.3	47.7	54.83037	-
7/31/2014	36.7	-	56.07408	1.02
08-01-14	38.3	-	57.14765	-
08-02-14	41.3	-	58.33303	0.51
08-03-14	44.1	-	59.54549	0.5
08-04-14	47.9	-	61.01667	-
08-05-14	50.6	-	62.65825	-
08-06-14	53.6	-	63.85853	-
08-07-14	56	-	63.17198	-
08-08-14	58.4	53.65	63.33297	-
08-09-14	52.4	47.8	64.35991	2.28
08-10-14	54.9	-	65.44247	-
08-11-14	58.1	57	66.62913	1.52
08-12-14	61.5	51.73	68.13684	-
8/13/2014	64	51.87	69.29176	-
8/14/2014	66.3	57.24	70.45102	-
8/15/2014	70	51.23	72.04063	-
8/16/2014	72.8	53.28	73.19808	-
8/17/2014	75.2	57.82	71.73778	-
8/18/2014	77.4	55.22	69.62621	-
8/19/2014	67	55.05	67.19072	2.28
8/20/2014	37.3	-	65.79595	7.87
8/21/2014	37.7	-	65.96996	-
8/22/2014	39.2	-	67.12788	-
8/23/2014	40.6	-	68.19645	-
8/24/2014	43	57.8	64.36356	-
8/25/2014	44.8	57.08	58.21345	-

Appendix B2: Duff sampling data (Plot 910 = 20% retention, 911 = 50% retention, 912 = 75% retention, 914 = Clear-cut, 918= Contol)

Date	Plot	Transect name	Duff depth	Wet weight	Dry weight	Bulk density	MC, %	Load
17-Jun-14	912	P1	3.47	128.29	58.66	117.05	110.18	4.07
17-Jun-14	912	P3	5.23	163.02	74.35	102.17	120.53	5.16
17-Jun-14	912	P5	4.88	283.89	121.06	180.74	129.87	8.41
18-Jun-14	911	P5	5.44	238.44	123.20	178.21	88.51	8.56
18-Jun-14	911	P8	6.48	299.86	131.09	135.77	109.27	9.10
18-Jun-14	911	P4	3.61	168.94	96.62	194.70	76.03	6.71
19-Jun-14	910	P8	5.02	191.83	85.42	122.12	110.55	5.93
19-Jun-14	910	P9	4.82	169.70	87.01	125.89	89.48	6.04
19-Jun-14	910	P4	4.26	179.44	66.58	116.62	158.38	4.62
21-Jun-14	914	P7	6.69	253.98	124.86	137.86	100.22	8.67
21-Jun-14	914	P4	3.79	134.12	62.29	114.65	111.62	4.33
21-Jun-14	914	P8	6.01	264.00	121.72	150.04	112.30	8.45
22-Jun-14	912	P5	5.52	267.64	116.54	146.67	125.43	8.09
22-Jun-14	918	P1	4.20	160.14	68.15	109.05	142.38	4.73
22-Jun-14	918	P3	5.28	158.12	74.16	96.19	116.29	5.15
22-Jun-14	918	P4	3.91	105.87	54.98	94.46	93.34	3.82
23-Jun-14	912	P1	3.91	125.03	58.44	110.18	107.68	4.06
23-Jun-14	912	P3	4.48	169.50	77.79	136.38	117.79	5.40
23-Jun-14	914	P4	3.90	146.56	68.40	120.00	103.91	4.75
23-Jun-14	914	P8	5.96	267.70	125.53	155.82	107.66	8.72
24-Jun-14	910	P8	5.20	181.03	86.10	118.94	102.23	5.98
24-Jun-14	910	P9	4.33	163.78	78.11	127.44	108.19	5.42
24-Jun-14	910	P4	4.26	201.67	83.36	150.89	139.14	5.79
24-Jun-14	914	P7	6.37	253.68	121.26	137.90	113.47	8.42
26-Jun-14	911	P5	5.80	247.97	116.20	146.09	103.78	8.07
26-Jun-14	911	P8	6.28	254.06	121.97	129.69	92.43	8.47
26-Jun-14	911	P4	3.66	187.44	99.28	197.27	88.61	6.89
28-Jun-14	918	P1	4.60	147.57	64.15	98.48	139.66	4.45
28-Jun-14	918	P3	4.91	154.42	72.17	98.96	116.86	5.01
28-Jun-14	918	P4	3.64	93.13	49.94	92.70	90.26	3.47
1-Jul-14	911	P5	5.72	276.86	126.32	153.37	104.30	8.77
1-Jul-14	911	P8	5.38	225.28	115.36	165.11	86.00	8.01
1-Jul-14	911	P4	3.70	158.07	86.12	157.25	87.99	5.98
1-Jul-14	912	P5	5.81	253.64	107.58	132.39	127.31	7.47
2-Jul-14	912	P3	4.49	208.00	99.18	157.18	113.40	6.89
2-Jul-14	914	P7	5.77	241.57	114.83	146.44	114.66	7.97
2-Jul-14	914	P4	4.22	180.67	85.93	127.40	102.15	5.97

2-Jul-14	914	P8	5.63	227.81	105.61	144.56	109.02	7.33
14-Jul-14	910	P8	4.78	175.03	86.23	123.86	97.38	5.99
20-Jul-14	912	P1	4.38	135.24	62.39	107.14	109.88	4.33
21-Jul-14	910	P9	4.10	176.89	79.81	135.51	114.79	5.54
21-Jul-14	910	P4	4.93	198.11	81.49	137.71	140.22	5.66
22-Jul-14	918	P1	5.08	149.34	63.48	88.07	142.78	4.41
22-Jul-14	918	P3	4.29	135.31	64.06	97.60	120.12	4.45
22-Jul-14	918	P4	3.73	94.14	52.64	95.69	77.81	3.66
23-Jul-14	912	P3	4.69	242.44	110.29	166.55	116.85	7.66
23-Jul-14	914	P7	5.27	223.90	109.95	150.05	109.14	7.64
23-Jul-14	914	P4	4.87	210.22	90.05	121.87	118.54	6.25
23-Jul-14	914	P8	4.91	192.26	97.40	145.59	97.36	6.76
27-Jul-14	910	P4	4.87	222.00	98.51	161.70	130.90	6.84
27-Jul-14	911	P8	5.04	207.17	108.63	164.57	83.35	7.54
27-Jul-14	911	P4	3.59	152.62	82.53	154.83	90.89	5.73
27-Jul-14	912	P1	4.40	133.80	60.98	104.57	113.19	4.23
27-Jul-14	912	P5	6.11	241.98	105.36	125.31	123.49	7.32
28-Jul-14	910	P8	4.78	172.26	87.40	125.33	90.45	6.07
28-Jul-14	910	P9	4.13	180.78	79.29	134.26	120.91	5.51
28-Jul-14	911	P5	6.09	269.52	118.04	133.07	109.27	8.20
29-Jul-14	918	P1	5.02	147.12	62.36	87.33	144.15	4.33
29-Jul-14	918	P3	4.40	136.20	65.73	98.02	114.18	4.56
29-Jul-14	918	P4	3.60	89.17	51.59	96.46	72.42	3.58
7-Aug-14	911	P5	6.39	299.97	130.36	139.83	111.64	9.05
7-Aug-14	911	P8	4.43	181.28	101.96	176.33	75.09	7.08
7-Aug-14	911	P4	3.59	149.18	76.32	142.51	100.08	5.30
7-Aug-14	912	P1	4.57	141.80	65.57	106.35	110.41	4.55
7-Aug-14	912	P5	6.16	242.53	106.43	125.45	121.36	7.39
8-Aug-14	910	P8	4.67	161.59	80.71	117.91	92.40	5.60
8-Aug-14	912	P3	4.81	263.56	112.44	165.91	129.48	7.81
8-Aug-14	914	P7	5.21	190.57	102.28	142.57	95.73	7.10
8-Aug-14	914	P4	4.99	218.56	92.88	123.23	121.59	6.45
8-Aug-14	914	P8	4.46	181.92	90.99	145.09	106.67	6.32
10-Aug-14	910	P9	4.67	195.11	79.58	125.34	141.77	5.53
10-Aug-14	910	P4	4.68	211.44	99.48	164.48	111.81	6.91
10-Aug-14	918	P1	5.44	164.46	73.04	92.67	133.14	5.07
10-Aug-14	918	P3	4.11	123.76	60.32	98.55	112.44	4.19
10-Aug-14	918	P4	3.48	74.80	44.64	87.21	69.59	3.10
11-Aug-14	911	P5	6.50	303.41	132.23	138.04	112.02	9.18
11-Aug-14	911	P8	4.18	170.61	97.02	180.73	72.71	6.74
11-Aug-14	911	P4	3.51	140.73	70.36	135.44	99.17	4.89

11-Aug-14	912	P1	4.82	152.58	66.38	99.13	121.43	4.61
11-Aug-14	912	P5	5.94	248.31	115.94	147.00	111.91	8.05
12-Aug-14	910	P8	4.70	159.70	79.55	114.62	92.87	5.52
12-Aug-14	912	P3	4.86	262.22	111.58	164.05	130.18	7.75
12-Aug-14	914	P7	5.12	176.34	89.43	122.72	103.48	6.21
12-Aug-14	914	P4	4.96	229.22	100.38	142.46	117.22	6.97
12-Aug-14	914	P8	4.54	170.92	83.27	123.78	111.29	5.78
13-Aug-14	910	P9	4.61	189.44	76.58	121.61	142.32	5.32
13-Aug-14	910	P4	4.86	226.44	111.84	177.59	105.58	7.77
13-Aug-14	918	P1	5.48	166.46	75.01	95.31	129.85	5.21
13-Aug-14	918	P3	4.06	117.20	56.54	92.90	113.65	3.93
13-Aug-14	918	P4	3.48	77.50	47.60	92.73	63.25	3.31
14-Aug-14	911	P5	6.79	310.97	136.27	136.47	113.22	9.46
14-Aug-14	911	P8	4.10	175.17	102.33	190.04	69.48	7.11
14-Aug-14	911	P4	3.24	129.84	60.80	129.90	104.19	4.22
14-Aug-14	912	P1	4.99	153.80	71.29	101.52	113.25	4.95
14-Aug-14	912	P5	6.10	249.09	118.83	145.90	107.95	8.25
15-Aug-14	910	P8	4.68	158.81	80.33	116.63	89.31	5.58
15-Aug-14	912	P3	4.87	271.78	111.78	163.93	139.60	7.76
15-Aug-14	914	P7	4.89	164.68	81.88	118.12	104.54	5.69
15-Aug-14	914	P4	5.01	232.00	102.35	144.31	116.40	7.11
15-Aug-14	914	P8	4.60	167.37	79.41	116.01	118.28	5.51
16-Aug-14	910	P9	4.48	191.33	75.14	123.85	150.14	5.22
16-Aug-14	910	P4	4.90	223.44	112.17	176.30	98.78	7.79
16-Aug-14	918	P1	5.38	169.57	76.05	99.19	131.34	5.28
16-Aug-14	918	P3	3.94	108.64	54.05	90.34	104.17	3.75
16-Aug-14	918	P4	3.80	89.33	54.46	98.64	65.82	3.78
17-Aug-14	911	P5	6.67	309.30	134.43	136.44	114.78	9.34
17-Aug-14	911	P8	3.92	173.06	100.24	191.70	72.30	6.96
17-Aug-14	911	P4	3.27	128.73	60.14	127.00	104.44	4.18
18-Aug-14	910	P8	4.56	161.81	83.10	125.52	86.78	5.77
18-Aug-14	910	P9	3.68	3.68	3.68	3.68	3.68	3.68
18-Aug-14	910	P4	5.26	227.67	115.98	170.61	96.01	8.05
18-Aug-14	918	P1	5.37	161.57	75.94	99.24	113.21	5.27
18-Aug-14	918	P3	4.07	112.64	57.54	93.39	100.91	4.00
18-Aug-14	918	P4	3.45	77.50	45.00	91.35	71.73	3.13
23-Aug-14	912	P1	5.04	159.80	72.46	102.53	122.14	5.03
23-Aug-14	912	P3	5.06	278.89	118.06	169.15	130.29	8.20
23-Aug-14	912	P5	6.24	247.09	118.53	141.99	106.45	8.23
23-Aug-14	914	P7	4.50	154.23	75.40	117.65	105.07	5.24
23-Aug-14	914	P4	5.37	246.67	111.72	148.97	115.44	7.76

23-Aug-14	914	P8	4.36	161.92	70.49	108.80	138.94	4.89
24-Aug-14	910	P8	4.62	166.70	85.79	128.55	86.81	5.96
24-Aug-14	910	P9	4.31	177.00	67.47	117.17	147.66	4.69
24-Aug-14	910	P4	5.30	236.89	119.98	175.74	99.22	8.33
24-Aug-14	911	P5	6.64	303.74	132.21	133.64	112.78	9.18
24-Aug-14	911	P8	3.72	170.28	97.91	193.35	74.97	6.80
24-Aug-14	911	P4	3.32	125.96	58.58	121.57	105.28	4.07
24-Aug-14	912	P1	5.21	165.13	75.24	104.17	121.59	5.22
25-Aug-14	912	P3	4.87	281.78	120.28	179.60	128.32	8.35
25-Aug-14	912	P5	6.28	239.98	115.19	133.18	104.13	8.00
25-Aug-14	914	P7	4.36	152.01	74.40	121.32	103.42	5.17
25-Aug-14	914	P4	5.70	255.56	115.27	145.11	120.79	8.01
25-Aug-14	914	P8	4.36	159.81	69.27	107.10	139.36	4.81
25-Aug-14	918	P1	5.42	166.23	79.16	102.48	111.31	5.50
25-Aug-14	918	P3	3.89	104.64	53.09	90.54	100.87	3.69
25-Aug-14	918	P4	3.00	69.00	42.00	97.22	64.29	2.92

Appendix C

Pictures

Picture of a trench (50 cm × 50 cm × 30 cm), ground vegetation and roots were removed from the trench.

Picture of a duff sample (12 cm × 12 cm × up to duff depth)