EFFECT OF DRYING INDUCED AFFORESTATION ON PEATLAND ECOHYDROLOGY: IMPLICATIONS FOR WILDFIRE VULNERABILITY

EFFECT OF DRYING INDUCED AFFORESTATION ON PEATLAND ECOHYDROLOGY: IMPLICATIONS FOR WILDFIRE VULNERABILITY

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ABSTRACT

Peatlands cover 170 million hectares of Canada's land and are long thought to be resistant to consumption by wildfire. However, boreal peatlands are likely to become increasingly vulnerable to wildfire as climate change lowers water tables and exposes deeper peat to burning. Currently, the Canadian Forest Fire Weather Index (FWI) System is used to assess vulnerability of peat to ignition and consumption, despite being developed for upland soils. Given the need to assess wildfire risk in peatlands, this study investigated the range and variability of key variables relevant to wildfire hydrology of the subsurface and canopy across five peatlands. Road impacted and drained peatlands were included to examine the influence of drying on afforestation (a surrogate for a future drier climate) and extend the range of parameterizations for peatlands.

Increased drying led to significant increases in canopy fuel loads coupled with increased interception (upwards of 97%) and canopy storage, highlighting failures of the current FWI rainfall routine. Increased drying led to enhanced transpiration across impacted (≈ 2.8 mm d^{-1}) compared to pristine sites (≈ 0.68 mm d^{-1}). However, increases in above ground vulnerability were somewhat offset by ecohydrological feedbacks serving to increase peat moisture retention in the drier sites. But the most severely impacted peatland displayed the poorest moisture retention qualities of all peatlands perhaps indicating the existence of a threshold response to drying induced afforestation on peat moisture retention properties.

Our findings suggest that modified FWI components are suitable for predicting the general moisture status and fire danger in boreal peatlands, highlighting key areas in the parameter to be improved.

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CHAPTER 1: INTRODUCTION

1.1 Boreal Peatlands

Boreal and subarctic peatlands cover ~3.46 x 10^6 km^2 of the global land mass and represent 87% of the world's peatlands (Joosten, 2002). Approximately one quarter of the boreal biome is occupied by peatlands, covering nearly 1.1 million km^2 in Canada alone (Wieder et al. 2009). In continental Western Canada (i.e., Alberta, Saskatchewan, and Manitoba), peatlands cover 21% of the land-base (~365,200 km^2; (Vitt, 2006a)). Half of these peatlands occur in the high Boreal region, where 63% of peatlands exist as fens, 9% are non-permafrost bogs, and 28% are permafrost-bogs (Vitt, 2000). Boreal regions are characterized by short growing seasons and cold, long winters. Consequently, tree communities have adapted to these conditions, with large expanses of coniferous forests, including spruce (Picea), fir (Abies), and pine (Pinus).

In Canada, peatlands are defined as ecosystems that have accumulated more than 40 cm of partially decayed plant material (peat). Peatlands are classified either as bogs or fens based on their hydrology, substrate, chemistry, and vegetation (Vitt, 2006b). Bogs are ombrotrophic peatlands, receiving nutrient and water inputs exclusively from precipitation and are characterized by low nutrient availability, acidic conditions, and low biodiversity (Belland and Vitt, 1995). In contrast, fens receive surface runoff and/or groundwater inputs from surrounding mineral sources contributing to minerotrophic conditions and leading to varying nutrient concentrations, acidity levels, and vegetation types (Vitt, 2006b). Additionally, across a spectrum fens can be further classified as poor

or rich by where poor fens are acidic, minerotrophic and Sphagnum moss dominated, while rich fens can be alkaline, basic to neutral and routinely dominated by true moss species (Vitt, 1994; 2006a).

Peat formation occurs as vegetation productivity exceeds the rate of decomposition and wildfire combustion. While rates of plant productivity are comparable between peatlands and upland stands, soil carbon residence times in deep organic layers are much larger in peatlands than in uplands (Turetsky and Ripley, 2005). Among peatland types, peat accumulates more rapidly in rich fens than in bogs due to increased carbon inputs from elevated plant productivity (Vitt, 1994). Decomposition is reduced in peatlands due to low temperatures coupled with generally anaerobic conditions (Vitt, 1994)). Most peat decomposition occurs in the aerobic surface layer of the peatland. While northern peatlands have long provided a net cooling effect on Earth's climate due to long-term peat accumulation (Frolking et al. 1996), changes in future climate will likely disrupt this ecosystem function. Ise et al. (2008) demonstrate the possibility of a destabilizing of the water table - peat depth positive feedback through increased sensitivity of decomposition to temperature. Long term simulations highlight the potential for 40% loss of soil organic carbon from shallow peat stores and 86% loss from deeper layers under an experimental warming of 4°C. This highlights that peatlands may respond rapidly to global warming by losing labile soil organic carbon during drying.

1.2 Boreal Peatlands and Drought Disturbances

Canada is especially sensitive to impacts of climate change given the existence of extensive sensitive high latitude ecosystems where changes are expected to be most significant. Such impacts have been widely studied (*e.g.,* Soja et al. (2006); Field et al. (2007)). General Circulation Model (GCM) scenarios show predicted mean annual temperature increases across Canada of 3–5°C by the end of 2100 (Lemprière et al. 2008). These increased temperatures by 2100 are expected to increase evapotranspiration rates, lower watertables (Roulet et al. 1992) and decrease soil surface and fuel moisture content, unless offset by large increases in precipitation. Moreover, GCM projections show that spatial trends in summer precipitation totals across Canada are expected to change, with some areas expecting increased rainfall while others will likely see a decrease (Flannigan et al. 2000). While the certainty in GCM precipitation predictions is much lower than for temperature for much of the Boreal region, increased precipitation totals will likely not offset the evaporative demand in a warming climate (Wotton et al. 2010).

As a consequence of this climate warming and drying, northern-forested peatlands are likely to become increasingly vulnerable to wildfire as increased moisture deficits expose deeper peat layers to burning (Turetsky et al. 2006; 2004). Wildfires were thought to have little impact on peatlands as high water tables inhibited combustion (Kuhry, 1994). However, recent research suggests wildfire plays an integral role in peatland carbon cycling through direct regional fire emissions and indirect sources post-fire (Turetsky et al. 2010). Indeed northern peatlands are already becoming increasingly vulnerable to wildfire as climate change enhances the severity of summer droughts, lowering water

tables and exposing deeper peat to burning (Turetsky et al. 2011). Nevertheless, uncertainty exists on the degree to which northern peatlands are vulnerable to enhanced drying and fire given that drying enhances peat water retention (Thompson, submitted), which may reduce wildfire severity and ignition potential.

To gain a better understanding of the effects of increased drying on boreal peatlands, several studies have examined drained peatlands and peatlands impacted by roads (Hillman et al. 1997; 1990; Macdonald and Yin, 1999; Rothwell and Silins, 1990). The altered hydrology of these land-use impacted sites provides insight to the magnitude of the response to sustained drought. That is, disturbances such as (some) roads and drainage networks within peatland complexes can be used as a proxy for long-term drying conditions. Moreover, these impacted peatlands can represent a significant threat to wildfire vulnerability and severity and as such represent an excellent system to examine future wildfire risk in northern peatlands.

Road impacted peatlands are linear disturbances in which a road built across a peatland intersects and impedes local hydrological flowpaths. Despite efforts to limit the hydrological impacts (e.g., drain, channels, culverts), in some hydrogeological settings roads impound water on the upslope side, thus resulting in drying of the peatland on the downslope side of the road. Road orientation to local flow patterns varies the magnitude of the impact of the disturbance. Road impacted peatlands have been shown to display large changes in forest characteristics and fuel loading, shrub and moss biodiversity

(Miller et al. 2012), biogeochemical cycling, as well as soil moisture content (Lieffers and Macdonald, 1990; Lieffers and Rothwell, 1987).

Peatlands have been drained for silviculture, resource extraction and agriculture in Canada and many other portions of the world. In a Canadian context, the Canadian Forest Service (CFS) and the Alberta Land and Forest (ALFS) established a network of drainage ditches in several forested peatlands in Alberta (including Fort McMurray, Salteaux, Goose River, McLennan, and Wolf Creek) in the mid 1980's, as part of the Wetlands Drainage and Improvement Program (Hillman et al. 1990; 1997). Ditches (~0.9 m deep, ~ 1.4 m wide) were dug 30, 40, and 50 m apart (Hillman et al. 1990; 1997) to decrease the water table position 20-50 cm (Hillman et al. 1990). The drainage also reduced soil moisture content, increased peat bulk density (Macdonald and Yin, 1999; Rothwell and Silins, 1990), increased rates of peat decomposition (Lieffers, 1988), and elevated peat surface temperatures (Swanson and Rothwell, 1989). Moreover, significant increases in tree diameter, height, basal area, and volume growth were noted following drainage (Hillman and Roberts, 2006; Macdonald and Yin, 1999).

While it may be argued that land-use changes do not serve as analogues for drought conditions, both road impacted and drained peatlands serve to decrease moisture availability for prolonged periods of time, in some cases causing an ecosystem response that is predicted to occur under a warmer climate. Consequently, understanding how wildfire and land-use disturbance press an ecosystem simultaneously is of primary importance to land managers, fire managers and climate scientists. However, while recent

research suggests the net effect of peatland drainage is an increase in the vulnerability to wildfire (Turetsky et al. 2011) and a decreased likelihood of recovery post-fire (Sherwwod, 2012) there is currently no suitable moisture code to characterize potential for combustion in Canadian peatlands (Waddington et al. 2012).

1.3 Peatlands and the Canadian Forest Fire Danger Rating System

Within the Canadian Forest Fire Danger Rating System (CFFDRS), the Canadian Forest Fire Weather Index (FWI) System is used by Canadian fire management agencies and other countries to predict fire danger (Stocks et al. 1989; Taylor and Alexander, 2006). The FWI System (Van Wagner, 1987) uses three codes as indicators of the moisture status of forest floor layers: dead surface litter and other cured fine fuels (Fine Fuel Moisture Code [FFMC]), loosely compacted decomposing organic matter (Duff Moisture Code [DMC]), and deep compact organic matter (Drought Code [DC]). High code values indicate drier fuel moisture conditions. Currently, peat is not incorporated into the FWI System as the FWI was parameterized in an upland soil (Turner, 1972; Van Wagner, 1977). A DMC and or DC value for a peatland regime is most representative of surface and deeper peat, respectively. However, peatland soils commonly extend deeper than upland soils; possess a water table at or close to the ground surface for extended periods of time (Ingram, 1983), and have a non-rigid dynamic surface layer (Price and Schlotzhauer, 1999) with strong capillarity (Price et al. 1997) that ensures a high VWC at the peat surface. Additionally, Waddington et al. (2012) demonstrated a number of

processes act to alter the slope of the DC and seasonal change in water table relationship within and among peatlands; those results suggested that the slope of the ΔWT –DC relationship might change from year to year as well. Also, the slope of the DC to VWC at a depth of 15cm relationship was not consistent among peatlands, suggesting that that peat moisture dynamics requires further examination in the context of wildfire danger (Waddington et al. 2012).

The primary goal of the FWI system was to provide a systematic method based solely on meteorological data to estimate forest fire danger levels by tracking moisture in different levels of the forest. The systems indices are calculated by the same set of equations across the country to provide fire managers a standard system to assess fire danger in a particular region. However, because the FWI treats all forests, as a closed pine forest it is not necessarily applicable for forest types typical of forested peatlands (e.g., black spruce, tamarack).

In general, fuel combustion is influenced by the availability (fuel loading & structure), fuel type and condition (e.g. fuel bulk density and moisture) of both aboveground and surface fuels, as well as fire weather and behaviour characteristics (Van Wagner, 1972). Smouldering is typically the dominant form of combustion in peat soils due to greater fuel packing ratio and increased soil moisture compared with other fuel types (Miyanishi and Johnson, 2002). Soil moisture and bulk density serve to influence smouldering combustion by affecting the amount of energy required to reach the heat of ignition

(Benscoter et al. 2011) and the quantity of the heat liberated that is propagated to the combustion front (Van Wagner, 1972).

The FWI system DC duff layer assumes a 25 kg m^{-2} layer (7-25 cm depth) (Wagner, 1987) corresponding to a bulk density of 140 kg m^{-3} again for a pine forest. This contrasts with bulk densities of 400 kg m^{-3} for most peat soils (Zoltai, 1991). This large discrepancy in bulk densities not only translates into large differences in the amount of carbon susceptible to combustion, but also the amount of energy available for downward propagation to combust subsequent fuel layers (Benscoter et al. 2011). Therefore, in these dense, organic systems, peatlands pose a large risk for deep consumption and carbon loss.

Waddington et al. (2012) showed that change in water table position, in many conditions fails to provide an adequate measure of surface moisture conditions highlighted by the poor correlation between DC and VMC. The authors suggested the need of a moisture code specifically designed for Canadian peatlands. Re-parameterization of the Drought Code will require the addition of several ecological and hydrological terms relevant to peatlands, including but not limited to a precipitation interception term similar to Wotton et al. (2005) or an entirely new Peat Moisture Code (PMC). While this would require extensive research, in developing the Fire Weather Index System, it was understood that changes might become desirable in particular instances. Not only did Van Wagner (1987) note that the first requirement of the fire danger rating system is that it should represent nature but he also suggested that the information produced be in a form useful to the fire

control agencies. Moreover, the literature highlights a need for peatlands to be accounted for as their own unique entity within the current FWI System, keeping with the philosophy that the "fire danger rating system will in the future continue to evolve in response to the needs of forest fire management throughout Canada"(1938). Indeed additional moisture codes and calculation methods have developed including the Accessory Fuel Moisture System; which provides numerous techniques for adjusting moisture codes to specialized stands (Lawson and Dalrymple, 1997; Wagner, 1977; Wotton et al. 2005; Wotton, 2009). Given that peatlands are unique in their behaviour to changing hydrologic regimes, differ significantly from typical upland stands and form a significant portion of the landscape (~170 Mha in Canada, Poulin et al. (2008)), they should be placed among other specialized ecosystems in the Accessory Fuel Moisture System.

1.4 Thesis Objective

Previous studies have highlighted possible changes in the environment during drying or disturbance leading to increased fire danger across much of the Boreal landscape, primarily peatlands (Lieffers and Macdonald, 1990; Lieffers and Rothwell, 1987; Waddington et al. 2012). It has been determined that tree characteristics change in response to roads/drainage (Lieffers and Macdonald, 1990; Lieffers and Rothwell, 1987) as a consequence of water table draw down. Although changes in tree physiology are understood, a better understanding of the interactions between tree growth and

hydrological processes such as canopy interception, evaporative shading controls and hydrophysical peat properties requires further investigation.

Given the recommendation by Waddington et al (2012) to develop a peat moisture code (PMC) by parameterizing a coupled atmospheric/ hydrological peat models for a limited number of peat and forest types, representing a range of Canadian peatlands, the objective of this thesis was to quantify the variability within key PMC parameters across several peatland types and disturbances in central Alberta. We took advantage of road impacted and drained peatlands to further extend the range of parameterizations of peatlands allowing the PMC to be used in sites where land-use change and disturbances will likely become more prevalent. Also, it is important to note that the peatland landscapes may increasingly become like these disturbed sites with climatic drying.

CHAPTER 2: STUDY AREAS

Five Northern Alberta peatlands were examined from May 1 to August 25, 2011: i) a pristine bog (hereafter referred to as site B (A.1.1), ii) a pristine fen (hereafter referred to as site F), iii) a road impacted bog (hereafter referred to as site RB (A1.2), iv) a road impacted fen (hereafter referred to as site RF (1.4), and v) a drained fen (hereafter referred to as site DF (1.5). Sites B and F were chosen as baseline reference sites, while sites RB, RF and DF were chosen to represent of increased (in order) disturbance (Figure 4.1). Air photos from multiple years were used to identify hydrological impacts due to road construction and ditching (Miller, 2011). Because fens are impacted greater by impeding local groundwater flow than bogs, the DF site represents the extreme 'end member' in our disturbance series and this was confirmed from air photo analysis (Miller, 2011). This study was not organized as a paired control and treatment experiment but rather was designed to examine how disturbance (RB, RF, and DF) leads to a wide range of variability among key parameters (see below) for the development of a PMC. The five study sites were located in study regions: (i) Utikuma Lake, AB and (ii) McLennan, AB. Both study regions are located in the Boreal Plain and encompass a similar climate region and were both part of an existing network of sites with relevant background ecohydrological monitoring (e.g., Thompson, 2012).

The Utikuma Lake peatland complex is located ~75km north of Slave Lake, AB (55.80^{o} N, 115.10^{o} W) and included the B, RB and RF sites. The peatland complex is classified as a continental, mid- Boreal forest (NWWG, 1986). The climate is characterized by long, dry winters and summer precipitation delivered by convective storms. Mean annual

precipitation at Slave Lake (1971-2000) was 502 mm, 146 mm of which falls as snow (Environment Canada, 2000). Mean annual temperature was 1.6 ^{o}C, with a mean July temperature of 15.6 ^{o}C (Environment Canada, 2000).

A hydrometeorological tower was installed in the pristine bog (site B) portion of the peatland complex and at a road impacted portion of the same bog (site RB) 300 m away in October 2007 and May 2011, respectively. Vegetation at sites B and RB was dominated by *Sphagnum* mosses in a pattern of high areas 30-40 cm in elevation and spanning 1 m^2 or more ("hummocks") and low features ("hollows"). Peat depth averaged 1.6 and 2.1 m at sites B and RB, respectively. Hummocks were largely composed of *Sphagnum fuscum* with a shrub canopy dominated by *Ledum groenlandicum* that can reach up to 30 cm in height. Other shrubs and forbs, including *Rubus chamaemorus, Maianthemum trifolia, Vaccinium oxycoccus,* and *V. vitus-idaea* occupy less than 25% of the hummock biomass (Thompson et al, 2011). Hollows are a mix of *Sphagnum angustifolium*, lichens in the pristine site and *Pleurozium schreberii*/ lichen mix in the impacted site. Tree cover at the B and RB sites is composed entirely of an open canopy of black spruce (*Picea mariana*) with a basal area of 11 and 18 m^2 ha^{-1}, respectively and an average height of approximately 2.3 m and 4.2 m for sites B and RB, respectively. Stem density was 16 000 and 18 300 stems ha^{-1} at sites B and RB, respectively. Canopy openness was equal to 64.5% at B, and in RB was calculated as 37.3%. Tree ring analysis dates both stands to approximately 70 years since fire assuming a re-colonization period of 5 years post-fire based on previous observations. Additionally, heavy loading of *Usnea Parmeliaceae* (Old Mans Beard lichen) was present in both stands.

A basic hydrometeorological station was installed at site RF, 40m perpendicular to the roadbed and less than 2 km from sites B and RB, in May 2011. Peat depth at the site averaged 2.6 m. Hummocks largely composed of *Sphagnum angustofolium* and fuscum with a shrub canopy dominated by *Ledum groenlandicum* with a heavy loading of *Rubus chamaemorus*, *Oxycoccus microcarpus, Vaccinium oxycoccus,* and *V. vitus-idaea* on the peat surface. Hummocks pattern the site ranging and lateral extent and in elevation of 2 m^2 and maximum of 55 cm respectively. Hollows are a mix of *Sphagnum fuscum*, *Sphagnum angustofolium, Dicranum undulatum*, *Pleeurozium schreberii*, bare peat and lichen. Tree cover at site RF is composed entirely of a closed canopy of black spruce (*Picea mariana*) with a basal area of 25.9 $m^2 ha^{-1}$ and an average height of approximately 4.3 m. Stem density was 17 760 stems ha^{-1} leading to a canopy openness of 26.2%. Tree ring analysis dates the RF forest (A1.4) to approximately 90 years since fire assuming a re-colonization period of 5 years post-fire based on previous observations. Also important to note is the heavy loading of *Usnea Parmeliaceae*, as the site has potentially reached climax it its trajectory.

The McLennan peatland complex is located ~200 km northwest of Slave Lake, AB (54.87° N, 116.92° W) and included the F and DF sites. The peatland complex is classified as a continental, mid- Boreal forest (NWWG, 1986). Annual precipitation and temperature are similar to the Utikuma lake sites. A portion of the McLennan peatland complex was drained in 1986, as part of the CFS and the ALFS Wetlands Drainage and Improvement Program (Hillman, et al. 1990; Hillman, et al. 1997). Ditching measured 0.9 m

deep and 1.4 m wide (Hillman, et al. 1990; Hillman, et al. 1997) resulting in a net water table decline of 20-50cm (Hillman, et al. 1990), and a reduction in soil moisture (Rothwell & Silins, 1990 and Macdonald & Yin, 1999). Following this, studies examined the differences in tree response to drainage (MacDonald and Yin 1999; Hillman and Roberts 2006) in addition to peat physical properties (Silins & Rothwell, 1998; Silins & Rothwell, 1999).

The DF site is on the southwest portion of the drainage network, while the F site is located 40 m from the ditches on the south side. Peat depth varies throughout the site, however measurements under the site center are 3 m and 1.4 m for the DF and F sites, respectively. Due to the extreme disturbance, vegetation between the control and treatment plots is visibly different from one another. The F site is predominantly S. fuscum, T. nitens, Salix spp., and L. groenlandicum, while the DF site is comprised of P. schreberi with very little shrub cover with limited to no Sphagnum mosses. Both sites have L. laricina and P. mariana trees with the ratio of these trees ranging from 70/30% and 73/27% at the F and DF sites, respectively. Stem densities are 12,550 stems ha^{-1} at F and 17 760 stems ha^{-1} at DF, while the mean basal areas for the F site is 44.0 m^2 ha^{-1} and 20.6 m2 ha^{-1} for the DF site. Canopy openness values for the F site, as it is approximately two times more open at F (45.9%) than DF (25.1%). The McLennan site last experienced fire 90 years ago, implying the canopy is ≈85years old.

CHAPTER 3: METHODOLOGY

3.1 Tree stand characteristics

Tree stand characteristics (basal diameter, age and stem density) were measured at three 100 m^2 plots within each site. All trees were sampled for species and basal diameter. Five trees each of the largest, average and smallest class sizes were cut and processed destructively providing a tree ring "cookie". Each "cookie" was analyzed using Regent Instruments WinDENDRO (2009) software to provide an estimate of the absolute stand age since fire, average stand age and the youngest cohort of recruitment. Tree stand characteristics at the RB and RF sites were measured adjacent to the meteorological tower locations, 40 m from the road. Canopy fuel load (CFL) was computed using allometric fuel loading models from regional forested peatlands Johnston (2012). CFL is equal to the sum of branch, foliage and lichen loading; however, stems are excluded as they rarely contribute to the energy source of the fire (Stocks *et al.* 2004).

3.2 Canopy openness

Light transmissivity and canopy openness were calculated using a Nikon D60 camera and a Sunex 185° Super Fisheye lens affixed upon a tripod and leveled parallel with the moss surface and aimed upwards above the shrub layer (30 cm). The hemispherical lens was aimed skyward perpendicular to the ground and a high-resolution digital photograph was taken of the canopy/void space. Photographs were captured across diagonal transects across the three tree plots at each site, providing 42 point measurements of light transmissivity and canopy openness. Additional hemispherical photos were taken in rain

gauge locations under trees (see below) and in non-treed open areas. Photographs were processed using GLA v.2 software for total light transmissivity, calculated LAI and canopy openness (Frazer *et al.* 1999), following calibration for the lens, site location, and date specifications.

3.3 Precipitation, throughfall and interception

Precipitation and throughfall were monitored throughout 2011 using a set of roving tipping bucket rain gauges. All calculations in the Utikuma Lake region referenced an open burned portion of the B site and in a clear-cut portion of the McLennan site for gross precipitation, P_G. Within the DF, the rain gauge collector was mounted 1m off the ground in-between trees, not under them directly. Unfortunately due to issues with animals eating wires and the large quantities of tree falling tree debris, gauges were often found malfunctioning, upset or clogged. We elected to periodically move rain gauges to increase the effective number of sampling points within the plot to reduce errors in throughfall sampling and to better capture the range of variability in throughfall (Kimmins, 1973; Kostelnik et al. 1989; Puckett, 1991).

The roving tipping bucket rain gauges consisted of nine tipping bucket rain gauges (TE-525M, Texas Electronics Inc., Dallas, TX equipped with Campbell Scientific Data loggers and one Davis Instruments Tipping Bucket Rain Collector connected to an Odyssey data recorder. A set of 14 manual gauge throughfall collectors were also randomly distributed throughout each site, providing even coverage of the entire plot

while capturing the full range of variation in stand characteristics. Manual and logging gauges placed in the same position were in agreement with precipitation totals collected roughly equal. The RB site exhibited logging measurements 28% of the manual gauges values, r=0.85. Alternatively, the RF site exhibited good agreement between the two gauge types with the manual gauges consistently over estimating throughfall by 9%, r=0.73. Gauges were relocated randomly throughout the site across a gradient including under tree bowls (used further in canopy storage calculations) and in open locations within the plot on three occasions.

$$\boldsymbol{I(\%)=[(P_g - P_T) / P_g]\cdot 100} \qquad [3.1]$$

Where P_g and P_T represent gross precipitation, throughfall, and stem flow respectively. Stemflow was considered to be zero as previous observations at site B showed no stemflow, even throughout large magnitude events, which agrees with the findings Price et al. (1997), where stemflow accounted for less than 1% of P_g in spruce canopies.

Only the RF and RB sites possessed sufficient data to undertake calculations of canopy storage capacity utilizing both the Leyton et al. (1967) and the Gash (1979) analytical methods. Leyton et al. (1967) introduced a graphical method of determining canopy storage capacity, S_{max}, calculated from regression analysis of daily or weekly event based precipitation and throughfall measurement.

For this analysis, rainfall events were used when cumulative P_G (0.3 mm, preventing condensation readings), led to P_T provided there was a minimum of six hours without rainfall between events. Cumulative rainfall records for each gauge and event were assessed manually to identify gauges failures, and the average P_T computed. Finally, the Leyton et al. (1967) method also notes that the canopy needs to first be dry to calculate canopy storage, but due to precipitation regimes, this was not possible. Many storms did not provide 'sufficient' time to evaporate previous canopy storage before the next event, hence the arbitrary six-hour minimum period between events. Consequently, S_{max} estimates may be a conservative value.

The Gash Analytical Model (1979) of interception can be applied to give estimates of S_{max} using measured event or daily rainfall data (Gash et al. 1980, 1995). The model also includes a formulation for stemflow and evaporation of water stored on wetted trunks. In this evaluation, we make the assumption that stemflow is negligible (Rothacher, 1963). The Gash analytical method involves using the same P_G / P_T (x, y) scatter as the Leyton et al. (1967) method using a graphical evaluation by identifying the inflection point in the P_G / P_T relation

3.4 Transpiration and evaporation

Sap flow was measured in periods of similar atmospheric conditions between sites and represents the flux of water per square meter of peatland according to sapwood density ratios. Transpiration (T) values presented represent 14-20 days of continuous

measurements in each site during ground ice free periods from July 1st- Aug 23rd. Transpiration measurements were made by measuring tree sap flow using the heat dissipation technique (Granier, 1985). Heat dissipation probes (30-mm long; model TDP-30; Dynamax Inc., Houston, TX) were implanted at a height of 30 cm height on the stems of the trees. The probes were operated through a CR1000 datalogger (Campbell Scientific, Inc., Logan, UT) at 20 min resolution with individual power sources for the CR1000 and the Dynamax AVRD heater element voltage regulator. Heater elements were supplied with a constant 3V supply throughout tests with solar panels trickle charging batteries. Plumbers putty and insulations encased the probes to prevent rain and the atmosphere from developing stem temperature gradients, which can affect the performance of the probes (Gutiérrez et al. 1994). The temperature of a heat source implanted in the sapwood of a tree is measured and referenced to the sapwood temperature recorded 2 cm below the heated needle enables the measurement of sap flow velocity from the empirical relationships between the difference in temperature between the heater needle and the thermistor needle (dT) and sap velocity as defined by a dimensionless parameter K (Granier, 1985). Sapflow observations were made in two trees in the DF site: representing the middle of the lower 60% and upper 40% of the within-site distribution of the basal area at each site. For the remaining sites, three trees were utilized of the middle lower 30%, middle 40% and upper 30% size classes.

Sapflow observations were made on representative trees of varying size class (basal diameter) for each site. Measurements of 31 trees revealed an average sapwood to basal

area ratio (As:At) of 0.44 which was used in the calculation of daily transpiration per unit area (Thompson et al. submitted). Daily T (mm d^{-1}) was then calculated as the weighted average of the daily sums of sapflow in each of the three trees. Evaporation was not measured in this study due to limited instrumentation, primarily the measurement of net radiation. However, measurements of evaporation for pristine sites are well documented from previous work (Thompson et al. submitted) and rapidly decrease with increased canopy shading and the emergence of feather moss.

3.5 Groundwater and soil water storage

Water table position (WT) was measured at all sites using a combination of logging and manual measurements. Odyssey capacitance WT loggers were placed in a transect at 10, 30, 60 m from the road at the RF and RB site. The DF site possessed no water table (absent 2.5m down to clay-peat interface) due to the highly successful drainage (Miller et al. 2011). WT was measured at site B using an Ott (Kempten, Germany) PLS pressure transducer. Across all sites, the initial WT position (WT_i) when measurements began ranged from 13 to 0 cm below the peat surface, while WT ranged from 13.3 cm above to 13.1 cm below the peat surface during the 2011 study period. Fuel moisture code trends were also compared to previous work, (Waddington et al. 2011) using the AB bog as the pristine bog in this study site. The previous study encompassed an unseasonably dry year (2009) with 137 mm of cumulative rainfall over same period, 55% of the precipitation compared to 2011.

The influence of road construction on ecosystem scale hydrology was also assessed using a transect of wells spanning 120 m perpendicular to either side of the road. Wells were installed 5 m apart close to the road and 20 m apart 40 m from the road. An additional two transects were placed on each side parallel to the main transect and extended to 60 m from road. All wells were installed and surveyed in with the use of a TopCon GPT-3200NW total station, accurate to 1 mm in the vertical axis. Potentiometric surface plots were generated to quantify road impacts.

Storativity was determined using the approach outlined by Van Der Schaaf (1999):

$$\mu = \frac{P*}{\Delta h} \qquad [3.2]$$

Discrete storm events were isolated and the precipitation sum over the observed time interval (P*) [cm] and the change in water table position over the same time interval (Δh) [cm] were calculated with precipitation corrected by site-averaged interception resulting in a weighted storage term, μ.

Volumetric soil moisture (*θ)* was measured at depths of 5, 15, and 30 cm at both hummock and hollow microforms using Campbell Scientific (Logan, UT) CS616 water content probes. Probes were installed as soon as ground ice thawed and soil moisture was

logged every 20 minutes using CS dataloggers. T-type thermocouples were deployed alongside the probes for use in their calibration using the mixing model approach of Kellner and Lundin (2001).

3.6 Saturated Hydraulic Conductivity

Saturated hydraulic conductivity (K_{sat}) was measured at the B, RB, RF sites at depths of 70 and 100 cm using polyvinyl chloride (PVC) standpipe piezometers (od = 3.3 cm, id = 2.7 cm). An intake of 17 cm length was slotted in the bottoms of the standpipe, which was sealed at its base a PVC insert. Care was taken to ensure the tolerances of each piezometers measurement remained consistent with the previous, resulting in four identical piezometers. The intake was of a design used by Surridge et al. (2005) and Baird et al. (2004) measuring 75 mm in length that were stacked in pairs. 10 mm gap between slots maintained structural integrity in the conduit. The piezometers were installed in the peat using a metal coring drift with dimensions smaller than piezometer pipe. Infill was removed to the depth of measurement before fully developing the piezometers to unclog pores through smearing and remnant debris post install.

Saturated hydraulic conductivity (K_{sat}) was evaluated at 70 and 100 cm depth in both microforms, with the exception of the pristine site. Average hummock elevation was equal to 30 cm, meaning that HUM100 and HOL70 cm represent the same absolute depth within the profile. Piezometers were installed and allowed 48 hours to reach equilibrium.

DipperLog pressure transducers (Heron Instruments, 1995) were then inserted into the well and left to stand for 1 hour logging hydraulic head and to determine h_o. A single slug of water was then inserted allowing the piezometers to fill and then left to recover, logging at 1Hz for 18 hours. Throughout recoveries, barometric pressure was logged and used to correct for changes in hydraulic head due to atmospheric conditions. Falling head curves were then evaluated using a procedure similar to Surridge et al. (2005).

3.7 Near Surface Saturated Hydraulic Conductivity

Near-surface transmissivity (T_a) was measured by pumping water from 25 cm square and 40 cm deep soil pits according to the approach by van Der Schaaf (1999) and converted to saturated hydraulic conductivity by the equation:

$$K_{sat} = \frac{T_a}{k} \qquad [3.3]$$

here k represents the thickness of the conducting layer. All loose debris is removed from the pits, and allowed to stand for at least 48 hours to ensure water table level stabilization occurs before the test. For each test, the pit was pumped during 1 to 5 min at a constant rate of 0.01–14 L min^{-1}, depending on the peat properties. A 12V battery powered centrifugal pump coupled with a screened intake was used to prevent large peat particles in the pit from clogging the pump. The discharge rate was controlled using an inline DC

voltage regulator between the battery and the motor. The discharge was measured during tests with a graduated cylinder and timer. Drawdown in the pit remained within a few centimeters from the equilibrium level to prevent too much of the upper and most permeable part of the upper peat profile from being excluded from the flow. Otherwise, a considerable underestimation of the transmissivity might result. Values were then evaluated following Van der Schaaf's (2004) methodology.

3.8 Moisture Retention

In late summer, 2011, four 0.5 m deep soil cores from each site composing of two hummocks and two hollows were randomly removed for the analysis of peat moisture-retention curves. Cores were extracted using 102 mm sharpened PVC cylinders and stored in capped, cylinders and frozen prior to transport minimizing compression. Each core was sectioned into 5 cm thick peat "pucks" while frozen using a butcher's band saw. Peat pucks were then thawed and retained in a 5 cm diameter PVC ring with a porous cheesecloth affixed to its base to prevent losses during sampling, maintain puck integrity and support hydraulic contact between sample and the porous plate. Samples were saturated in de-aired deionized water for 24-48 hours allowing the peat to saturate fully before determining the moisture retention characteristics. The Van Genuchten parameters were derived using the Levenberg-Marquardt algorithm for nonlinear least squares to compute non-robust fits in MATLAB for the VWC- tension plots.8

The moisture retention system consisted of a Soilmoisture Equipment Corp. (Santa Barbara, CA) model 1725D22 saturated porous plates with an air-entry pressure of 1 bar all connected to a vacuum system. Samples were under constant negative pressures of 5, 10, 15, 20, 30, 40, 50, 75, 100, 150, 200, and 500 mb for a minimum of 24 hrs. or until water outflow had ceased at each pressure step. Peat pucks were weighed following equilibration at each pressure step, the plates filmed with water to re-establish hydraulic contact between pucks and the plate surface at start of each pressure increment. Sealed chambers held porous pressure plates, samples and open plastic containers of water within the chambers to eliminate evaporation potential by maintaining a high RH% environment. Furthermore, the inside chamber surfaces were misted to reduce condensation potential. Losses were found to be a maximum of 0.21 mm d^{-1}, more commonly 0.042 mm d^{-1} under a freely evaporating surface.

Peat pucks were measured for volumetric shrinkage both after saturation and after oven drying after completion of all pressure steps. Volumetric water content (VWC) was determined by weighing each peat puck on a laboratory scale at the end of the equilibration period for each pressure step and from the measured volume of the peat pucks. Water content at saturation (VWC_s) ($\Psi = 0$ mb) was determined by calculating the porosity of each puck sample from the bulk density and using a particle density value of 1.47 (Päivänen, 1973). Following all moisture retention measurements the peat pucks were dried for 10 days in a 65°C drying oven to constant mass to determine bulk density. Peat pucks woody content (volume) was then determined by manually separating peat

mass from remnant wood debris. Woody fraction by volume was determined through displacement in a measuring cylinder to determine a site average woody density. Moisture retention curves were corrected for their non-peat volume and shrinkage throughout. Since considerable volume reduction occurs with drying, bulk density of oven dried peat represents a condition rarely, observed in situ. Bulk densities were therefore calculated based the wet bulk volume (Blake and Boelter, 1964). Furthermore, specific yield (S_y) was calculated as the volume of water lost between saturation and the first pressure step (5 mb) in the water retention laboratory analysis. For comparison purposes, samples were examined directly for 30 and 100 mb pressure steps. Road impacted sites generally still exhibit a Δh of 30-40 cm 20 years post road construction corresponding to 30 mb tensions. Moreover, the DF site was trenched using one meter deep ditches, corresponding to an initial $\Delta h = 1m$ (100 mb).

3.9 Drought Code and Duff Moisture Code

FWI System moisture code values were computed for each site using the variables from micro meteorological towers. Relative humidity (RH%) and air temperature (T) observations at local noon standard time and the prior 24 h accumulated rainfall were used to calculate the DC and DMC components of the FWI System using equations outlined in Van Wagner (1987). The Drought Code (DC) is a numerical rating of the average moisture content of deep, organic layers of the forest. The DC is an indicator of seasonal drought effects on the stand fuels, and potential amount of smouldering in deep duff layers and large logs with values between 0-79 representing the lowest possibility of

ignition and values greater than 400 representing the highest risk of flammability. The DC uses a simple estimate of daily evapotranspiration based on the model by Thornthwaite and Mather (1955) to estimate daily loss of moisture and assumes that a fraction of rain that falls on the forest floor is absorbed.

Based originally on the Stored Moisture Index (SMI), which directly expressed the moisture equivalent in hundredths of an inch up to a maximum of 800 (8 inches of water), the DC was modified to capture the exponential drying characteristics in deep soils (Van Wagner, 1987). The SMI was converted to the DC using:

$$\mathrm{DC} = 400 \ln\left(\frac{800}{\mathrm{Q}}\right) \qquad [3.4]$$

where Q is the moisture equivalent or the former SMI. The constant represents a theoretical maximum moisture content of 400%.

The DMC follows a similar method where moisture lost from the layer to the atmosphere is a function of T and RH and a monthly estimate of drying day length. Moisture gains come directly from rain input, the fraction of rain absorbed being related to initial moisture content and rainfall amount itself.

3.10 Statistical Rationale

Student's t-test is used to compare two means. However, to compare multiple means across a number of treatments, a t-test is inappropriate and would create the multiple tests problem (i.e. the confidence in the statistical test decreases due to inflated alpha and results in increased occurrence of Type I errors) and would require a Bonferroni correction.

To test means across a number of treatments, an Analysis of Variance (ANOVA) is suitable with a post hoc comparison of means. ANOVAs partition the total variance in the data set into within- and among-group components. To successfully employ an ANOVA, the observations must be independent, the experimental errors must be normally distributed, and the variance should be homogeneous. SAS's JMP (JMP, 1989-2007.) was used to perform the statistical analysis and test the assumptions of the ANOVA. Bartlett's test was used to verify the assumption that variances across groups were equal (i.e. homoscedasticity) and a plot of the residuals determined the normality in this study. Finally, in this thesis, if the ANOVA yielded significant results a Tukey post hoc analysis of means was used to determine significant differences between sites.

CHAPTER 4: RESULTS

4.1 Tree stand characteristics and canopy openness

Picea mariana (Black Spruce) was the dominant species at all sites except site F, which had a mix of Black Spruce (73%) and Larch (27%). Stem density for site B was 13 300 stems ha^{-1} while RB showed an increase in stem density to 18 400 stems ha^{-1}. Both disturbed fen peatlands, RF and DF, possessed stem densities of 17 800 stems ha^{-1}. Additionally, mean basal diameter increased across the disturbance gradient (Figure 4.1). Site B had a mean basal diameter of 2.9 ± 0.1 cm (mean ± stdev), increasing to 3.0 ± 0.2, 3.5 ± 0.1, and 4.5 ± 0.1 cm for the RB, RF and DF sites, respectively. Mean basal area also increased from 17.4 ± 7.3 m^2 ha^{-1} at site B to a maximum of 44.0 ± 1.4 m^2 ha^{-1} at DF with road impacted sites falling in between, 17.9 ± 16.5 and 25.9 ± 8.6 m^2 ha^{-1} for RB and RF, respectively.

Canopy openness decreased with a similar trend. The RB site (64.5 ± 1.1 %) demonstrated a statistically significant 40% reduction in canopy openness over its un-impacted counterpart (37.3 ± 1.4 %) $p < 0.05$. Increasing canopy extent led to a further reduction in canopy openness within road impacted and drained fens, reaching a potential maximal in canopy closure of 26.5 ± 1.2 % and 25.1 ± 2.2 % correspondingly.

Following previous trends, the B site had the lowest CFL followed by the RB, RF and finally DF site. The road disturbance resulted in a 55% increase in CFL compare with site B (7 167 kg ha^{-1}) to the RB site, (11 136 kg ha^{-1}). Comparing both road-impacted sites, the RF site (15 537 kg ha^{-1}) was 40% greater than RB. Finally, the DF site highlighted the largest CFL examined (25 603 kg ha^{-1}), a 260% increase over the pristine site and 65% larger CFL than the RF.

4.2 Precipitation, throughfall and canopy interception

Total precipitation (P_{Tot}) for the 2011 study period was 249 and 351 mm for the Utikuma Lake and McLennan regions, respectively (Figure 4.2). Precipitation for May-August was 83% and 155% of the long-term climate normal for the Utikuma and McLennan regions, respectively (Environment Canada, 2011). For the same period, 32 discrete storm events separated by 6 hours or more occurred in the Utikuma region, with 46 storm events for the McLennan site.

Average rainfall interception at site B was 43.9 ± 7.3%, while the road disturbance (site RB) marginally increased that amount to 46.9 ± 16.5 %. The disturbed fens had the largest increases in interception, with DF intercepting 83% more than RF (97.1 ± 1.4% vs. 53.8 ± 8.6%).

Canopy storage capacity utilizing the Leyton method at site RB was 4.8 mm while RF retained more rainfall, 6.0 mm. Similarly using the Gash method, RF had higher canopy storage values than the RB site, values of 7.3 mm and 5.2 mm, respectively. The Gash method provided consistently larger estimates of canopy storage for sites, 25% more for the RB site and 40% larger in the RF when compared to the Leyton method.

4.3 Transpiration

Transpiration (T) for site B was 0.67 ± 0.05 mm d^{-1} averaged over the season, while the road impacted bog pair (RB) demonstrated a slight decrease to 0.41 ± 0.06 mm d^{-1}. Transpiration increased with level of disturbance at the fen sites, increasing from 1.17 ± 0.14 mm d^{-1} at RF to 2.75 mm d^{-1} in DF (Figure 4.3). The drained fen site is reported without an error term to limited sample size. The difference in variance between groups excluding the DF site was statistically significant ($P = 0.004$). If we relax the assumption of equal variances, all sites are significantly different from one another ($P < 0.001$) with the exception of the B and RB sites ($P = 0.079$). Transpiration was linearly correlated to mean basal diameter as well as to basal area (adj r=0.96, 0.97).

Although not the primary focus of this investigation, key daily averaged metrological variables such as vapour pressure deficit (VPD), mean daily vapor pressure deficit normalized by light hours (D_z) from Gower *et al*. (2005), daily sum of photosynthetically active radiation (PAR), and temperature were used to model transpiration. Daily and 20 min time step data was used for all sites. Collectively examined, correlations were weaker

than when modeled individually by site. The strongest single predictor was PAR (PAR; $R = 0.45$; $F_{65} = 52$; $P < 0.0001$) while a model combining all independent variables led to an increase in model fit (PAR, Dz, VPD; $R = 0.56$; $F_{65} = 28$; $P < 0.0001$). When PAR was evaluated per site, Bog (PAR; $R = 0.80$; $F_{36} = 145$; $P < 0.0001$), road impacted fen (PAR; $R = 0.61$; $F_{10} = 23$; $P < 0.0001$) and finally road impacted bog (PAR; $R = 0.70$; $F_{64} = 52$; $P = 0.0008$) goodness of fit improved in all cases.

4.4 Groundwater and soil water storage

The largest variation over the season in WT of all sites was at the pristine bog (-4.2 ± 8.1 cm) followed closely by the pristine fen (6.51 ± 3.87 cm). The tower location of RF showed decreases in WT fluctuations (6.33 ± 2.11 cm) as did RB tower local, being the least variable out of all sites (5.40 ± 1.86 cm). Comparing the range of WT table positions of the RB site 60 m from the road to the B site shows they behave similarly as one would expect (Range= B:14.1cm, RB:14.9 cm).

Variability in WT throughout the field season was also investigated within road-impacted sites, varying in distance from disturbance. The RB and RF sites demonstrated differing responses to WT variability, examined using standard deviations and ranges. The tower location (5.40 ± 1.86 cm, range= 8.91 cm) of the bog had drastically different water table responses compared to the road and 60 m locations, (18.41 ± 3.23 cm, range=17.64 cm) and (15.6 ± 3.08 cm, range=14.94 cm) respectively. Contrarily, RF demonstrates the least

variability and range of WT values in the 60 m (12.77 ± 1.27, range=6.79 cm) location followed by the tower (6.33 ± 2.11, range=11.86 cm), and finally the road being the most variable (M=7.33 ± 2.60, range=16.13 cm).

To compare road-impacted sites to the pristine site, tower wells were used. A one-way between sites ANOVA was conducted to compare the effect of site on weighted μ in the tower locals of the sites. There was a significant effect of site on weighted μ for the three sites ($F_{2, 27}$ = 24, P <0.0001). *Post hoc* comparisons using the Tukey HSD test indicated that mean weighted μ for the RF (0.12, ± 0.02) was significantly different than the B (0.29 ± 0.02) or RB (0.26 ± 0.02) tower sites, which were not significantly different from one another. A one-way between sites ANOVA was conducted to compare the effect of local on weighted μ in the RF site. There was a significant effect of local within the site on weighted μ ($F_{2, 30}$ = 18, P < 0.0001). A *post hoc* comparisons using the Tukey HSD test showed that mean weighted μ for the tower local (0.12 ±0.027) was significantly different than both the road (M = 0.40, SD = 0.11) and the 60 m (0.42 ± 0.19) sites, which were not significantly different from one another. Additionally, variability in μ at the tower was significantly less than the other two locations within the site (Bartlett's test, P <0.0001) (Figure 4.7).

Moreover, a one-way between sites ANOVA was conducted comparing the effect of local on weighted μ in the RB site. There was a significant effect of local on weighted μ level ($F_{2, 30}$ = 9, p = 0.001). A Tukey HSD test showed that mean weighted μ for the road local

(0.41 ± 0.10) was significantly different than both the tower (0.26 ± 0.06) and the 60 m (0.26 ± 0.12) sites, which were not significantly different from one another. Although weighted μ for the tower and the 60 m are identical, the 60 m measurements are far more variable than the tower location. This is consistent with findings for the RF site.

In both road-impacted sites, variability in storage was largest at large distances from maximum disturbance (60 m) and decreased rapidly for tower locations. Additionally, one would expect mean μ for the tower local at B (μ=0.29) to be the same as the 60 m RB (μ=0.26) site due to diminishing effects of the road at great distances. An independent t-test concluded this was true, that the means of the two locations are not statistically different from one another, P =0.46.

4.5 Saturated Hydraulic Conductivity

Mean K_{sat} increased with increasing disturbance (B > RB > RF), and with decreasing depth (HUM70 > HUM100 > HOL70 >HOL100) within each site (Figure 4.4). K_{sat} became less variable with depth as the standard deviation of values for HUM 70cm was three, four and seven times greater than HUM100, HOL70, and HOL100 respectively. Moreover, K_{sat} was shown to be more variable in hummocks as well as shallower depths (HOL 70/100; $\sigma = 6.49 \times 10^{-6} / 3.19 \times 10^{-6}$) than hummock equivalents (HUM 70/100; $\sigma = 2.35 \times 10^{-5} / 9.14 \times 10^{-6}$) (Figure 4.5).

Road impacted sites demonstrated larger variability in K_{sat} throughout the profile compared to site B. Generally, K_{sat} was less in hollows and decreased with depth. K_{sat}

variability for road- impacted sites was higher over the depths investigated than for non-impacted sites. Mean surface K_{sat} of site B was 4.5 $x10^{-3}$ ± 0.9 $x10^{-3}$ m s^{-1}, declining to 1.6 $x10^{-4}$ ± 2.2 $x10^{-5}$ m s^{-1} at site RB, marginally more than RF, 4.1 $x10^{-4}$ ± 1.9 x 10^{-4} m s^{-1}.

4.6 Near Surface Saturated Hydraulic Conductivity

Within sites, surface K_{sat} differences in the degree heterogeneity between hummock and hollow microforms existed, (Bartlett's test, P <0.0001). Although not statistically different from one another due to the high degree of heterogeneity within sites, generally, hollow surface K_{sat} exceeds that of hummocks. Maximum surface K_{sat} was observed for a B hollow (9.75 $x10^{-3}$), while two orders of magnitude lower, an RB hollow was the minimum (9.26 $x10^{-5}$ m s^{-1}) (Figure 4.6).s

Pristine hollows and hummocks demonstrated differing mean values, though exhibited similarly large variabiltiy in surface K_{sat}, 5.29 $x10^{-3}$ ± 0.003 m s^{-1} and 3.69 $x10^{-3}$ ± 0.002 m s^{-1}. RB displayed similar trends between microtopography as the B site at a much lower conductivity, 1.6 $x10^{-4}$ ± 8.5 $x10^{-5}$ m s^{-1}, 1.5 $x10^{-4}$ ± 4.6 $x10^{-5}$ m s^{-1}, for hollows and hummocks respectvly. Similarily, RF demonstrated trends previously examined in microtopography, as well as increased variability for hollows and hummocks; 5.9 $x10^{-4}$ ± 7.3 $x10^{-4}$ m s^{-1}, 2.4 $x10^{-4}$ ± 2.1 $x10^{-4}$ m s^{-1}.

4.7 Bulk Density

Values of bulk density (ρ_b) before log transformation varied from 8 to 198 kg m^{-3} and were positively skewed (Figure 4.7). There was a significant interaction between site and $\log_{10}(\rho_b)$ ($F_{3,170} = 4.96$, $P < 0.001$), as well as between microform and $\log_{10}(\rho_b)$ ($F_{1,173} = 60$, $P < 0.001$), with mean ρb in hollows (83 kg m^{-3}) greater than that in hollows (43 kg m^{-3}). A Tukey's HSD post-hoc test revealed that ρ_b at sites DF (85 kg m^{-3}) and RB (62 kg m^{-3}) were not statistically different from one another. Likewise, sites RF (47 kg m^{-3}), B (56 kg m^{-3}), and RB were similar. Therefore, the only sites statistically different from one another in terms of ρ_b were the DF from the B and RF site. ρ_b showed a weak linear dependence on depth in both hummocks and hollows ($r = 0.36$; $F_{1,139} = 76.7$; $P < 0.001$). Finally, drainage and road disturbances appeared to have no effect on hummock or hollow ρ_b at the near surface.

4.8 Specific Yield

Specific yield (Figure 4.8) and volumetric water content at 100 mb of tension (VWC_{100})(Figure 4.9) was largely dependent on bulk density, which was weakly correlated with depth ($r= 0.36$; $p < 0.001$). The relationship between ρ_b and both S_y and VWC_{100} was heteroscedastic, increasing variance with increased ρ_b. Influences on VWC_{100} were similar to ρ_b, with microtopographical interaction with VWC_{100}. One-way ANOVAs of site and microtopography revealed that like ρ_b, microform showed the strongest control, microtopography had the greatest influence in determining VWC_{100} ($F_{1,139} = 38$, $P < 0.001$) and sites were not significantly different from one another.

4.9 Moisture Retention

A one-way ANOVA of VWC_{100} by depth revealed that peat depth strongly influenced VWC_{100} ($F_{9,131} = 16.3$, $P < 0.001$), though Tukey's HSD test showed three distinct zones of similarity, 0-10 cm, 15-30 cm and finally 20-45 cm. Regression analysis of VWC_{100} showed that both ρ_b ($r = 0.50$; $F_{1,139} = 140$; $P < 0.001$), and depth ($r = 051$; $F_{1,139} = 142$; $P < 0.001$) were significant predictors of VWC_{100} but also demonstrated and interaction effect.

The Van Genuchten model (1981) parameter α describes the convex or concave behaviour of the moisture retention curve and is inversely related to the air entry pressure. α was the more varied of the two parameters. Values of α before log transformation varied from 258 to 0.02 corresponding to pore sizes of 36 cm to 30 µm. A two-way ANOVA showed $\log_{10}(\alpha)$ was influenced by topography ($F_{7,133} = 4.07$; $P < 0.001$), where hummocks exceed hollows, but site or an interaction between site and microform was not a significant factor. Bulk density was poor at predicting $\log_{10}(\alpha)$, explaining only 48% of total variance ($F_{1,139} = 133.4$; $P < 0.001$). A linear relationship was observed between $\log_{10}(\alpha)$ and the specific yield following the form: $\log(\alpha) = 3.02*S_y - 1.05$; $r = 0.83$; $F_{1,139} = 688$; $P < 0.001$.

$\text{Log}_{10}(\alpha)$ generally decreased in hummocks with depth across sites, with small increasing trends at depths of 35 cm in all impacted sites. This trend was not consistent for site B hummocks. Likewise, α in hollows decreased with depth for all sites. However, at 25 cm

depth the DF and RB sites possessed a zone of increasing $\log_{10}(\alpha)$ also present 5cm shallower in the RF site. The zone of increasing α was present at 30 cm depth for the pristine site, the same depth $\log_{10}(\alpha)$ begins to decrease once more for impacted sites. Near surface $\log_{10}(\alpha)$ was tested using a two way ANOVA and demonstrated that site and microtopography had significant effects ($F_{7,40} = 3.15$; $P < 0.001$) but no interaction effect was present. A Tukey HSD test revealed that only the RF and DF sites differ statistically, with mean $\log_{10}(\alpha)$ values of 1.49 and 0.89 respectively.

The dimensionless n parameter in the Van Genuchten model (1991) is an exponent that determines the slope of the moisture retention curve. Large values of n (e.g., 3) indicate the curve is steep, with a rapid decrease in VWC as tension becomes more negative increases. If n is small (e.g., 1), the change in water content is gradual. N varied substantially less than α, ranging from 1.18 through 3.21 with a mean for all samples of 1.52 ± 0.016. Generally, n was lower and less varied across deeper denser samples than in less dense samples (surface in particular), which showed elevated variance. There was a weak correlation between n and log10(α) ($r = 0.16$; $t_{139} = -5.2$; $P < 0.001$).

4.10 Effect of Drying on Near Surface Peat

The effect of drainage and road construction was most evident on near surface samples (0-10 cm). Near surface samples from hummocks and hollows were compared at 30 mb and 100 mb tensions for reasons previously stated (Figure 4.11). Residual moisture

content at a tension of 30 mb (VWC_{30}) for hollows was significantly higher in the B site compared to site RB (B= 38.4 ± 4.2%, RB= 0.2 ± 6.6%, P =0.004) despite no statistical difference in porosity between near surface samples. Furthermore, VWC_{100}, VWC_r and S_y were statistically different between B and RB for hollows. Across sites, B and RF were not statistically different from one another as was RF, RB, and DF sites for VWC_{30}, VWC_{100}, VWC_r and S_y. In contrast, there was no difference between the sites for hummocks for VWC_{30}, VWC_{100}, VWC_r or S_y. Additionally, no significant difference existed in porosity between surface samples in hummocks or hollows. Both bog sites were statistically different than the DF site when examining VWC_r ($F_{3,20} = 5.4$; P = 0.007, respectively). S_y of hummocks was significantly different in RF compared to RB and B, which were not statistically different from one another ($F_{3,20} = 5.6$; P = 0.006).

Near surface bulk density was not statistically different among sites at depths of 0, 5, and 10cm or as a grouped average. To compare sites to one another, VWC_{100} and VWC_{30} vs. were investigated simulating both road impact and drainage (Figure 4.9). At both tensions, trends remained consistent with higher bulk densities resulting in higher residual moisture contents. For a given bulk density, the road impacted sites retained a larger amount of water at 30 and 100 mb tension. Subsequently, the pristine site (plotted with another undisturbed bog site for confirmation) retained the least water for a given tension than the road impacted site but surprisingly more than the drained fen for a given bulk density.

4.11 Fuel Moisture Code Modelling

Several peatlands studied had extensive microtopography features and thus the position of the groundwater well may not have been representative of the mean WT position for the peatland. To account for this peat surface variability when comparing FWI System fire codes – ΔWT relationships between sites, WT dynamics as the change in WT position from the start of the season (ΔWT) were examined (Figure 4.12).

While the changes in seasonal WT and DC were strongly correlated within sites, the slope of this relationship ranged greatly between fens (–0.04) and bogs (–0.12). Moreover, the slopes were similar at the RF (–0.05) and RB (–0.031) sites. Interestingly, both bog and fen pristine sites show strong relationships between ΔWT and DC (B, $r= 0.78$; F, $r= 0.87$) compared to their road impacted (RB, $r= 0.17$; RF, $r= 0.40$) counterparts. Furthermore, correlations in 2009 were higher ($r= 0.98$) than during 2011 ($r= 0.78$) for B, all trends significant at the $p = 0.001$ level.

To examine if slopes or intercepts differed across sites or years for the DC- ΔWT relationship, an ANCOVA was used. In all cases, the regressions for fitted lines were statistically significant, $p < 0.001$. To fit lines with differing intercepts and slopes, a full factorial design of SITE, DC and SITE*DC was used. Due to the SITE*DC interaction being significant ($p < 0.001$), it was concluded that lines were not parallel. Refitting the model without the interaction term and utilizing DC and SITE, a small p- value (< 0.001)

indicates that lines do not share similar intercepts. In all combinations of SITES, lines were concluded to be statistically different with respect to slope and intercept at a 0.99 confidence level.

Site-specific DC–ΔWT relationships were used to estimate the ΔWT at a DC value of 400, which has been associated with wildfire vulnerability in uplands. Using a dry year for the same site in a previous study, this value corresponded to drop in WT position of 25 cm for site B for both wet and dry years. Coincidently, site B demonstrated the largest change in ΔWT to achieve a DC value of 400, compared to site F, which required ΔWT = -1 cm to achieve the same DC value. The RB site becomes more 'vulnerable' than its un-impacted counterpart, with a ΔWT = -5.4 cm, while the RF site (ΔWT=-9.3) appears more 'resilient' than site F.

In general, significantly ($P < 0.0001$) strong correlations between DMC and ΔWT existed ($r = 0.70–0.78$, $P < 0.001$) with the exception of site B in 2011 ($r = 0.32$, $P < 0.001$). Across sites, a DMC value of 150 corresponds to a ΔWT as high as –64 cm in the pristine bog or as low as –32 cm in the pristine fen.

During dry periods, a strong correlation between DC and 5 and 15 cm VWC at B in 2009 ($r = 0.91$ and 0.99, respectively, $P < 0.001$) existed. However, the total range in the VWC data over 2009 was very small VWC_{5cm} only decreased from 13% to 12% at a hummock and from 28% to 24% at a hollow during a period when DC increased from ~250 to over 500. During 2011 (wetter), weaker correlations between DC and 5 and 15 cm VWC ($r = 0.78$ and 0.78, respectively, $P < 0.001$) existed at site B. The same 5 cm hollow increased 31% to 90% where DC decreased from ~385 to 202 in the span of 35 days. In contrast to the consistent drying throughout the 2009 summer, the alternating drying then wetting conditions in the 2011 season yielded large ranges in DC for a given VWC. For example, a VWC of 50% in the pristine bog corresponded to DC values ranging from 180 to 275. During periods of extended drying, the slope of the VWC-DC relationship is larger than for the short periods of wetting and drying (Figure 4.13)

With a DC value of 400 considered a critical level of dryness in uplands, moisture throughout the profile was examined measuring exceedance of the corresponding VWC at DC400 levels for each site. Values of 100% indicated the nominal depth of the microform remained at a VWC below a corresponding to a DC value of 400 or higher, while all other probe depths not listed are 0% (Figure 4.14). Presumably, probes closer to the zone of intermittent saturation will satisfy the DC400 condition less frequently. Although the 5cm hummock at the bog site had no moisture data available, it is fair to assume it would be equally as dry as 10 cm deeper in the profile. In comparison to the road-impacted portion of the site, the pristine bog does not reach critical moisture status for the same duration of

time. Interestingly, the road impacted fen exceeded moisture values for a DC of 400 much less often for comparable depths in the RB site but still more than the pristine fen (Figure 4.9).

DMC was well correlated only with 5 and 15 cm VMC during periods of prolonged drying at the pristine bog in 2009 ($r = 0.87–0.99$, all $P < 0.001$). Correlations for 2011 were much weaker ($r=0.28–0.60$, all $P < 0.001$). Similar to the DC–VWC relationship, the total range of the VWC data set was very small in the pristine bog site in 2009. In contrast, 5cm HOL VWC increased from 30%-90% in the span of 35 days while the DMC decreased from 61 to three. 2011 marked a more variable year in VWC for a given DMC value among sites. For example, a 50% VWC in the pristine bog, DMC ranged from 0-40 (Figure 4.10).

CHAPTER 5: DISCUSSION

5.1 Peatland drying and afforestation

Results from this study confirm that peatland disturbances that lead to a water table decline, such as road impacts and drainage, promote afforestation and positive feedbacks that further enhance the drying of forested peatlands. Previous studies (e.g., Hillman and Roberts, 2006; Lieffers et al.1987b) demonstrated similar results with an increase ins forested fen of black spruce and tamarack growth rates following peatland drainage and road impacted sites (Lieffers et al. 1990). Our results demonstrated that trees from sites with greater depth to water table also had the larger basal areas. Moreover, canopy closure and stem density appeared to reach maximum asymptotes for the RF and DF sites in our study, potentially suggesting a saturation effect or a competition for resources in nutrient limited environments.

Drying positively influenced tree growth, which coincided with enhanced canopy fuel loads (CFL). The CFL of this study were higher than reported in (Johnston, 2012) for pristine bogs of identical ages. While Johnston reported CFLs of 0.668 kg m^{-2} compared to our results of approximately 1.1 kg m^{-2}, our results incorporated tree lichen loading for all trees following Johnston (2012) allometric equations, who was able to determine if each individual tree had lichen. Utilizing a chronosequence of un-impacted sites, Johnston's CFLs ranged to a maximum of 0.94 kg m^{-2}, surpassed by many of the road impacted and drained sites of our study (1.1 to 2.6 kg m^{-2}). Moreover, site DF has a CFL well within the accepted range of upland black spruce stands in Canada (2.6 kg m^{-2})

(Johnston, 2012).

Potentially more important than drying associated tree growth are the positive feedbacks that couple drying and tree growth, which until now have been little investigated in peatlands (e.g., Thompson et al. submitted). The drying enhancement in disturbed sites proposed by Miller et al. (2012) is substantiated by this study. The drawdown in water table has lead to increased rooting depth and root aeration enhancing tree productivity. This increase in canopy density leads to increases in canopy interception of precipitation. Increased interception and evapotranspiration losses by larger more productive trees were previously suggested (Rothwell et al. 1996) as amplifying decreases in water table levels post-drainage, and what our work has shown. We have shown increases in CFL, increase in interception, increase in transpiration and finally decrease in average seasonal water table position as a function of disturbance.

Canopy interception increased with increasing stand size, canopy openness, and stem density. This reduction in water supply to the peat surface highlighted the presence of a reinforcing drying cycle to water table drawdown. Both the Leyton and Gash methods to determine canopy storage highlighted that road-impacted bog and fen forest canopy storage were much greater than what is currently utilized in the FWI model for calculating DC (Van Wagner, 1987). The DC model requires a 2.8 mm precipitation event to begin wetting of the fuel layer, after which roughly 17% is lost, greatly over estimating the amount of water reaching the peat surface, thus marginalizing the wildfire severity and organic available for combustion. Although not investigated in this study,

increased snow interception and subsequent sublimation with higher tree cover would also likely serve to enhance increase previous summer soil moisture deficits. Black spruce have shown to both intercept snowfall (e.g. Pomeroy et al. 2002) and to enhanced mid-winter ablation via longwave radiation from stems and foliage (Davis et al. 1997). The compounding summer and winter effects of trees on precipitation serves to decrease the total quantity of water or snow water equivalent reaching the peat surface, thereby perpetuating the positive drying feedback.

Transpiration dominates water losses in boreal forest catchments in closed canopy forests when soil evaporation is near zero except during snowmelt and after large rain events (Wang, 2008). A higher density of lager trees on the landscape leads to a positive drying feedback in two ways.

For example, Sarkkola et al. (2010) determined that a tree stand increase of 10 m^3 ha^{-1} led to a 1 cm water table drop due to increases in transpiration for spruce and pine stands. The importance of water loss through transpiration was also highly evident in our study. The pristine bog transpired 34% of total seasonal precipitation while site DF transpired 94% of the study period bulk seasonal precipitation. We expected increasing rates of transpiration across the disturbance gradient. This was true with the exception of the RB site, which transpired less than site B. Because bogs are known to be nutrient limited it is possible that the larger trees at RB were nutrient and water stressed (Hillman and Roberts, 2006; Lieffers and Macdonald, 1990, Macdonald and Yin, 1999). When sites were

grouped and transpiration was modelled together, PAR and VPD correlations were much weaker than when modeled individually by site. This may indicate differing water use efficiencies and nutrient status for each stand (Angstmann et al. 2012; Choi et al. 2007; Islam and Macdonald, 2004). Furthermore, bog species were shown to be more resilient to drainage (Miller et al. 2012) than other peatlands in the region, and thus may not show differing rates of transpiration.

Although surface evaporation was not measured in this study, Thompson et al. (submitted) evaluated E values of 1.9 mm d^{-1} for the B site as part of a 2010 study. These values fit within the expected range for Sphagnum evaporation of 1.5 mm d^{-1} to as little as 0.5 mm d^{-1} in densely shaded areas(Heijmans et al. 2004).

Increases in shading and drying have been shown to lead to decreases in Sphagnum and promotion of feather moss and lichen (Miller et al, 2012). Feather mosses evaporate significantly less than Sphagnum in the field (Bisbee et al. 2001) and also feature high surface resistance ($r_{s)}$ values regardless of WT (Bond-Lamberty et al. 2011). Bond-Lamberty (2011) showed that many species of feather mosses and Sphagnum mosses show a similar increase in r_s to evaporation with drying. For this reasons evaporation rates of feathermoss should also decrease with drying, further decreasing already low evaporation rates. Therefore with drying, evaporation rates in theory should decrease with a shift to feather moss species emergence and reduced Q* as a result of decreased light transmission through the canopy.

5.2 Impact of Afforestation Induced Drying on Peat

The effect of drying induced afforestation of peatlands extends to the subsurface, in particular peat hydrophysical properties. Moreover, our results are consistent with the findings from Rothwell et al. (2002), where K_{sat} over the profile decreased with depth and drainage. While K_{sat} decreased with depth in all sites, drying appears to have resulted in increasing K_{sat} variability at depth while making near surface K_{sat} more homogeneous. Decreases in K_{sat} can be attributed to the loss of macropores resulting in increased ρ_b after dewatering and subsidence (Price, 2003). Near surface peat is often a largely heterogeneous medium, potentially contradicting one of the main assumptions Van Der Schaaf (2004) makes. Within this heterogeneous system, wood debris, root casts and differing oxidation rates among species contribute to zones of to low and high K values within decimeters (Van Der Schaaf, 2004), explaining the larger variability in sites with enhanced zones of oxidation and tree growth. This finding was further substantiated by zones of increasing log10(α) at depth.

Agreement between RB 60 m WT variability and the B tower location, which should be identical to one another as the 60 m from the RB sites serves as a control for the road impact was found. WT was most variable in bogs compared to fens. Groundwater inputs could serve to moderate water table fluctuations in fens and perhaps safeguarding fens against short-term drought. More interestingly, the largest variability in WT was in pristine sites. Our findings contradict findings Talbot et al. (2010) and Price et al. (2003),

that drained and harvested sites were characterized by enhanced seasonal variability in water table depth. The lack of variability in WT position coupled with the increases in K_{sat} at 70 and 100 cm depth are consistent with an increase in storage at depth. Coring of the peat at both road-impacted sites showed relatively un-decomposition of sphagnum from 30 cm to the clay contact boundary at 200+ cm when compared to the B site. Recent studies as well as those by Waddington et al. (2011) highlighted decreased pore water residence times (or decreases in rainfall rates) led to an increase in phenol and dissolved inorganic carbon concentrations that serve to inhibit microbial respiration. This in turn provides a negative feedback to the decay of peat, keeping its larger pore structure and associated hydraulic properties intact. Trees not only limit rainfall rates but the roadbed prevents small subsurface flow throughout the peatlands. This perhaps creates zones of static water preventing flushing of pores old pore water and the accumulation of phenols and other decomposition limiting chemicals (Waddington et al. 2012).

Previous work (Waddington et al. 2012) demonstrated that ΔWT response to rainfall was larger for bogs than for fens, consistent with the findings from this research as well as in the road impacted sites. Furthermore, near surface peat samples showed that all bog types (pristine and road impacted) differed statistically from the fens of this study for θ_{30}, θ_{100} in this study. Potential causes for this are differences in peat water storage properties. The difference in peat properties is seen when examining log10(α). There was a significant topographical relationship but no site interaction. Although ρ_b was lower at the surface and higher at depth; consistent with widely held assumption that ρ_b generally increases

with depth (Zoltai, 1991), the weak relationship between log10(α) and ρ_b suggesting that the type of peat/species influences moisture regimes more than peatland type.

In general, near surface bulk density was surprisingly not affected by disturbance. As previously discussed, moss type at the surface likely complicates the distinction of bogs vs. fens and road impacted vs. non-impacted sites. The hydrophysical properties of the peat are attributed to the composition of mosses that make up a site. Shifts in moss community composition with the replacement of *S. fuscum* on dry, shaded hummocks by feather mosses are a result of peat surface drying attributed to vertical peat accumulation and increased canopy shading by black spruce (Benscoter and Vitt, 2008). Furthermore, *Sphagnum* species have been shown to decline in abundance, replaced with feather mosses after drainage in treed poor fens (Miller et al. 2012). Shifts in moss composition have important feedbacks to soil moisture, as living *Sphagnum* and *Sphagnum*-derived peat have greater moisture retention capacity than those of feather mosses (Benscoter et al. 2011) (Figure 4.13).

Most importantly, our findings show that for a given bulk density, road impacted sites retained more water than pristine counterparts and drained sites at 30 and 100 mb. However, more extensive drying (i.e., our DF site), exhibited poorer soil water retention for comparable bulk densities to any of the other sites investigated (Figure 2.13, 2.14). It should be noted that the curve fit for the DF should not remain linear even though this investigation portrays it as such. This demonstrates an irreversible shift in the

hydrophysical properties of heavily dried peat like demonstrated in laboratory experiments, (Szajdak and Szatylowicz, 2010) as well as field based observations, (Rovdan et al. 2002; Schwärzel et al. 2002). Schwärzel et al. (2002) showed the effect of hydrophobicity on soil wetting at the end of the summer drought by where wetting inhibitory surfaces formed during desiccation led to an abnormally high wetting resistance of the strongly earthified peat layers. Rovdan et al. (2002) also collaborate these findings where the moisture retention of drained peat soils at more advanced stages of decomposition is lower.

5.3 The Fate of Drying Peatlands and the CFFDRS

Trends observed in FWI System fuel moisture codes reinforced the change in the peat substrates with drying and its implications for smouldering susceptibility. Strong relationships between DC and ΔWT_i at our sites, lead to confidence that WT position can be used as a broad predictor of moisture status in peatlands (Bubier et al. 2003). Reinforcing previous work, slopes of varying magnitudes of the DC - ΔWT relationships and consistency between a wet and dry year were discovered. Describing the resiliency of a peatland to wildfire as requiring a larger decline in the WT to achieve a DC value of 400, the un-impacted bog sites were the most resilient, while pristine fens were most vulnerable with small changes in WT. This finding highlights the inaccuracies of developing fuel moisture codes based strictly on changes in water table position as well as where utilizing the current DC fails. Other such circumstances include the locations of

increased interception (Wotton et al. 2005) and when short term fire weather timescales are used in conjunction with long lag time fuel moisture models such as the 52 day lag time in the DC. Furthermore, this demonstrates a DC equal to 400 or any other such "magic number" cannot operationally across the wide range of peatlands types. Although the pristine fen requires a 1 cm decline in the WT to reach a DC of 400, peat several centimeters below the surface remain at nearly saturated conditions (Figure 4.10), highlighting a false positive for critical moisture content of the expression. This substantiates other findings where critical moistures of a DC of 400 were attained more often in impacted sites compared to pristine sites. Reasons for this decreased vulnerability of bog have been cited due to the drought tolerance of the species composition, while fens due to their ground water inputs possess no such adaptation (Miller et al. 2012). In general, road impact served to increase the vulnerability of bogs while decreasing it in fens, all while road- impacted bogs were more vulnerable than fens corresponding to a smaller decline in WT needed to achieve a DC of 400 (Table 1).

To further assess the vulnerability of peatlands, FWI System fuel moisture code – VWC relationships were evaluated and found that DC- VWC had weaker correlations in the wetter 2011-field season of this study than for previous studies in 2009 (Waddington et al. 2012) for the pristine bog, a result of the much larger range in VWCs for an identical microform. This contributed to a larger range in VWC for a given DC value in 2011 due to the alternating wetting and drying regimes. Our results demonstrate that the Thornthwaite and Mather (1955) ET component of the DC model accurately estimates daily losses under continual drying scenarios. However, the ET model does not accurate

account for losses and gains likely due to basic simplification that the fraction of absorbed rain is proportional to initial moisture content and rainfall amount. The variety of mosses on the peat surface possesses hydraulic properties (i.e.: specific yield, field capacity etc.) that complicate the intermittent wetting routines as compared to relatively homogenous upland duff.

Hummock-forming Sphagnum moss (e.g., *S. fuscum*) inhibits deep peat burning due to its ability to retain moisture (Benscoter et al. 2011; Shetler et al. 2008). Declining Sphagnum cover as a result of drying and afforestation is likely to reduce surface soil moisture, leading to increased risk of fire and deep burning of peat. Likewise, the conversion to drier feather moss communities yields a greater potential for deep burning, similarly intensifying ignition and combustion risk of peat (Benscoter et al. 2011). Following recommendations from Waddington et al. (2012), this study supports the need for a handful of peat types to be included in a future PMC, as peat/species type is thought to contribute to the hydraulic properties more so than changes in peatland. The likely drying and afforestation of future peatlands under future climate scenarios and land-use developments will serve to lower water table position and increased woody fuel loading associated with drainage. Both are likely to influence both fire frequency as well as the severity of fuel combustion in Western Canadian peatlands (Turetsky et al. 2011).

5.4 A drained vs. un-drained Case study

Differences in subsurface moisture regimes have large implications for wildfire

susceptibility, and no more is this evident than within the McLennan drainage site. Drainage has led to a paired study site in which both the wettest and driest of all sites examined existed. Moisture content was heavily stratified within the pristine fen (site F). Mean seasonal VWC for the hummock at 5 cm depth; 13 ± 0.1 %, while 10 cm deeper VWC remained consistently saturated over that same period (88 ± 0.008 %). Moisture within the drained portion of the site was distributed differently. 15 cm depth represented the driest zone (10.0 ±0.02%) within the profile followed closely by the surface 5 cm (11.4 ±0.03%), likely in atmospheric equilibrium due to the presence of feather moss. The un-drained site likely is actively wicking moisture from the WT below through capillarity (Clymo and Hayward, 1982). Despite the vast differences between sites, VWC remained within 2% of one another at 5 cm depth for both sites, with site DF VWC 2 % less on average.

Between sites, near surface wetting and drying routines were examined. For a given precipitation event, the change in VWC (ΔVWC) due to wetting was noted as was the proceeding 24 hour drying period. Both sites respond identical for drying and wetting periods with the slope of 0.94 (r= 0.89). Interestingly, during wetting events, both sites respond similar to wetting despite the fact that the DF intercepts 97% of rainfall. This may be attributed to feather moss having a much lower moisture field capacity (about 20%) with VWCs around 10%, as compared to *Sphagnum* (40% moisture field capacity) and 35% VWC in the drained site. The loose nature of the moss located at the un-drained site (*S. fuscum, T. nitens)* hummocks freely shed excess moisture, thus contributing to retained moisture similar to the drained feather moss. Both feather moss and fuscum

demonstrate similar VWC for low bulk densities in previous studies.

Fire susceptibility is related to the moisture content of the fuel layers. Investigating how the FWI system is computed in vastly differing sites highlights the models weaknesses as well as strengths. The drained fen VWC-DMC relationship was the strongest correlation (r=0.80) in the 2011 season, while the DC was most correlated with the pristine fen 5cm HUM followed by the drained site 30 cm depth (r= 0.85, 0.75). Strong correlations reinforce findings from Jukaine et al. (1995) who after drainage witnessed more species gradually replaced by forest vegetation. It is not surprising that strong correlations exist for the drained site to the FWI System codes developed for uplands, in particular the DC. The DF site was the only site to remain at a corresponding moisture content for a DC of 400 for the duration of the summer study period at all depths investigated. However, based on calculations using the nearest meteorlogical station, the FWI System did not calculate DC indices reaching these critical levels. Alternatively, only the highest microforms in site F remained at this critical moisture level throughout the season. At a depth of 15 cm within the same hummock, the critical moisture value is never reached. Despite these major discrepancies in moisture allocation between sites, both would be assigned identical DC and DMC values under the current FWI system. Despite the stark differences between the McLennan sites, both would be assigned identical FWI Fuel moisture values since they are located 100 m from each other, sharing the same meteorological data.

CHAPTER 6: CONCLUSION

This study took advantage of road impacted and drained sites to investigate a wider range of several hydrological parameters in response to prolonged drying as a surrogate for future climate scenarios relevant to a future PMC. A better understanding of interactions between tree growth and hydrological processes such as canopy interception, evaporative shading controls and finally the peat properties have been suggested. Road impacts served to promote drying through enhanced tree growth and above ground susceptibility to wildfire via reinforcing positive feedbacks, but also led to decreases in resilience of below ground peat stores to smouldering via decreases in residual moisture content for a corresponding negative tension. Coupling these positive feedbacks produces a dual positive feedback under future drying scenarios (Figure 5.1). In order to better characterize this new wildfire risk in forested peatlands, recommendations of this and previous research, need to be implemented into a PMC or revised moisture code in the FWI. In developing a PMC modeling framework, it is also not possible to represent the variability in boreal peatland moisture dynamics by one stand type as seen across our disturbance gradient. Varying degrees of afforestation led to large discrepancies in above ground moisture regimes, and should be characterized accordingly. Accordingly, interception and transpiration terms specific to stand densities/ canopy openness are easily adjusted parameters in the current system. Moreover, evapotranspiration can be modeled using a modified Penman approach (Monteith 1965) that will utilize existing weather station data to link to surface boundary exchange mechanisms. It is anticipated that most of the peat type variability that occurs throughout boreal peatlands can likely be captured by using differing classes of peats ranging from highly fire prone (feather moss)

to tolerant (fuscum) with several in between. The peat types would each be parameterized for their hydrophysical properties (S_y, S_s, K_{sat}, field capacity, and moisture retention-alpha). This research also highlights that no "magic number" exists to capture the range of variability with the current DC moisture relationships across the peatlands studied. All peat types will also not exist across all stand types. For instance, heavily decomposed peat that is more susceptible to combustion will likely only be found in mature densely populated stands due the feedbacks presented in this study. Not only do these recommendations produce a more robust fuel moisture model for future scenarios, but also they allow the PMC to be used in landscapes where land-use change and disturbances will likely become more prevalent, and a zone of increased of human produced fires.

It is clear that drought will lead to complex responses between peatland vegetation structure, hydrology, and peat characteristics as shown in this research. This study has shown the net effect of complex interactions will result in increased wildfire vulnerability throughout forested Boreal peatlands. With the predicted increase in fire activity (e.g., Wotton et al. 2010) and forecasted 100% increase in area burned by 2100 for Canada (Flannigan et al. 2000), peat fires will appear more frequently on the landscape as will escalating suppression costs associated with mop- up of smouldering peat fires. However, we will not need to wait until 2100 to see the effect of drought on peatland wildfire vulnerability. Recently, wildfire coupled with a long-term drought period occurring in the central European Nonchernozemic region, was responsible for extensive damage totaling

upwards of 1.5$ billion with an added $336 million in suppression costs covering the 621,000 ha, primarily dried peatlands. With this in mind, our research provides a solid foundation to begin construction of a coupled atmospheric/ hydrological peat model (PMC), providing fire managers with a new tool for predicting critical areas to avoid costly deep burning peat fires.

LIST OF FIGURES

Figure 4.1 - Hypothesized disturbance gradient along hydrosequence, sites in order of magnitude of disturbance.

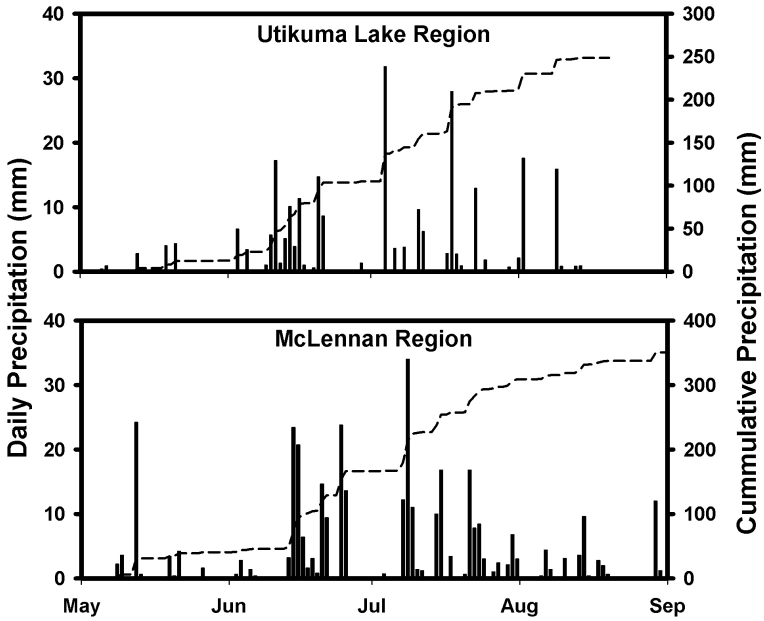


Figure 4.2 – Daily and cumulative precipitation for McLennan and Utikuma Lake study regions during 2011.

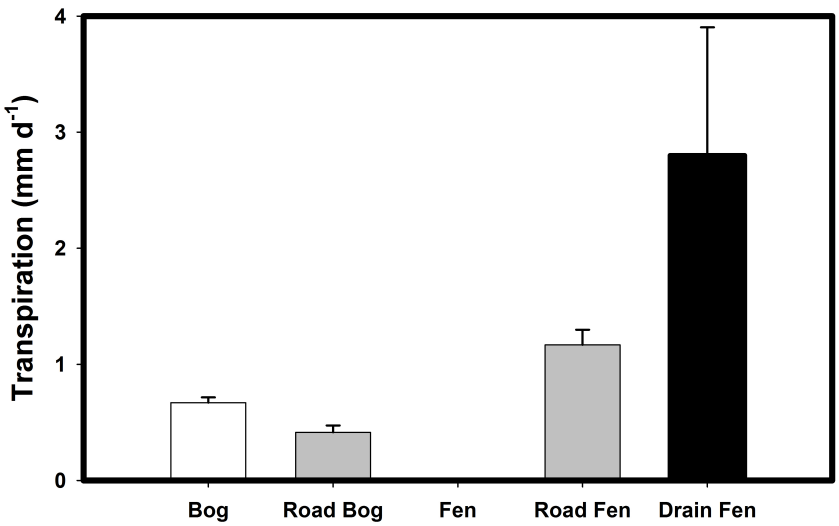


Figure 4.3 – Mean daily transpiration (mm) generally increasing with disturbance from 0.67 to 2.75mm day^{-1}.

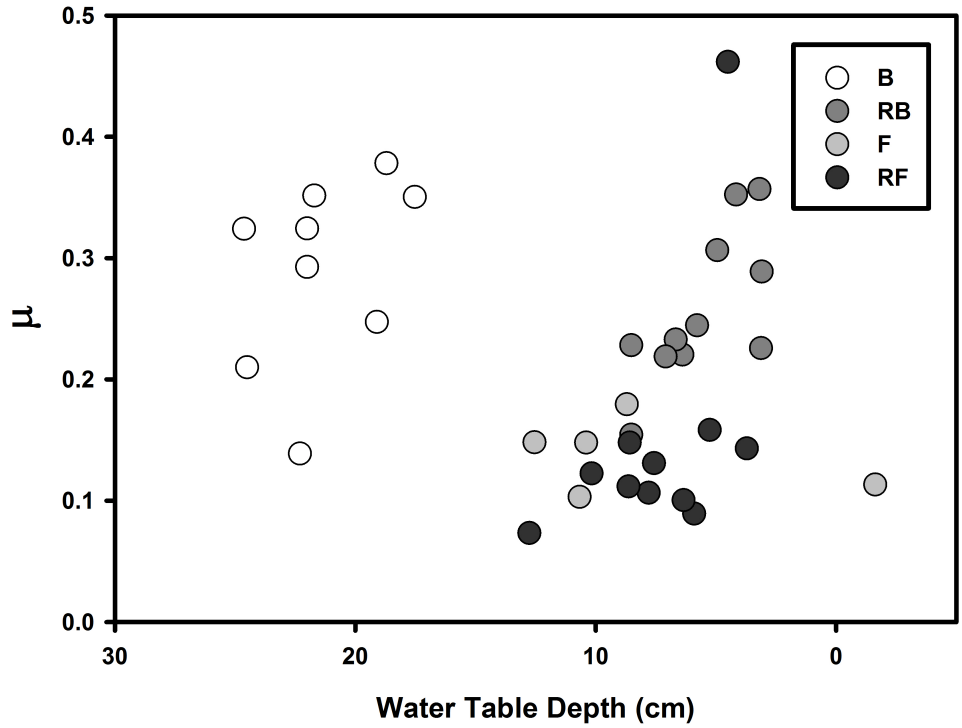


Figure 4.4 –Storativity (μ) versus phreatic level for pristine and road impacted sites.

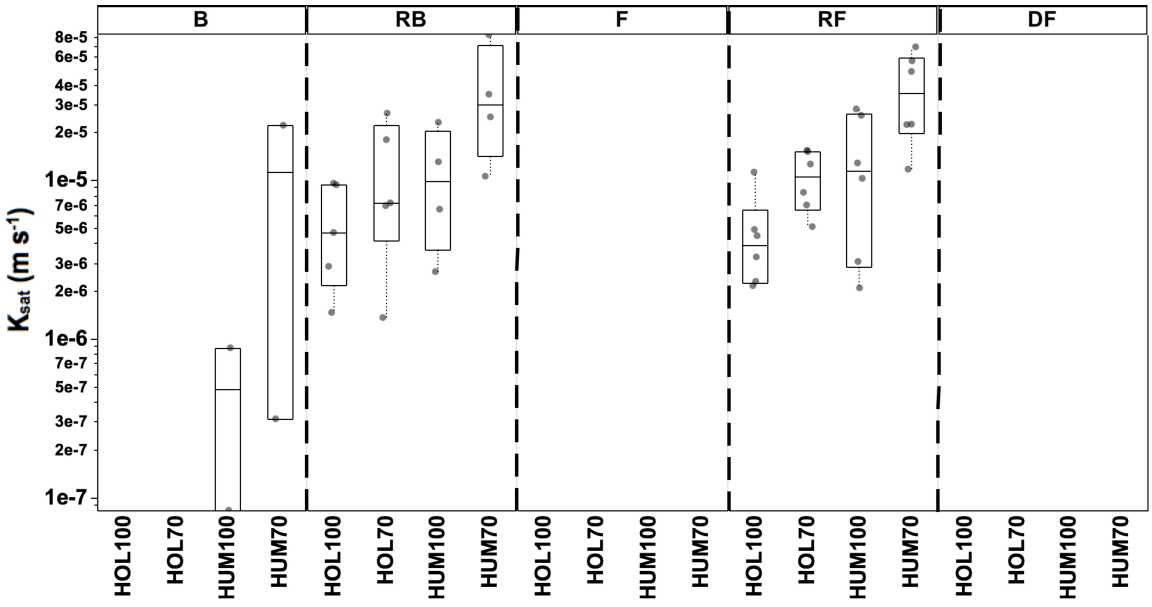


Figure 4.5 - Boxplots of K_{sat} at nominal depths of 70 and 100 cm for hummocks and hollows decreasing with depth. Decreased variability with depth and within hollows.

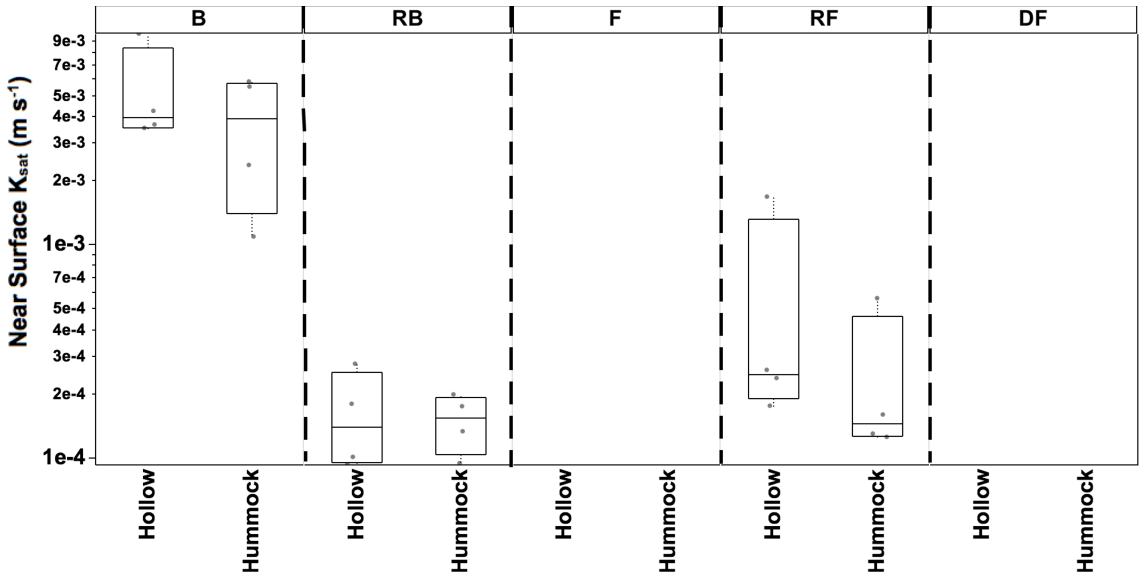


Figure 4.6 – Single pit pumping test determined near surface K_{sat} of hollows lower than hummocks with largest variability in surface K_{sat} for a pristine bog. *note log scale of y-axis.

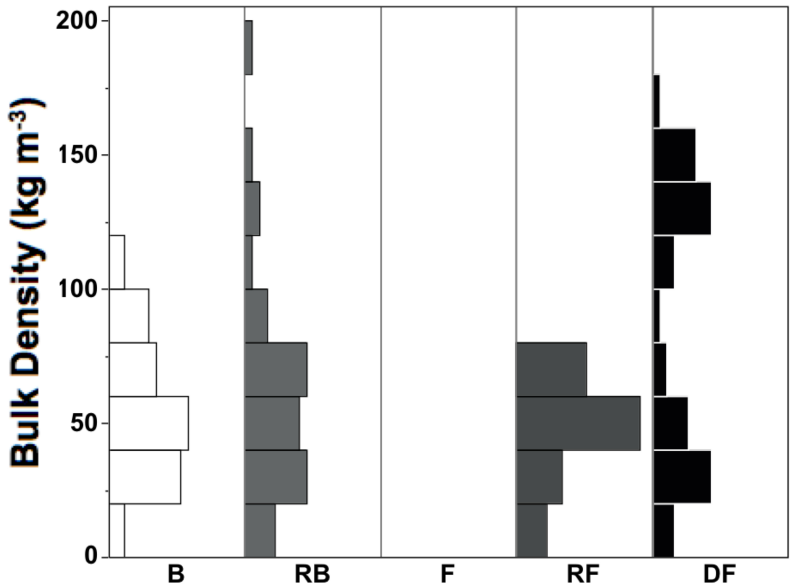


Figure 4.7 – Bulk density distributions by site of peat samples for shallowest 50 cm of profile.

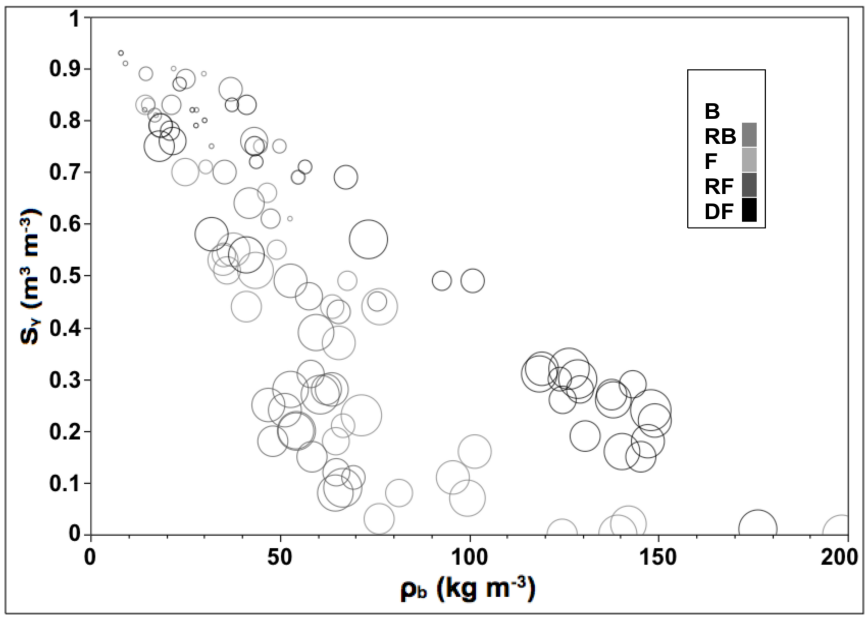


Figure 4.8 – Specific Yield as a function of bulk density by site. Bubbles size is proportional to sample depth, 0-50 cm.

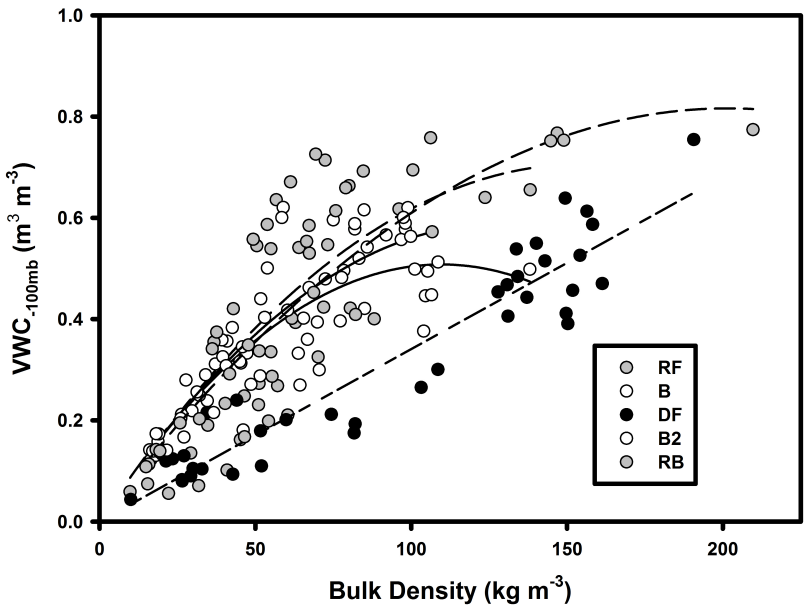


Figure 4.9 – Plot of volumetric water content at -100 mb pressure (θ_{100}) as a function of bulk density. Hypothesized increasing slope with disturbance. Samples divided by site into 3 major site types; pristine (solid lines), road impacted (dashed) and drained (long-short dash).

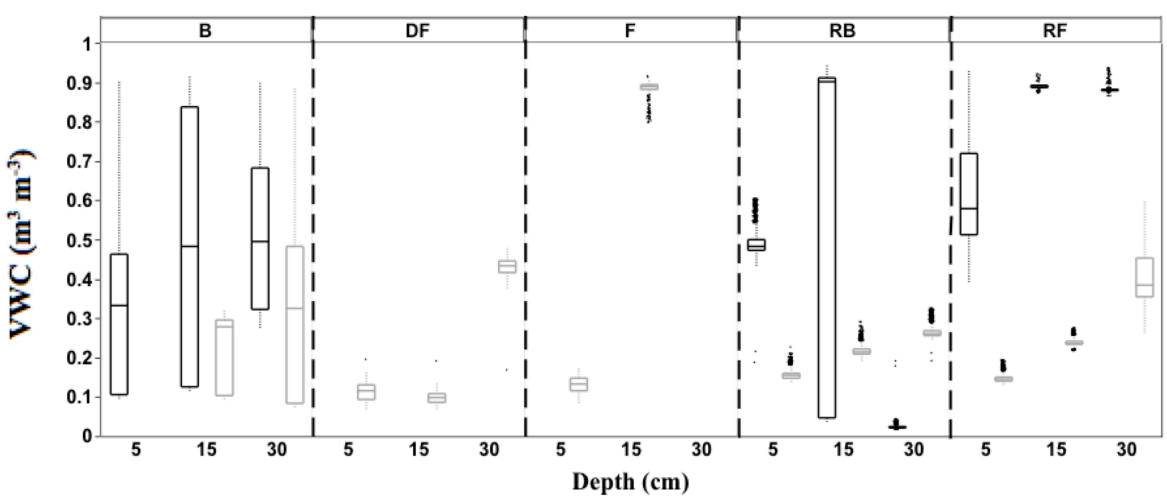


Figure 4.10 – Boxplots of seasonal VWC as a function of depth for each site. Dark boxplots represent hollows while light grey boxes denote hummocks.

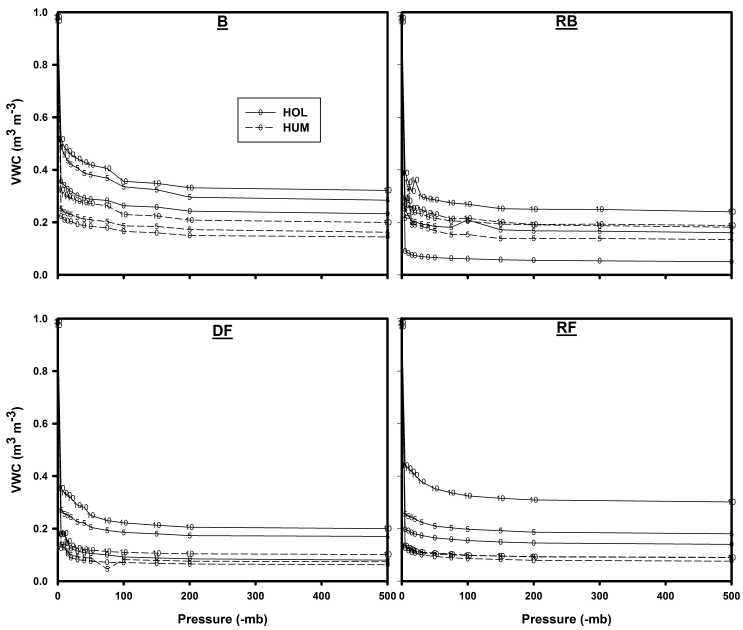
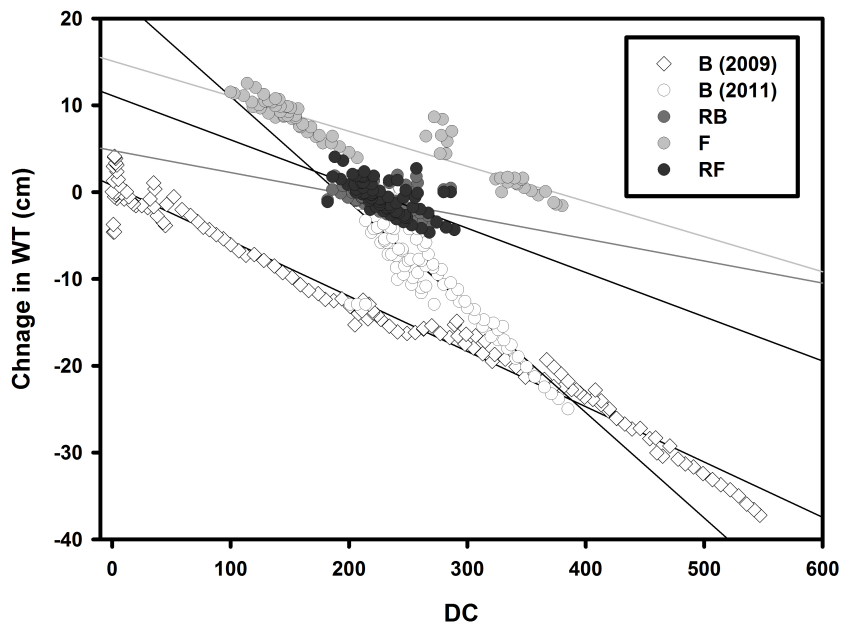


Figure 4.11 – Moisture retention curves for near surface peat samples (0-10cm depth) Lines shown are mean moisture retention curves of 2 individual samples, not replicate



runs.

Figure 4.12 – Change in water table position from the start of the growing season versus drought code in 4 peatlands in 2011, and between a wet (2011) and dry (2009) year for a pristine bog.

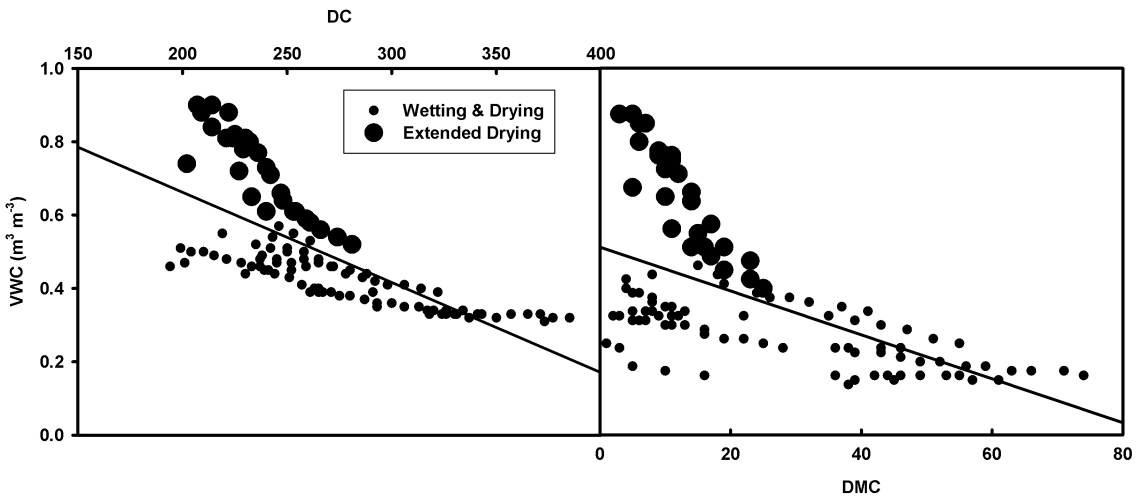


Figure 4.13 – 5 cm hollow VWC in the pristine bog as a function of drought code and duff codes in 2011. Larger points representing periods of extended drying, forming two distinct slopes of wetting and drying cycles.

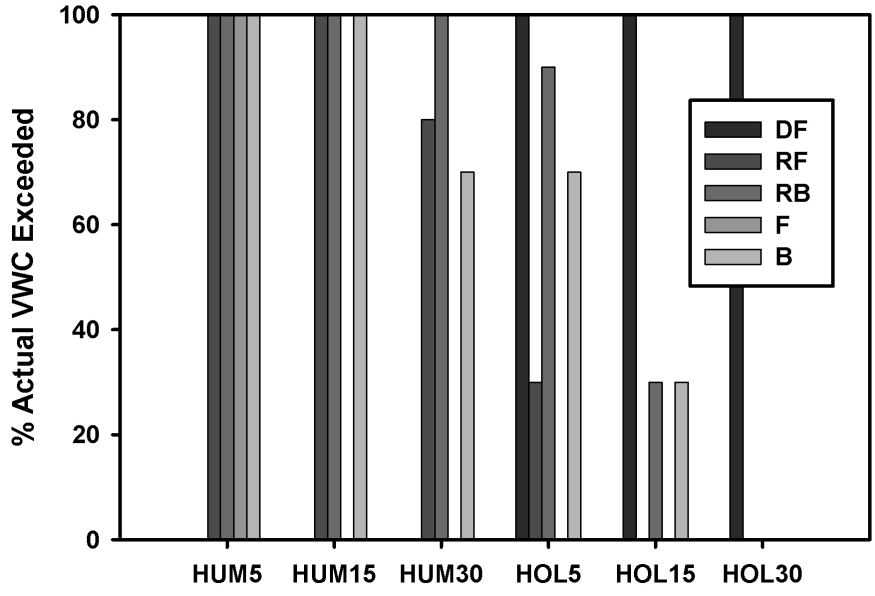


Figure 4.14 – VWC at a drought code of 400 computed based on bulk density of samples using empirical GWC relationships for each site. Values of 100% indicate the nominal depth of the microform remained at a critically dry VWC corresponding to a DC value of 400 or higher, while all other probe depths not listed are 0%.

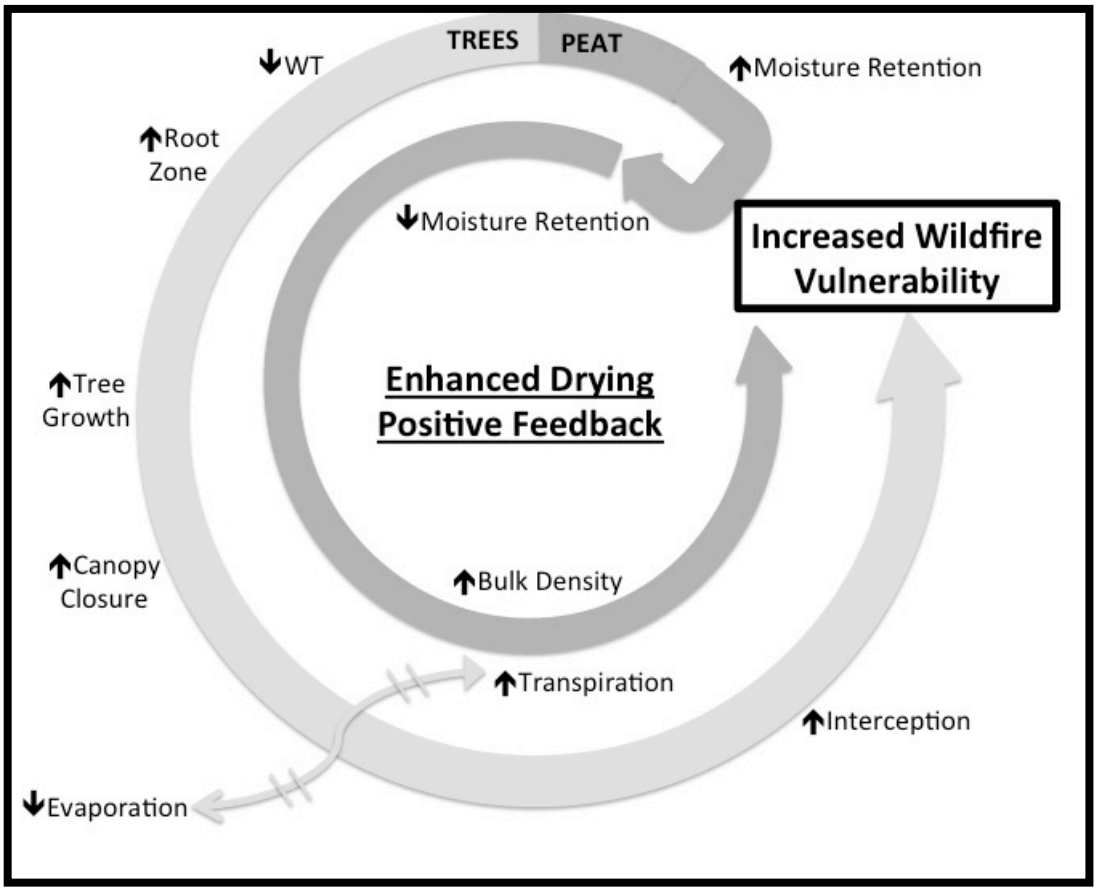


Figure 5.1- Conceptual diagram for above and belowground process feedbacks with potential peat substrate threshold response to drying. Positive processes beginning in top moving CCW = enhancing positive feedback.

Table 1. Summary of water table (WT) position for Drought Code (DC) of 400.

Site	Equation	r	ΔWT for DC@400 (cm)
B 2011	ΔWT = 23.16 - 0.12*DC	0.78	-25.35
B 2009	ΔWT = 0.74 - 0.06*DC	0.98	-25.72
F	ΔWT = 15.16 - 0.04*DC	0.87	-1.09
RB	ΔWT = 4.80 - 0.03*DC	0.17	-5.37
RF	ΔWT = 11.11 - 0.05*DC	0.40	-9.26

APPENDIX A

Figure 1.1- Utikuma Lake Pristine Bog Site (B)

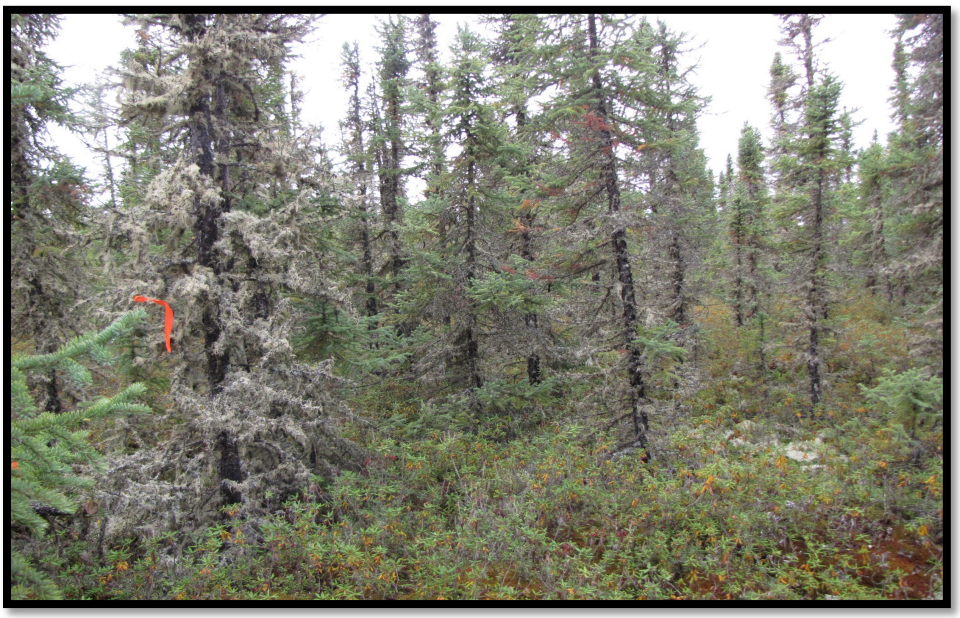


Figure 1.2- Utikuma Lake Road Impacted Bog Site (RB)

Figure 1.3- McLennan Pristine Fen Site (F)

Figure 1.4- Utikuma Lake Road Impacted Fen site (RF)

Figure 1.5- McLennan Drained Fen Site (DF) with instrumentation

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