INFLUENCE OF HYDROGEOLOGICAL SETTING
ON PEATLAND BURN SEVERITY

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A Thesis Submitted to the School of Graduate Studies in Partial Fulfillment of the Requirements for the Degree Master of Science

McMaster University

MASTER OF SCIENCE (2014) McMaster University (School of Geography and Earth Sciences)

TITLE: Influence of Hydrogeological Setting on Peatland Burn Severity

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NUMBER OF PAGES: ix, 98

ABSTRACT

Organic soil depth of burn in Canadian boreal peatlands cited in the literature generally ranges from 0.05 to 0.10 m despite fire manager reports that suggest higher burn severity (> 0.50 cm) may exist on the landscape. It was hypothesized that hydrogeological setting imposes different landscape patterns of peat bulk density and moisture content leading to greater variability in organic soil burn severity across the landscape than previously thought. To examine this, depth of burn was measured in three peatlands located along a hydrogeological and topographic gradient that were affected by the May 2011 Utikuma Complex forest fire (SWF-057, ~90,000 ha) in Canada's Western Boreal Plain. The results demonstrate that peatland margins, due to fluctuating water tables, burned significantly deeper (0.25 ± 0.01 m) than the middle (0.06 ± 0.01 m) of peatlands. Additionally, in a coarse textured glaciofluvial outwash, a bog with ephemeral groundwater connections had the greatest depth of burn (0.51 ± 0.02 m) and a low-lying flow-through bog had the lowest burn severity (0.07 ± 0.03 m). An expansive peatland in the lacustrine clay plain showed an intermediate depth of burn (0.16 ± 0.01 m). To further investigate the role of groundwater connectivity in the outwash, GWC and smouldering energy dynamics were modelled at several unburned peatlands across a topographic gradient. It was shown that the peatland with the most groundwater connectivity showed the lowest vulnerability, while the ephemerally perched peatland was the most vulnerable. The peatland at the highest topographic position and least groundwater connection showed intermediate vulnerability. This research indicates that groundwater connectivity and subsequent influence on water table fluctuations in peatland margins can have a dominant control on soil carbon combustion, it is therefore suggested that a hydrogeological ‘template’ be used to identify deep burning ‘hotspots’ on the landscape a priori, so as to increase the efficacy of wildfire mitigation strategies.

ACKNOWLEDGEMENTS

I would first like to thank my supervisor, Dr. Mike Waddington, without whom I wouldn't have been able to write this thesis. His patience, advice, and lightning fast responses to emails were invaluable along the way. His willingness to join me in countless meetings to discuss concepts was instrumental and helped me grow as a researcher.

I would also like to thank Dr. Kevin Devito, who had innumerable 'big-picture' talks with me about URSA and encouraged me to think like a scientist (and also to go fishing every day). Regarding all my trips to Alberta, the Little-Devito family's hospitality made even Edmonton feel like a warm place.

My experience would have been a lesser one, had it not have been for the collaborative and supportive nature of the Mac Ecohydrology group. Much of this work was done in conjunction with Maxwell Lukenbach, to whom I owe great thanks. I couldn't have asked for a better lab mate and collaborator. And to Paul: those mid-week squash games were almost as beneficial as your MATLAB assistance. Almost. I would also like to thank Cam Irvine and Sarah Irvine for their dedication in the field. If I knew how many holes we were going to have to dig, I would have warned you to stay in Ontario.

Thank you so much to my friends Chris, Jeff, Heather, Kara, and Lindsey, whose letters, packages, visits, and late night phone calls were so very important to me. You all made Virginia seem not so far away.

And finally, to my parents: thank you for always supporting me, even if it means your only daughter moving to Canada and living in a trailer park.

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CHAPTER 1: INTRODUCTION

Peatlands, ecosystems with an organic soil depth exceeding 40 cm (NWWG, 1988), cover an estimated 5 million km^2 globally (Vasander and Kettunen, 2006). These peat deposits are one of the largest carbon stocks in the world, containing an estimated 147 Pg Carbon in Canada alone (Tarnocai, 2006). While peatlands cover between 25-30% of boreal regions and only 2-3% of global land surface, they represent over 30% of the world's soil carbon pool (Gorham, 1991). While this carbon stock is generally resilient, dry forested peatlands are especially susceptible to fire. Wildfire is one of the most dominant forms of disturbance in the boreal forest (Johnson, 2002), with 2 million ha burned annually (Stocks et al., 2002) and in continental Western Canada (Alberta, Saskatchewan and Manitoba) approximately 580 km^2 of peatlands are burned each year (Turetsky et al., 2002). Peatlands or, more generally, wetlands, in the Western Boreal Plain (WBP) of Alberta exist in a climate where PET>AET>P most years, which leaves them particularly vulnerable to wildfire (Bothe and Abraham, 1993; Brown et al., 2010). Wetlands cover 25 to 50% of the Western Boreal Plain and are very important components of the landscape, as they are the only self-sustaining land unit and help moderate water movement throughout the WBP. Recent studies estimate that greenhouse gas emissions from peat fires alone are equivalent to approximately 15% of man-made emissions (Poulter, 2006). Peatland long-term rates of carbon accumulation, on average, range from 17 – 24 g C m^{-2} yr^{-1} (Vasander and Kettunen, 2006). Given that average combustion rates during a peat fire are 2.4 kg C m^{-2}, this is equivalent to approximately 100 to 140 years of carbon storage (Turetsky et al., 2011a; Benscoter and Wieder, 2003;

Turetsky and Weider, 2001). This carbon loss is further exacerbated by the increase in organic matter mineralization post-fire (Wieder et al., 2009).

1.1 SMOULDERING AND PEAT BURN SEVERITY

It is well accepted that smouldering is the dominant form of combustion in organic soils (Frandsen, 1997; Rein et al., 2008; Miyanishi and Johnson, 2002). Smouldering is the slow, low temperature (500-700+ °C) flameless form of combustion where the oxidation reaction and subsequent heat release takes place on the surface of the fuel. Whereas during flaming combustion, as observed in grass and crown fires, the oxidation reaction takes place in the gas phase above the fuel at a much higher temperature (1500 °C) (Ohlemiller, 2002; Rein et al., 2008; Drysdale, 2011). Organic soils are exclusively consumed by smouldering combustion primarily because of their high lignin content, which does not release the volatile gases needed for flaming combustion and high packing ratio (Miyanishi and Johnson, 2002). The transition from flaming combustion to smouldering occurs when fuel particles exhibit a packing ratio greater than 10%, which is the ratio of the volume occupied by solid fuel and the total fuel bed volume. It is also easily expressed by the ratio of fuel bulk density to fuel particle density (Rothermel, 1972). This ratio exceeds 10% when there is a prevalence of small compact fuel particles, such as in duff and organic soils (Frandsen, 1991a).

Smouldering fires can be problematic, not because of their rate of spread, which only ranges on average from 3 to 8 g_{peat} hr^{-1} (Frandsen, 1991a), but because of the difficulties related to their initial detection and extinguishing them. Some smouldering fires can go unnoticed by fire managers for weeks and can persist for days, months or even over winter underneath the snow pack (Flannigan et al., 2008). Moreover, because these peat fires are flameless and can persist underground they can be difficult to detect and manage, causing extensive mop-up efforts and costs. Moreover, smouldering fires can spread over extensive areas and burn up to depths greater than 5 metres (Hadden et al., 2012) causing the direct loss of stored carbon to the atmosphere (Turetsky et al., 2002).

The amount of organic matter consumed, most easily measured through the vertical extent of combustion, is a common metric for fire severity due to the various long and short term effects on forest ecology and recovery (Keeley, 2009). Sustained smouldering has short-term effects, such as weakening the soil structure, affecting the stability of the ground and tree roots which leads to enhanced erosion or structural collapse. Moreover, when smouldering reaches the mineral layer it can lead to the loss of nutrients or in extreme cases, the sterilization of local soils (Certini, 2005).

Smouldering is considered a two-stage (or zone) process. In the first stage, pyrolysis occurs, which is an endothermic thermal degradation of the fuel that creates a solid carbonaceous char. In the second ‘char’ stage, an exothermic solid-phase oxidation reaction occurs on the surface of the fuel, which provides the heat necessary for stage one (Drysdale, 2011). Therefore, when the heat produced by the oxidation reaction (i.e. combustion) is not enough to initiate pyrolysis in virgin fuel, the smouldering front ceases to advance. Factors that affect depth of burn are those that either change the amount of heat produced in the oxidation reaction or affect the rate of heat transfer from that reaction to the virgin fuel (Miyanishi and Johnson, 2002).

Numerous previous studies, both with commercial milled peat and natural monoliths, have shown that these controlling factors include bulk density, moisture content and inorganic content (e.g. Benscoter et al., 2011; Frandsen 1987,1991a,1997; Lawson et al., 1997; Reardon et al., 2007; Van Wagner 1972; Rein et al., 2008). While it may seem natural that oxygen availability should be a limiting factor in the depth of burn, Ohlemiller (1985) notes that despite varying fuel type and configuration, oxygen seems to only limit the rate of spread and not the actual depth of propagation, which is controlled by reaction kinetics (i.e. energy availability and transfer). Since the inorganic content of natural peat is near zero (Frandsen, 1991b) the two primary controls are moisture content and bulk density.

The primary heat transfer mechanism to the pyrolysis zone in solid fuels is conduction (Pyle and Zaror, 1984). This implies that the physical properties of the fuel that influence the quantity and rate of heat movement within the fuel, bulk density and moisture content, will be the dominant controls over where in the fuel profile smouldering can no longer be self-sustained (Drysdale, 2011). Thermal conductivity is the energy flux through the fuel and thermal diffusivity is the rate of heat movement (Oke, 1987). Denser peat both releases more heat when combusted and has a higher thermal conductivity, and can therefore transfer more heat more efficiently than less dense peat. Moisture content is a fairly straightforward control on smouldering in fuel beds. The latent heat of vaporization (2.25 MJ/kg) required to drive off the moisture is a considerably large heat sink and drastically decreases the amount of heat available for pyrolysis.

In order to initiate a smouldering event, enough heat must be transferred to the peat surface to cause ignition. This is modelled in the PSI (Peat Smouldering and Ignition) model (Thompson et al., 2014, submitted), which shows that fuel loading and antecedent surface moisture have the greatest effect on ignition probability. Increased fuel loading, which is represented by the crown fuel load, increases the radiative heat transfer to the surface (Forestry Canada Fire Danger Group, 1992).

At depth, both soil moisture and bulk density play important roles in either sustaining or terminating smouldering. Individually soil moisture and bulk density cannot be used to accurately predict the depth of burn, but they do interact and have a synergistic influence (Benscoter et al., 2011). One commonly used parameter that captures both moisture content and bulk density is gravimetric water content, which is the ratio of the volume of water to the total volume of the fuel. Gravimetric water content (GWC) is a useful variable because it can be used to represent both a fuel's major sink for heat (moisture) and source of heat (density). Consequently, the prime conditions for a deep burn are a dry and dense profile with no sharp or drastic increases in GWC.

Because organic soil consumption is of interest to both fire managers and researchers it is advantageous to be able to predict at the peatland and landscape scale what areas are more vulnerable to deep smouldering. Areas that these conditions (i.e. low GWC and adequate fuel loading) readily exist will likely be areas that are exposed more frequently to lowered water tables and/or disconnection from shallow subsurface flow. Areas that are drier for longer periods of the year will support more woody vegetation needed to sustain a crown fire, and transfer enough heat to the peat surface (Lieffers and Rothwell, 1987; Van Wagner, 1987). Moreover, areas with frequent and severe water table fluctuations will also likely exhibit lower GWC (e.g. periods of low moisture content and generally higher bulk densities) than areas or regions with stable high water tables. The increased bulk density is due to a complex feedback loop, wherein a water table drawdown causes an increase of the effective stress placed on the peat and causes surface subsidence, which in turn causes a decrease in porosity and an increase in bulk density (Whittington and Price, 2006). The decreased storativity further magnifies the flashiness of the water table and exposes the peat to oxic conditions more frequently. This leads to increased decay rates, which again, further increases bulk density (Boelter, 1968). These areas prone to water table fluctuations will obviously experience more dry periods than areas with stable high water tables, and will have lower moisture contents at the surface.

When examining vulnerability on the scale of individual peatlands, the higher bulk densities and more frequent periods of lower moisture should be found nearer the margins of the peatland. Although it appears that margins are especially vulnerable to deep burns, the role of the margin in fire severity has only recently been studied (Lukenbach et al., 2014, submitted). It has been found that the water table is lower at the margin (Bhatti et al., 2005), which would indicate that there exist higher rates of decomposition and more frequent dry periods. In sub-humid regions, such as the Western Boreal Plain, wetlands typically have a smaller storage deficit that forested uplands, which makes them a net source of water to the uplands, which is contrary to observations made in more humid climate (Dimitrov et al., 2014). This creates a gradient such that water flows from the peatland into the forested upland (Redding, 2009; Devito et al., 2012). This water table decline further increases in the summer when the demand from the upland vegetation increases during the growing season and evaporative demand from the atmosphere increases with increasing temperatures (Petrone et al., 2007).

1.2 THE WESTERN BOREAL PLAIN AND HYDROLOGIC RESPONSE AREAS

The Western Boreal Plain (WBP) is characterized by pond-peatland complexes, where patterns of shallow groundwater flow paths connect forested uplands, wetlands and open water ponds and commonly exist as ‘flow-through’ systems (NWWG, 1988; Smerdon et al., 2005). These patterns are complex and not solely determined by topography, but rather their hydrogeological setting and climate (Meyboom, 1966; Devito, 2005). Typically, as in humid climates, water flows from topographic highs to topographic lows, and the water table mirrors the surface topography (Freeze and Witherspoon, 1967). In the WBP, evapotranspiration often equals or exceeds precipitation, which leads to a propensity for vertical flow, large ET demands, and large vadose zone storage rather than lateral flow (Bothe and Abraham, 1993; Brown et al., 2010; Devito, 2005). Precipitation, evapotranspiration demand, and subsurface geology have a greater control than topography over local hydrology. Thus, it is more suitable to use the hydrogeological setting to delineate hydrologic response areas (HRA), which is composed of smaller discrete hydrologic units (HU) (Devito et al., 2012). An HRA is an area with similar geology and hydrological properties (e.g. permeability) that has a characteristic and holistic response to hydrologic fluxes (e.g. ET, precipitation) and climate change/cycles. Because of the generally low topographic relief in the WBP, groundwater levels in lower HUs can rise and overcome the relatively small topographic highs and flow into higher HUs. The primary example of this being that, contrary to humid regions, wetlands often drain into forested uplands. Wetland HUs have a long-term average surplus of water and due to the presence of organic soils (i.e. peat) layering over mineral soils, they experience more dynamic near surface water tables less storage deficits than forested HUs. Forested HU's are typically composed of deeper more drained soils and have higher storage deficits (Devito et al., 2012). Although topography may not play the dominant role in controlling water movement between HUs, within one HU it may be the driving force controlling the movement of subsurface water (Ferone and Devito, 2004).

The hydrogeological setting of an HRA also has a large impact on a given peatland HU's water balance and water table behaviour and it's sensitivity to climate (Devito, 2005). The pond-peatland-forested upland complexes typical of the WBP are set on deep surficial glacial deposits (coarse sand outwashes, fine-grained moraines, and lacustrine clay plains) (Devito et al., 2012) that result in extremely variable soil storage potentials (Smerdon, 2005). The type of sediment will therefore have a considerable influence on the location and connectedness of wetlands, how water moves within the HRA, and how it reacts to changes in climate and vegetation.

Coarse-grained sediment increases the rates of infiltration and subsurface flow, which results in deep watershed connectivity. Due to their deep extensive connectivity, the division of coarse-grained HRAs and HUs are not typically determined by topographic divides, but by subsurface soil texture differentiations (Figure 1.1; Haitjma and Mitchell-Bruker, 2005; Winter et al., 2003). On regionally topographic lows, wetlands are expansive and are commonly groundwater discharge zones, while on regionally topographic highs, forested uplands are located on locally topographic highs and wetlands are located in small depressions that are perched above the regional groundwater system on thin less permeable lenses (Devito et al., 2012). The implications being that low-lying wetland HUs are commonly connected to larger-scale flow systems, with stable water tables, and small perched wetlands can easily become disconnected from the larger flow system, which makes them highly vulnerable to local water table fluctuations or long term declines. Therefore topographic position of a peatland in a coarse grained HRA should play a large role is determining the hydrophysical characteristics of the peatland, such as bulk density. For example, a small peatland at a high topographic position without a continuous impermeable lens that endures frequent extensive periods of disconnection from the regional water will exhibit periods of high carbon accumulation rates followed by high rates of decomposition and therefore deeper and denser peat more vulnerable to combustion during wild fires (Whittington and Price, 2006). Peatlands in a low lying position that are constantly hydraulically connected to nearby lakes and groundwater flow systems should have consistently shallow and stable water tables and therefore have less decomposed, less dense, and less vulnerable peat.

In fine-textured HRAs, silts and clays decrease rates of infiltration and lateral subsurface water transmission (Figure 1.2). This limits the connectivity between peatland and upland HUs and leads to larger surface water movement within a peatland flow system compared with coarse-textured HRAs, which are regionally connected to deep ground water flow systems. Contrary to coarse-textured HRAs, whose hydrologic connectivity is controlled by regional topography, the hydrologic gradients of fine-textured HRAs are controlled by local surficial topography (Ferone and Devito, 2004), where flat terrain is characterized by interconnected expansive wetlands and hummocky terrain is characterized by small isolated wetlands (Devito et al., 2012). Local shallow flow patterns exist within these large expansive peatland HUs, which contribute to larger flow systems connecting ponds. Peatland margins that are in or nearer groundwater discharge zones towards the bottom of the flow patter, should have more consistently high, stable water tables that are often near the surface, as opposed to peatland margins near a more isolated portion of the peatland with little contributing area, that are more susceptible to water table drawdowns during extended dry periods where evaporation demand exceeds precipitation (Siegel, 1998).

1.3 THESIS OBJECTIVES AND STRUCTURE

The primary objective of this study is to determine local and landscape controls on peatland burn severity in the Western Boreal Plain. This objective was addressed using two different approaches, direct observation (Chapter 2) and modelling (Chapter 3). Depth of burn, a common measure of fire severity, was measured at several peatlands, which are located on two different HRA's in different landscape positions, affected by the 2011 Utikuma complex fire. Additionally, smouldering energy dynamics were modelled at several peatlands located in various landscape positions within one HRA using data collected in the field.

The specific objectives of this study are:

(a) To determine which area (margin vs. middle) of a single peatland is more vulnerable to deep smouldering,

(b) To determine if peatland vulnerability has identifiable hydrological controls within an HRA, such as contributing area (fine grained HRA's) or topographic position (course grained HRA's).

(c) To determine if peatland vulnerability has hydrogeological controls between HRA's, for instance if all course grained systems exhibit higher vulnerability to deep smouldering than fine grained systems.

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FIGURES

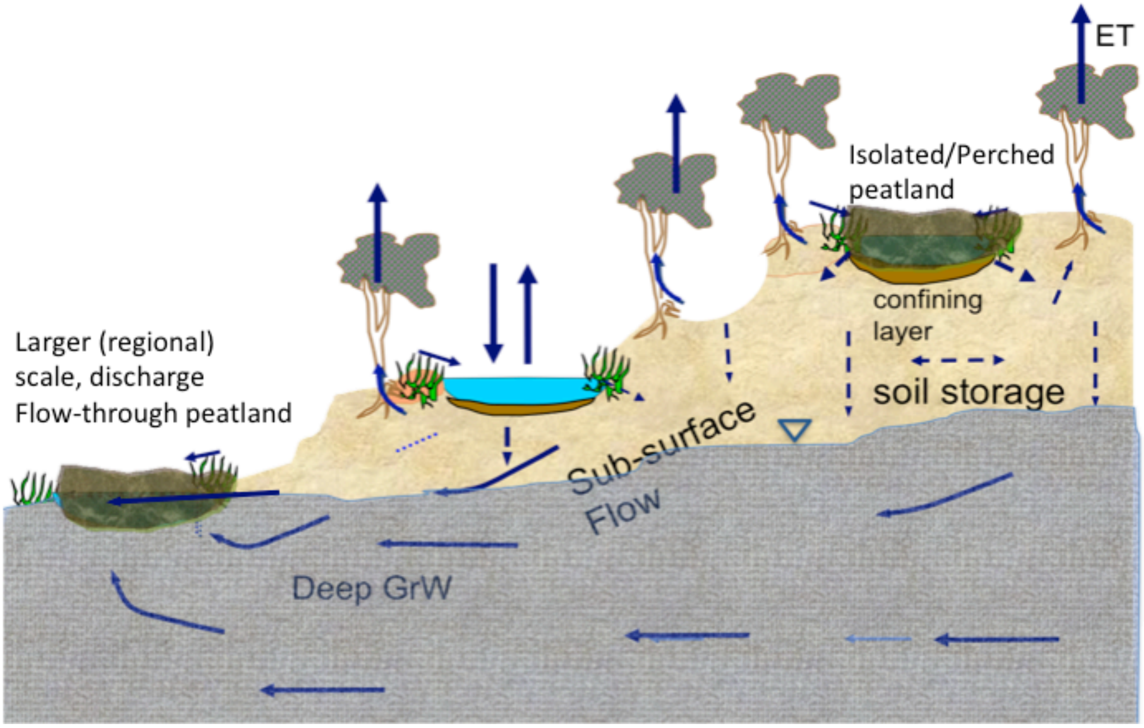

Figure 1.1: Conceptual diagram of the coarse textured hydrologic response area (adapted from Devito et al., 2012).

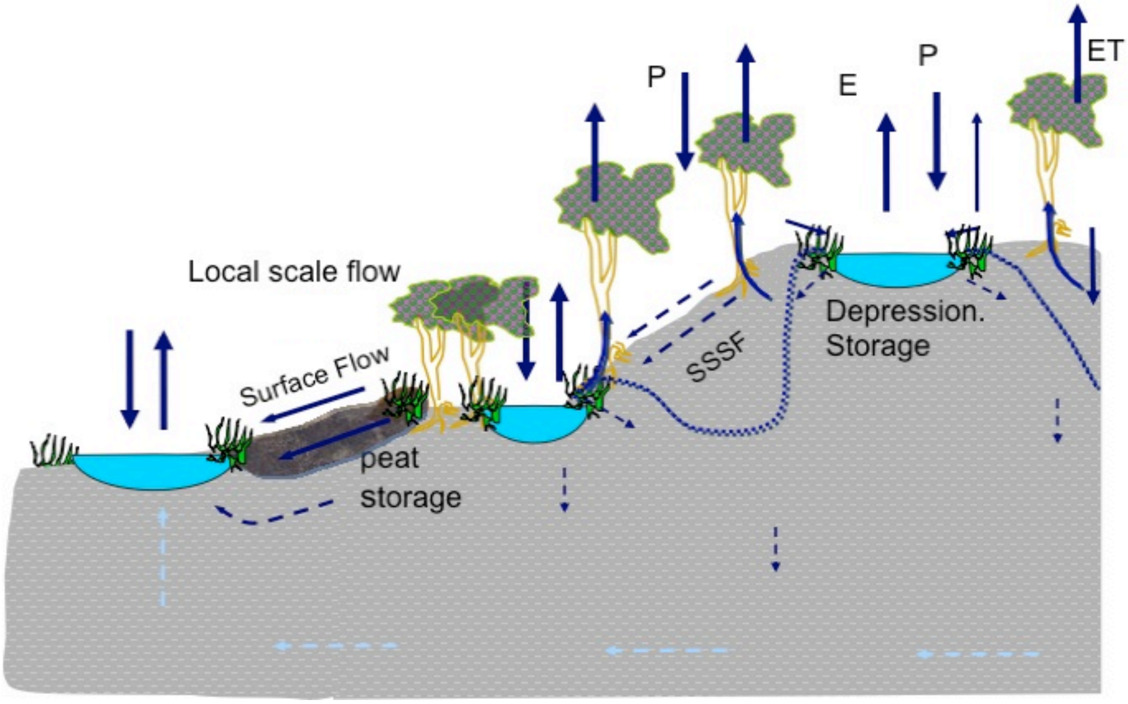

Figure 1.2: Conceptual diagram of the fine textured hydrologic response area (adapted from Devito et al., 2012), where SSSF is shallow sub-surface flow.

CHAPTER 2: PEAT BURN SEVERITY IN THE WESTERN BOREAL PLAIN: INFLUENCE OF HYDROGEOLOGICAL SETTING

2.1 INTRODUCTION

Peatland ecosystems store approximately one-third of the world's soil carbon (C) (Gorham, 1991) and in Canada alone these peat deposits are estimated to store 147 Pg C (Tarnocai, 2006). While this carbon stock is generally resilient to disturbance (Turetsky, 2002; Strack and Waddington, 2007), forested peatlands in continental western Canada are especially susceptible to wildfire, with a return interval of ~120 years (Turetsky et al., 2011a). Given the typical burn depths of 0.05-0.10 m, which represents combustion emissions of 2–3 kg C m^{-2} (Benscoter and Wieder, 2003; Shetler et al., 2008), it is estimated that 4.70 ± 0.62 Tg C is lost from peatlands annually due to fire in western Canada (Turetsky et al., 2002). However, Lukenbach et al. (2014) suggest that peat burn severity in natural peatlands of the Western Boreal Plain (WBP) may be underestimated by ignoring dry and dense peat along peatland margins, where depths of burn can exceed 1.0 m (10-85 kg C m^{-2}) and burn up to eight times as deep as the middle of a peatland. Several studies have identified peat bulk density and moisture content as the primary factors controlling organic soil smouldering combustion (e.g. Benscoter et al., 2011; Frandsen 1987, 1991, 1997; Lawson et al., 1997; Reardon et al., 2007; Van Wagner 1997; Rein et al., 2008), and Lukenbach et al. (2014) argue that peatland margins are 'hotspots' for deep burning due to the presence of a dry and dense peat profile with no sharp increases in gravimetric water content (GWC).

The water table (WT) is generally lower at peatland margins in the WBP (Devito et al., 2012) because WBP peatlands typically have a smaller storage deficit than forested uplands which creates a hydraulic gradient from the peatland into the adjacent forested upland (Dimitrov et al., 2014). This groundwater loss and concomitant peatland margin WT decline is greatest in summer when upland vegetation water demand increases (Petrone et al., 2007). Moreover, because ET often equals or exceeds precipitation, there is a propensity for vertical flow and large vadose zone storage (Bothe and Abraham, 1993; Brown et al., 2010; Devito, 2005). The pond-peatland-forested upland complexes typical of the WBP are set on deep and extremely heterogeneous surficial glacial deposits (coarse sand glaciofluvial outwashes, fine-textured moraines, and lacustrine clay plains) (Devito et al., 2005) which results in extremely variable soil storage potentials (Fenton et al., 2003; Paulen et al., 2004). As such, the type of mineral substrate within a hydrogeological setting has a considerable control on wetland connectivity to groundwater flow systems and influences the frequency of low WT positions within a peatland complex (Redding, 2009; Winter et al., 2003). Therefore, because peat undergoes enhanced compaction (Whittington and Price, 2006) and decomposition during periods of low WT positions; (Blodau et al., 2004), peat soils with frequent and severe WT fluctuations will likely exhibit lower GWC (i.e. periods of low moisture content and generally higher bulk densities) than peatlands with stable high water tables during periods of drought. Consequently, we hypothesized that peat burn severity will be controlled by peatland hydrogeological setting. The aim of this research was to examine the effect of WBP peatland hydrogeological setting on depth of burn. Here-in by taking advantage of an ~90,000 ha wildfire that burned peatlands in various landscape positions representative of both coarse-textured and fine-textured hydrological response areas (HRAs) (Devito et al., 2012).

Coarse-textured sediment increases the rates of infiltration and subsurface flow, which results in deep watershed connectivity. Therefore the division of WBP coarse-textured landscape units are not typically determined by topographic divides, but by subsurface soil texture differentiations (Haitjma and Mitchell-Bruker, 2005; Winter et al., 2003). On regionally topographic lows, wetlands are commonly groundwater discharge zones while on regionally topographic highs, wetlands are located in small depressions that are perched above the regional groundwater system on thin less permeable lenses (Devito et al., 2012). Therefore, low lying wetlands are commonly connected to larger-scale flow systems and are characterized by a stable WT, while small wetlands on topographic highs can easily become disconnected from the larger flow system during dry periods making them highly vulnerable to local WT fluctuations or long-term WT declines. Consequently, peatland topographic position in a coarse-textured HRA likely plays a large role on peat bulk density and GWC and by extension peat smouldering potential.

In fine-textured HRAs, silts and clays decrease rates of infiltration and lateral subsurface water transmission. This limits the connectivity between peatlands and uplands and leads to larger surface water movement within a peatland flow systems. Consequently, hydrological gradients in fine-textured HRAs are controlled by local surficial topography (Ferone and Devito, 2004), where flat terrain is characterized by interconnected expansive wetlands and hummocky terrain is characterized by small isolated wetlands (Devito et al., 2012). Local shallow flow patterns exist within the large expansive peatlands, which contribute to larger flow systems connecting ponds. As such, peatland margins farther along the shallow groundwater flowpath within peat, should have a relatively high (and more stable) WT due to a higher contributing area than peatland margins near a more isolated portion of the peatland. In this area the smaller contributing area allows for larger WT drawdowns during extended dry periods when evapotranspiration demand exceeds precipitation (Siegel, 1988).

Here we report on the first study to examine larger landscape scale controls on organic soil combustion by comparing peat burn severity in several peatlands in various landscape positions and hydrogeological settings in the same wildfire. Specifically, we hypothesized that based on predicted peatland-upland interactions and WT fluctuations: (1) within an individual peatland, peatland margins will burn deeper than peatland middles, (2) within a coarse-textured outwash HRA, landscape position will play the dominant control on burn severity, wherein an ephemerally perched peatland will burn significantly deeper than a regionally low lying peatland, (3) within an expansive peatland on the lacustrine clay plain, areas with large peatland contributing area will burn less severely than areas with limited peatland contributing area, and (4) burn severity will be lower in an expansive peatland on the fine-textured lacustrine clay plain than that of a perched peatland in the coarse-textured outwash.

2.2 METHODS

To test our hypotheses we measured depth of burn in several peatlands in a coarse and fine textured HRA in the Utikuma Region Study Area (URSA). The URSA is part of a long-term hydrogeological study that has examined the local and regional hydrology of dozens of pond-peatland-upland complexes since 1999. Long-term hydrological data (including water table dynamics) was available for several peatlands that were affected by the 2011 Utikuma complex fire (SWF-057, ~90,000 ha).

2.2.1 Study sites

The URSA is located 370 km north of Edmonton, Alberta in the WBP region of Canada. The URSA is in a sub-humid climate with annual potential evapotranspiration (PET) often exceeding annual precipitation (517 mm and 481 mm respectively) (Marshall et al. 1999, Bothe and Abraham, 1993). The region is characterized by low topographic relief, deep heterogeneous glacial substrates with low lying lacustrine clay plains, fine-textured disintegration moraines and coarse-textured glaciofluvial outwashes overlying marine shale (Vogwill, 1978; Devito et al., 2012). Much of the URSA region was affected by the May 2011 Utikuma Complex forest fire (Figure 2.1) providing us the opportunity to examine wildfire impacts from peatlands located in different hydrogeological settings where previous hydrological data had already been collected. We studied three peatlands located along a hydrogeological and topographic gradient at the URSA with sites in lake 16 and 208 catchments located on a coarse textured outwash and a site in lake171 catchment located on the lacustrine clay plain.

The outwash ephemerally perched (16-OEP) site, is an ~0.5 ha bog portion of an ~3 ha peatland complex. It lies adjacent a regional topographic high and receives ephemeral connections from both local flow from intermediate groundwater flowing between larger lakes in the region (Smerdon et al. 2007). The outwash flow through (208-OFT) site, within the lake 208 catchment is a small (~1 ha) kettle hole bog located on a regional topographic low that intersects the large scale groundwater flow system with in a large glacial-fluvial plain intersected by several large lakes (~450 - 900 ha). These large deposits of coarse material moderates the WT position throughout the valley (Smerdon et al. 2005, 2008), minimizing extreme WT fluctuations at the peatland margin during periods of drought (Redding 2009). The clay plain expansive peatland site (171-CPE), constitutes a large portion of the lake 171 catchment. The low-lying expansive pond-peatland complex comprised of a 70 ha peatland that terminates in an 11.5 ha pond to the west, and was initially described by Ferone and Devito (2004).

2.2.2 Peatland hydrology

Historic water levels have been maintained by the HEAD project (Devito unpublished data) at various pond peatland complexes across the URSA from 1999 to present. This well data, coupled with well measurements taken during the study period (Summer 2012 -2013) were compiled here.

In order to assess the overall peatland hydrology and evaluate the effect of relative contributing area on WT behaviour at 171-ECP, continuous water levels were measured at two disparate locations in the peatland during the study period using pressure transducers (Solinsts) at 20-minute intervals from May to September 2013 in 0.05m PVC wells. Head gradients were surveyed using a real-time kinematic GNSS surveying system (Trimble R8) using both an existing network of wells in addition to new locations specific to this survey in the middle of the peatland.

2.2.3 Peat burn severity

Depth of burn (DOB) was measured by using methods similar to those used by Davies et al. (2013), Kasischke et al. (2008) and Mack et al. (2011) where the pre-fire surface was estimated using adventitious roots and/or surfaces unaltered by the fire. DOB was measured at 10 random locations within randomly located 0.25 m^2 quadrats at the margins and middles of each peatland: the ephemerally perched bog (16-OEP) (margin: n = 240, middle: n = 240) and flow through bog (208-OFT) on the outwash HRA (margin: n = 140, middle: n = 160), and at the expansive peatland on the lacustrine clay plain (171-CPE) (margin: n = 480, middle: n = 290). We defined the peatland margin to be the transitional riparian zone bordering the forested upland (often 8 to 10 m wide) characterized by a limited LFH layer (i.e. little to no transition between the surface litter layer and the underlying humus), a lack of the sphagnum hummock microtopography typically found in the peatland middle, and prominent gradients of peat depth, water table depth and vegetation cover leading from the forested upland to the peatland proper. Dimitrov et al. (2014) refers to this zone as a boreal ecotone between forested uplands and peatlands and offers a brief overview of the historic categorization of this zone.

In order to assess burn depth, we assumed the pre-fire surface between multiple reference points was flat and the difference between the burned surface and the reconstructed surface was taken to be the depth of burn. Black spruce trees in other unburned peatlands in the URSA have no adventitious roots exposed with an average of 0.055 ± 0.004 m (n=210) of peat and/or live moss layer above the roots, suggesting that our depth of burn measurements are conservative. This is consistent with Kasischke et al. (2008) that reported black spruce adventitious roots were 0.051 ± 0.002 m below the pre-fire peat surface.

Given that previous studies have shown that *Sphagnum fuscum* hummocks are generally resistant to combustion due to their low bulk density and high water retention, thereby preventing self-sustained downward combustion (Shetler et al., 2008; Benscoter et al., 2011) we focused our depth of burn measurements in hollow microforms. Both field observations and laboratory studies have demonstrated a higher tendency for combustion in hollow microforms (Benscoter and Wieder, 2003; Shetler et al., 2008; Benscoter et al., 2011). We estimated *S. fuscum* hummock burn severity using the approach of Lukenbach et al. (2014), where hummocks were categorized as either lightly singed (depth of burn = 0 cm) or severely burned (depth of burn = 2 - 3 cm).

2.2.4 *Estimating carbon loss*

To estimate the mass of carbon lost from peat combustion during the wildfire, peat cores were removed from the margins and middle (hollows only) of unburned reference peatlands adjacent to our burned study sites. Peat cores were analyzed for bulk density at 4 cm intervals, and extrapolated into 1 cm increments for calculating vertical fuel profiles. Because we didn't observe hummock DOB greater than 3 cm, only surface samples (0-5 cm) were taken from nearby unburned S. fuscum hummocks. It was assumed that 52% of the mass of peat was carbon (Gorham, 1991). The vertical distribution of carbon in the reference peatlands was used to calculate total carbon losses at the burned peatlands by weighting depth of burn measurements by the spatial coverage of hummocks and hollows using aerial imagery. An unmanned aerial vehicle was flown over the sites at a height of 25m to create a multiband 8-bit RGB orthomosaic image. Radiometric enhancement was then used to create greater contrast between hummock and hollow microforms. A suite of remote sensing techniques, including principal component analysis and scatter diagram region analysis was used to create a supervised classification scheme based on the unique radiometric characteristics of each microform type (Richards and Jai, 2006). Areas such as seismic lines, which did not burn, were excluded from all calculations, so as not to overestimate carbon loss.

For the middle of sites the average DOB for hollows and the spatial survey of hummock DOB was applied to each respective landform area evenly. The amount of carbon lost on the margins at each site was calculated by spatially weighting the average measured DOB in each margin location.

Due to a lack of normality within the data, when comparing bulk density and depth of burn data between peatlands or within a single peatland, the Mann-Whitney U test was used.

2.3 RESULTS

2.3.1 *Peatland hydrology*

At 16-OEP, long-term WT position at various locations in this peatland complex demonstrates that the middle of a peatland exhibits minimal fluctuations (< 0.6 m) (Figure 2.2). However, WT positions at a well located near a bog margin, show large annual and inter-annual fluctuations of greater than 2.5 m (Figure 2.2).

Also in the coarse textured outwash, historical WT position at wells located in the middle and at the margin of 208-OFT all exhibited minimal fluctuations (<0.8 m) over a 10 year record (Figure 2.2). Water table depths at the margin were only slightly (<0.3 m) deeper than middles.

At 171-CPE, water level elevations based on well measurements and an August 2013 survey of near surface elevations indicate that the eastern side of the peatland is a domed bog, with the predominant flow direction towards the west (2.3). Water levels indicate minimal connectivity with groundwater flow systems and the margins surrounding this isolated peatland receive their water primarily from the peatland itself, as the hydraulic gradient often flows from the peatland into the upland. Hydrogeological data indicate that the shallow groundwater peatland flow system interacts with the region as a recharge area (data not shown), and originates in the isolated domed bog to the east and flows west forming a poor fen peatland, until it intersects with larger shallow groundwater flow through system between the lakes with a minimal gradient (0.002). Long-term WT positions at a well at the peatland margin shows much larger fluctuations (2.5 m) than at the middle of the peatland well (0.5 m) (Figure 2.2).

Peatland WT behaviour in the isolated bog at the head of the peatland complex (171-71W), an area with limited hydrological contributing area, is highly responsive to rain events (e.g. steeper rising and falling limbs and larger peaks of the phreatic responses) compared to the western end of the peatland with considerably more contributing area (171-15W), which has more stable water levels close to the ground surface, maintaining high moisture contents at the peatland surface (Figure 2.3).

2.3.2 *Peat burn severity*

Within all peatlands, margin depth of burn (0.245 ± 0.008 (Mean ± SEM) m) was significantly ($p<0.01$) greater than depth of burn at the middles of peatlands (0.057 ± 0.002 m) (Figure 2.4). At the middle of each peatland, spatial surveys of hummock burn severity, showed that severely burned hummocks (0.02-0.03 m depth of burn) comprised

84, 8, and 21% of total hummock area at the 16-OEP, 208-OFT, and 171-CPE sites, respectively.

Within the coarse textured HRA, depth of burn at the margin of the bog the periodically is isolated from groundwater connections (Site 16-OEP), (0.514 ± 0.018 m, range: 0.101-1.300 m) was significantly greater ($p<0.01$) than the depth of burn at the middle of the peatland (0.058 ± 0.005 m, range: 0.0-0.315 m; Figure 2.5). The flow-through bog (208-OFT) had the least severe burn, with margin DOB (0.072 ± 0.002 m, range: 0.0 - 0.150 m) significantly greater ($p<0.001$) than middle DOB (0.034 ± 0.003 m, range: 0.0 - 0.138 m; Figure 2.5).

On the lacustrine clay plain, DOB on the margins bordering the more isolated domed bog portion (n=200, mean=0.176 ± 0.9cm, range: 0.0 – 0.720 m) was considerably greater than the DOB observed at the margins closer to the larger groundwater flow path (Figure 2.6). The largest DOB (> 0.70 m) was observed in the eastern bog portion in an area with a high aspen upland to peatland ratio (Figure 2.6J). The north-westernmost margin exhibited DOB measurements that were categorized as less than 0.05 m. Precise DOB measurements could not be determined at this particular margin (~1200 m long) at the time of the study. However, evidence provided by the surviving tussocks, similar to the approach adopted by Mack et al. (2011), leads us to believe that DOB was minimal. The post-fire recovering vegetation type (mostly sedges) leads us to believe that the pre-fire margin frequently experienced wet periods, typical of a fen.

Average burn severity by HRA followed the trend (from most severe to least severe burn): ephemerally connected bog (16-OEP) (0.514 ± 0.018 m) > isolated bog on the lacustrine clay plain (171-CPE) (0.176 ± 0.009 m) > outwash flow through peatland (208-OFT) (0.072 ± 0.002 m) > fen with large contributing area on the lacustrine clay plain (171-CPE) (< 0.05 m).

2.3.3 *Peatland carbon loss*

Both of the unburned references for the ephemerally perched bog on the outwash and the expansive peatland complex on the clay plain showed significantly denser peat ($p < 0.05$) at the peatland margins than at the middles (Figure 2.7) at all but the surface layer on the clay plain. However, the outwash flow-through bog had similar bulk density profiles at both the margin and the middle (Figure 2.7). The average surface bulk density of unburned S. *fuscum* hummocks was 18.7 ± 1.3 kg m^{-3}.

Carbon loss was highest at 16-OEP (6.5 ± 0.6 kg C m^{-2}), while 208-OFT and 171-CPE show comparable losses (0.6 ± 0.1 and 0.5 ± 0.1 kg C m^{-2} respectively) (Figure 2.8). Margins accounted for ~90% of total C loss at the ephemerally perched bog (19.9 ± 2.0 kg C m^{-2}), ~80% at the flow through bog (1.7 ± 0.4 kg C m^{-2}), and ~50% at the expansive peatland on the clay plain (5.0 ± 0.6 kg C m^{-2}). In the middle of the ephemerally perched bog (16-OEP), the flow through bog (208-OFT) and expansive peatland on the clay plain 171-CPE), hollow microforms contributed twenty-four, thirteen, and one and a half times (respectively) as much total carbon as compared to *S. fuscum* hummocks.

2.4 DISCUSSION

Our peatland middle DOB values (0.057 ± 0.002 m) are comparable to a previous study documenting organic soil combustion in a pristine WBP peatland (0.07 ± 0.01 m) (Turetsky et al., 2011b). However, when we consider the peatland margins, the DOB reported here was up to seven-fold greater than previous studies (0.072 ± 0.002 to 0.514 ± 0.018 m). As mentioned earlier, peatland middles exhibit a much more stable WT than peatland margins (Figure 2.2), making margins the most hydrologically dynamic portion of a peatland, thereby leaving them vulnerable to smouldering (Whittington and Price, 2006). Lukenbach et al. (2014) presented DOB results from an extreme smouldering event in the WBP (a margin at the same ephemerally perched bog presented here) and suggested that the dominant controls on burn severity were bulk density and moisture content. While that study showed the importance and vulnerability of peatland margins at that particular peatland, this study aimed to expand the scope of Lukenbach et al. (2014) by examining peatland vulnerability to wildfire at the landscape scale and assessing the representativeness of the high burn severity presented.

While the pattern reported in Lukenbach et al. (2014) remains the same across the landscape, as demonstrated by our middle (0.057 ± 0.002 m) and margin (0.245 ± 0.008 m) burn depths, there were departures in the magnitude of burning observed in different hydrogeological settings. Our results show that peatlands prone to isolation from the larger flow systems have larger disparities between margin and middle DOB patterns than peatlands well connected to GW flow systems. However, the mechanisms explaining this difference differ between hydrogeological settings as the dominant source of water to the peatlands differ. We show that local near surface contributions from connected peatlands is a controlling factor in the clay plain, while regional topographic position and type of groundwater interaction is the control in the coarse textured outwash.

The ephemerally perched bog in the coarse textured setting (16-OEP) had the highest burn severity (0.514 ± 0.018 m). We suggest that the combination of hydrogeological setting and topographic position of this peatland played the dominant roles in its vulnerability to deep burning by fostering large water losses from the edges and longer periods of disconnection from regional groundwater. The flow-through bog (208-OTF) in the same hydrological response area experienced the lowest burn severity (0.072 ± 0.002 m) due to its relatively stable WT behaviour, which is due to topographic position and large groundwater flow through from coarse textured glacial deposits.

The expansive nature of the peatlands found on the clay plain have an added benefit of a low perimeter to area ratio minimizing the influence of upland vegetation on the peatland hydrology. The low hydraulic conductivity of the uplands also limits the connectivity with the peatland. The margin with the highest burn severity (0.331 ± 0.034 m; Figure 2.6 J) had both limited contributing area and a high upland to peatland ratio. The margin with the lowest burn severity (< 0.05 m; Figure 2.6 A) had both a high contributing area and a lower upland to peatland ratio.

We argue that the hydrogeological setting imparts crucial controls over the hydrophysical properties of the peat (especially at the margins) which, in certain settings, can leave peatland margins vulnerable to deep burning by increases in bulk density and decreases in moisture content.

The primary implication of higher peat consumption at the margins is that previous studies have most likely underestimated carbon losses due to combustion. We measured an average carbon loss for the middle of the peatlands of 0.1 to 0.7 kg m^{-2}. However, when only considering the hollow microforms, carbon losses increased to 0.4 to 0.9 kg m^{-2} which is similar to values and patterns reported by Benscoter and Wieder (2003), who showed carbon loss due to combustion was two times higher in hollows than hummocks. These values for peatland middles are also comparable to those reported for the burned pristine WBP peatland in Turetsky et al. (2011b). The carbon losses in the margins ranged from 1.7 to 19.9 kg m^{-2}, which is more similar to that of a drained peatland (16.8 ± 0.2 kg m^{-2}; Turetsky et al., 2011b), however the carbon losses at the ephemerally perched bog ranged from 1.5 ± 0.1 to 130 ± 18.2 kg m^{-2}.

Not only is the burn severity higher at the margins, but the peat is also significantly denser and therefore has a higher carbon density than peat found in the middle of a peatland (Figure 2.7). The middle of each peatland, regardless of hydrogeological setting, contributed less total carbon than the margins. Even at the largest peatland (site 171-CPE, the expansive peatland on the clay plain; ~70 ha), where the margin area (3.8×10^4 m^2) was an order of magnitude less than the middle (6.7×10^5 m^2), the margin contributed ~51% of the total carbon lost. At the smaller peatlands, the margins contributed between ~80 and ~90% of total carbon loss. This is likely an under estimation of C loss is greater in hydrogeological settings that have a high frequency of small isolated peatlands, such as the coarse textured outwash at high landscape positions, due to an increase in the perimeter to area ratio. This is commonly associated with stagnant ice moraines and glacial fluvial deposits that promoted perched basin, and combine make up a large portion of the surficial geology of the WBP of Alberta (Fenton et al. 2013). Future studies are needed to assess the frequency of each peatland setting across the landscape in order to better understand regional peatland carbon emissions during wildfire.

Climate change has altered the fire regime in boreal Canada, increasing the frequency of large fire years, total area burned, and late season fires, leaving boreal peatlands especially vulnerable (Kasischke and Turetsky, 2006; Turetsky et al., 2011a; Turetsky et al., 2011b; Gillett et al., 2004). Because peatlands account for over 30% of the world's soil carbon pool (Gorham, 1991), they can be a large source of carbon when subject to combustion. It is currently estimated that peat fires in western Canada emit approximately 6 Tg of carbon annually (De Groot, 2012). In order to accurately estimate the carbon loss due to smouldering, knowledge of the spatial variability and severity of peat smouldering at multiple spatial scales is necessary.

Due to the different effects of hydrogeological setting on peatland hydrology and subsequent vulnerability to wildfire, we argue that the effect of climate change on peatlands in various hydrogeological settings may be markedly different. For example, peatlands whose water balance primarily relies on atmospheric inputs may be particularly vulnerable. Alternatively, peatlands well connected to groundwater flow systems may be less susceptible to drying. However, if groundwater flow systems are affected by climate change (Smerdon et al. 2012), these susceptibilities will be exacerbated since the spatial distribution and vertical extent of peatland burn severity could have considerable influence over post-fire ecosystem recovery.

Previous studies have shown that wildfire alters the thermal regimes and hydrophysical properties of surface peat, which have direct effects on ecosystem recovery. Shallow burns can lead to reduced evaporation rates and increased water tables (Kettridge et al., 2012), while deep burns can expose dense peat and lead to decreases in specific yield and increase ecosystem vulnerability to drought (Sherwood et al., 2013) potentially shifting peatlands from a carbon accumulating moss-dominated system to a non-carbon accumulating shrub-grass ecosystem (Kettridge et al., in prep). This new ecosystem is likely to experience a low intensity, high frequency wildfire regime, which will further deplete the legacy of stored peat carbon (Kettridge et al., in prep).

Currently, the lack of landscape-scale controls on wildfire vulnerability has limited the ability of fire managers to predict smouldering ‘hotspots’ and allocate resources with any efficacy. We suggest that these results, for the first time, allow fire managers to better position their resources and thereby minimize costs and human impacts.

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2.6 FIGURES

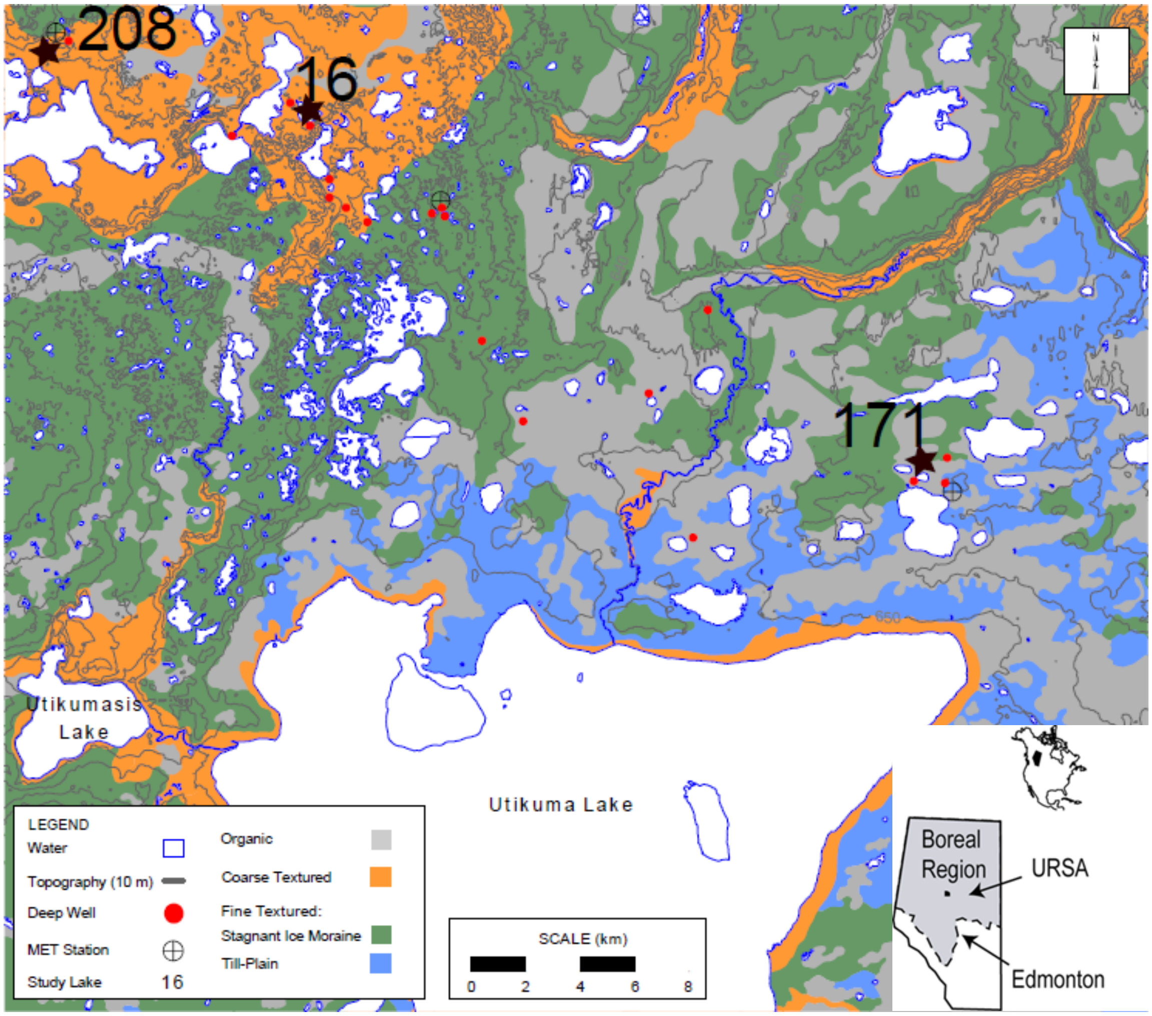

Figure 2.1: Map of Utikuma Region Study Area, adapted from Smerdon et al. (2008).

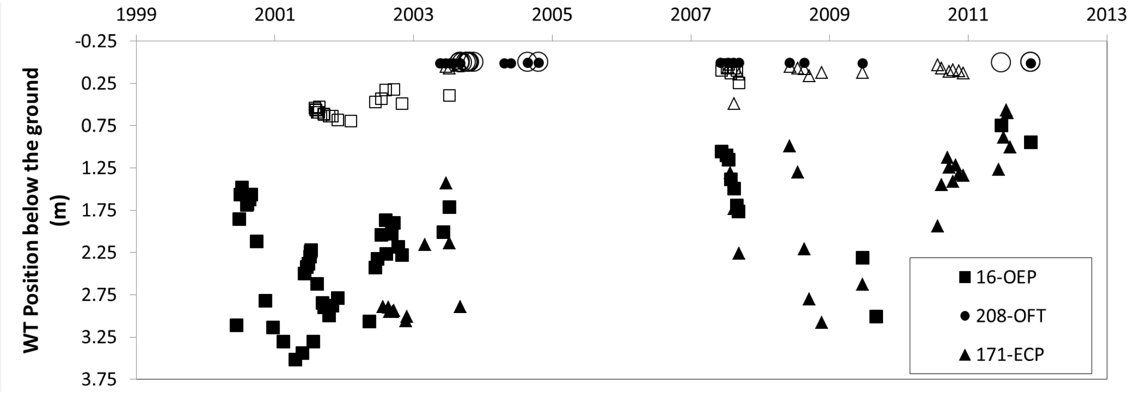

Figure 2.2: Water table positions from 2000 to 2012. Solid markers represent peatland margins, while open markers indicate peatland middles.

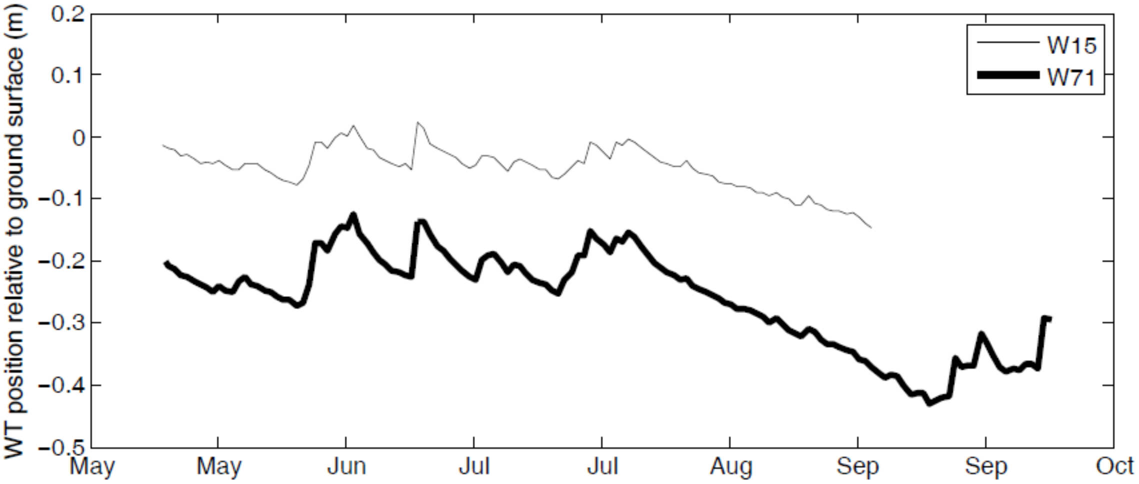

Figure 2.3: Water table position at domed bog (171-71W) and the fen (171-15W) portion of the expansive wetland on the clay plain, summer of 2013

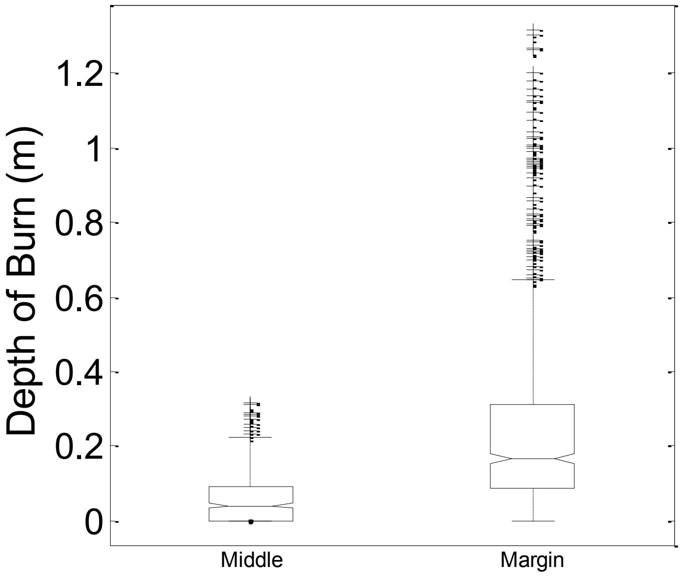

Figure 2.4: Depth of burn for peatland margins and middles from all sites. The notches indicate the 95% confidence interval for the median.

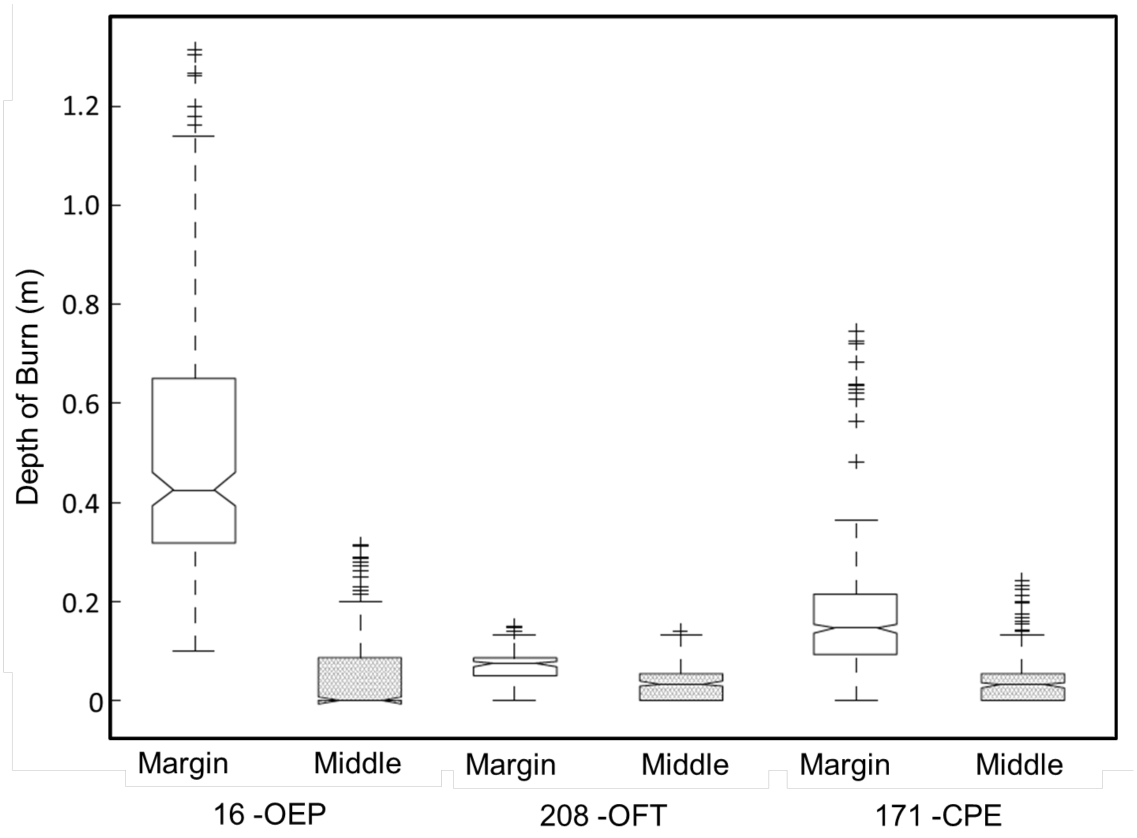

Figure 2.5: Depth of burn at the middle and margins at the ephemerally perched (16-OEP) and through flow (208-OTF) located on the outwash landform, and the expansive peatland on the clay plain (171-CPE). The notches indicate the 95% confidence interval for the median.

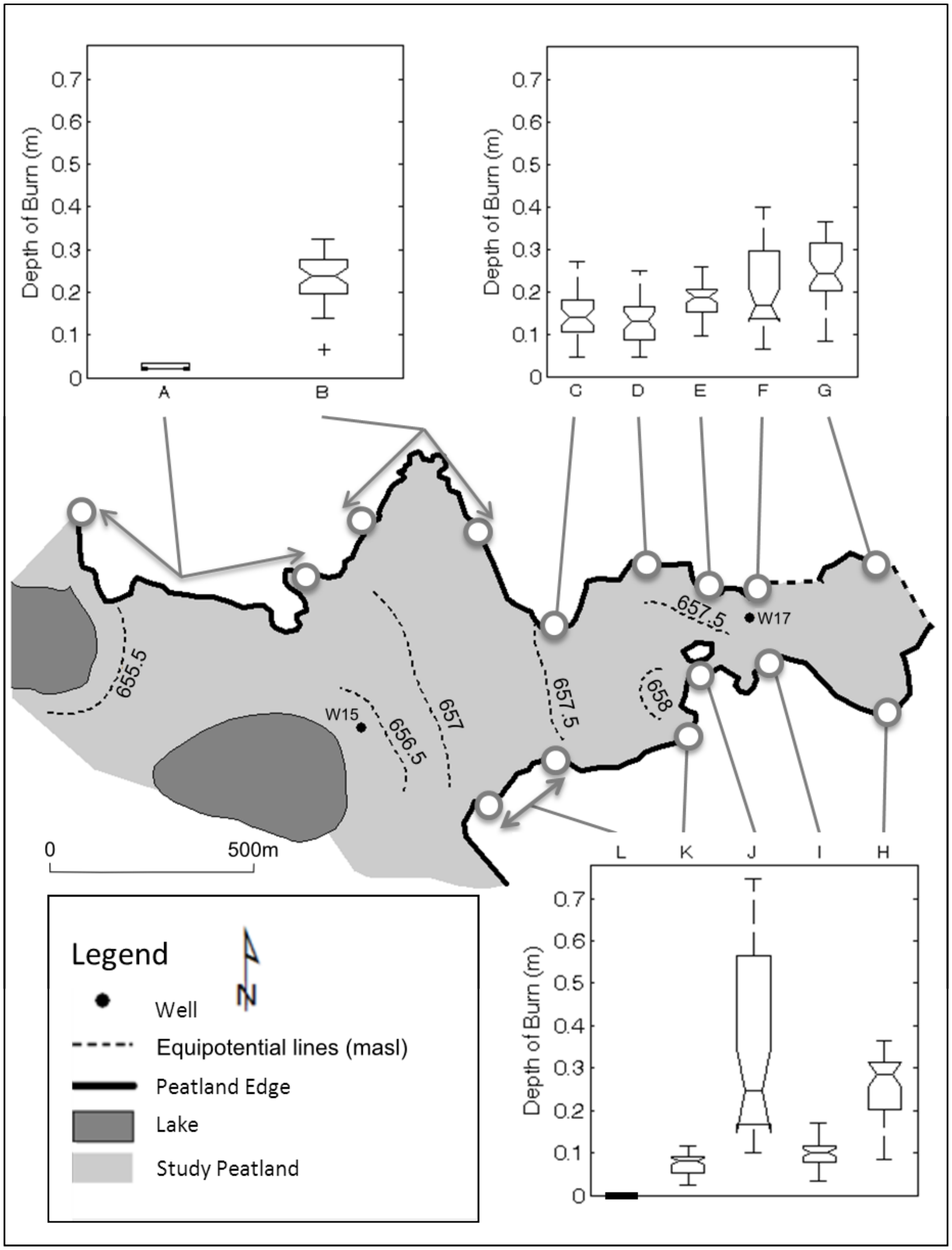

Figure 2.6: Map of site 171-ECP, showing the equipotential lines, well locations and spatial distribution of depth of burn.

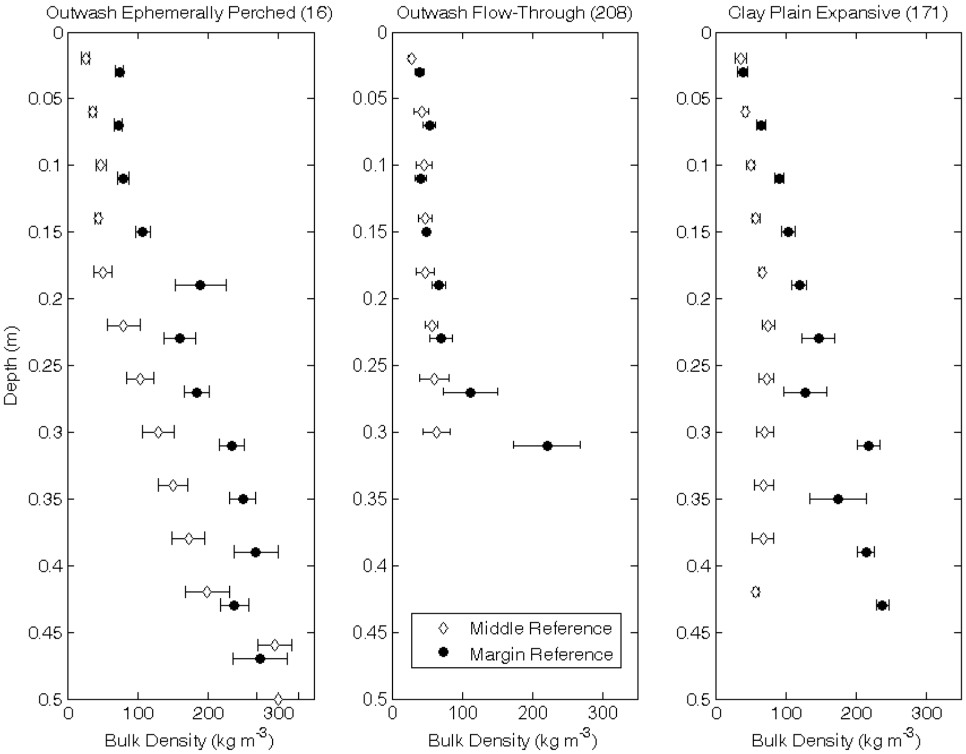

Figure 2.7: Bulk density profiles at the unburned peatlands, serving as references for sites 16-OEP (margin: n = 18; middle: n = 9), 208-OFT (n = 12; n = 6), and 171-CPE (n = 6; n = 4). Error bars indicate standard error.

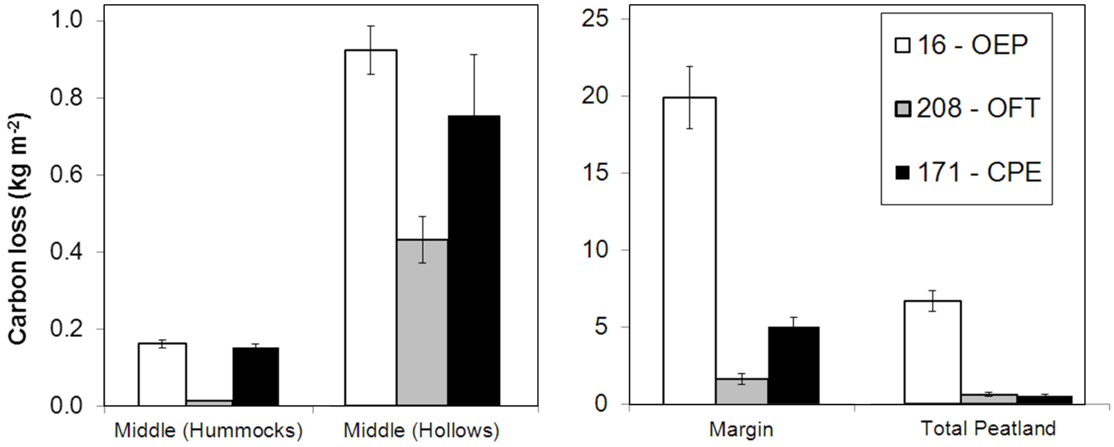

Figure 2.8: Carbon loss normalized for area, showing contributions from each landform and position.

CHAPTER 3: PEATLAND VULNERABILITY TO DEEP ORGANIC SOIL COMBUSTION IN A COURSE TEXTURED LANDSCAPE IN THE WESTERN BOREAL PLAIN

3.1 INTRODUCTION

Peatlands cover 25 – 30% of boreal regions, 2 – 3% of global land surface, and account for one-third of the world's soil carbon pool (Gorahm, 1991). The dominant disturbance in the boreal biome is wildfire (Johnson, 1992), and despite their wet conditions, boreal peatlands are also susceptible to wildfire (Turetsky et al., 2002). Greenhouse gas emissions from global peat fires are equivalent to ~15% of anthropogenic emissions (Poulter, 2006) while forested peatlands in continental western Canada (AB, SK and MB) burn ~580 km^2 yr^{-1} releasing an estimated 3.1 Tg C yr^{-1} (Turetsky et al., 2002). The hydrological conditions that foster deep smouldering (i.e. low gravimetric water content) exist in areas on the landscape with moderate to deep organic soils that are also exposed more frequently to lowered water tables and/or disconnection from shallow subsurface flow (see Chapter 2). As such, peatlands in a sub-humid climate, where evapotranspiration often equals or exceeds precipitation, such as Canada's Western Boreal Plain (WBP) are especially vulnerable to wildfire (Lukenbach et al., submitted). In the WBP there is a propensity for vertical flow, large ET demands, and large vadose zone storage rather than lateral flow (Bothe and Abraham, 1993; Brown et al., 2010; Redding and Devito, 2008). However, Devito et al. (2012) have demonstrated that the type of sediment and relation to regional water tables will have a considerable influence on the location and connectedness of peatlands and therefore wildfire vulnerability (Chapter 2).

Results from chapter 2 identified the coarse textured outwash as experiencing highest burn severity in the 20011 Utikuma Complex Fire when compared to other hydrogeologic settings in the WBP. The aim of this research was to examine the vulnerability of peat smouldering in this hydrogeological setting in order to develop a more comprehensive understanding of these significant but not well understood smouldering events. These smouldering peat fires can be problematic for fire managers because they are flameless, persist underground, and can over-winter under snowpacks resulting in extensive 'mop-up' efforts and costs.

Coarse-textured sediment increases the rates of infiltration and subsurface flow, which results in deep watershed connectivity. On regionally topographic lows, peatland complexes are expansive and are commonly groundwater discharge zones (Siegel, 1988). Conversely, on regionally topographic highs, peatlands are located in small depressions that are perched above the regional groundwater system on thin less permeable lenses. Consequently, low lying peatlands are commonly connected to larger-scale flow systems and isolated peatlands, which only rely on only atmospheric inputs of water, can become disconnected from the regional flow system (Devito et al., 2012; Riddell, 2008). This disconnection makes them highly vulnerable to local water table fluctuations or long-term declines. Consequently, topographic position of a peatland in a coarse textured setting likely plays a large role in determining the hydrophysical properties of the peat and consequently its vulnerability to combustion.

Results from chapter 2 demonstrated that, within the coarse textured outwash hydrological response area in the WBP, between a low lying flow through bog and an ephemerally perched bog, the ephemerally perched bog burned significantly deeper. This study aims to expand on those findings and characterize various peatlands with regard to their vulnerability to deep organic soil consumption during wildfires by examining the hydrophysical properties of unburned peat at various landscape positions, and subsequently evaluating each fuel profile using a discretized energy balance approach modified by Benscoter et al. (2011). In order to examine large-scale hydrological controls on the bulk density of the peat in question, various peatlands were selected along a hydrogeological gradient within a single hydrological response area. Several natural undisturbed peatlands at various topographic positions were selected in the glaciofluvial outwash of the Utikuma region of Alberta. Wildfire vulnerability was evaluated by estimating smouldering energy dynamics, which is a strong indicator of potential organic soil consumption (Lukenbach et al., submitted; Benscoter et al., 2011) by using bulk density values collected from the field under various simulated moisture conditions.

We hypothesized that (1) peatland margins are more vulnerable than the middle of peatlands, indicating that peatland margins would have significantly denser and drier organic soil profiles than peatland middles and therefore be more vulnerable to severe burning and (2) low lying flow-through peatlands will be least vulnerable, while peatlands with increasing disconnection from the regional groundwater will be increasingly vulnerable.

3.2 METHODS

3.2.1 Study site

This study was conducted on the glaciofluvial outwash region at the Utikuma Region Study Area (URSA) located 370 km north of Edmonton, Alberta in the WBP region of Canada (Devito, 2005). Annual PET often exceeds annual precipitation (517mm and 481 mm respectively) (Marshall et al. 1999, Bothe and Abraham, 1993; Brown et al., 2010). The URSA is characterized by low topographic relief, deep heterogeneous glacial substrates with low lying lacustrine clay plains, fine-textured disintegration moraines and coarse-textured glaciofluvial outwashes overlying marine shale (Vogwill, 1978; Devito et al., 2012). Six peatlands were selected along a gradient of topographic position in the coarse textured outwash hydrologic response area at the URSA. The end members of this gradient are a perched peatland located in the lake 19 catchment (19-P, ~1.2ha), which receives water solely from atmospheric inputs and has no connection to regional flow systems (Riddell, 2008), and low lying kettle hole bog complex in the lake 208 catchment that intersects a large flow through system (208-FT, ~3ha). The three intermediate peatlands located in the lake 16 catchment (~4ha) are ephemerally perched and are intermittently disconnected to the regional water table (WT) throughout various climate cycles (16- EP A, B, and C; Figure 3.1) (Smerdon, 2005).

3.2.2 Peatland hydrology and topographic position

Long-term WT data was collated from several previous studies for the middle and margins of the study peatland complexes (Riddell, 2008; Redding, 2009; Smerdon, 2006; HEAD project: Devito, unpublished data). Additional WT measurements were taken over one study season (May – September, 2013). A digital elevation model was used to create a synoptic cross section of the glaciofluvial outwash to evaluate topographic relationships of the peatlands.

3.2.3 Peat properties

At each sampling site, a transect was established perpendicular to the peatland margin, along which we measured organic depth, vertical humification profiles, and bulk density. The degree of humification was evaluated using the von Post (VP) method (Stanek and Silc, 1977; Von Post and Granlund, 1926) at 0.05 m depth intervals from the peat surface to the peat mineral interface every 2 m along a 20m transect using a manual hand auger. Peat monoliths were collected at the margin and in the middle of each peatland. Peat monoliths were collected by cutting the peat using both serrated blades and a 0.05 m x 0.05 m box corer. The monolith was cut at 0.04 m depth intervals in the field and subsequently transported to a lab, after which the samples were placed in a drying oven at 70°C until a constant mass was reached in order to determine the bulk density. Although the peat monoliths were, on average, 0.52 m deep, the humification profiles were taken from the peat surface to the mineral soil to better characterize less accessible peat.

Previous studies have shown strong relationships between VP humification classification and bulk density (Silc and Stanek, 1976; Boelter, 1969), so in order to assess the representativeness of the sample cores and the conditions of deeper, less accessible peat we generated a relationship between measured von post and bulk density in the lab based on samples taken from the study peatlands. A select number of bulk density samples (n = 630) were also classified using the von Post humification index.

In order to better assess peatland vulnerability, samples were only collected from hollow microforms where peat combustion vulnerability is greatest (Shetler et al., 2008; Benscoter et al., 2011; Benscoter and Wieder, 2003; Chapter 2).

In order to evaluate the vulnerability at a variety of water table orientations, we elected to model the moisture content profiles using an approach similar to Lukenbach et al. (submitted). Briefly, we used an exponentially declining tension profile, with depth, described by:

$$\Psi(z) = \Psi_{max}\left(\frac{z - hp}{|hp|}\right)^{0.5} \tag{1}$$

where, Ψ is the pore water tension (cm of water), Ψ_{max} is the difference between expected pore water tension at the surface under hydraulic equilibrium and actual pore water tension, z is the depth below the soil surface (cm), hp is the 'hinge point,' (cm) or where in the soil profile the tension profile transitions into hydraulic equilibrium with the water table. Below the 'hinge point' the pore water tension is equal to the distance to the water table. Ψ_{max} and hp were informed by field measured tensions in the study peatland complexes under various WT conditions (Lukenbach et al., in prep).

Peat moisture retention curves were collected from several previous studies (n=420; Baisley, 2012; Moore, 2013; Lukenbach et al., submitted). A sigmoidal curve (Moore, 2013) was then fit to each tension scenario:

$$\frac{\theta_{\psi}}{\phi} = \frac{\alpha^{-1} \cdot \rho_b}{\sqrt{1 + (\alpha^{-1} \cdot \rho_b)^2}} \tag{2}$$

where θ is the volumetric water content (m^3 water m^{-3} fuel) at a specific pore water pressure, Ψ (mb), ρ_b is the fuel bulk density (g fuel m^{-3} total volume), Φ is the porosity and α is a parameter which describes the slope at the origin. For this study, α was found empirically using the aforementioned retention curves, for both (a) sphagnum peat (n = 316, R^2 = 0.9678) and (b) non-sphagnum peat (n = 104, R^2 = 0.9417):

$$\alpha = 28.2\, ln\Psi + 8.4 \tag{3a}$$

$$\alpha = 32.3\, ln\Psi + 86.2 \tag{3b}$$

By using our measured bulk density and modelled tension profiles, we were able to create profiles of GWC for each site under previously observed WT conditions. Moisture profiles for each peatland margin and middle was modelled under both wet and dry conditions.

3.2.4 Assessing peatland vulnerability to wildfire

In order to evaluate peatland vulnerability to smouldering during a wildfire, we utilized a simple energy balance approach. This method, first used by van Wagner (1972) to model duff consumption in pine stands, has recently been successfully parameterized to explain hydrophysical controls over depth of smouldering in peat (Benscoter et al., 2011).

The energy required to ignite a layer of fuel can be calculated as:

$$H'_{ign(i)} = h_{(i)}\rho_{b(i)}x_{(i)} \tag{4}$$

where H'_{ign} is the cumulative heat required for ignition of a particular fuel horizon (*i*) (J m^{-2}), *x* and ρ_b are, respectively, the thickness (m) and bulk density (g m^{-3}) of a particular fuel horizon (*i*) , and *h* is van Wagner's (1972) heat of ignition (J g^{-1} fuel). Johnson (1992) showed that *h* can be calculated by:

$$h = mC_w(T_V - T_A) + L_V m + C_f(T_{comb} - T_A) + S \tag{5}$$

where *h* is the heat of ignition (J g^{-1} fuel), *m* is the fuel gravimetric water content (GWC; g water g^{-1} fuel by dry weight), C_W is the heat capacity of water (4.186 J $g^{-1}C^{-1}$), C_f is the specific heat of the dry fuel (1.92 J g^{-1} fuel C^{-1} for peat from Oke, 1987), T_V is the vaporization temperature of water (100°C), T_{comb} is the combustion temperature of duff (300°C from Van Wagner, 1972), T_A is the ambient temperature (°C), L_V is the latent heat of vaporization of water (2250 J g^{-1}), and S is the energy required to liberate water molecules sorbed to organic material (50.4 J g^{-1} from Van Wager, 1972). The energy created by the combustion of a particular fuel horizon ($H_{comb(i)}$, J m^{-2}) can be calculated as:

$$H_{comb(i)} = \rho_{b(i)} x_{(i)} E_{comb} \tag{6}$$

where E_{comb} is the low heat of combustion per unit mass of peat (14 200 J g^{-1} from Frandsen, 1991), x and ρ_b are, respectively, the thickness (m) and bulk density (g m^{-3}) of a particular fuel horizon (*i*).

Similar to Lukenbach et al. (submitted), we use the ratio of energy release of an overlying layer of peat ($H_{comb(i-1)}$) to the energy required to combust the subsequent layer of peat ($H_{ign(i)}$) to evaluate peat smouldering potential. H_{comb}/H_{ign} ratios < 1 have little to no potential to smoulder because there is not enough available energy from the combustion of the overlying layer to ignite the lower layer. However, an H_{comb}/H_{ign} ratio of two indicates that only 50% of the energy produced by the combusting peat layer would need to be transferred downward to the underlying layer in order for smouldering to propagate, which falls into the range of previously reported downward efficiencies (Frandsen, 1998; Schneller and Frandsen, 1998). While we are not attempting to model precise depths of burn, we believe this approach suitably assesses a peat profile's vulnerability to deep smouldering and is a sound method of evaluating peatland vulnerability on a landscape scale.

3.2.5 Statistical methods

Due to lack of normality, bulk density profiles were compared using the Mann Whitney U test for statistical significance. In order to assess errors associated with the GWC model, synthetic data was created. A random sample (n =2000) was generated from a normal distribution based on the original distribution and associated errors of $\alpha(\Psi)$ (eq. 3), which was taken from empirical data, for each sampling location and accompanying depth. From this synthetic data, standard deviation and 95% confidence intervals were derived, the latter of which was used to determine statistical significance of GWC and H_{comb}/H_{ign} ratios within sites, between sites, and during wet and dry scenarios.

3.3 RESULTS

3.3.1 *Peatland hydrology and topographic position*

Site 19-P is a completely perched wetland, meaning it has permanent, laterally isolated, perched water tables confined by layers of low permeability substrates overlying unsaturated coarse textured sediments (Figure 3.2a; Riddell 2008). Historic (2002-2008) water levels show a stable, near surface WT in the middle of peatland, ranging from 0.03 m below the surface to 0.21 m above the peat surface. At the margin there is a steep decline in the WT, leaving a very narrow zone (~2 to 3 m) of peatland exposed to dry conditions. The WT on the margin (0.35 m of peat) ranged from 1.14 m below to 0.13 m above the peat surface, while only 3 m laterally towards the upland (0 m of peat) the WT ranged from 2.72 m below to 1.46 m below the ground surface. While the perched WT varied greatly on the edge between wet and dry periods, it did not affect the peatland middle WT greatly (Figure 3.2a).

16-EP A, B and C are all located in an intermediate topographic position, where they are ephemerally connected to regional water tables. During the study period, these peatlands were hydraulically mounded (Figure 3.2b & c). The water table decline at the margins is more gradual than at site 19-P exposing a larger volume of peat to dry conditions.

208-FT is located on a regional topographic low that intersects the intermediate groundwater flow system connecting several large lakes (~450-900 ha; Figure 3.2c). These large groundwater-fed lakes moderate water table position, minimizing extreme water table fluctuation at the peatland margin during periods of drought. Historic (2003-2005; 2008-2012) water table positions at wells located in the middle and at the margin of the peatland all exhibited minimal fluctuations (< 0.65 m) over a 10-year record. Water table depths at the margin were only slightly (< 0.35m) deeper than the middle during dry periods and the maximum and minimum water table orientations differ only slightly (Figure 3.2d).

A synoptic cross section (Figure 3.2e) shows the relative topographic positions of each peatland and their relation to the regional WT.

3.3.2 *Peat properties*

Bulk density increased significantly with depth at most sites (Table 1). Both the margin and middle at site 208-FT, and the margin at site 16-EP A did not increase statistically significantly with depth. Peat bulk density at the middle of site 19-P increased with depth moderately significantly ($p<0.05$), while all other sites had bulk densities increase with depth highly significantly ($p < 0.001$). At 16-EP B, 16-EP C, and 19-P the margins were significantly denser than the middles ($p < 0.05$) at all but two depths. At sites 208-FT and 16-EP A the bulk density at the peatland margin did not vary significant from the middle. The margin at site 208-OFT was significantly less dense ($p<0.05$) than all other peatland margins at all but two depths (0.04 – 0.08 m and 0.24 – 0.28 m). The margin at site 19-OP was significantly less dense ($p < 0.05$) than both 16-OEP C and 16-OEP B at from 0.28 to 0.44 m below the peat surface.

The humification profiles were visually assessed to evaluate the representativeness of the cores taken for bulk density analysis. All but one site appeared to support their respective humification profiles. Site 19-P had a very narrow margin from which to sample from (~2 m). The humification profiles for site 19-P (Figure 3.3a and 3.3b) show that over 75% of the first 0.4 m of the transect ranges from completely undecomposed (VP = 1) to slightly decomposed (VP = 4), which corresponds to a bulk density range of 15 to 120 kg m^{-3} (Figure 3.4). Over 80% of the upper 0.1 m ranges from completely undecomposed to almost entirely undecomposed (VP = 2). Sits 16-EP C, an ephemerally perched peatland,

and sites 208-FT, a low lying flow through bog, are shown in Figures 3.3c and 3.3d, respectively, for comparison purposes.

GWC profiles were simulated for each peatland margin and middle under measured high ('wet') and low ('dry') water table scenarios (Figure 3.5). There were no statistical differences between the intermediate sites under either scenario. However, under the dry scenario site 208-FT exhibited significantly higher ($p < 0.05$) GWC than all other sites at all but one depth. Site 19-P was similar to the intermediate sites under dry conditions, but more similar to 208 under wet conditions.

Under dry conditions, sites 19-P and 16-EP C exhibited significantly drier ($p < 0.05$) profiles in the peatland margins as compared to the middles. Under wet conditions, 16-EP B, 16-EP C and 19-P all showed significantly drier ($p < 0.05$) profiles in the margins.

3.3.3 *Assessing peatland vulnerability to wildfire*

16-EP C showed significantly higher ($p < 0.05$) H_{comb}/H_{ign} ratios at the margins under dry conditions, while 19-P showed significantly higher ratios under both wet and dry conditions. 208-FT, 16-EP B, and 16-EP A showed no significant difference between margins and middles under either scenario.

Under dry conditions at the margins, H_{comb}/H_{ign} ratios ranged from 0.6 ± 0.1 (standard deviation) to 0.78 ± 0.2 at site 208-FT, from 1.1 ± 0.3 to 1.9 ± 0.1 at 16-EP A, from 1.1 ± 0.3 to 2.3 ± 1.0 at 16-EP B, from 1.2 ± 0.2 to 2.3 ± 0.6 at 16-EP C, and from 1.0 ± 0.5 to 1.6 ± 0.2 at site 19-P. The H_{comb}/H_{ign} ratios at all of the ephemerally perched sites were comparable. Under wet and dry scenarios, the margin at site 208 showed significantly lower H_{comb}/H_{ign} ratios than the ephemerally perched sites at most depths. Overall, the margin at site 19-P under dry conditions showed lower H_{comb}/H_{ign} ratios than the ephemerally perched sites, but was only statistically significant at two depths.

3.4 DISCUSSION

Results from chapter 2 showed that a peatland located on a regionally topographic high in the coarse textured outwash lost 19.9 ± 2.0 kg C m^{-2} due to combustion in the margin, as compared to 1.7 ± 0.4 kg C m^{-2} at a low lying peatland in the same outwash during a 2011 wildfire. This study expanded the topographic gradient in the previous study to include completely perched sites, and examined the bulk density, modelled GWC and H_{comb}/H_{ign} ratios at five unburned peatlands across a topographic gradient to assess and compare vulnerability to deep smouldering during a wildfire.

While some studies report GWC limits to smouldering between 93% and 145% (Frandsen, 1987, 1997; Rein et al., 2008; Reardon et al., 2007; McMahon, 1980) others report GWC limits ranging from 250% to 295%. Watts (2012) observed 0.09 m of vertical peat consumption at 250% GWC, Benscoter et al. (2011) observed smouldering of peat with GWC values of 295% and Davies et al. (2013) reported GWC values of over 252% in unburned reference cores while smouldering was occurring nearby in the same blanket bog. It is also important to note that Benscoter et al. (2011) observed smouldering at depth at higher GWC limits than that required for surface ignition. The ephemerally perched sites reported here exhibited the lowest GWC profiles, ranging from 310 ± 14% to 322 ± 5% at the surface and from 152 ± 1% to 281 ± 27% at depth.

GWC, a ratio of volumetric water content and bulk density, is a useful metric because it represents both a fuel's major heat sink (moisture) and heat source (fuel density). Expectedly, H_{comb}/H_{ign} ratios followed GWC trends closely at all sites, wherein low GWC profiles resulted in high H_{comb}/H_{ign} ratios. H_{comb}/H_{ign} ratios equaling one translates into a fuel profile whose heat of combustion exactly equals the heat required to both drive off the moisture and combust the fuel in the next layer, assuming no heat is lost by mechanisms such as radiative or convective heat loss. Downward heat efficiencies reported by previous studies range from 0.3 to 0.9 with a mean of 0.7 (Schneller and Frandsen, 1998; Frandsen, 1998). A downward efficiency of 0.7 would require an H_{comb}/H_{ign} ratio of 1.4 for successful downward combustion between layers. The margins at 16-EP A, B, and C in the dry scenario meet this requirement at almost every depth. Site 19-P, under dry conditions, only met this condition at four depths, and site 208-FT never exhibited H_{comb}/H_{ign} ratios over 1.

The least vulnerable peatland was site 208-FT, the low lying flow-through bog, whose H_{comb}/H_{ign} ratios never exceed 1, and which had, by far, the highest GWC profiles. The relatively low GWC profiles and high H_{comb}/H_{ign} ratios suggest that the peatlands in the intermediate topographic positions (16-EP A, B, and C) are the most vulnerable to deep smouldering. They have the highest incidence of H_{comb}/H_{ign} ratios exceeding 1.4. While the margin at site 19-P has comparable H_{comb}/H_{ign} ratios under the dry scenario at some depths, it generally exhibited lower H_{comb}/H_{ign} ratios than the intermediate sites, and we classify this site as less vulnerable.

At all but two sites the margin and middle followed a similar trend, wherein the peatland middle was less dense, with higher GWC and lower H_{comb}/H_{ign} ratios, than the peatland margins. This supports findings by Lukenbach et al. (submitted) and results from chapter 2 that both reported margins contributing between 50% and 90% of total carbon loss due to combustion, despite the fact that the margins only accounted for between 6% and 30% of total area. Site 16-EP A, however, showed the opposite trend. This site was not a classic bog dominated by *Sphagnum* hummock and hollow microtopography, but was a mature wooded swamp with no live moss at the surface. The increased density of mature trees and lack of *Sphagnum fuscum* hummocks, which are generally resistant to smouldering, leaves this site with a much higher area of dense peat as compared with other peatlands. This could be of particular concern, as this would not be characterized by traditional peatland mapping techniques (Krankina et al., 2008). Site 208-FT showed no difference in GWC and H_{comb}/H_{ign} ratios between the margin and middle.

Groundwater connectivity is the primary corollary of topographic position in the coarse textured outwash of the URSA. The high permeability of the sandy substrate fosters deep connectivity and relatively flat water tables that do not mimic surficial topography. We show that low lying peatlands that intersect the regional WT are the least vulnerable to deep smouldering and that peatlands that easily become detached from the regional water table are the most vulnerable. These peatlands are hydraulically mounded, resulting in deep WT at the margins, which cause densification and drying of the peat (Whittington and Price, 2006). Site 19-P has no connection with the regional WT, and one would expect it to be the most vulnerable to wildfire, especially in times of drought. However, the site conditions at 19-P under maximum and minimum WT orientations are such that only a very narrow portion of the peatland is exposed during dry conditions. The WT hinge at the margin is very sharp and moves laterally depending on the water balance of the peatland. This severe WT decline is likely due to the sharp lithological transition of the silt and clay underlying the peatland to the sandy silt and fractured clay surrounding the peatland (Riddell, 2008). This hydrostratigraphy allows the peatland at site 19-P to exist under saturated conditions in a sub-humid climate perched ~12 m above the regional water table. The humification profiles (Figure 3.3) show the generally low levels of decomposition at this site (3.3a and 3.3b), as compared that of an intermediate site (3c).

The intermediate sites were hydraulically mounded, and may have had intermittent inverted water tables. While site 19-P is permanently perched well above the regional WT, the intermediate sites do not require such unique hydrostratigraphy as is present at 19-P, as they are transiently connected with the regional WT during certain climate cycles. They do not rely as heavily on atmospheric inputs over large time scales. This ephemeral connection results in drying and densification of margin peat deposits. Smerdon et al. (2005) showed the disconnection from the regional WT of lakes located at intermediate topographic positions in the outwash. Without the stratigraphy to help maintain the water balance, these peatlands are at a large water deficit during climatic dry cycles (Devito et al., 2012).

We suggest those wetlands which experience the most disconnection from regional groundwater exhibit moderate behaviour; a concept that is paralleled in other fields of research. Our vulnerability pattern is strikingly similar to Webster et al. (1996) who found that topographic position of lakes had an effect on chemical responses to drought. The lake most disconnected from groundwater inputs, comparable to our site 19-P, showed intermediate Ca and Mg responses, while those most connected had the greatest response and the lakes receiving intermediate groundwater inputs showed the lowest response.

Although the regional cross section (Figure 3.2) shows both high and low WT configurations at each site, those configurations do not occur simultaneously. Subtle changes in lithology, relationship to the regional WT and surrounding lakes cause the various small landscape units (i.e. peatlands) to reach their maximum and minimum water levels out of sync (Smerdon et al., 2005; Devito et al., 2012). If future efforts are aimed to model water levels and fire risks at peatland margins across the landscape for a given period of time, more sophisticated regional scale hydrogeological modelling is required.

3.5 CONCLUSION

We suggest that, in the sub-humid WBP, regional topographic position, and therefore regional groundwater connectivity, is the controlling factor for peatland vulnerability to wildfire in the Western Boreal Plain. Low-lying flow-through peatlands that intersect the regional WT (site 208) are the least vulnerable to deep smouldering and peatlands that are only ephemerally connected to the regional WT (16-EP A, B and C) are most vulnerable.

Climate change has altered the fire regime in boreal Canada, increasing the frequency of large fire years, total area burned, and late season fires, leaving boreal peatlands especially vulnerable (Kasischke and Turetsky, 2006; Turetsky et al., 2011a; Turetsky et al., 2011b; Gillett et al., 2004). Additionally, if groundwater flow systems are affected by climate change (Smerdon et al. 2012), the vulnerability pattern presented here will be intensified.

While our goal was not to precisely model depths of burn, we believe this approach suitably evaluates a peatland's relative vulnerability to deep smouldering and is a sound method of assessing peatland vulnerability on a landscape scale. Although this model, or its utilization in this particular study, may not be directly applicable for fire managers, it is, however, helpful in developing a tool for determining vulnerability of peatland types within a particular hydrologic response area. Having a priori knowledge of potential smouldering hotspots in the landscape is very beneficial for fire managers, allowing them to efficiently allocate resources and reduce emergency response time to smouldering events.

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3.7 FIGURES

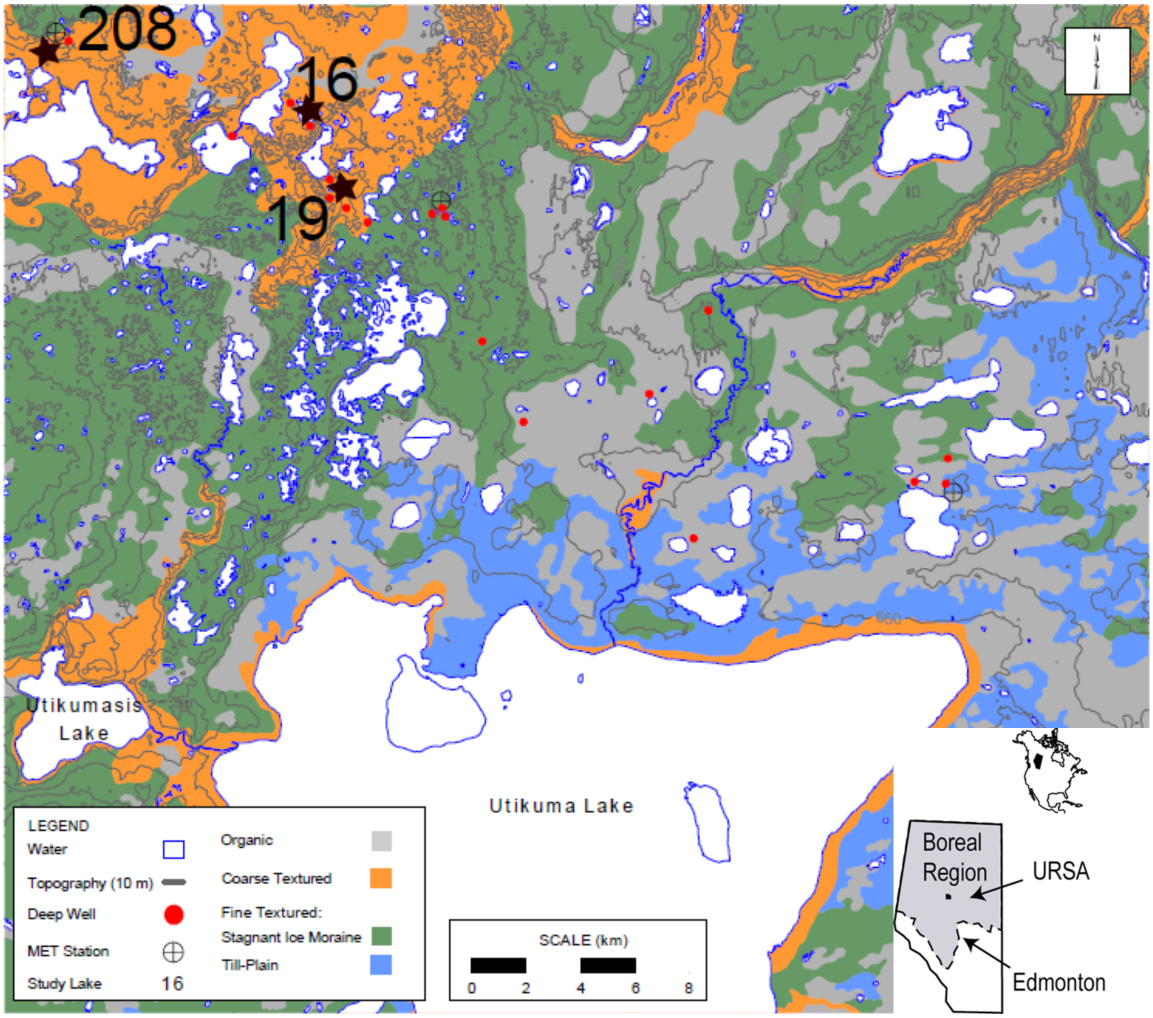

Figure 3.1: Map of Utikuma Region Study Area, adapted from Smerdon et al. (2008).

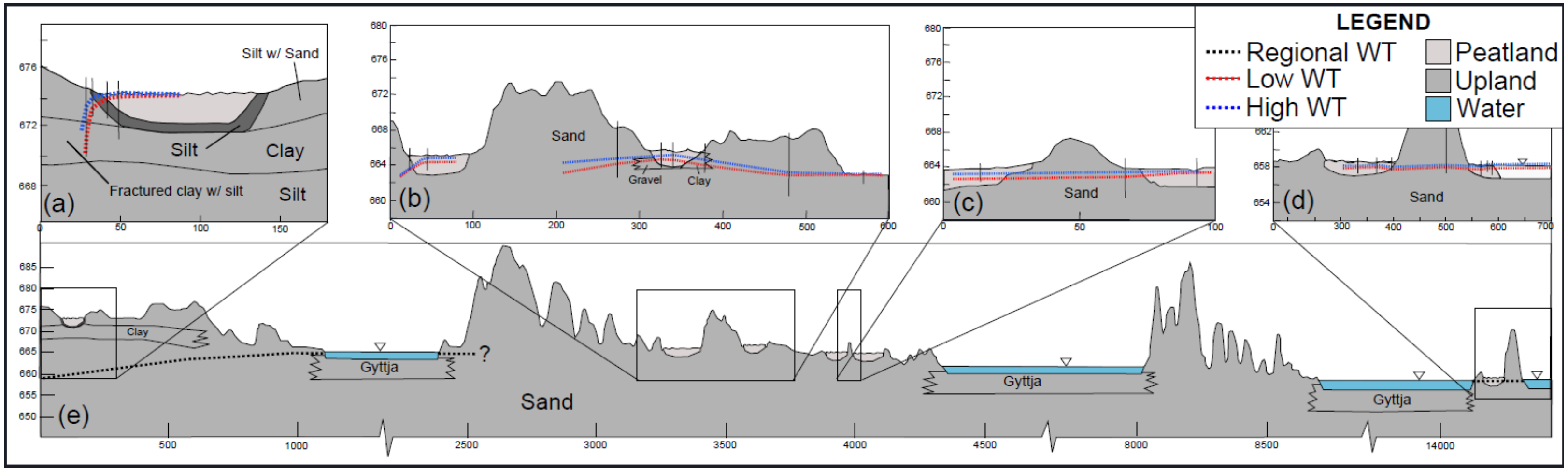

Figure 3.2: Schematic Cross sections showing high and low WT orientations, where on the figure from left to right (a) 19-P, (b) 16-OP C, 16-OP B, (c) 16-OP A, (d) 208-FT, and (e) regional cross section of the coarse textured outwash at the URSA.

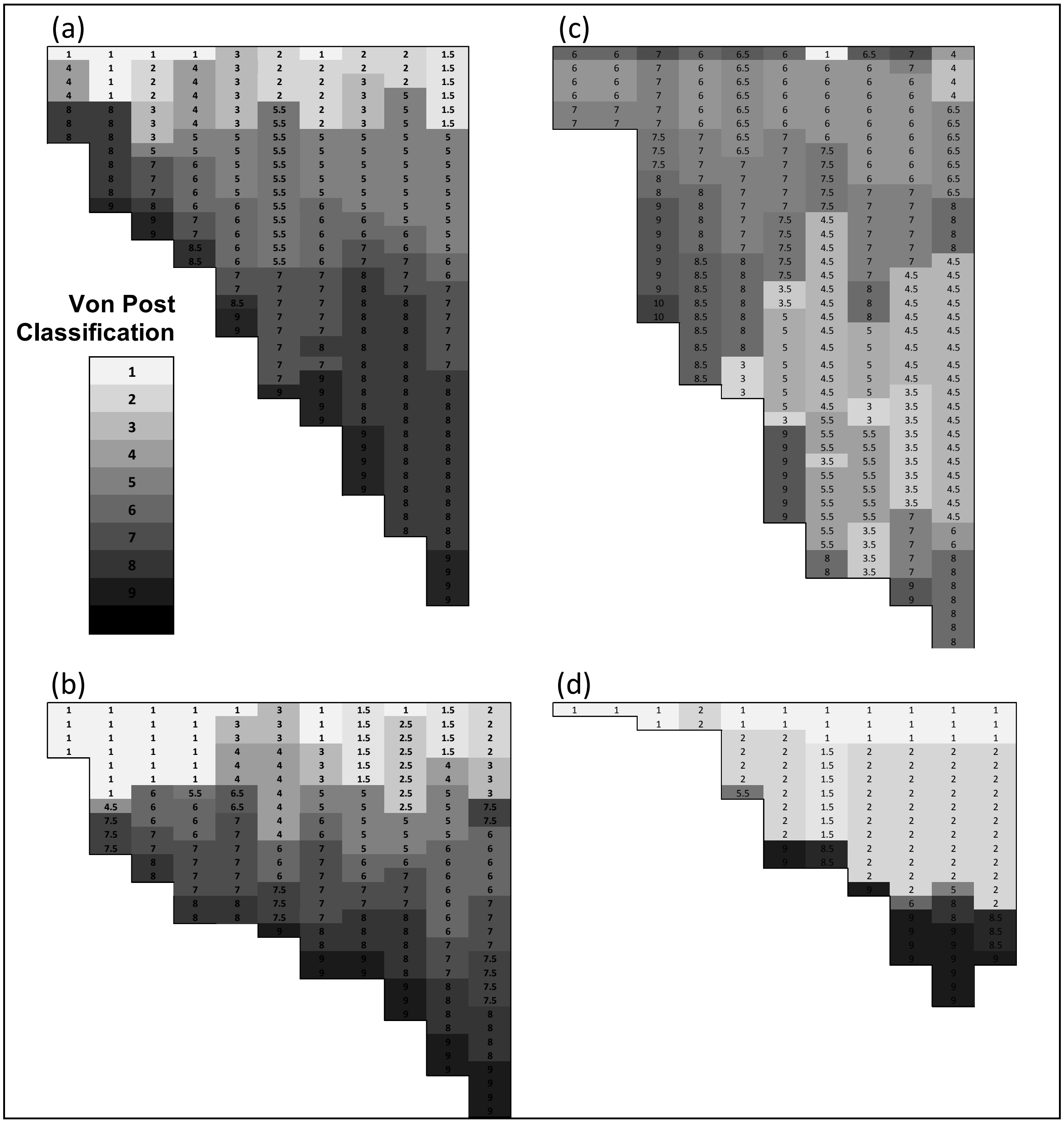

Figure 3.3: Von Post humification profiles from sites at different topographic positions, where (a) & (b) are taken from site 19-P, (c) 16-EP C, and (d) 208-FT. Each cell represents a 0.05m deep by 2m wide block of peat. The classification scheme is shown, where a VP of 1 corresponds to completely undecomposed peat, a VP of 5 corresponds to moderately decomposed peat, and a VP of 10 corresponds to completely decomposed peat.

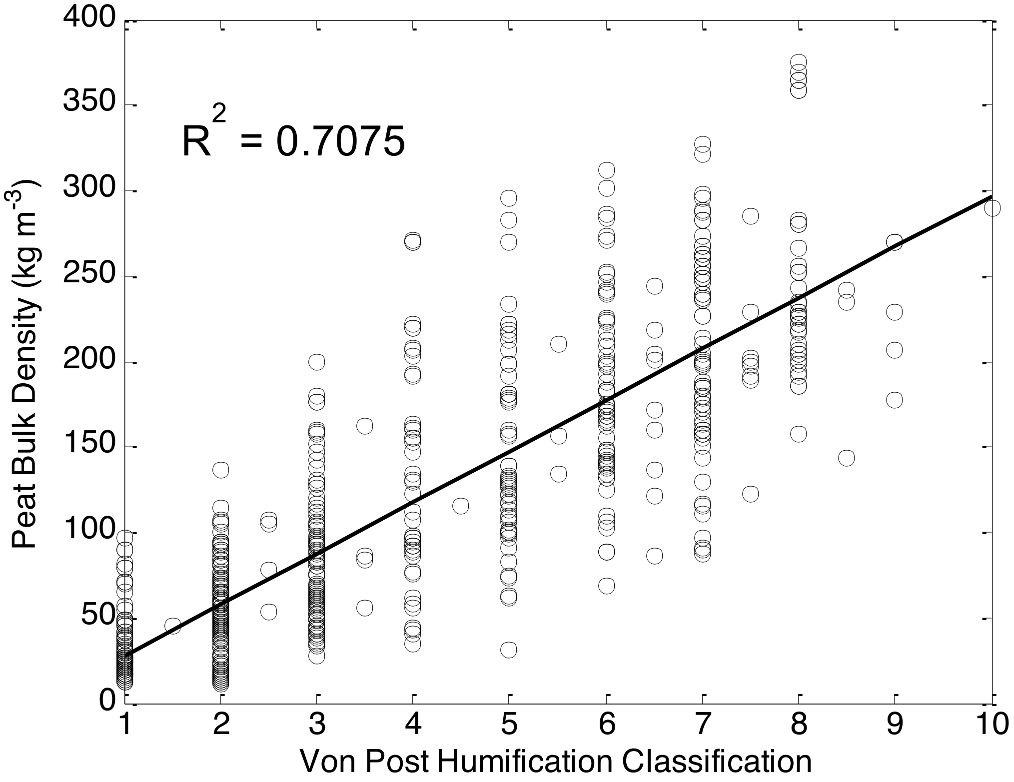

Figure 3.4: Showing the relationship between peat bulk density and von Post humification classification (n = 630).

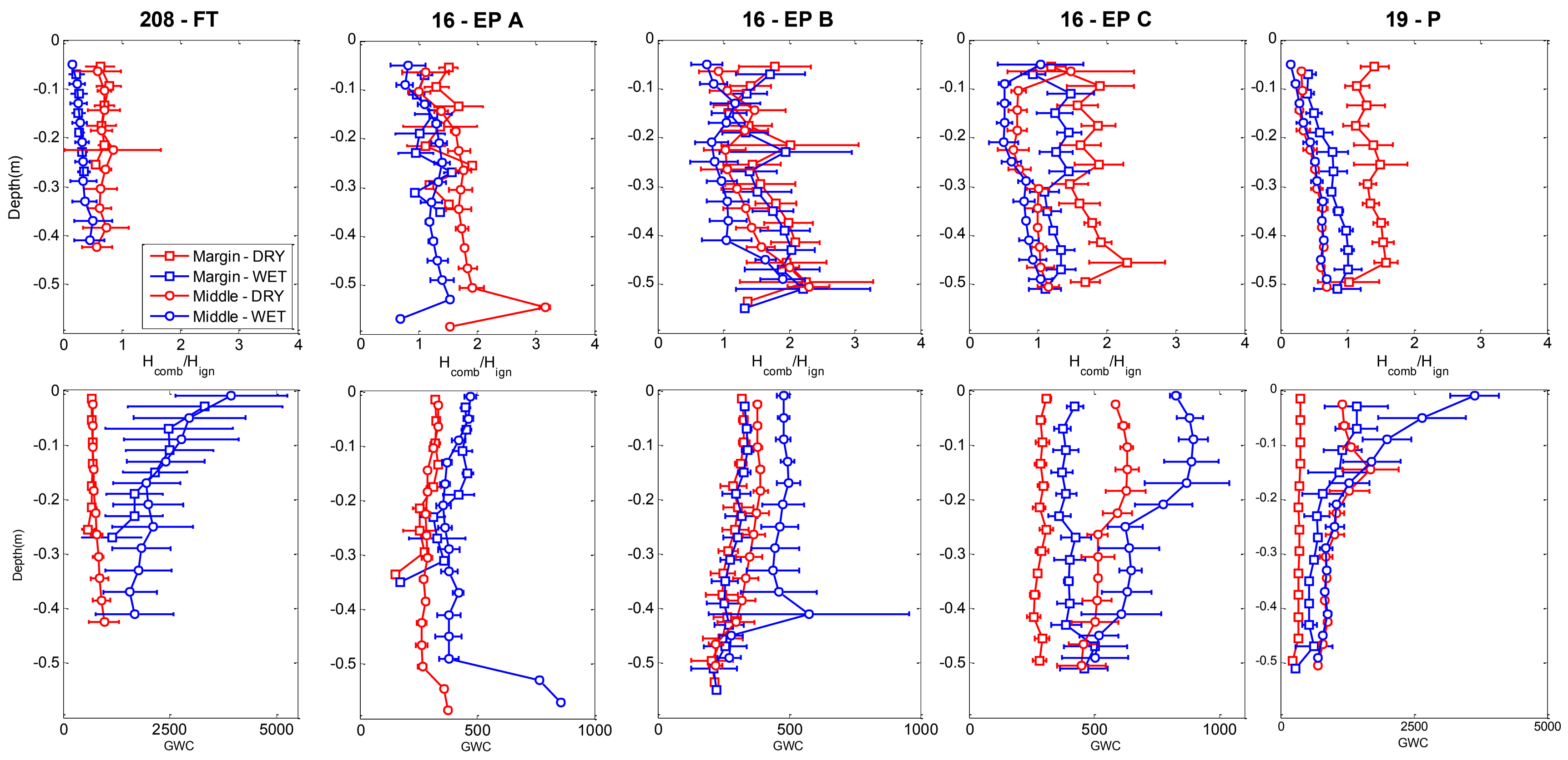

Figure 3.5: Showing the H_{comb}/H_{ign} ratios and modelled GWC (%) at each peatland margin and middle under both wet and dry conditions.

Depth (m)	Flow-Through Bog (208-FT)				Ephmerally Perched (16 - EP A)				Ephmerally Perched (16 - EP B)				Ephmerally Perched (16 - EP C)				Perched (19 - P)			
	Margin		Middle		Margin		Middle		Margin		Middle		Margin		Middle		Margin		Middle	
	n	ρ_b (kg m^{-3})	*n*	ρ_b	*n*	ρ_b	*n*	ρ_b	*n*	ρ_b	*n*	ρ_b	*n*	ρ_b	*n*	ρ_b	*n*	ρ_b	*n*	ρ_b
0 to 0.04	12	40.04(6.51)	6	27.47(3.88)	3	72.44(6.99)	3	49.44(11.17)	16	79.41 (5.12)	7	26.14 (5.87)	7	95.83 (10.32)	3	48.94 (2.82)	6	74.24 (8.48)	3	27.43 (1.83)
0.04 to 0.08	12	53.46(8.60)	6	42.28(10.11)	3	75.70(6.39)	4	66.52(3.35)	15	75.90 (6.22)	7	36.05 (4.45)	7	143.45 (10.55)	3	37.82 (11.10)	6	71.30 (7.29)	3	39.80 (6.24)
0.08 to 0.12	9	41.12(8.13)	6	46.34(10.97)	3	98.03(21.45)	5	110.71(9.59)	16	85.02 (7.57)	7	48.07 (7.12)	7	138.60 (15.90)	3	42.87 (10.58)	6	86.76 (9.09)	3	50.39 (5.77)
0.12 to 0.16	9	49.12(4.81)	6	47.69(9.41)	3	87.81(5.15)	3	155.57(8.96)	15	117.46 (8.07)	7	43.76 (3.84)	7	157.09 (13.14)	3	53.32 (16.66)	6	100.38 (14.31)	3	61.67 (10.18)
0.16 to 0.20	9	66.64(9.32)	6	47.98(13.03)	3	125.49(31.55)	5	166.76(7.06)	15	168.62 (19.60)	7	51.24 (12.86)	4	149.80 (17.22)	3	67.58 (24.14)	6	132.77 (17.35)	3	78.37 (10.36)
0.20 to 0.24	6	70.15(15.88)	6	56.57(9.50)	3	218.95(30.30)	5	180.45(10.81)	14	156.13 (25.07)	7	80.18 (23.26)	5	178.59 (17.52)	3	92.32 (15.91)	6	146.53 (18.06)	3	90.01 (5.97)
0.24 to 0.28	3	112.45(39.10)	4	60.83(21.09)	2	230.82(101.49)	5	183.01(9.33)	13	175.70 (18.53)	7	103.11 (19.13)	6	143.82 (15.06)	3	129.82 (11.09)	5	130.16 (5.43)	3	94.35 (7.93)
0.28 to 0.32	2	220.98(47.83)	4	63.92(19.25)	1	199.16(--)	5	188.84(12.53)	13	217.07 (13.43)	7	129.21 (22.76)	6	173.09 (13.97)	3	135.80 (17.06)	5	145.92 (6.15)	3	110.27 (7.72)
0.32 to 0.36	1	231.14(--)	4	75.29(29.98)	1	410.04(--)	5	209.31(9.71)	12	252.22 (19.57)	7	150.36 (20.94)	6	199.83 (3.71)	3	139.45 (1.52)	5	165.49 (8.23)	3	107.20 (2.29)
0.36 to 0.40	1	289.13(--)	3	75.75(28.08)			3	205.32(6.64)	11	271.90 (33.90)	7	171.86 (23.55)	6	215.77 (11.60)	3	146.32 (15.17)	5	167.00 (7.29)	3	111.57 (1.21)
0.40 to 0.44			4	92.43(42.37)			5	226.25(11.83)	9	240.11 (22.57)	7	198.96 (31.64)	5	224.42 (18.45)	3	155.22 (22.42)	4	169.13 (17.81)	3	105.37 (4.73)
0.44 to 0.48							3	227.77(21.34)	9	276.94 (43.17)	4	294.56 (24.13)	6	182.78 (16.47)	3	173.62 (17.99)	4	171.85 (32.05)	3	115.43 (1.82)
0.48 to 0.52							5	225.42(11.24)	6	343.04 (55.74)	3	298.99 (29.72)	6	195.98 (15.15)	3	183.24 (26.12)	2	297.49 (46.41)	1	129.71 (--)
0.52 to 0.56							1	119.63(--)	1	301.68 (--)										
0.56 to 0.60							1	107.54(--)												

Table 1: A summary of samples taken for bulk density analysis, used to calculate H_{comb}/H_{ign} ratios and simulate GWC. Where n values are dissimilar within the same depth interval at one site, either mineral was reached for that particular sample core or large tree roots invalidated the peat sample.

CHAPTER 4: CONCLUSION

This study took advantage of a ~90,000 ha wildfire that affected several peatlands across a topographic and hydrogeological gradient. The primary objective of this study was to determine local and landscape controls on peatland burn severity in the Western Boreal Plain. This fairly large scale objective was addressed using two different means, direct observation and modelling. Depth of burn, a common measure of fire severity, was measured at three peatland complexes located on two different hydrologic response areas in different landscape positions affected by the 2011 Utikuma complex fire. Additionally, peatland vulnerability was assessed at several unburned peatlands located in various landscape positions within one hydrologic response area by comparing potential smouldering energy dynamics, which were derived from modelled gravimetric water content profiles and measured bulk density profiles.

It was shown that, with regards to an individual peatland, the margin was the area most vulnerable to deep burning. Long-term hydrological records showed that WBP peatland margins are susceptible to large annual and inter-annual WT declines. These WT fluctuations lead to both densification and drying of peat, leaving them especially vulnerable to deep consumption by smouldering during wildfire. Through observing burn severity in burned peatlands and modelling H_{comb}/H_{ign} ratios in unburned peatlands, this study showed that margins are more vulnerable and can burn upwards of seven times as deep as the middle of peatlands. This pattern is evident at peatlands existing at all landscape positions in both fine and coarse textured HRAs. Previous studies have focused primarily on the middles of expansive peatland complexes in fine textured HRAs and while peatland middles account for a much larger land area, this study showed that despite only occupying 5 to 30% of total area, they can contribute between 50 and 83% of total carbon emissions due to combustion.

Our burn severity characterization at the three peatlands support our initial hypotheses based on hydrogeological setting. Specifically, at the coarse textured HRA, site 208-FT was the least vulnerable to organic soil combustion, while site 16-OEP was the most vulnerable, where burn severity was correlated with topographic position. In the fine textured HRA, Site 171-ECP had generally intermediate burn severities at the margin, but showed intrasite variability which was correlated to contributing area, or distance to intermediate flow systems.

This study shows that peatland vulnerability in the coarse textured HRA is controlled by topographic position, and therefore groundwater connectivity. These findings were confirmed when H_{comb}/H_{ign} ratios and GWC profiles of different unburned peatlands were compared across a topographic gradient. However, vulnerability and groundwater connectivity aren't necessarily a linear relationship. Regionally high peatlands are often perched or ephemerally perched and therefore are isolated from intermediate groundwater but lose water readily to the surrounding coarse textured mineral uplands. Peatlands most disconnected from the regional groundwater rely on unique hydrostratigraphy to maintain low storage deficits and are not as vulnerable as ephemerally perched peatlands. Regionally low peatlands are directly connected to the larger scale groundwater system and are least vulnerable.

This study also demonstrates that the vulnerability of a peatland margin located on the fine textured HRA is more influenced by hydrological contributing area, suggesting that if a large flow system intersects a peatland, more water is transmitted to the peatland margins thereby limiting wildfire vulnerability. Alternatively, if a portion of the peatland is distal to the larger flow system and hydrologically isolated, it is more vulnerable to wildfire. However, the low permeability of the silts and clays found on the lacustrine clay plain somewhat limit water transmission from the peatland and help moderate water loss to the uplands.

This is the first study to examine larger landscape scale controls on organic combustion by comparing peat burn severity and vulnerability in several burned and unburned peatlands in various landscape positions and hydrogeological settings. This study has helped show that landscape scale controls can affect peatland vulnerability to severe smouldering. Knowledge of the spatial variability of peatland burn severity will assist both scientists and fire managers in the WBP to understand peatland fire behaviour. Because this research indicates that groundwater connectivity is a dominant control on soil carbon combustion, it is therefore suggested that a hydrogeological setting 'template' be used to identify deep burning 'hotspots' on the landscape a priori, so as to increase the efficacy of wildfire mitigation strategies by reducing response times and better allocating resources to reduce wildfire "mop up" costs.