# PEATLAND CARBON ACCUMULATION FOLLOWING WILDFIRE

# PEATLAND CARBON ACCUMULATION FOLLOWING WILDFIRE ON THE BOREAL PLAINS: IMPLICATIONS FOR PEATLAND RECLAMATION AND WILDFIRE MANAGEMENT

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TITLE: Peatland Carbon Accumulation Following Wildfire on the Boreal Plains: Implications for Peatland Reclamation and Wildfire Management

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## Abstract

Peatlands in the sub-humid Boreal Plains of Alberta exist at the limit of their climatic tolerance and are vulnerable to wildfire. This is especially true at the interface between the peatland and forestland (margins) due to water table fluctuation resulting in high peat bulk density and low moisture content during dry periods in some peatland systems. Deep burning at the margins may reduce a peatland's ability to recover to its previous state, leading to a reduction in area and/or collapse following fire, and bringing into question the long-term stability of Boreal Plains peatlands on the landscape under current and future climate predictions. Previous research has identified small peatlands located at a mid-topographic position on coarse sediments as hotspots for deep burning, as these peatlands are not regularly connected to regional groundwater flow. The ability of these peatland systems to recover lost carbon from both the interior and margin within the fire return interval, however, has not yet been investigated. This thesis further examines the relationship between surficial sediment assemblages and the impact of wildfire on overlying peatlands through assessment of organic soil carbon accumulation following wildfire across the Boreal Plains landscape. Peatland organic soil recovery along a chronosequence was assessed in the interior and margin of 26 ombrotrophic bogs located at various positions on the post-glaciation landscape of Northern Alberta using estimates of organic soil carbon accumulation calculated through loss on ignition of peat above the uppermost charcoal layer in peat cores from each site, as well as characterization of peat properties along a transect from the adjacent forestland into the peatland interior. Soil organic carbon accumulation with time since fire was greater in studied peatland interiors than margins. Underlying sediments were found to have little effect on total soil organic carbon accumulation in the interior and margins of the studied peatlands, indicating that organic soil carbon accumulation rates following wildfire estimated in this study can be extended to ombrotrophic bogs across the Boreal Plains landscape. Though total soil organic carbon accumulation following wildfire does not appear to be influenced by hydrogeological setting, the ability of a peatland to recover the quantity of carbon lost within the fire return interval will be dependent on the amount of carbon which was released through smouldering, which is influenced by hydrogeological setting for peatland margins. Based on published measurements of organic soil carbon loss during wildfire and organic soil carbon accumulation rates estimated in this thesis, peatlands located at topographic lows on coarse grained glaciofluvial outwash sediments or on low-relief, fine grained sediment deposits from glaciolacustrine or subglacial paleoenvironments are predicted to be resilient to wildfire on the Boreal Plains landscape. Peatlands which experience severe smouldering at the margins, such as ephemerally perched systems on glaciofluvial outwash sediments, will likely undergo permanent loss of legacy carbon stores. The resilience of peatlands which are perched above regional groundwater on glaciofluvial outwash or stagnant ice moraine deposits is unknown at this time; further investigation into water table dynamics, margin peat properties, and smouldering depths in these systems is required. Identification of peatland systems which are at risk of permanent carbon loss at the margins and those which are most resilient to wildfire in this thesis can be applied to wildfire management strategies and the design of peatland systems for reclamation of oil sands leases. The stability of natural and created peatlands through time on a landscape where wildfire is frequent is an important consideration in terms of both lasting ecosystem services and the potential risk to fire suppression and community safety that vulnerable systems pose.

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## Table of Contents

## List of Figures

## List of Tables

## List of Appendices

## List of Abbreviations

ANCOVA – Analysis of Covariance

BP – Before Present

CFS – Canadian Forest Service

HRA – Hydrological Response Area

LIS – Laurentide Ice Sheet

NECB – Net Ecosystem Carbon Balance

$NEP_U$ – Net Ecosystem Production of the Understory

URSA – Utikuma Region Study Area

WTD – Water Table Depth

## Declaration of Academic Achievement

The written material presented in this thesis has been prepared solely by this author. The collection of data included herein was collaborative in nature, with the contributions of this author including site selection and below-ground organic soil and sediment data collection and analysis. Considerable candidate site selection effort was provided by Craig Allison and Kristyn Housman. Significant field and lab data collection assistance was provided by Sophie Wilkinson, Cameron McCann, Kristyn Housman, Sam Stead, and Kelly Biagi. Dr. Paul Moore provided critical advice regarding statistical analyses used herein. Complimentary above-ground vegetation survey information and characterization of site age at each study site has been analyzed separately by Kristyn Housman.

# 1. Introduction

## 1.1 Boreal Plains Peatlands

Peatlands, defined as ecosystems with a minimum depth of 0.40 m of partially decomposed soil organic matter (Warner and Rubec, 1997), are globally important systems for carbon storage. In fact, peatlands store approximately 25% of the total organic soil carbon pool on Earth (Turetsky *et al.*, 2015; Yu, 2012). In Canada, a number of these systems exist in the Boreal Plains ecozone which extends across Alberta, Saskatchewan, and Manitoba, covering approximately 21% of the land surface and storing 2.1% of the world's terrestrial carbon (Turetsky *et al.*, 2002). In addition to their influential role in carbon storage, peatlands on the Boreal Plains landscape are essential for water storage and supply to surrounding forests through water uptake by forest vegetation root systems during dry periods and runoff from the peatland during wet times (Devito *et al.*, 2012). Because peatlands have smaller total water storage capacities than the surrounding forests, they are able to more quickly generate excess water during wet seasons (Devito *et al.*, 2012). All together, the mosaic of peatlands, ponds, and upland forests across the Boreal Plains landscape functions as one of the most important waterbird habitats in North America (Ducks Unlimited Canada, 2000).

During the last glacial maximum (approximately 18 000 years before present (BP)), Alberta, Saskatchewan, and Manitoba were covered by the Laurentide Ice

Sheet (Jackson *et al.*, 2011; Dyke, 2004). Glaciation of the area, along with deglaciation and all of the associated subglacial; supraglacial; glaciolacustrine; and glaciofluvial processes, led to the deposition of a complex array of thick heterogeneous sediments upon which current ecosystems on the landscape exist (Atkinson, 2009; Balzer *et al.*, 1995; Henderson, 1959; Pawley and Atkinson, 2012). Carbon dating of the basal peat in several peatlands in west-central Canada has revealed that peatlands initially developed in the Boreal Plains as early as ~ 7 900 yr BP (Kuhry *et al.*, 1993), in a climate which was both more moist and cooler than today (Halsey *et al.*, 1998).

The current climate in the Boreal Plains is characterized by a long-term water deficit, with lower annual precipitation than potential evapotranspiration (481 mm: 517 mm respectively; Smerdon *et al.*, 2005) except for the rare wet period in the climate cycle where annual precipitation exceeds potential evapotranspiration; this occurs approximately once every 10-15 years (Smerdon *et al.*, 2005; Devito *et al.*, 2012). Annually, the area experiences wet and dry seasons, with 50 to 60% of the annual precipitation falling between June and August, followed by a dry autumn season and on average less than 100 mm of snow during the winter (Ferone and Devito, 2004). Average temperatures for summer and winter are 15.6 and -14.5 °C respectively (Ferone and Devito, 2004). Based on these moisture and temperature conditions and the thermal seasonal aridity index discussed by Halsey *et al.* (1998), it is unlikely that peatlands would naturally develop on the Boreal Plains of Canada in today's sub-humid climate.

Wildfire is the largest disturbance to peatland ecosystems on the Boreal Plains landscape (Turetsky *et al.*, 2002), bringing into question the long-term stability of these peatlands under a changing climate. Wildfire affects approximately 1 470 ± 59 $km^2$ peatland area annually and results in the release of large quantities of stored organic soil carbon into the atmosphere (about 4 704 ± 618 Gg C $yr^{-1}$ from peatlands; Turetsky *et al.*, 2002). Peat burns predominantly through the process of smouldering, which is flameless, slow, low-temperature burning (Rein, 2013). Smouldering of the organic soil in peatlands can occur even under low temperature, high moisture, and low oxygen conditions (Turetsky *et al.*, 2015), and can continue for an extended period of time following ignition, propagating deep into the peat profile (Rein, 2013). Hydrological feedbacks within peatland systems generally work to minimize smouldering risk through the maintenance of steady water tables and saturated conditions within the peatland (Waddington, *et al.*, 2015); drying of these systems leads to increased risk of smouldering combustion advancing deep into the peat profile and releasing long-term stored carbon (Turetsky *et al.*, 2015). Consequently, the increase in frequency and severity of droughts under climate change predictions is expected to lead to increased release of stored peatland carbon as additional peat from within the profile will be available for smouldering combustion due to lowered water tables

(Flannigan *et al.*, 2005; Turetsky *et al.*, 2004; Grosse *et al.*, 2011; Page *et al.*, 2011; Turetsky *et al.*, 2011; Turetsky *et al.*, 2015). In fact, wildfires in the North American Boreal Plains have already increased in size and severity over the second half of the last century (Kasischke and Turetsky, 2006) and are expected to continue to do so as the frequency and intensity of drought increases under climate change scenarios (Flannigan *et al.*, 2005; Turetsky *et al.*, 2004; Turetsky *et al.*, 2015). The frequent and widespread occurrence of wildfire coupled with sub-humid climate conditions in the Boreal Plains generates the question of whether peatlands in this area are able to fully recover their carbon loss within the fire return interval, or if they will switch from carbon neutral or storing systems to sources of carbon to the atmosphere. This question is significant both in terms of fire management strategies and the design of self-sustaining, carbon storing peatland systems for reclamation of oil sands mining leases.

## 1.2 Peatland Organic Soil Carbon Accumulation

### *1.2.1 Long-term peatland carbon accumulation rates*

Several studies have endeavored to measure the long-term rate of carbon accumulation in northern peatlands over the course of the Holocene. Mean weighted carbon accumulation rates from this time vary depending on the method of calculation. For example, apparent carbon accumulation rates calculated using the age of basal peat and total amount of carbon accumulated in peat cores (*e.g.* discussed in Loisel *et al.*, 2014; Yu *et al.*, 2009; Yu, 2011) are higher estimates than those based on average peat depth, bulk density (BD), and carbon content (*e.g.* Clymo, 1984; Gorham *et al.*, 2012), but underestimate total carbon uptake of peatland systems due to a loss of stored carbon by decomposition, wildfire, or other disturbances (Yu, 2012). Back-calculation of the net carbon balance (NCB) of peatlands using apparent carbon accumulation rates from the Holocene and a decay model which accounts for carbon loss through peat decomposition has been proposed as a new method of discussing the role of peatlands in the global carbon cycle (Yu, 2011, 2012). Each method of calculation has inherent uncertainties associated with it (Yu, 2012), but can still offer valuable insight into peatland carbon dynamics during the Holocene. Carbon accumulation rates varied annually, however have been estimated at a mean of 17.2 g C $m^{-2}$ $yr^{-1}$ (based on average peat depth, BD, and carbon content; Gorham *et al.*, 2012), 19 g C $m^{-2}$ $yr^{-1}$ (NCB; Yu, 2012), and 23 g C $m^{-2}$ $yr^{-1}$ for northern peatlands (peat cores; Loisel *et al.*, 2016) over the Holocene, with an apparent carbon accumulation rate specifically for peatlands located in western Canada reported at 20.3 g C $m^{-2}$ $yr^{-1}$ (peat cores; Yu *et al.*, 2009). There is a general agreement that the Holocene carbon accumulation rate was greatest during the early Holocene (Loisel *et al.*, 2016; Yu, 2012) due to the effect of warmer than current temperatures (Loisel *et al.*, 2016; Yu *et al.*, 2009, 2010) or the botanical origin of early successional peat (Loisel *et al.*, 2016). Maximum estimated rates are 25–28 g C $m^{-2}$ $yr^{-1}$ at 9 000 – 11 000 yr BP (apparent carbon accumulation via peat cores; Loisel *et al.*, 2016) and 38 g C $m^{-2}$ $yr^{-1}$ at 8 000 – 9 000 yr BP (NCB; Yu, 2012). A cooler climate during the late Holocene (Neoglacial cooling) coincided with the minimum estimated carbon accumulation rates of 18 – 19 g C m$^{-2}$ yr$^{-1}$ between 1 500 – 3 000 yr BP (apparent carbon accumulation via peat cores; Loisel *et al.*, 2014, 2016) and 5.6 g C m$^{-2}$ yr$^{-1}$ between 2 000 – 3 000 yr BP (NCB; Yu, 2012).

### *1.2.2 Recent peatland carbon accumulation rates*

The low rates of carbon accumulation over the past millennia have since increased to contemporary carbon accumulation rates of approximately 20 – 30 g C m$^{-2}$ yr$^{-1}$ (mean NCB of 25 ± 31 g C m$^{-2}$ yr$^{-1}$; Yu *et al.*, 2011). For peatlands in western Canada, a mean rate of 19.4 g C m$^{-2}$ yr$^{-1}$ over the past 1 000 years is reported by Vitt *et al.* (2000). Recent rates of carbon accumulation, based on near-surface peat accumulation over the past 150 years, have also been reported at 40 – 117 g C m$^{-2}$ yr$^{-1}$ for ombrotrophic peatlands in eastern Canada (Turunen *et al.*, 2004); and at 100 – 111 g C m$^{-2}$ yr$^{-1}$ for northern continental bogs in western Canada over the preceding 100 years (Turetsky *et al.*, 2000). Estimates of carbon accumulation from young, near-surface peat are considerably greater than those made using older peat columns, as net carbon accumulation rate decreases over time due to the slow decay of deep, anoxic peat layers (Turunen *et al.*, 2004; Tolonen and Turunen, 1996). As peatlands in western Canada are highly impacted by wildfire, it is of interest whether their function as carbon stores during the Holocene is at risk under current and changing climate (Wieder *et al.*, 2009; Frolking *et al.*, 2011), with net peatland carbon balance on a landscape scale being most sensitive to fire frequency and intensity changes (Frolking *et al.*, 2011). In response to this question, Wieder *et al.* (2009) estimated post-fire carbon dynamics at 10 bogs in western Canada along a chronosequence (which the current study expands upon), through combined measurement of net ecosystem production of the understory ($NEP_U$) and black spruce biomass accumulation. As several pathways of carbon loss affecting peatlands in the short- and long-term are not able to be accounted for under the methods used (*e.g.* methane and dissolved organic carbon losses, peat decomposition), reported rates of $NEP_U$ by Wieder *et al.* (2009) likely overestimate carbon accumulation rate (although emissions of methane from bogs on this landscape are quite low and are expected to be only a minor component of carbon flux (Wieder *et al.*, 2009)). Indeed, rates ranging from 84 – 152 g C $m^{-2}$ $yr^{-1}$ (Wieder *et al.*, 2009), are much higher than estimated contemporary carbon accumulation rates reported by some authors (*e.g.* Yu *et al.*, 2011; Vitt *et al.*, 2000), but are only slightly greater than recent carbon accumulation rates reported by Turetsky *et al.* (2004) for bogs on the same landscape.

Limitations to the use of $NEP_U$ as a means to estimate carbon accumulation do exist. In an investigation of the change in the organic carbon stock of a midcontinental northern bog in eastern Canada over a six year period, Roulet *et al.* (2007) caution that carbon loss and gain due to methane and dissolved organic carbon movement also need to be accounted for in addition to $NEP_U$ to gain a complete net ecosystem carbon balance (NECB) if carbon accumulation rates are to be compared with long-term estimates. While the calculation of contemporary NECB as conducted by Roulet *et al.* (2007) can provide values of carbon accumulation rate which are similar to estimates of both long-term and contemporary carbon accumulation rates calculated from peat cores, a large degree of inter-annual variation is present in this calculation (Roulet *et al.*, 2007). In addition, fundamental differences between these two carbon stock estimate methods (measuring NECB or measuring carbon accumulation in peat cores) exist which can cause divergence in estimates made across short time intervals (Frolking *et al.*, 2014). For example, the large loss of carbon from decomposition of near-surface peat can play into estimates of apparent carbon accumulation but may be missed by calculations of NECB; conversely, release of carbon from the decomposition of deep peat is captured in NECB but not in apparent carbon accumulation rate (Frolking *et al.*, 2014). Despite these limitations, estimates of $NEP_U$ by Wieder *et al.* (2009) may still be valuable in assessing post-fire carbon recovery, and offer a first-estimate of carbon accumulation following wildfire in western Canada to which results of this thesis can be compared.

## 1.3 Peatland Margins and Margin Hydrology

### *1.3.1 Margin burn severity*

The interface between peatland and adjacent forestland, henceforth referred to as the peatland margin, has been observed to be especially vulnerable to smouldering in some peatland systems. Typical peatland smouldering depths in the Boreal Plains range from 0.05 to 0.10 m (Benscoter *et al.*, 2011). Some peatland margins, however, have been observed to exhibit much higher burn depths (0.42 ± 0.02 m on average; Lukenbach *et al.*, 2015b). In the system where these severe depths of burn were observed, the interior of the peatland experienced typical smouldering depths resulting in a depth of burn at the margins which was five times greater than in the interior (Lukenbach *et al.*, 2015b), and accounted for up to 90% of the carbon released from the peatland (Hokanson *et al.*, 2016). In this peatland, margin vulnerability is expected to have been caused due to a fluctuating water table which led to the formation of high density, dry peat at the margins (Lukenbach *et al.*, 2015b).

### *1.3.2 Margin hydrology*

While margin hydrology appears to be linked to burn severity, very little research currently exists regarding the hydrology of peatland margins in the Boreal Plains of Canada. Some studies have investigated margin hydrology in peatland systems located in a humid climate, however comparison with the limited studies which have investigated this topic in the sub-humid climate of the Boreal Plains suggest that there are both similarities and significant differences in margin hydrology between these climates (Bhatti *et al.*, 2006; Paradis *et al.*, 2015; Langlois *et al.*, 2015; Lukenbach *et al.*, 2015b).

Peatland margins in both humid and sub-humid climates have thinner, more dense peat accumulations than the interior of the peatlands (Baird *et al.*, 2008; Bhatti *et al.*, 2006; Ferone and Devito, 2004; Paradis *et al.*, 2015). In humid climates, saturated hydraulic conductivity within the margin decreases rapidly with depth and is significantly lower than in the peatland interior, resulting in a low conductivity layer of peat that is believed to limit lateral water loss from a raised bog and allow the bog to grow higher than would otherwise be possible (Baird *et al.*, 2008; Howie and Tromp-van Meerveld, 2011). As peat within sub-humid margins has also been noted to be denser than in the interior of the peatland (Hokanson *et al.*, 2016), and increased peat density means smaller pores sizes and lower saturated hydraulic conductivity (Boelter, 1969; Ingram, 1978), sub-humid margins may also limit water loss from the peatland interior. Water table depth (WTD) in the margin compared to the interior of the peatland, on the other hand, may show differing trends for humid versus sub-humid climates. Margins in both areas experience large water table fluctuations (Paradis *et al.*, 2015; Lukenbach, 2015b); however, deeper water tables were recorded at margins in the Boreal Plains when compared to the peatland interior (Bhatti *et al.*, 2006), whereas the shallowest water tables were observed at the margins of bogs in a humid climate, frequently resulting in ponded water (Langlois *et al.*, 2015). In the Boreal Plains, peatland margins are less likely to experience long-term shallow water tables as observed at the margins in a humid climate (termed laggs) due to the annual water deficit which is experienced most years. Furthermore, aspens which are located next to peatlands are able to draw water out of the wetland and redistribute it to the aspens located further from the peatland through extensive root networks (Petrone *et al.*, 2007; Devito *et al.*, 2012). This connection of aspens to peatland margins as a water source is essential for the aspen stands to survive natural disturbances and climate cycles in the Boreal Plains landscape, but for the peatlands acts as a water loss which could result in water table drawdown at the margins.

The degree of connection that a peatland experiences to regional groundwater systems and to local groundwater from adjacent peatlands is also important for margin hydrology as it has been found to influence the amount of water table fluctuation experienced at peatland margins (Hokanson *et al.*, 2016; Lukenbach *et al.*, 2015a, 2017). In the Boreal Plains, observations of peatlands situated on different sediments and at different topographic positions, and as a result experiencing varying groundwater connection, showed that a peatland with an ephemeral regional groundwater connection experienced large water table fluctuations at the margins (Hokanson *et al.*, 2016; Lukenbach *et al.*, 2015b); this led to high peat bulk densities through subsidence and increased decomposition at the margin, as well as low moisture conditions during dry periods (Lukenbach *et al.*, 2015b). Though they were not specifically investigated during the study, systems which are continually perched above regional groundwater and receive water primarily from precipitation are likewise expected to be susceptible to drying during drought conditions (Hokanson *et al.*, 2016), and thus may experience large water table drawdowns at the margins (Ferone and Devito, 2004; Redding and Devito, 2010; James *et al.*, 2017). In contrast, a peatland with continual regional groundwater flow-through experienced limited water table fluctuation at the margins (Hokanson *et al.*, 2016; Lukenbach *et al.*, 2017).

### *1.3.3 Post-fire margin recovery*

The sediment that a peatland is located on also plays an important role in determining margin hydraulics following wildfire (Lukenbach *et al.*, 2015b): if the dense margin peat responsible for limiting lateral water loss from a peatland is lost during wildfire, the level of water table drawdown that the entire peatland experiences as a result is dependent on the permeability of the underlying sediment (Lukenbach *et al.*, 2015b), as a coarse grained sediment would allow for high water loss while a fine grained sediment may function similarly to the dense marginal peat which was lost. In the aforementioned observed ephemerally connected system, steep water table declines at the margins were experienced during periods of drought following wildfire (Lukenbach *et al.*, 2016). Coupled with the migration of solute rich groundwater from adjacent uplands during wet periods, these steep water table declines at the margins led to low moss recolonization (Lukenbach *et al.*, 2015a, 2016). Rather, upland vegetation was observed to colonize the margins of the ephemerally connected system (Lukenbach *et al.*, 2016, 2017), indicating that peatland margins of such systems may not recover to their previous state following deep smouldering. In contrast, the groundwater flow-through system which was observed at the same time experienced low burn severity during wildfire and a high level of bryophyte recovery following fire due to excellent water availability (Lukenbach *et al.*, 2015a, 2015b, 2016, 2017). Recovery in peatlands completely perched above regional groundwater was not assessed following fire, however these systems are expected to experience intermediate vulnerability to deep burning (Hokanson *et al.*, submitted) and require further investigation. As margin hydrology has been linked to both burn severity and recovery following wildfire, additional research on margin hydrology and the influence of hydrogeological setting in the Boreal Plains is necessary to identify peatland systems which may be at risk of becoming carbon sources under a changing climate.

### 1.4 Glacial Sedimentology and Peatland Hydrogeological Setting

The hydrogeological setting in which a peatland is located, and therefore its degree of connection to regional groundwater; connectivity to adjacent peatland and forestland systems; and level of water table fluctuation at the margins, is dependent on the sediments on which the peatland formed; its topographic position; and morphology of the landscape. This, in turn, is linked to the paleoenvironment in which the sediments were deposited. On the Boreal Plains of Alberta, thick, heterogeneous surficial sediments with complex hydrological and hydrogeological functions exist as a remnant of past glaciations. While areas of the province have been affected by multiple glaciations (Jackson *et al.*, 2011; Barendregt and Duk-Rodkin, 2004), the most extensive and most recent glaciation occurred during the Late Wisconsin (Jackson *et al.*, 2011). At the time of the Last Glacial Maximum (approximately 18 000 years BP), ice cover across North America was continuous, with the continental Laurentide Ice Sheet (LIS) extending across the province of Alberta and abutting montane Cordilleran ice along the Rocky Mountain foothills in Alberta and along the eastern margin of the Mackenzie Mountains in the Northwest Territories (Barendregt and Duk-Rodkin, 2004). Sediment which had been entrained and transported within the glacial ice, picked up from pre-existing unconsolidated sediment deposits, or eroded from the soft bedrock in the area, was deposited in a range of environments during glaciation and subsequent deglaciation. Deposition in a variety of environments led to a range of sediment textures, sorting, and topography on the Albertan landscape. In turn, various types and sizes of wetlands have developed on the landscape, with a range of regional groundwater connection and hydrologic connectivities. Of particular interest on the Boreal Plains are sediment assemblages and landscape geomorphology resulting from glaciolacustrine and glacial outwash paleoenvironments, as well as from deglaciation via stagnating ice conditions.

### *1.4.1. Glaciolacustrine paleoenvironments*

During the Late Wisconsin, the advance of the LIS west and southwest across Alberta was in opposition to the regional slope of the Interior Plains of Alberta, as well as that of the Rocky Mountain foothills (Jackson *et al.*, 2011). This caused blockage of trunk stream systems draining runoff from the west and led to the formation of extensive lake systems bounded by glacial ice to the east (Jackson *et al.*, 2011). Likewise, during deglaciation expansive ice-dammed lakes were formed along the retreating edge of the LIS as it withdrew eastward (Mathews, 1980; Lemmen *et al.*, 1994). One of these lakes was Glacial Lake Peace, which formed in the Peace River Valley of central Alberta from the accumulation of Laurentide and Cordilleran meltwater. Deglaciation of the Great Slave Basin after 10 500 years BP caused Lakes McConnell and Mackenzie to join with Lake Peace, forming the second largest Pleistocene lake in North America (Mackenzie Phase of Lake McConnel; Lemmen *et al.*, 1994). On the current day landscape, remnants of these past glacial lakes include thick deposits of silt- and clay-rich sediments, as well as large basins with minimal topography change across their extent (Balzer *et al.*, 1995). In the area south of Lesser Slave Lake, as well as in the Peace River-Winagami area, glaciolacustrine deposits consist of massive to thickly laminated silty clay and fine sandy silt with occasional dropstones (Pawley and Atkinson, 2012; Balzer *et al.*, 1995). Occasional fine- to medium grained, well-sorted sands and pebbly sands or cobbly, wave-washed veneer deposits record former lacustrine shorelines in the area (Pawley and Atkinson, 2012).

Relief of the glaciolacustrine deposits tends to be less than two meters, but may reach five meters in places (Balzer *et al.*, 1995). The landscape ranges from being predominantly flat with occasional ridges and flutes, to containing hummocks comprised of massive to laminated silts, clays, and fine sand formed by the melting of ice blocks buried by glaciolacustrine sediments (Balzer *et al.*, 1995).

Within expansive glaciolacustrine basins, limited drainage and persistent wet conditions have led to the formation of vast peat deposits (Atkinson, 2009; Balzer *et al.*, 1995; Henderson, 1959; Pawley and Atkinson, 2012; Devito *et al.*, 2012). These peatlands are large in size, with limited regional groundwater connectivity, but strong near-surface local groundwater flow systems and high connectivity among peatland systems (Devito *et al.*, 2012; Ferone and Devito, 2004). Here, the dominant source of water is from other connected wetlands, and a high amount of runoff from the wetland systems occurs on the landscape during wet periods (Devito *et al.*, 2012).

### *1.4.2 Stagnant ice moraine landforms*

Deglaciation in the western interior of North America is believed to have been characterized by significant thinning of the LIS, followed by ice stagnation (Mandryk, 1996). As deglaciation of the LIS occurred along its western edge, heterogeneity in the amount of sediment incorporated within and on top of different areas of glacier ice would have resulted in varying amounts of insulation and therefore differential melting rates of the ice sheet (Kjaer and Kruger, 2001; Benn and Evans, 2010). As parts of the ice sheet melted more quickly than others, areas of ice which were more insulated would have formed individual ice blocks which remained buried by sediment on the landscape for an extended period of time (Mandryk, 1996). This mode of deglaciation created large areas of undulating terrain on the Canadian Prairies and Boreal Plains of Alberta landscape referred to as 'stagnant ice moraine' (also called hummocky moraine, dead-ice moraine, ablation moraine, and disintegration moraine; Eyles *et al.*, 1999). This landscape feature is characterized by rolling topography which contains round to oval shaped forms including closely spaced mounds separated by depressions which may be ring shaped, mounds or raised rims which contain a circular depression in the center (forming a doughnut-like shape), and rims circling central plateaus formed by the infilling of depressions with lacustrine sediment (Gravenor, 1955; Eyles *et al.*, 1999; Mollard, 2000; Boone and Eyles, 2001). Anastamosed linear ridges may also be present within stagnant ice moraine. The size of the mounds and rims within stagnant ice moraine are highly variable (Gravenor, 1955; Eyles *et al.*, 1999; Mollard, 2000), with heights ranging from one to two meters in rolling terrain to up to 25 meters in high relief areas (Eyles *et al.*, 1999).

Multiple processes for the formation of stagnant ice moraine have been proposed, each with implications for the hydrology, hydrogeology, and long-term maintenance of the accompanying peatlands. The leading formation theories involve either reworking and redeposition of supraglacial and englacial sediments, or the redistribution of wet subglacial tills from high pressure to lower pressure areas at the base of the ice sheet (Gravenor and Kupsch, 1959; Eyles *et al.*, 1999; Mollard, 2000; Boone and Eyles, 2001; Kjaer and Kruger, 2001; Clayton *et al.*, 2008; Benn and Evans, 2010). Stagnant ice moraine formed via deposition of supraglacial and englacial sediments has been described as commonly non-compact, loose, and non-fissile with high proportions of gravels and stones present, and occurrences of crudely sorted sediments due to an abundance of meltwater present during deposition (Gravenor and Kupsch, 1959). Conversely, sediment within interpreted subglacially formed stagnant ice moraine includes fine grained till which can be quite compact (Stalker, 1960; Eyles *et al.*, 1999). While highly heterogeneous, supraglacially formed stagnant ice moraine may provide more opportunity for rainwater infiltration, groundwater recharge, and regional groundwater connection than moraine formed subglacially. It is likely that the stagnant ice moraine formed at the western margin of the LIS did not form via only one of the possible proposed methods; rather, it is probable that these landforms in western Canada are polygenetic in origin (Mollard, 2000), leading to further heterogeneity in stagnant ice moraine sediment deposits and hydrogeology.

Small peatlands are commonly found within local topographic depressions on stagnant ice moraine, while upland areas are dominated by forestland (Devito *et al.*, 2012). Sediment texture is dominated by fine grains with low hydraulic conductivity, resulting in limited lateral movement of water and thus minimal connection of peatlands to regional groundwater systems (Devito *et al.*, 2012; Ferone and Devito, 2004). Connectivity between peatland systems is controlled mainly by local topography on this fine-textured landform (Devito *et al.*, 2012); due to the highly variable relief, wetlands tend to be small and isolated. Water movement is dominated by flow from wetlands to forestland, and forestland dominates the water balance with a net moisture deficit, large soil storage, and groundwater recharge (Devito *et al.*, 2012).

### *1.4.3 Glaciofluvial deposits*

Advance and subsequent retreat of ice sheets in western North America did not only lead to the deposition of sediments subglacially, in glaciolacustrine basins, and in stagnant ice moraine; rather, drainage of meltwater from glacial ice led to the formation of fluvial deposits on the landscape as well (Atkinson, 2009; Balzer *et al.*, 1995; Henderson, 1959; Pawley and Atkinson, 2012; Devito *et al.*, 2012). Sediment deposits formed in braided streams, ice-walled channels, outwash plains, and deltas can be found across Alberta; among these deposits, sediment grain size and sorting are variable due to changing water velocity and sediment sources, however deposits tend to be more coarse than the average grain size found within glaciolacustrine and stagnant ice moraine landforms (Pawley and Atkinson, 2012; Williams and Rust, 1969; Anderson, 1989; Miall, 1977, 2014; Gustavson and Boothroyd, 1987). In the southern Lesser Slave Lake area, glaciofluvial deposits consist of moderate- to well-sorted sand and gravel deposited as bars in paleochannels; horizontal- and cross-bedded coarse grained pebbly sand with boulder to cobble lags formed in outwash plains and glaciofluvial deltas; as well as matrix-supported sandy gravel sheets separated by silty sand beds forming irregular hills and hummocks with 5 to 10 meter relief (kames; Pawley and Atkinson, 2012). Eskers are also present on the landscape, consisting of ridges of sand and gravel which extend across outwash plains and stagnant ice moraine for up to two kilometers. Outwash deposits in this area are typified by abundant kettle holes produced by the melting of ice blocks buried by glaciofluvial sediments, and can be associated with stagnant ice moraine (Pawley and Atkinson, 2012).

In glaciofluvial outwash areas, coarse-textured sediment deposits with high hydraulic conductivity coupled with high evapotranspirative demand of forest vegetation lead to regional water tables which do not mimic surface topography (Smerdon *et al.*, 2005; Ferone and Devito, 2004; Devito *et al.*, 2005; Devito *et al.*, 2012; Hokanson *et al.*, 2016). The level of regional groundwater connectivity of an individual peatland is highly dependent on its topographic position on the coarse-textured landscape and its resultant ability to intersect the regional groundwater table (Siegel, 1988; Riddell, 2008; Hokanson *et al.*, 2016; Lukenbach *et al.*, 2017). Peatlands located in regional topographic highs tend to be small and isolated from regional groundwater flow and from other wetland systems (Devito *et al.*, 2012). Conversely, in regional topographic lows, groundwater discharge leads to the formation of peatlands which are connected to large-scale regional groundwater flow and are also connected to adjacent wetland systems, often forming a network of continuous expansive wetlands. Peatlands in low topographic positions may also receive excess water which has spilled from wetlands perched above on topographic highs (Devito *et al.*, 2012).

## 1.5 Thesis Objectives

The primary objective of this thesis is to investigate whether peatlands on the Boreal Plains of Canada are able to fully recover carbon lost due to wildfire within the fire return interval, or if they will switch from carbon neutral or storing systems to sources of carbon to the atmosphere following wildfire. This objective was addressed using field and lab observations of peat characteristics above and below charcoal formed during previous wildfire events at each of 26 peatlands located on sediment assemblages deposited in the three main glacial paleoenvironments on the Boreal Plains. This allowed for:

a) Assessment of organic soil carbon accumulation following the most recent wildfire along a chronosequence (space for time comparison) in both the peatland interior and margin of peatland systems. Moreover, this allowed for an assessment of vertical peatland organic soil carbon accumulation in the peatland interior (to assess whether peatlands are shrinking in depth), as well as horizontal recovery through comparison of peatland interior and margin organic soil carbon accumulation (to assess whether peatlands are shrinking in expanse) in the context of time since fire.

b) Assessment of peatland interior and margin organic soil carbon accumulation in different hydrogeological settings based on the surrounding sedimentology and interpreted depositional glacial paleoenvironments, informed by observations from long-term groundwater monitoring at various peatlands across the Boreal Plains landscape at the Utikuma Region Study Area.

## 2. Methodology

### 2.1 Study Site Selection and Categorization

#### *2.1.1 Potential study site identification*

In the winter and spring of 2016, numerous peatlands on the Boreal Plains landscape in Alberta which had been affected by wildfire within the last 115 years were identified. This was undertaken in order to utilize a chronosequence approach to study peatland recovery following wildfire in this natural setting. Within a chronosequence study design, a space for time substitution is undertaken in which multiple sites at different stages in development are used to investigate temporal change in a site characteristic of interest (*e.g.* Benscoter and Vitt, 2008;

Wieder *et al.*, 2009). Within this study, special consideration was made to identify the glacial sediments underlying the peatland sites, as this information could be combined with observations of local and regional hydrology of pond-wetland-forestland complexes located on various glacial landforms in the Boreal Plains of Alberta from the long-term hydrogeological research program in the Utikuma Region Study Area (URSA; Devito *et al.*, 2012, 2017) to provide information on potential hydrogeological setting of the chosen study sites. Potential peatland study sites were identified using a weighted overlay of classes within the Boreal Plains Wetland Classification System (Smith *et al.*, 2007), Alberta Geological Survey surficial geology data (Fenton *et al.*, 2013), and Canadian National Fire Database fire perimeter layers (Natural Resources Canada, 2017) in ArcGIS Desktop 10.3.1® (ESRI, Redlands, CA). During this process, preference was given to ombrotrophic bogs classified within the Boreal Plains Wetland Classification System. Potential sites were constrained to the Central Mixedwood and Lower Boreal Highlands Natural Subregions within the Boreal Forest Natural Region of Alberta (Natural Regions Committee, 2006). Once sites had been identified and isolated in ArcGIS, Alberta Environment and Parks air photos were utilized to further delineate peatland-forestland boundaries; confirm that peatlands within Canadian Forest Service (CFS) fire perimeters were burned (as surface and canopy fuels are not always evenly distributed and able to propagate surface and crown fire in Boreal bogs; Johnston *et al.*, 2015); to verify the date of burn; and to look for any evidence of peatland recovery, ecosystem collapse, and/or afforestation which may have occurred post-fire. As a result of this process, 312 potential study sites were identified as possibilities for detailed ground-truthing. Accessibility of the peatlands was also taken into account from a logistics and safety perspective, with the distance of the site from the nearest road considered. Potential sites were limited to within a 200 km road distance of either the junction of Bicentennial Highway 88 and Highway 750, or the town of Sandy Lake (Pelican Mountain), Alberta. Potential sites were ranked as more favourable based on: confinement of the peatland by surrounding hillslopes (with the goal being confinement on all sides), confirmation of burn in the air photo imagery, and accessibility.

Beginning in May of 2016, ground-truthing of the identified sites for potential analysis was undertaken. Site visits were conducted during which vegetation, evidence of previous wildfire, sedimentology, and degree of confinement were observed with the following goals: i) to identify if the site vegetation was indicative of an ombrotrophic bog, as this type of peatland was identified as experiencing severe burning at the margins during wildfire in some hydrogeological settings (Hokanson *et al.*, 2016; Lukenbach *et al.*, 2015b) and was therefore crucial to assess in terms of recovery following wildfire; ii) to ensure that the site was burned during the wildfire identified by the CFS fire perimeters, and, if possible, confirm that the fire also burned peat at the site and was not confined to the tree canopy; iii) to verify that the sedimentology observed from a hand-auger hole at the site aligned with that expected from the surficial geology map of the area; and iv) to identify sites which were as close as possible to being fully confined by hillslopes on all sides, as hydrological connection to other peatland sites could present an additional factor influencing the recovery rate of a peatland through alteration of water availability.

### *2.1.2 Site selection and categorization*

Following ground-truthing of potential peatland sites, a total of 26 sites were selected for more detailed field investigation (Figure 1). These sites were selected based on their relative age (time since fire) and sedimentology from the initial site visits and Alberta Geological Survey surficial geology data (Fenton *et al.*, 2013) in an effort to have an equal representation of all age categories and sedimentologies. Following data collection, the sedimentology and age categories were modified slightly based on field observations into the final categories used in analyses (Table 1).

Each of the 26 peatland study sites was given a paleoenvironmental classification (*e.g.* glaciolacustrine) based on the glacial environment in which the sediments were interpreted to have been deposited, as well as a textural and surficial landform descriptor (*e.g. Fine: Expansive*) used to infer the degree of hydrogeological connection of the site to regional groundwater sources (see Table 2).

Regional surficial geology classifications by the Alberta Geological Survey, represented on Map 601: Surficial Geology of Alberta (Fenton *et al.*, 2013), were used as a guideline for site paleoenvironmental classification, and were modified based on specific site observations. Observed sediment textures and assemblages in the upland and underlying the peat at each site were compared to published descriptions of sediment characteristics of glacial paleoenvironments present in Northern and Central Alberta (Atkinson, 2009; Balzer *et al.*, 1995; Benn and Evans, 2010; Henderson, 1959; Paulen and McClenaghan, 2015; Pawley and Atkinson, 2012; Nichols, 2009). Since multiple glacial paleoenvironments can lead to the deposition of similar sediment textures and assemblages, the variability in surface elevation around each site was determined using air photos and a digital elevation model constructed in ArcGIS Desktop 10.3.1® (ESRI, Redlands, CA) to further constrain the depositional environment of sediments found at the site. The main purpose of this exercise was to determine if each peatland site was situated in an area of hummocky topography (often indicative of stagnant ice moraine or glaciofluvial outwash paleoenvironments in this area of Alberta; Pawley and Atkinson, 2012), or if the surrounding area was characterized by low slope and lesser topographic variability (expansive glaciolacustrine or subglacial/till sheet paleoenvironments; Pawley and Atkinson, 2012). Graphs of the observed slope of the sediment surface running from adjacent upland hillslope into the peatland interior were also referred to as an indication of local elevation changes. Four main paleoenvironments were interpreted based on observed sedimentology: Stagnant Ice Moraine, Glaciofluvial outwash; Glaciolacustrine; and Subglacial Till Sheet. Additional details regarding the characteristics of the interpreted paleoenvironments can be found in Appendix A.

Site textural classifications were made based on saturated hydraulic conductivity values and textural classes for different soil types found in the literature (Freeze and Cherry, 1979; Fetter, 2000; Brady and Weil, 2008). Soil textures of coarse sand; sand; loamy sand; sandy loam; and fine sandy loam were defined as *coarse*, silt; silt loam; loam; and very fine sandy loam were defined as *somewhat coarse*, and clay loam; sandy clay loam; silty clay loam; sandy clay; silty clay; and clay were defined as *fine*. Four categories of overall sediment texture at each site were used: Mainly Fine; Coarse; Heterogeneous, predominantly fine; and Heterogeneous, predominantly coarse. Combination of the paleoenvironmental and textural classifications for each site resulted in five final site categories: *Coarse, Coarse: Heterogeneous, Moraine: Fine, Moraine: Heterogeneous,* and *Fine: Expansive* (Table 2), which can be further summarized into three categories of: *Fine: Expansive, Coarse,* and *Moraine*. Examples of observed sedimentology within each of the three summarized categories is shown in Figure 2. The five final site categories used in this thesis are similar to Hydrological Response Areas (HRAs) defined by Devito *et al.* (2012, 2017), which have characteristic grain size, permeability, water storage, and flow processes. Categories of *Fine:*

*Expansive* and *Moraine: Fine* in this thesis fit within the Fine textured HRA designation (Devito *et al.*, 2012), which has been further subdivided into clay-plain and hummocky moraine HRAs (Devito *et al.*, 2017). *Coarse* study sites in this thesis would be designated as Coarse textured HRAs. *Coarse: Heterogeneous* and *Moraine: Heterogeneous* labels used here may fit within a Veneer-type HRA classification (Devito *et al.*, 2012) or hummocky moraine HRA (Devito *et al.*, 2017), however sites within these categories were often observed to have complex sediment layering of inter-bedded fine and coarse grains which was not always distinctly coarse over fine or fine over coarse as described for the Veneer-type HRA (Devito *et al.*, 2012) and contain a quantity of coarse material which may be greater than designated for hummocky moraine HRA of Devito *et al.* (2017). Final sedimentological and paleoenvironmental classification categories used in this thesis may be referred to as HRAs in short based on the above description. Relation of the sedimentological categories used to classify sites within this thesis to the HRAs described by Devito *et al.* (2012, 2017) allowed for observations of typical levels of regional groundwater connectivity and local connectivity to other wetland systems within HRAs from long-term monitoring at URSA to be applied to sites in this thesis. Reference to hydrogeological setting of study sites in this thesis, therefore, is based off of long-term hydrogeological studies conducted at URSA; however, it should be noted that detailed hydrogeology has not been investigated at the peatland study sites analyzed here and it could be argued that reference to hydrogeological settings in this thesis as surficial sediment categories would be appropriate.

## 2.2 Detailed Site Investigation

Each final study site was revisited for detailed measurement during June – August 2016. At each site, a random compass direction generator was used to establish a transect from the interior of the peatland to the forested upland perpendicular to the peatland-upland interface (margin) boundary. In cases where a portion of the transect was unburned or unconfined, or where a human disturbance was present (cutline or path), a new random transect was established in an effort to capture typical site conditions along the transect.

### *2.2.1 Peat characteristics with depth*

At each of the selected study sites, hand-augering was conducted in the upland, margin, and interior to observe key peat properties with depth. For the majority of sites, this involved three upland, three margin, and three peatland interior locations along the transect. Botanical origin of the peat was observed as this property has been linked to peat porosity, bulk density, and therefore water transfer (Rycroft, 1975; Gnatowski *et al.*, 2010). Peat was mainly feathermoss or sphagnum in origin, however lichen was also observed. In cases where the botanical origin was unknown or the peat was too decomposed for identification, N/A was recorded. The level of decomposition of the peat was identified using the von Post scale of decomposition (von Post, 1922) where each von Post Index value represents a different level of decomposition of peat, ranging from completely undecomposed at von Post 1 through moderately decomposed at von Post 5 to completely decomposed at von Post 10. Any depths below ground surface where the botanical origin or peat decomposition changed were measured and recorded. Also observed were the depth at which charcoal and charred peat occurred and the thickness of these layers, as they are records of fire action in the past. The uppermost charcoal layer was assumed to have been formed during the most recent fire, the timing of which is known from the air photos and CFS fire perimeters (Natural Resources Canada, 2017) or was estimated from the oldest sampled tree.

Vertical peat cores were removed from the margin and a hollow within the peatland interior for use in evaluation of the organic soil carbon accumulation following wildfire at each site. Cores were collected by hand using 0.60 m long, 0.10 m diameter PVC tubing. Once 0.60 m of peat was reached or sediment was encountered, the core was removed (thus some of the cores - in the margin especially - collected less than 0.60 m of peat). Effort was made to minimize compression of the peat within the core as much as possible during collection. Following removal from the ground, peat cores were frozen and cut into 0.05 m (length) sections which were then air or oven dried at 65°C until no weight change was observed, equalling a minimum of 48 hours.

### *2.2.2 Sedimentology*

At each auger hole location, sediment characteristics were also observed to aid in the characterization of site hydrogeological setting (discussed previously in section 2.1.2). Depth to sediment was measured, and the type of sediment present was hand textured using the Guide to Texture by Feel provided by the Natural Resources Conservation Service (USDA, n.d.). Observations of sediment sorting, moisture, density, colouration, and structures such as laminations were also taken, as they may provide insight into past depositional environment and current hydrological conditions.

### *2.2.3 Hydrological measurements*

When possible, WTD was measured in the auger hole closest to the middle of the peatland margin and at the auger hole furthest into the peatland interior. This data was collected in an effort to gain information on the level of water table drawdown which may be present in the margin. Initially, measurements were intended to be taken in the upland as well; however, the water table was not accessible by hand augering in the upland at the majority of the sites. In order to relate WTD measurements within a site, ground surface microtopography was measured along the transect using a Smart Leveler® (Digital Leveling Systems, 2015). The average transect length was 30 – 40 m, with microtopography measurements taken every meter. Some sites had wide margins which necessitated increasing the transect length to approximately 70 m, in which case microtopography measurements were taken every two meters.

## 2.3 Post-Fire Organic Soil Carbon Accumulation

Peat cores removed from the margin and a hollow within the peatland interior of each study site were used to estimate the rate of organic soil carbon accumulation following the most recent wildfire. Accumulated organic soil carbon post-fire was calculated through the combination of peat bulk density, organic matter content, and charcoal location measurements as follows:

$$\text{Accumulated organic soil carbon } (\text{kg m}^{-2}) = 0.05\text{ m} \cdot 0.526 \cdot \sum_{i=1}^{n} [OM_i \cdot \rho_{bi}] + (h - 0.05n) \cdot OM_{n+1} \cdot \rho_{b\,n+1}$$

Where:

*h* = total depth of peat above the uppermost charcoal layer (m), which can be further divided into 0.05 m sections and a remaining section of peat < 0.05 m thick

*n* = number of full 0.05 m sections of peat above the uppermost charcoal layer

*n+1* = peat section less than 0.05 m thick above the uppermost charcoal layer

*0.526* = ratio between organic matter content and organic carbon content for high-latitude peat in western Canada (Bauer *et al.*, 2006)

$OM$ = calculated organic matter content of the peat section being considered (unitless)

$\rho_b$ = calculated bulk density of the peat section being considered (kg $m^{-3}$)

The bulk density of each 0.05 m section of core was calculated through division of the weight of the peat after oven drying by the volume of the section when wet. To increase accuracy, the measured dry weight and estimated wet volume of wood pieces present within the peat cores were subtracted prior to bulk density calculation. The location of the uppermost charcoal layer within each peat core was visually identified and peat depth above was measured; this charcoal layer was assumed to have been formed during the most recent wildfire. Organic matter content of the peat was determined through loss on ignition (LOI) of oven dried peat samples taken from above the uppermost charcoal layer and processed using methodology similar to that presented in Chambers, Beilman and Yu (2011), Bhatti and Bauer (2002), and Payne *et al.* (2015). Specifically, peat samples were burned at 550°C for 4 hours; the weight lost from each sample during this process was taken to be organic matter. Organic matter content was calculated through division of the weight lost during LOI by the original sample weight. Based on an estimated 52.6% of organic matter being organic carbon for high-latitude peat in western Canada (Bauer *et al.*, 2006), the organic carbon content of each peat sample was approximated and used to calculate the total amount of accumulated organic soil carbon following fire at each study site. The rate of accumulation was calculated by division of the total accumulated carbon by the time since the most recent fire. Sources of error in this methodology include unknown and likely variable burn severity within individual peatland sites (*e.g.* Benscoter and Wieder, 2003) and among sites, as well as the subjective nature of charcoal layer identification. This was especially true in cases where charcoal layers were indistinct and appeared non-continuous, or where diagonal charcoal layers ranging in depth were present.

### 2.4 Statistical Analyses

Values of total organic soil carbon accumulation, carbon accumulation rate, and accumulated peat depth following wildfire were assessed for statistically significant differences between hydrogeological categories and between locations within a peatland (margin or interior). In addition, total organic soil carbon accumulation values with time since fire calculated in this study were compared to values of Net Ecosystem Productivity of the understory ($NEP_U$) measured by Wieder *et al.* (2009) in an earlier chronosequence study investigating Boreal Plains’ peatland recovery following wildfire.

Statistical analyses were conducted using JMP 13 Statistical Software (© SAS Institute Inc.). All datasets were investigated for normality of distribution via visual analysis of boxplots and normal quantile-quantile plots, as well as with the Shapiro-Wilks test for normality. A 95% confidence interval was used for the

Shapiro-Wilks test, with values outside of this interval rejecting the null hypothesis that the data is from a normal distribution. Datasets tended to be non-normally distributed and were therefore rank transformed in order to achieve a distribution which was closer to normality and allow for parametric statistical analysis methods to be employed.

### *2.4.1 Location within a peatland (margin versus interior)*

Paired t-tests were used to assess if location (margin or interior) based differences within each study site existed for recovered peat depth and for accumulated organic soil carbon. To assess whether a significant trend in the level of decomposition of surface peat (represented by von Post Index values) with time exists within peatland margins and interiors, a Mann-Kendall trend test was employed. This test was also used to identify if a significant trend in the decomposition of peat with depth was present in peatland margins and interiors.

### *2.4.2 Hydrogeological setting*

An Analysis of Covariance (ANCOVA) was used to investigate both the potential effect of time since fire on total organic soil carbon accumulation, as well as the possible influence of hydrogeological setting. Data sets containing total carbon accumulation values for the interior of all sites and for the margin of all sites were analyzed separately to allow for any differing effects of hydrogeological category on different locations within the peatlands to be clear. All statistical analyses were conducted using all five hydrogeological categories (with heterogeneous categories included) and were conducted using the three summarized hydrogeological settings. The use of five or three hydrogeological categories did not change the overall result of the test in terms of significance of hydrogeological setting as a factor; significance values reported in results are for analysis using all five hydrogeological categories.

### *2.4.3 Comparison to Wieder et al. (2009)*

Total organic soil carbon accumulation in the interior of peatland study sites calculated in this thesis were compared to carbon accumulation values measured as $NEP_U$ by Wieder *et al.* (2009) in their post-fire peatland chronosequence study in the Boreal Plains of Alberta. This was done through linear regression of carbon accumulation values against time since fire for the two data sets, with full factorial analysis to assess if a significant difference in the slope of the two carbon accumulation with time trendlines existed based on the dataset that they were from.

Confidence intervals of 99%, 95%, and 90% were used for the paired t-test, Mann-Kendall trend test, ANCOVA, and full factorial analysis, each corresponding to a different level of significance as follows:

| | |
|---|---|
| $p < 0.01$ | strongly significant |
| $0.01 < p < 0.05$ | significant |

| | |
|---|---|
| $0.05 < p < 0.1$ | weakly significant |

Additional details regarding the statistical analysis methods used can be found in Table 3.

## 3. Results

### 3.1 Post-Fire Organic Soil Accumulation (Depth)

Organic soil accumulation following wildfire in the interior and margin of each site was first assessed in terms of peat depth (Figure 3). The depth of newly accumulated peat increases with time since fire in both the interior and margin, but at a greater rate in the peatland interior than in the margin. Thus, at any given time since fire, recovered peat depth in the interior is greater than that in the margin. This difference in interior and margin accumulated peat depth post-fire within each individual site was found to be strongly significant (paired t-test: $p = 0.004$, t-Ratio = - 3.158). Hydrogeological setting does not appear to play a large role in the depth of accumulated peat in either of these areas (Interior: $p = 0.675$, F Ratio = 0.589; Margin: $p = 0.838$, F Ratio = 0.355).

### 3.2 Peat Properties

#### *3.2.1 Location within a peatland (margin versus interior)*

Representative plots of near-surface peat decomposition (von Post) along a transect within select sites (>80 years since fire) from margin to interior are shown in Figure 4. Peat at the surface in the furthest interior location observed was completely undecomposed (von Post 1), while surface peat in the margin had begun to decompose in two of the three example sites. In the example *Moraine: Heterogeneous* site, decomposition of surface peat in the interior was observed to be greater with proximity to the margin, with the greatest level of decomposition observed within the margin. This is contrasted both with the example *Fine: Expansive* site where all interior surface peat observed was undecomposed (von Post 1) regardless of proximity to the margin, and surface peat decomposition was greater only in the margin; and with the example *Coarse: Heterogeneous* site where all observed surface peat was undecomposed, even within the margin. Both the *Moraine: Heterogeneous* and *Fine: Expansive* example sites displayed a decrease in surface peat decomposition towards the upland-margin interface (the extent of the lines plotted in Figure 4). Frequently, the peat in the margin was covered by a thin layer of leaf litter. While exceptions do exist (as seen with the example *Coarse: Heterogeneous* site in Figure 4), a general trend of more decomposed peat being present in the margins at surface and also at depth was observed across the landscape. Several other sites (data not shown here) also displayed a higher von Post in the margin and toward the upland than was seen moving along the transect into the peatland interior.

At depth, peat which had accumulated since the most recent wildfire within the margin was also observed to be generally more decomposed than that in the interior (Figure 5a). Greater levels of decomposition were observed in near-surface margin peat (up to von Post 6 representing moderately highly decomposed peat was observed within the first 0.10 m below ground surface) than were seen in interiors (up to von Post 4 representing slightly decomposed peat within the first 0.10 m). In the peatland interior, high levels of decomposition were not observed in recovered peat until much greater depths below ground surface (von Post greater than 5 was not observed until a depth of 0.45 m below ground surface), and low levels of decomposition were observed at much greater depths than in the margin (von Post 3 representing very slightly decomposed peat was observed at depths greater than 0.60 m in interiors, but only up to approximately 0.15 m below ground surface in margins). These von Post Index values representing peat accumulated since the last fire demonstrate that margin peat may be more decomposed than peat found in the interior near-surface and at depths up to the observed 0.60 m below ground surface. In both margins and interiors, a significant trend in von Post with depth was observed at the majority of the studied peatlands for which trend analysis was run: 19 of 25 margins and 23 of 25 interiors had a significant trend in von Post with depth (Table 4). Of these, the trend was increasing at 19 margins and 21 interiors.

Similar observations to the level of decomposition were made regarding bulk density of peat in the margin compared to the interior, with peat found in the upper 0.60 m of the margin peat profile being generally equally or more dense than that observed at an equivalent depth in the interior (Figure 6a). While the total range of bulk densities observed in margins and interiors are quite similar (6.1 to 263.9 kg $m^{-3}$ in margins; 13.3 to 257.1 kg $m^{-3}$ in interiors), the distribution of bulk density values with depth differs between the two areas. High bulk densities are reached at shallower depths in margins than similar values in interiors. For example, a bulk density of 185.3 kg $m^{-3}$ is observed at 0.10 m below ground surface in the margin, while a similar value of 193.6 kg $m^{-3}$ is not observed until 0.30 m depth in interiors; likewise, the maximum bulk density observed in interiors of 257.1 kg $m^{-3}$ is seen at 0.45 m depth, while a similar value of 252.4 kg $m^{-3}$ is present 0.30 m shallower (at 0.15 m depth) in the margins. In margins, the general rate of increase in bulk density with depth below ground surface is $5.8 \cdot 10^2$ kg $m^{-3}$ per m, while interior bulk density increases at a rate of approximately $3.7 \cdot 10^2$ kg $m^{-3}$ per m (based on Figure 6a). Due to the locational differences in the rate of increasing bulk density with depth, peat at depths greater than 0.20 m in the interior can still have quite low bulk density in comparison to peat at equal depth in the margin. At 0.25 m, for example, the minimum bulk density observed in margins is 98.8 kg $m^{-3}$, while that observed in interiors is 42.5 kg $m^{-3}$; this difference in bulk density at a given depth in margins and interiors is even more pronounced deeper in the peat profile, where a minimum value of 219.3 kg $m^{-3}$ is observed at 0.50 m below ground surface in margins, while interiors have a minimum value of 56.9 kg $m^{-3}$ at equivalent depth. Thus, peat in the margin has the potential to be both more decomposed and more dense than that in the interior at an equivalent depth below ground surface (Figures 5a and 6a).

### *3.2.2 Time since fire differences*

Differences in peat decomposition and bulk density with depth also exist based on time since fire (Figure 5b and c, 6b and c). In sites which have experienced fire greater than 80 years previous, recovering peat is completely to almost entirely undecomposed (von Post 1 to 2) at surface in the peatland interior, and was not observed to exhibit high levels of decomposition (greater than von Post 5) until depths greater than 0.45 m (Figure 5b). Sites 21-80 years post-fire mirror this trend, with only very slightly more decomposed peat present at the surface and a lesser depth of recovered peat observed. Young sites (20 years since fire and younger), however, were observed to exhibit peat which was up to slightly decomposed (von Post 4) at the surface and increased in decomposition more rapidly with depth than older sites. In the margin, the trend of young sites exhibiting higher levels of decomposition was more pronounced (Figure 5c). While completely undecomposed peat (von Post 1) was observed at the surface in young margins, peat which was moderately decomposed (von Post 5) was also observed at the surface of the peat profile and moderately highly decomposed peat (von Post 6) was observed at depths as shallow as 0.06 m below ground surface. As in the interior, sites >80 years post-fire tended to exhibit peat which had not undergone high levels of decomposition at surface (completely undecomposed to very slightly decomposed; von Post 1 to 3), but unlike in the interior the decomposition of peat in old sites increased to moderately decomposed (von Post 5) within 0.15 m below ground surface in the margins. As observed previously in Figures 3 and 5a, the depth of recovered peat in margins was less than in interiors, thus low levels of decomposition are not observed to continue to as great of depths below ground surface in the margins as in the interior. Bulk density with depth in margins also appears to exhibit age dependent trends, with young and medium sites (0-20 and 21-80 years since fire) tending to exhibit a range of bulk density values at a given depth which extend to greater magnitude than old sites (>80 years) within the upper 0.35 m of the peat profile. For example, at a depth of 0.10 m, bulk density ranges from 29.2 to only 79.2 kg $m^{-3}$ in old sites, but from 41.1 to 175.9 kg $m^{-3}$ in medium age sites, and from 39.1 up to 185.3 kg $m^{-3}$ in young sites. The rate of increase in bulk density with depth in the margins is greatest in medium and young sites, followed by old sites ($6.7 \cdot 10^2$, $6.3 \cdot 10^2$, and $5.3 \cdot 10^2$ kg $m^{-3}$ per m respectively). A trend of decreasing rate of change of bulk density with depth as site age increases is also apparent in site interiors. In interiors, bulk density with depth increases at a rate of approximately $4.2 \cdot 10^2$ kg $m^{-3}$ per m in young sites, $3.6 \cdot 10^2$ kg $m^{-3}$ per m in medium aged sites, and $3.2 \cdot 10^2$ kg $m^{-3}$ per m in old peatlands.

### *3.2.3 Decomposition of surface peat with time*

The investigation of sites along a chronosequence allows for potential changes in the decomposition of peat present at the ground surface over time to be assessed. Peat recently exposed at the surface due to wildfire is expected to be more decomposed than recently formed peat, as it will have been located deeper in the peat profile prior to wildfire and decomposition tends to be greater at depth. As time since fire increases and peat begins to recover, the level of decomposition of peat at surface is expected to decrease based on the observation of greater potential levels of decomposition in recovered peat in sites 0-20 years post-fire than sites 21-80 years since fire, which in turn have the potential to be more decomposed than sites >80 years since fire. Indeed, a significant trend in the decomposition (measured as von Post) of surface peat with time is present in the studied peatland interiors ($p = 0.033$, $\tau = -0.347$ ); Figure 7a shows that this is a decreasing trend up to a point when all peat observed at the surface is entirely undecomposed (von Post 1; approximately 65 years). This trend does not appear to be influenced by hydrogeological setting. In peatland margins, a decrease in the decomposition of surface peat with time is present, but is not as pronounced visually (Figure 7b); the decomposition of peat at surface in the margin of old sites was at times observed to be greater than completely undecomposed (von Post 1), while peat at surface in the interior of old sites was always completely undecomposed. However, moderately and slightly decomposed peat (von Post 5 and 4) is not observed at surface in the margins after approximately 65 years; after

80 years, peat which has undergone very low levels of decomposition (von Post 2 and 3) is only observed in moraine sites while all other sites have completely undecomposed peat at the surface. This suggests that there may be a stronger trend of decreasing decomposition of surface peat at margins of sites which are located in fine expansive and coarse settings than on stagnant ice moraine, however an increased sample size would be needed to properly assess this relationship. Overall, the trend in observed decomposition of surface peat in margins with time is weakly significant ($p = 0.076$, $\tau = - 0.279$).

### *3.2.4 Decomposition across the charcoal layer*

A comparison between the level of decomposition of peat exposed by the most recent wildfire (directly below the uppermost charcoal layer in a peat profile) and the decomposition of peat accumulated following wildfire (immediately above the uppermost charcoal layer) may provide insight into the position of a peatland margin prior to wildfire. Given that peat within the margin has the potential to be more decomposed than that at an equivalent depth in the interior (as previously presented); decomposition of peat shows an increasing trend with depth (and consequently age of the peat); and peatland margins have been observed to experience greater depths of burn than the interior (Lukenbach *et al.*, 2015b; Hokanson *et al.*, 2016), the peat exposed at the surface in the margin following wildfire is expected to be more decomposed than that in the interior. Consequently, the difference in level of decomposition between exposed, pre-fire peat and newly recovered peat in the margins is expected to be large in magnitude and could provide a way to assess past margin position. However, when differences between observed levels of decomposition below and above the uppermost charcoal layer in the middle of peatland margins are calculated, it becomes apparent that a large range of differences are present in sites across the landscape (Figure 8). In some sites, moderately to highly decomposed peat was observed below the uppermost charcoal layer, resulting in large differences in decomposition between the pre- and post-fire peat (up to a difference of 4 von Post Index values) as expected. However, peat with low levels of decomposition was also exposed by wildfire in some sites, leading to zero or only small differences in decomposition across the charcoal layer. Such a range in levels of decomposition of peat exposed by wildfire and differences in pre- and post-fire peat decomposition across the uppermost charcoal layer suggest that the use of this method to determine previous positions of the margin is limited. Visual inspection of plots of peat decomposition (represented by von Post Index values) and differences in peat decomposition with depth along a transect at each study site did not identify a pattern which could be applied to all sites to identify margin positions prior to wildfire based on levels of peat decomposition (data not shown here).

## 3.3 Post-fire Organic Soil Carbon Accumulation

### *3.3.1 Location within a peatland (margin versus interior)*

Within both the peatland interior and margin, a general increasing trend in total recovered organic soil carbon with time since fire was observed across the Boreal Plains landscape (Figure 9a and b). This relationship is strongly significant within peatland interiors and margins (Interior: $p < 0.0001$, F Ratio = 26.819; Margins: $p < 0.0001$, F Ratio = 60.210). Visual comparison of the linear regression trendline of organic soil carbon accumulation with time in peatland margins with that in interiors indicates that recovery in these two locations is quite similar, however may be slightly greater in interiors (0.081 kg C $m^{-2}$ $yr^{-1}$ on average in margins versus 0.091 kg C $m^{-2}$ $yr^{-1}$ on average in interiors; Figure 9c). Based on the trendlines of organic soil carbon accumulation with time (Figure 9c), a peatland interior in the Boreal Plains would accumulate approximately 9.1 kg C $m^{-2}$ in 100 years following wildfire, while the margin would accumulate approximately 8.1 kg C $m^{-2}$ in the same amount of time. Indeed, the mean difference between total organic soil carbon accumulation in the observed margins and interiors is weakly significantly different than zero ($p = 0.103$, t-Ratio = 1.691), indicating that the trend of average organic soil carbon accumulation being greater in the interior of peatlands than in margins observed in Figure 9c is weakly significant. While some individual peatlands were observed to experience greater organic soil carbon recovery in the interior, others experienced equal or greater total organic soil carbon accumulation in the margin;

on a landscape scale, however, peatland margins have slightly less organic soil carbon accumulation following wildfire than peatland interiors. While total organic soil carbon accumulation showed a weakly significant difference based on location within a peatland, the mean difference in organic soil carbon accumulation rate calculated on a site-by-site basis in the interior and margin is not significantly different than zero ($p = 0.743$, t-Ratio = 0.331), indicating that the rate of organic soil carbon accumulation is not dependent on location within a peatland. While total organic soil carbon accumulation was strongly significantly influenced by time since fire in both the margins and interiors across the landscape, time was only weakly significant to the measured organic soil carbon accumulation rate in peatland interiors across the landscape and was not significant to organic soil carbon accumulation rate in peatland margins (Interior: $p = 0.094$, F Ratio = 3.094; Margin: $p = 0.430$, F Ratio = 0.649).

### *3.3.2 Hydrogeological setting*

Hydrogeological setting was observed to have less of an effect on organic soil carbon recovery than time since fire. In the interior of the studied peatlands, post-fire organic soil carbon accumulation was not significantly influenced by hydrogeological setting ($p = 0.704$, F Ratio = 0.546; Figure 9a). This is as expected, as the depth of peat in the peatland interior (up to 3.13 m observed in our study sites) and high specific yield of near-surface peat serves to moderate the effect of underlying sediment on water availability near ground surface

(Waddington *et al.*, 2015). Contrary to expectations, hydrogeological setting was also not a significant factor for organic soil carbon accumulation following wildfire in the margin of peatlands (p = 0.259, F Ratio = 1.437; Figure 9b). Similarly, the rate of organic soil carbon accumulation in both interiors and margins was not significantly influenced by hydrogeological setting in the investigated study sites (Interior: p = 0.966, F Ratio = 3.094; Margin: p = 0.226, F Ratio = 1.550). Thus, hydrogeological setting was not observed to affect organic soil recovery following wildfire in peatlands on the Boreal Plains of Alberta.

Additional details regarding the results of statistical analyses can be found in Table 4.

## 4. Discussion

### 4.1 Location within a Peatland (Margin versus Interior)

Dynamic water table behaviour and complex water chemistry at the margins of peatlands in the Boreal Plains were previously observed to influence bryophyte recolonization and resultant vegetation species trajectory within three years following wildfire (Lukenbach *et al.*, 2017). In certain hydrogeological settings, peatland margins experienced flooding during times of excess water followed by rapid water table declines during dry periods. Also receiving an influx of dissolved solutes and nutrients from mineral substrates, these margins experienced limited vegetation establishment post-fire, with vegetation which was able to recolonize being characteristic of post-fire recovery in upland areas rather than peatland interiors. This was not the case for observed peatland interiors, which experienced vegetation species recovery post-fire characteristic of interiors (Lukenbach *et al.*, 2017). As such, the observations in this study of a significant difference in accumulated peat depth in the margin and interior, and in organic soil carbon accumulation post-fire between these two areas is as expected.

While the difference in accumulated peat depth in the margin and interior of the studied peatlands is strongly significant, the difference in organic soil accumulation in these two areas is only weakly significant (see Results sections 3.1 and 3.3.1 or Table 4). This can be explained both in terms of differing peat properties in these two areas, as well as the strength (or lack thereof) of hydrological differences between the study site margins and interiors. As margin peat tends to be more decomposed than interior peat at an equivalent depth below ground surface (Figure 5a), a resultant higher bulk density of margin peat than interior peat could lead to a lesser difference in total organic soil carbon accumulation post-fire than accumulated peat depth between the margin and interior of a peatland. In other words, an equivalent depth of peat accumulated in the margin post-fire could represent a greater amount of stored carbon than in the interior, so greater differences in peat depth would be necessary to produce significant differences in organic soil carbon accumulation in the two areas. A stronger significance of the difference in peat depth in margin and interior than organic soil carbon accumulation in the two areas is therefore logical. In addition, the strength of the difference in organic soil carbon accumulation in the margin and interior may have been less than expected due to the apparent lack of effect of hydrogeological setting on margin organic soil carbon accumulation (discussion to follow in section 4.3). Sites with poor connectivity to regional groundwater were expected to experience large and frequent water table fluctuations in the margin, especially if the underlying sediments had high hydraulic conductivity (Hokanson *et al.*, submitted; Lukenbach *et al.*, 2017). This would result in limited water availability at the margin during dry periods and, as water availability has been identified as a control on moss productivity (Waddington *et al.,* 2015), resultantly less moss recolonization and peat accumulation than in the peatland interior (Lukenbach *et al.*, 2017). However, as there was no significant difference due to hydrogeological setting observed in this thesis, it is possible that this effect on water availability was not prevalent at our study sites. Drawdown of the water table in the margins of our study sites may not have been drastically different from that experienced in the peatland interiors, resulting in a lesser difference in organic soil carbon accumulation in the two areas than anticipated. In fact, unpublished data on water table fluctuation in the margin and interior of multiple study sites suggests that the margin may not experience greater water table drawdown than the peatland interior in all cases (Waddington, personal communication). In addition to a possible limited influence of hydrogeological setting on water table dynamics at our study sites, peatland sites immediately following wildfire may experience lesser water table drawdown at the margins than prior to wildfire due to a reduction in the amount of transpiration of surrounding forest vegetation; while redistribution of water from the peatland to the surrounding forest does still occur following wildfire via aspen root networks, the amount of mature aspen present following wildfire is decreased from that present pre-fire, which could cause a reduction in the total amount of water removed from the margins shortly following wildfire (Depante, 2016). Combined with water re-distribution mechanisms within peatlands following wildfire, wherein limited evaporation within certain areas of the peatland due to the WTD – moss surface resistance and albedo feedback (Waddington *et al.*, 2015) allow for improved water availability in severely burned locations (Lukenbach *et al.*, 2016), this could result in a smaller difference in WTD between peatland margin and interior than was experienced pre-fire and therefore a smaller difference in water availability for recovery between these two areas.

## 4.2 Decomposition across the Charcoal Layer

While knowledge of past margin positions would provide valuable insight into the occurrence of margin shifts following wildfire, the use of changes in the level of decomposition observed across the charcoal layer created during the most recent fire for this purpose is thus far unsuccessful. In practice, it appears that this method is limited due to the wide range of levels of decomposition of peat exposed by wildfire and of recovering peat, resulting in a range of values of change in von Post calculated across the charcoal layer with no apparent spatial trend within a peatland.

Several limitations to this method exist which should be addressed to improve its efficacy. While undertaking this method, we recognized that the decomposition of peat exposed at the surface by wildfire would have continued following wildfire, so the von Post Index value of the peat below the charcoal layer would not be equivalent to what it was immediately post-fire; however we assumed that recovered peat above the charcoal layer underwent similar decomposition with time as the peat below the charcoal layer. Thus, the difference between the two levels of decomposition was assumed to still be representative of the decomposition of peat present before wildfire (as peat accumulated immediately following wildfire should have a von Post of 1), and therefore be valuable in determining past margin position. However, it is possible that the rate of decomposition of exposed peat immediately following wildfire was accelerated due to increased oxygenation of the peat, especially for peat which was poorly decomposed prior to wildfire. Peat in the interior of the peatland where lower levels of decomposition are expected (due to higher decomposition at equivalent depths in the margin as previously reported, and the possibility for deeper smouldering in the margin) may have undergone decomposition following wildfire which increased its von Post Index value to levels similar to peat found in the margin, thus reducing the possibility for past marginal peat to be identified based on von Post differences across the charcoal layer. Spatial differences in the decomposition of accumulated peat following wildfire could also contribute to indistinct differences in the change in decomposition across the charcoal layer based on location within the peatland. In addition, it is possible that differences in bulk density and therefore specific yield of peat exposed by wildfire and that of recently accumulated peat allow for varying water retention capacities and consequent variations in decomposition rate of peat below and above the charcoal layer. Furthermore, uncertainties in the correlation of charcoal layers observed at different locations along the transect from forestland to peatland interior due to possible differences in the preservation of charcoal following wildfire across the peatland, irregular fire behaviour, and differing burn depths could have played a large role in the lack of success of this method thus far. Should these uncertainties and limitations be addressed, this method may have more success in determining previous margin positions in the future.

## 4.3 Post-Fire Organic Soil Carbon Accumulation

### *4.3.1 Long-term and recent peatland carbon accumulation rates*

The average carbon accumulation rate of 91 g C $m^{-2}$ $yr^{-1}$ for peatland interiors and 81 g C $m^{-2}$ $yr^{-1}$ for peatland margins reported in this study is much greater than estimated average Holocene long-term carbon accumulation rates (Gorham *et al.*, 2012; Yu *et al.*, 2009; Yu, 2012; Loisel *et al.*, 2016) and some estimates of contemporary carbon accumulation rate (Yu *et al.*, 2011; Vitt *et al.*, 2000). This is to be expected, as the rate of carbon accumulation calculated from the top of a peat profile considerably overestimates long-term carbon accumulation due to continued decomposition of near-surface peat (Roulet *et al.*, 2007). That being said, our rates of carbon accumulation do compare well to recent rates of 40 – 117 g C $m^{-2}$ $yr^{-1}$ in eastern Canadian ombrotrophic bogs calculated for the last 150 years (Turunen *et al.*, 2004), and 100 – 111 g C $m^{-2}$ $yr^{-1}$ during the preceding 100 years at two northern bogs in western Canada (Turetsky *et al.*, 2000). In addition, as shown in Figure 9, our estimates are similar to measurements of $NEP_U$ by Wieder *et al.* (2009); statistical analysis of carbon accumulation with time since fire indicates that measurement by Wieder *et al.* (2009) or by the author of this thesis has no significant effect on the carbon accumulation rate (Table 4), indicating that our values are comparable and that observations of carbon dynamics following wildfire made by Wieder *et al.* (2009) likely hold true on a landscape scale.

Alignment of our carbon accumulation rates with recent rates of carbon accumulation in ombrotrophic bogs measured in both eastern (Turunen *et al.*, 2004) and western (Turetsky *et al.*, 2000) Canada indicates that the peatlands investigated in this study are able to accumulate organic soil carbon following wildfire which is similar to systems located in a humid climate, and is on par with sites which have not been recently impacted by wildfire. While the organic soil carbon accumulation rates post-fire measured in this study and $NEP_U$ measured by

Wieder *et al.* (2009) may be overestimates of the total amount of carbon which accumulates long-term, they still provide highly valuable estimates for assessing the resilience of peatlands to recurrent fire on the Boreal Plains of Canada (discussed further in section 4.4.1).

### *4.3.2 Hydrogeological setting*

Hydrogeological setting was not observed to significantly influence organic soil accumulation following wildfire in the studied peatland interiors or margins. This finding is in line with expectations for peatland interiors, however was not anticipated to be the case at peatland margins. Moss productivity is dependent on water availability (Waddington *et al.*, 2015), and accordingly, water availability was identified by Lukenbach *et al.* (2016) as a primary control on peatland recovery patterns following wildfire. Lukenbach *et al.* (2016) also indicated that the hydrogeological setting of a peatland system should influence post-fire recovery due to its effects on water availability following wildfire through both pre-fire vegetation patterns and post-fire water table fluctuation. Pre-fire vegetation patterns influence the spatial coverage of hydrophobic burnt peatland vegetation following wildfire, which in turn governs the tensions required to access water in these areas and the ability of moss species to recolonize following wildfire (Lukenbach *et al.*, 2016). Moreover, Lukenbach *et al.* (2016) noted that capillary flow from the water table is a key water source for bryophyte recolonization; thus, we would expect the amount of water table fluctuation within a peatland interior and at the margin post-fire to influence bryophyte recolonization and resultant organic soil accumulation.

In peatland interiors, the effect of underlying sediments on water table fluctuation at the peat surface is dampened in comparison to that which occurs at the margin (*e.g.* James, 2017). As presented previously, peat within the margin tends to be more decomposed and more dense than peat at an equivalent depth in the interior (Figure 5a, 6a). More decomposed peat has smaller pore sizes and thus lower specific yield than peat which still contains fibres strong enough to resist deformation under the stress of overlying organic matter (Waddington *et al.*, 2015). With lower specific yield, margin peat will experience a greater change in WTD than surface peat in the interior for any given gain or loss of water from or to sediments directly underlying the peat profile. Within the interior, highly decomposed peat with low specific yield at depth within the peat profile could experience rapid water table change similar to the margin for a given volume of water added to the system, however the rate of water table change would be decreased when higher specific yield peat near the surface was encountered as per the WTD – specific yield feedback (Waddington *et al.*, 2015); likewise, less decomposed peat near the surface of the interior would decrease the magnitude of water table decline in comparison to the margin for a given volume of water removed from the system. Thus both the level of groundwater connectivity providing water to a peatland, and the hydraulic conductivity of surrounding sediments which could receive water from the peatland have the potential to exert a greater influence on water availability in the peatland margin than the interior. Additional negative WTD feedbacks, such as the WTD – moss surface resistance and albedo feedback; WTD – transmissivity feedback; WTD – peat deformation feedback; and WTD – decomposition feedback, also act to limit the severity of water table drawdown in the peatland interior (Waddington *et al.*, 2015), while the extent of these feedbacks is unknown in the margin. Furthermore, thick peat in the interior of the peatland could provide an additional buffer to changes in WTD which may occur at the surface due to the sediments underlying a peatland. It is possible that hydrogeological setting could influence water availability and resultant moss recolonization in peatland interiors through lateral water loss at the margins rather than vertical water loss to underlying sediments; the loss of low hydraulic conductivity peat in the margins through severe burning in some hydrogeological settings could allow for lateral water loss from the peatland interior to surrounding sediments, as horizontal hydraulic conductivity within peat profiles is generally high in comparison to vertical conductivity (Beckwith *et al.*, 2003; Lukenbach *et al.*, 2015b). However, a lack of significant difference in carbon accumulation in peatland interiors located in different hydrogeological settings suggests that lateral water loss from peatland interiors to sediments at the margin was not influential to organic soil recovery in the studied peatlands. This being said, our methodology wherein we focussed our site selection on ombrotrophic bogs means that we would not have captured systems where an ecosystem shift had occurred due to fire, which could be a consequence of peatland drainage resulting from the loss of water conservation mechanisms at the margin (Lukenbach, 2017).

Contrasting with expectations for peatland interiors, hydrogeological setting was expected to influence post-fire organic soil recovery in peatland margins. Acting as the interface between the peatland proper and the adjacent forestland, peatland margins experience large water table fluctuation (Devito *et al.*, 2012). Within the forestland, large storage potential and high vegetation water demand result in deep water tables below the influence of vegetation (Devito *et al.*, 2012). At the peatland margin, the WTD often decreases in comparison to the peatland interior due to a hydraulic gradient from the peatland to the adjacent forestland (Dimitrov *et al.*, 2014) caused by a smaller storage deficit in the peatland, as well as uplift via aspen root networks which transfer water from the peatland to be used by forestland vegetation (Depante, 2016; Petrone *et al.*, 2007; Devito *et al.*, 2012). Hydrogeological setting also directly influences the amount of water table fluctuation at the margin, as it controls the degree of connection to local and regional groundwater flow systems, thus influencing the amount of groundwater received by the peatland (Hokanson *et al.*, 2016; Redding, 2009; Devito *et al.*, 2012). Additionally, the HRA in which a peatland is situated influences the amount and frequency of runoff received by the peatland from connected wetlands at higher positions in the groundwater flow system, and from adjacent forestlands which have exceeded their storage (Devito *et al.*, 2012). This large potential for water table fluctuation at the peatland margin within some hydrogeological settings was expected to lead to noticeable differences in post-fire moss recolonization. Nevertheless, hydrogeological setting was not significant in terms of organic soil accumulation at the margins in this study.

It is possible that in some study sites the pre-existing margin was burned to the depth of underlying sediment and that recovery was then highly influenced by the properties of the sediment; however, if this was the case and a large amount of organic soil accumulation had not occurred since the time of wildfire, we would not have been able to identify the location as a margin. Thus, in all of our study sites, some amount of peat was present within the margin. Though total peat depth in the margin is not as great as in the interior of the peatland, it is possible that enough highly decomposed, low hydraulic conductivity peat existed following wildfire in the margins of our study sites that the effects of underlying sediments on water availability were dampened. While this would not eliminate differences in peatland connectivity to regional groundwater flow systems or other local peatland systems, or eliminate differences in the storage space of adjacent forestlands, it may have been able to reduce the effects of these factors on water availability and moss productivity.

In addition, while possible differences in the magnitude of WTD occurring during times of drought at the margins of sites located in separate hydrogeological settings could be great, differences in the overall effect of varying WTD on water availability for recovering mosses could be less significant. Moss production is strongly correlated non-linearly with tissue gravimetric water content, which is in turn governed by WTD (Waddington *et al.*, 2015). An optimal water content exists where a moss species (such as *Sphagnum sp.*) will experience the greatest level of production; water contents above and below this range will inhibit photosynthesis (Waddington *et al.*, 2015). Thus, if the WTD in the margin of a peatland was to experience drawdown that reduced water content at the surface to below the optimal range for recovering moss species, additional drawdown of the water table would not have a further profound effect on moss production. In this way, margins experiencing differing magnitudes of water table drawdown could have similar moss production at the surface. Additionally, if a margin were to have excess water present, moss productivity could be decreased due to unfavourably high water contents. During a period of water surplus relative to the 30-year precipitation mean, Lukenbach *et al.* (2016 and 2017) measured high water availability at the margins of a peatland which underwent severe burning, lowering the elevation of the peat surface. A similar effect could be experienced at the margins of peatlands located on fine grained sediments (and in fact, these margins were often observed to be flooded during 2016 field work), which could inhibit the recovery of some moss species. This could also reduce the differences in overall moss recovery at margins located in various hydrogeological settings.

Finally, differences between organic soil accumulation at the margins of sites located in different hydrogeological settings could be less significant in this study than the differences in burn depth observed by Hokanson *et al.* (2016) due to the complexity and heterogeneity of the sediment assemblages observed across the landscape and ultimately underlying the study sites used in this analysis. While the study sites used by Hokanson *et al.* (2016) had relatively distinct sedimentologies (*e.g.* well sorted sands on a glaciofluvial outwash plain) and unique topographic positions, equally distinct sediment assemblages were not found to be present across the Boreal Plains landscape while site searching. Often, the sediments found in expected outwash areas were either thin, less coarse than anticipated, or quite heterogeneous. This resulted in a set of *Coarse: Heterogeneous* study sites that had predominantly coarse grained sediments, but also contained inter-bedded fine grained sediments and were interpreted to be ultimately overlying fine grained diamict. Rather than having underlying sediments deposited in a large, long-lived outwash plain or esker deposit as with the Hokanson *et al.* (2016) coarse grained study sites, these *Coarse: Heterogeneous* study sites are interpreted to have sediments deposited by numerous or shifting, shorter lived glacial outwash streams at varying proximity to the ice front, above sediments previously deposited subglacially. These are similar to sediment assemblages within the *Moraine: Heterogeneous* category, where predominantly fine grained tills deposited subglacially are found with coarser sediments interpreted to be from local fluvial systems draining meltwater from stagnating ice blocks. In addition to similarities between sediment assemblages in the *Coarse: Heterogeneous* and *Moraine: Heterogeneous* categories, the *Moraine: Fine* and *Fine: Expansive* categories each have sedimentologies which are dominated by fine grained, clay-rich deposits (subglacial tills and glaciolacustrine deposits). While sediment sorting and compaction will be different based on the different paleoenvironments, hydraulic conductivities of the regional sediments; frequency of upland runoff; and availability of regional groundwater will likely be quite similar between sites in these categories. Similar sediment assemblages between categories could result in similar water table behaviour, and consequently could possibly reduce the observed differences between organic soil carbon accumulation in the hydrogeological categories used in this study. Besides inter-category variability, the amount of intra-category variability could be high in the *Coarse* and *Coarse: Heterogeneous* groups due to possible unaccounted-for differences in regional groundwater connection. As coarse grained sediment assemblages were not the only HRA being investigated in this study, it was not feasible to study several sites in each of a range of topographic positions; thus the sites investigated do not all sit within the same topographic position, which could contribute to intra-category variability in organic soil carbon accumulation. In addition, the fine grained till presumed to be present beneath some of the *Coarse: Heterogeneous* study sites could limit the amount of regional groundwater flow in the area. Thus, we suggest that the expansion of the number and location of study sites from that used in Hokanson *et al.* (2016) likely resulted in additional inter- and intra-category variability that could mask hydrogeological based differences in post-fire peatland margin recovery on the Boreal Plains landscape.

## 4.4 Implications

### *4.4.1 Organic soil carbon re-accumulation*

Greater depths of burn at peatland margins than interiors (up to 8 times greater in some hydrogeological settings; Hokanson *et al.*, 2016; Lukenbach *et al.*, 2015b), but lesser soil organic carbon accumulation in the margin measured in this study indicates that peatlands on the Boreal Plains landscape could be shrinking in lateral extent following wildfire. As severity of burn at the margins of some peatlands is influenced by hydrogeological setting (Hokanson *et al.*, 2016), the ability of a system to recover the amount of carbon lost through smouldering of the margins within the fire return interval will also be affected by hydrogeological setting. Using the estimated rate of organic soil carbon accumulation in interiors (91 g C $m^{-2}$ $yr^{-1}$ * time since fire (yr), $R^2 = 0.636$) and in margins (81 g C $m^{-2}$ $yr^{-1}$ * time since fire (yr), $R^2 = 0.603$) from this study combined with the carbon loss estimates from Hokanson *et al.* (2016) and Lukenbach *et al.* (2015b), the amount of time required to re-accumulate lost carbon can be predicted. In each of the three hydrogeological settings measured by Hokanson *et al.* (2016; 'Outwash, Ephemerally Perched', 'Outwash, Flow Through', and 'Clay Plain, Expansive'), estimated carbon loss of 0.4 to 0.9 kg C $m^{-2}$ within peatland interior hollows could be recovered within 4 to 10 years. Greater estimates of carbon loss of 0 to 4 kg C $m^{-2}$ in the interior of the 'Outwash, Ephemerally Perched' system by Lukenbach *et al.* (2015b) would require 0 to 44 years (11 on average) to recover. These estimates of required recovery time for organic soil carbon loss in peatland interiors are well within the estimated fire return interval of 120 years (Turetsky *et al.*, 2004). As burn severity in peatland interiors was not found to be significantly influenced by hydrogeological setting (Hokanson *et al.*, 2016), it is likely that peatlands across the Boreal Plains landscape are not at risk of permanent carbon loss from the interior, and are therefore not expected to decrease in depth in the interior as a consequence of wildfire. Average estimated carbon losses of 1.7 kg C $m^{-2}$ at the margin of an 'Outwash, Flow Through' bog and 5.0 kg C $m^{-2}$ at the margin of a 'Clay Plain, Expansive' bog (Hokanson *et al.*, 2016) require a predicted 21 and 62 years to recover, respectively. While these systems will take a greater amount of time to recover carbon lost from the margins than the interior, they are currently predicted to recover within the fire return interval (Figure 10: *Stable Peatland*). More frequent drought and wildfire due to climate change (Flannigan, *et al.*, 2005; Turetsky, *et al.*, 2004; Turetsky, *et al.*, 2015) however, could jeopardize these types of peatland systems in the future by increasing carbon loss and decreasing the amount of time available to recover lost carbon;

under current climate conditions they are not at risk of permanent carbon loss from the margins. Severely burned peatland margins, on the other hand, are more likely to experience irreparable carbon loss. Carbon loss at the margin of the 'Outwash, Ephemerally Perched' system was most severe; an estimated 19.9 kg C $m^{-2}$ on average (Hokanson *et al.*, 2016) or 10 to 85 kg C $m^{-2}$, averaging 27 kg C $m^{-2}$ (Lukenbach *et al.*, 2015b) was lost during wildfire. This would require approximately 120 to 1050 years to re-accumulate lost carbon, averaging 250 (Hokanson *et al.*, 2016) or 330 (Lukenbach *et al.*, 2015b) years. These estimates indicate that the ephemerally perched bog on the Boreal Plains landscape studied by Hokanson *et al.* (2016) and Lukenbach *et al.* (2015b) is unable to recover the lost legacy carbon stores from the margin within the average fire return interval, and is therefore likely an overall carbon source to the atmosphere. Furthermore, this peatland system is likely to shrink in lateral extent due to irreplaceable carbon loss during wildfire. Other peatlands on the Boreal Plains landscape which experience similar hydrological conditions at the margin, leading to severe burning and extensive carbon loss during wildfire, are predicted to be similarly unable to recover lost margin carbon stores within the fire return interval (Figure 10: *Vulnerable Peatland*).

Estimates of carbon loss at the margins of peatlands located on stagnant ice moraine sediments, and those located on topographic highs in coarse outwash paleoenvironments are not available at this time, therefore calculations of the time required for carbon re-accumulation in these systems cannot currently be made. However, inferences can be made based on measured hydrology and peat properties at the margins found in the literature and observed during this study.

Recent work by Hokanson *et al.* (submitted) suggests that a peatland which is completely perched above the regional groundwater table on glaciofluvial outwash sediments may experience intermediate vulnerability to smouldering during wildfire above that of a flow through system, and below that of an ephemerally perched peatland. While predicted overall vulnerability of the investigated perched system was less than the ephemerally perched peatland, simulated gravimetric water contents and peat smouldering propagation potential (a ratio of the energy released by overlying peat to the energy necessary to combust the layer of peat below) in the perched system indicated that smouldering could still be propagated to depth in the margin under dry conditions (Hokanson *et al.*, submitted). Based on the calculated required recovery interval for the ephemerally perched system discussed previously, a similarly severely burned margin in a perched peatland system is unlikely to be able to recover the lost legacy carbon within the fire return interval. The overall severity to the peatland system of permanent carbon loss at the margins will be influenced by the width of the margin, perimeter to area ratio of the peatland, and the consequent proportion of the total peatland area that the margin comprises. At the specific perched system studied by Hokanson *et al.* (submitted), the water table dropped sharply into the mineral soil at the forestland edge of the margin and the width of the margin was thin, enabling the margin to compose a smaller total proportion of the peatland system than in the ephemerally perched bog. As such, if deep smouldering were to occur at the margin of the observed perched peatland, it could represent a smaller percentage of total peatland carbon loss than in the ephemerally perched system. However, water table drawdown is highly dependent on the sediment texture and layering of underlying sediments which can be quite complex. Work by James *et al.* (2017) suggests that perched peatland systems which have wider margins and experience water table drawdown below margin peat also exist on the Boreal Plains landscape.

To my knowledge, predictions of peatland margin vulnerability to smouldering on stagnant ice moraine sediments in the Boreal Plains of Alberta have not been published at this time. Peatland systems on this landform are generally hydraulically isolated (perched), disconnected from regional groundwater flow systems due to limited lateral movement of water in the underlying low hydraulic conductivity sediments (Ferone and Devito, 2004; Devito *et al.*, 2012). These systems may behave similarly to peatlands perched on overall coarse grained sediment landforms, however could experience different water table dynamics at the margin due to adjacent fine textured sediments with low hydraulic conductivity. Unpublished data on water table fluctuation in the margin and interior of multiple peatlands on stagnant ice moraine suggests that water table fluctuation at the margin can be quite high (Waddington, personal communication). While not specifically investigating water table dynamics in the margin, Ferone and Devito (2004) and Redding and Devito (2010) report WTDs along pond-peatland-hillslope and hillslope-peatland transects at a peatland on stagnant ice moraine sediments which show water table drawdown to depths beneath the peat extending up to tens of meters laterally under the peatland during dry conditions. This observation is concerning, as it indicates that these systems could develop highly decomposed, dense peat at the margins if the water table was to frequently or persistently drawdown to depths below marginal peat as observed. Isolated peatlands located on stagnant ice moraine sediments could be vulnerable to deep smouldering at the margins during wildfire, and are thus critical systems for further evaluation. Additional research on the severity of burn at the margins of stagnant ice moraine peatlands should be conducted to determine whether the landscape scale recovery rate of marginal peat measured in this study is great enough to recover lost carbon stores during wildfire within the wildfire return interval.

### *4.4.2 Wildfire management*

This study supports the findings of Hokanson *et al.* (2016 and submitted) and Lukenbach *et al.*, 2015b) which identify ephemerally perched peatland systems as deep burning ‘hotspots’ on the Boreal Plains landscape which are critical systems to allocate wildfire management resources towards, as these sites are at risk of permanent carbon loss from the margins during wildfire. Peatlands experiencing such severe burning at the margins as observed by Hokanson *et al.* (2016) and Lukenbach *et al.* (2015b) will shrink over time, becoming a net carbon source, and may lose the ability to provide key ecosystem services. The severity of burn at the margins of completely perched peatlands on coarse grained sediments, and those found on stagnant ice moraine sediment deposits is unknown; however, these peatlands may experience high water table fluctuation and deep water table drawdown at the margin, allowing for the development of dense marginal peat with low water content during times of drought. These peatlands warrant additional research attention, and should be kept in mind as potential systems at risk of irreparable carbon loss during wildfire.

### *4.4.3 Peatland reclamation*

Following oil sands mining operations, energy regulators in Alberta are required to restore equivalent land capability to the landscape (Alberta Environment, 2009). As the dominant land cover prior to development in the oil sands mining region was peatlands (Rooney *et al.*, 2012), design and construction of peatland systems which will serve as both water sources and carbon stores on the reclaimed landscape following oil sands mining is essential (Nwaishi *et al.*, 2015; Ketcheson *et al.*, 2016; Devito *et al.*, 2012). That these systems be self-sustaining and secure into the future is also of utmost import (Ketcheson *et al.*, 2016). Therefore constructed peatland systems must be those which are able to fully recover carbon lost from wildfire before subsequent wildfire occurs. While organic soil carbon accumulation following wildfire in the interior and margin of sites investigated in this thesis was not found to be significantly affected by hydrogeological setting, the ability of a system to re-accumulate lost organic soil carbon following wildfire depends on the magnitude of carbon loss from peat smouldering, which is in turn influenced by hydrogeological setting (Hokanson *et al.*, 2016). Thus, vulnerability to severe burning during wildfire and the magnitude of potential carbon loss should be a primary consideration when designing systems for landscape reclamation. Peatlands which experience mild depths of burn at the margins are not at risk of irreplaceable carbon loss, while those experiencing more severe margin smouldering are likely not able to sustain themselves on the landscape. Based on estimations of peatland vulnerability to wildfire made by Hokanson *et al.* (2016 and submitted), peatlands with a high degree of connection to regional or local groundwater flow systems are not at risk; conversely, peatlands which experience ephemeral connection to regional groundwater and resultantly develop a large amount of dense peat at the margins should be avoided on the reclaimed landscape, as they are unlikely to recover carbon lost during wildfire and will shrink over time. Small, isolated peatlands perched above regional groundwater flow systems on fine grained clays or coarse sediments may be able to recover lost carbon at the margins, or may experience deep burning which leads to permanent organic soil carbon loss. This will be dependent on water table dynamics and peat properties at the margins of these systems, which is an area in need of further attention. If a perched peatland system could be designed for the reclaimed landscape which had water table dynamics in the margin such that in times of drought the water table declined sharply once reaching the outer edge of the margin, but did not drawdown beneath the margin, this system could be highly beneficial in terms of long-term carbon storage and water supply to surrounding uplands. In addition, such a system would not require extensive local groundwater input from adjacent hillslopes or connection to regional groundwater which may contain levels of salinity or napthenates harmful to the growth of some peat forming bryophytes (Trites and Bayley, 2005, 2009; Price *et al.*, 2010; Rooney and Bayley, 2011; Nwaishi *et al.*, 2015; Daly *et al.*, 2012). While landscape reconstruction incorporating designed fen systems has several merits (Daly *et al.*, 2012; Pollard *et al.*, 2012; Nwaishi *et al.*, 2015; Ketcheson *et al.*, 2016), the possibility exists that an ephemerally connected ombrotrophic bog with high vulnerability to smouldering could result through the process of peatland succession (Nwaishi *et al.*, 2015), if not under current climate then under future climate predictions where the level of connectivity to regional groundwater flow could be reduced due to more frequent and severe drought (Flannigan *et al.*, 2005; Turetsky *et al.*, 2004; Turetsky *et al.*, 2015). An optimal strategy for peatland design on the oil sands landscape may involve incorporation of perched peatland systems in topographic highs as described above which are self-sustaining during dry periods (dependent solely on precipitation inputs to meet their water needs;

James *et al.*, 2017), but spill excess water to peatland systems (such as reconstructed fens) located at lower topographic positions on the landscape during wet periods due to a smaller storage deficit than forestland hydrologic units (Devito *et al.*, 2012) which would otherwise be in place. Incorporation of expansive ombrotrophic bogs on fine grained sediments into reclamation designs could also be a worthwhile strategy, as these systems are not dependent on regional groundwater connectivity, but are predicted to be able to recover lost carbon at both the interiors and margins within the fire return interval.

In addition to providing a means to identify peatland systems which will be resilient to wildfire following reclamation, organic soil carbon accumulation rates estimated in this study can be used to assess the viability of opportunistic wetlands found on the reclamation landscape developing into systems which will satisfy the equivalent land capability criteria (Alberta Environment, 2009). Currently, there is much discussion regarding the future development of opportunistic wetlands into either peatlands or 'wet forests' over time (*e.g.* Little-Devito *et al.*, 2017). We suggest that recent organic soil carbon accumulation rates for the opportunistic wetlands can be compared to those calculated for ombrotrophic bogs on the natural Boreal Plains landscape in this study to inform whether peatland succession is likely to occur at the opportunistic wetlands. If the organic soil carbon accumulation function of opportunistic wetlands observed on the post-mining landscape tracks along the trajectory of peatlands measured in this study, then their development into long-term carbon stores on the landscape is probable.

## 5. Conclusion and Implications

Through the investigation of 26 ombrotrophic bogs located across the Boreal Plains of Alberta which had experienced wildfire at various times in the past, the organic soil recovery of peatlands on this landscape following wildfire was assessed. While peatland recovery along a chronosequence following wildfire has been investigated previously (*e.g.* Wieder *et al.*, 2009; Benscoter and Vitt, 2008), this thesis provides information on the previously disregarded peatland margins, and puts organic soil carbon accumulation following wildfire into the context of underlying sediment assemblages and interpreted hydrogeological settings. Results of this thesis are central to addressing the question of whether peatlands on the Boreal Plains of Canada are able to fully recover lost legacy carbon between successive wildfires, or if they will switch from carbon neutral or storing systems to sources of carbon to the atmosphere following wildfire.

The amount of organic soil carbon accumulation in peatland interiors was found to be weakly significantly different from that in margins, with average rates of carbon accumulation in the interior estimated at 91 g C m$^{-2}$ yr$^{-1}$ and at 81 g C m$^{-2}$ yr$^{-1}$ in margins. While this difference in accumulated carbon in the two within-peatland locations may appear small on short times scales, it could be considerable over long periods of accumulation and in peatlands which have a small proportion of margin area to total interior area. Hydrogeological categories designated in this study did not have a significant influence on the measured organic soil carbon accumulation, indicating that the amount of recovered organic soil carbon in peatland interiors and in peatland margins at a given time since fire will be similar in ompbrotrophic bogs across the Boreal Plains landscape.

The ability of a peatland system to recover lost carbon following wildfire within the fire return interval, however, is influenced by hydrogeological setting, as the severity of burn at some peatland margins has been linked to regional groundwater connectivity (Hokanson *et al.*, 2016; Lukenbach *et al.*, 2015b). Based on carbon loss estimates following smouldering in peatlands on the Boreal Plains (Hokanson *et al.*, 2016; Lukenbach *et al.*, 2015b) and average organic soil carbon accumulation rates from this study, peatland interiors across the landscape are expected to fully recover lost carbon before subsequent wildfire, indicating that vertical loss of peat in the interiors is not of concern. Likewise, lateral loss of peatland area in systems experiencing continual regional groundwater connection or high levels of local groundwater connectivity due to a low topographic position on outwash sediments or development on expansive fine grained glaciolacustrine or till sheet deposits respectively is not expected to occur. These peatlands are predicted to recover carbon released by wildfire in both the interiors and at the margins within the fire return interval. Peatlands which undergo severe smouldering at the margins, however, are unlikely to accumulate an equivalent or greater amount of carbon as that which was lost during wildfire and are thus at risk of becoming carbon sources to the atmosphere. Ephemerally perched peatlands located at mid-topographic positions on coarse grained sediment assemblages have been identified as one such type of system (Hokanson *et al.*, 2016; Lukenbach *et al.*, 2015b). Peatlands which experience similar levels of water table drawdown and consequent peat decomposition and densification in the margin as the ephemerally perched system are likely also at risk of permanent carbon loss following wildfire. This may include perched systems located on sediments deposited in stagnant ice moraine or glaciofluvial outwash paleoenvironments, as water table at the margins of some of these peatlands has been observed to drop below margin peat (Ferone and Devito, 2004; Redding and Devito, 2010; James, 2017).

The results of this thesis have implications to both wildfire management and peatland design for oil sands lease reclamation. Peatlands which have previously been identified as at risk of severe smouldering are critical systems to devote wildfire management resources towards, as they are unlikely to recover lost carbon before a successive fire occurs. Further effort should go towards the assessment of burn severity at peatlands perched on stagnant ice moraine or outwash sediments, as the resilience of these systems to wildfire is thus far unknown. When designing peatland systems for the reclaimed landscape, the resilience of peatlands to wildfire should be a key factor which is considered. Peatlands located on expansive clay plains, or which experience continual connection to the regional groundwater flow system are expected to recover lost carbon following wildfire, though the latter type of system may become vulnerable if the level of groundwater connectivity is compromised in the future climate. Peatlands which are perched but experience minimal water table fluctuation within the margin itself may be a possibility for reclamation, however further investigation into water table dynamics and smouldering in these systems is necessary.

Thus, water table dynamics and the severity of smouldering experienced during wildfire in perched ombrotrophic bogs on stagnant ice moraine and on glaciofluvial outwash sediments are key pieces of information which are needed to fully assess peatland organic soil carbon recovery following wildfire on the Boreal Plains. Additionally, further investigation into the organic soil carbon accumulation of peatlands at distinct topographic positions on coarse grained sediment assemblages would be useful in elucidating potential effects of hydrogeological setting on margin peat recovery which were not observed in this thesis.

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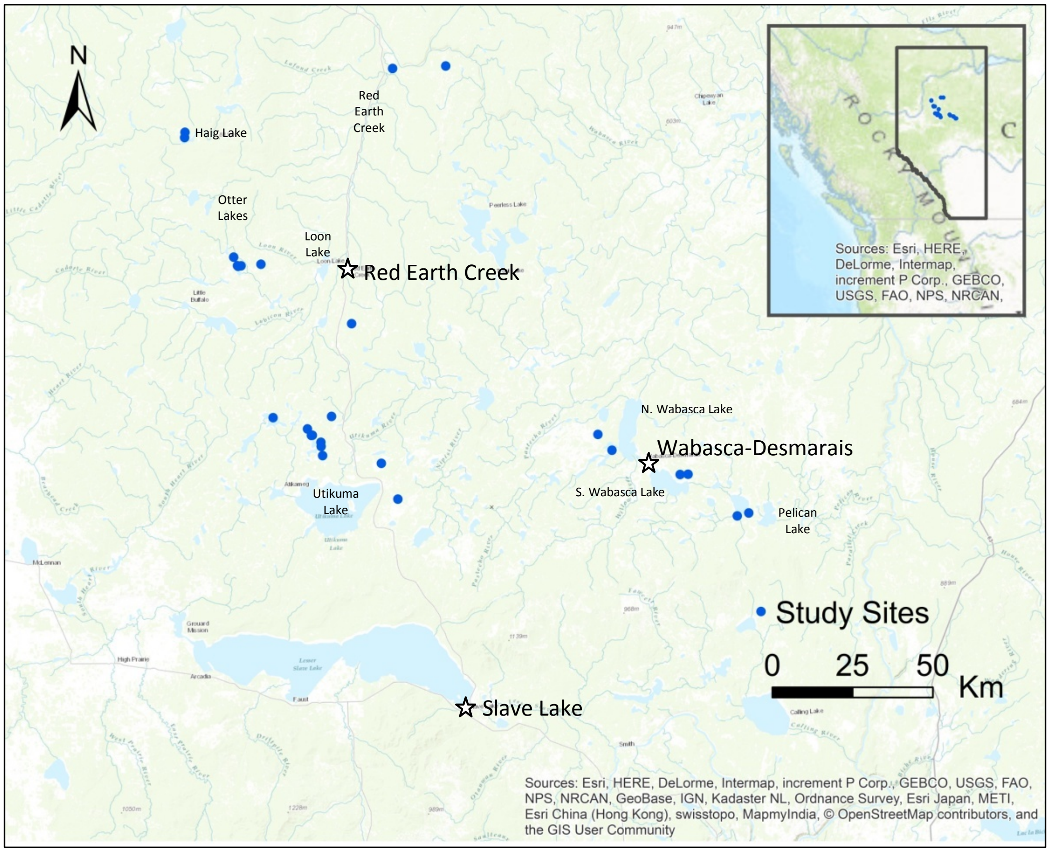

Figure 1: Location of 26 chronosequence peatland sites on the Boreal Plains of Alberta, with the water features for which the study sites are named indicated. Nearby settlements are indicated with a star.

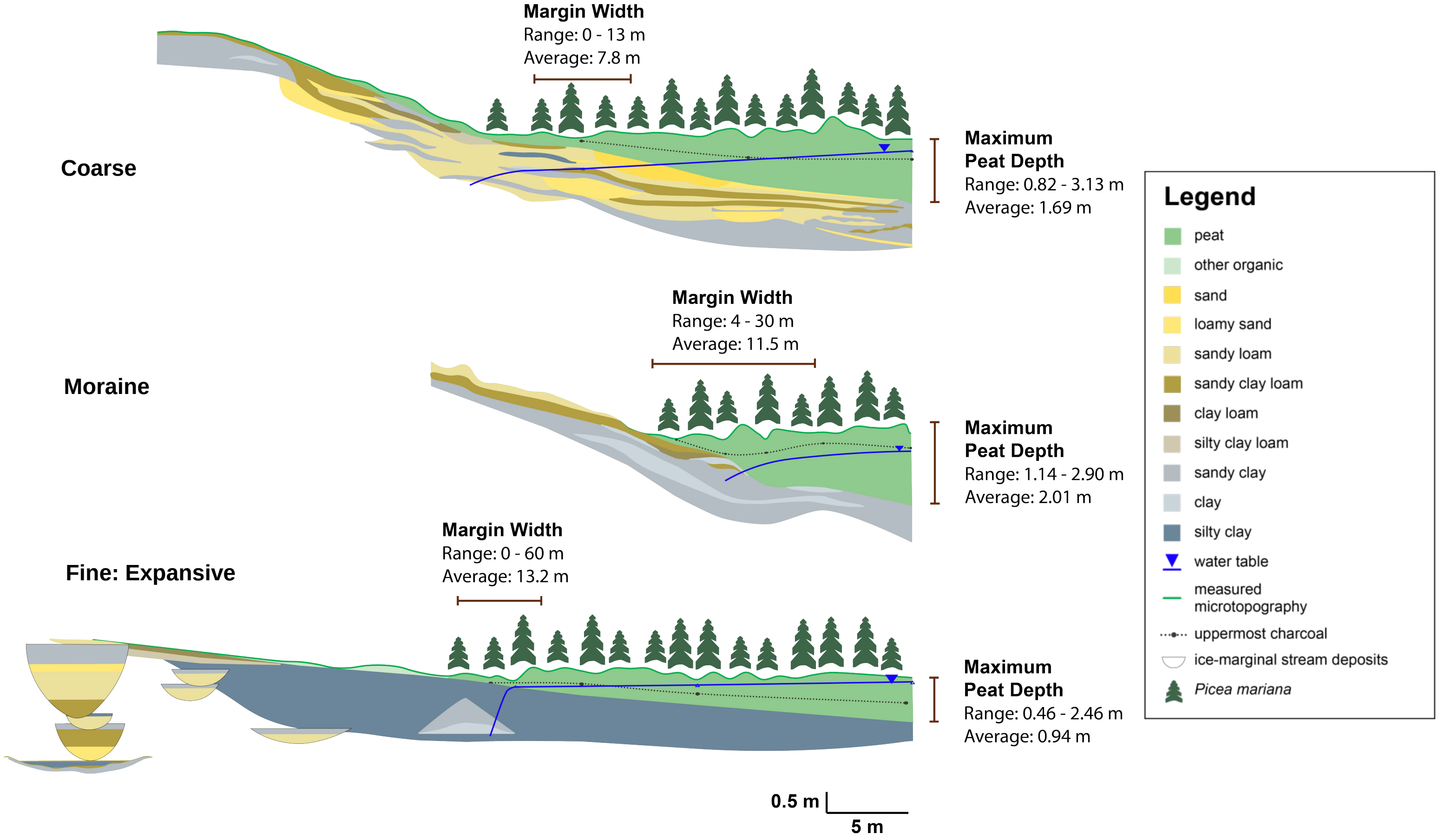

Figure 2: Observed sediment and peatland characteristics within the three main hydrogeological categories. Sedimentology, microtopography, water table depth, and location of the uppermost charcoal layer are drawn based on field observation of HAIG1940B (Coarse), UTIK1956B (Moraine), and UTIK1935 (Fine: Expansive). Maximum peat depth and margin widths are calculated based on all study sites within the three main hydrogeological categories.

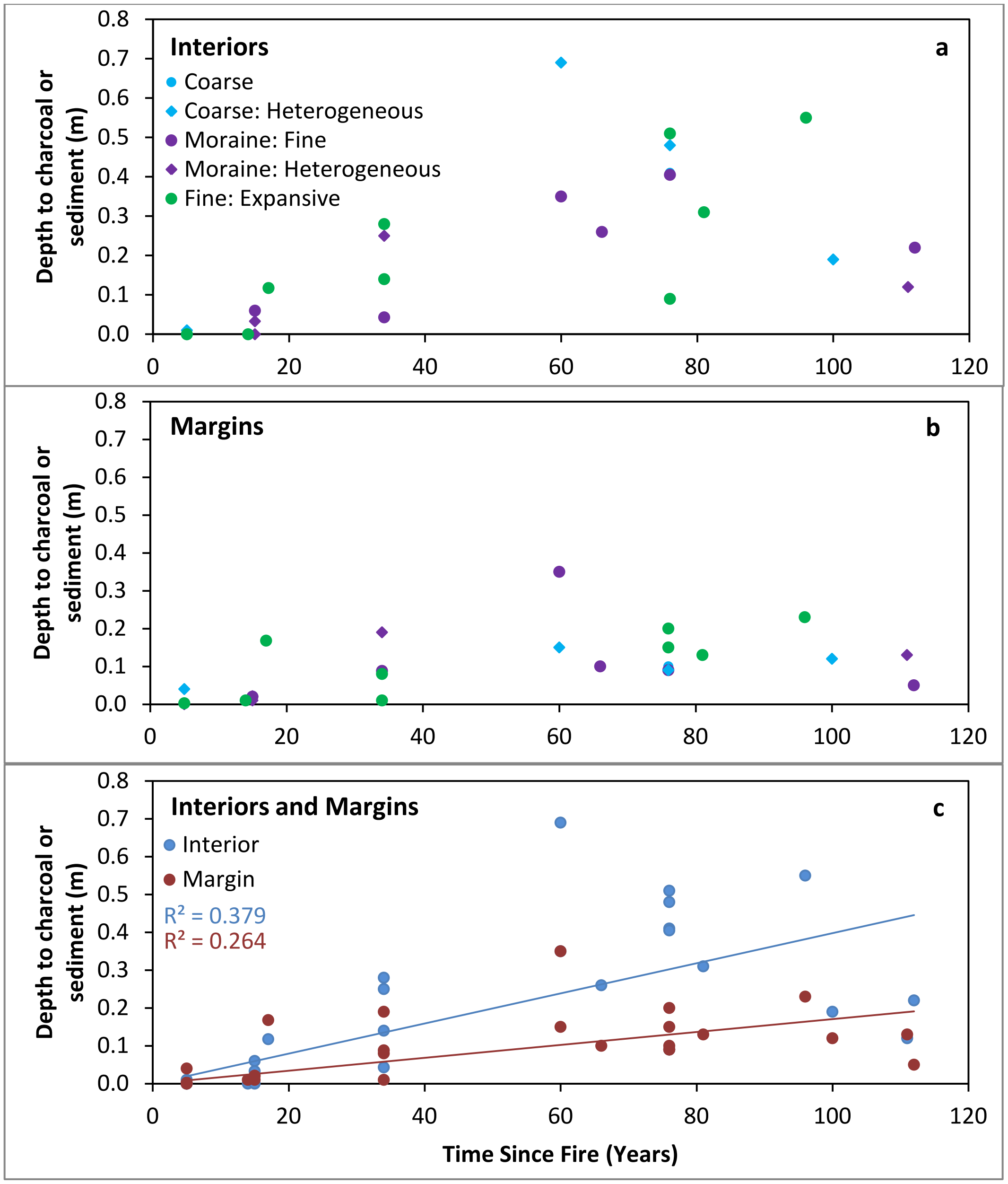

Figure 3a,b,c: Organic soil depth recovered following fire in observed peatland interiors (a) and margins (b), plotted against time since fire. Coloured points indicate interpreted hydrogeological setting of each site. Comparison between all interior and margin points, with trendlines showing the average rate of organic soil depth accumulation within investigated peatlands is shown in (c).

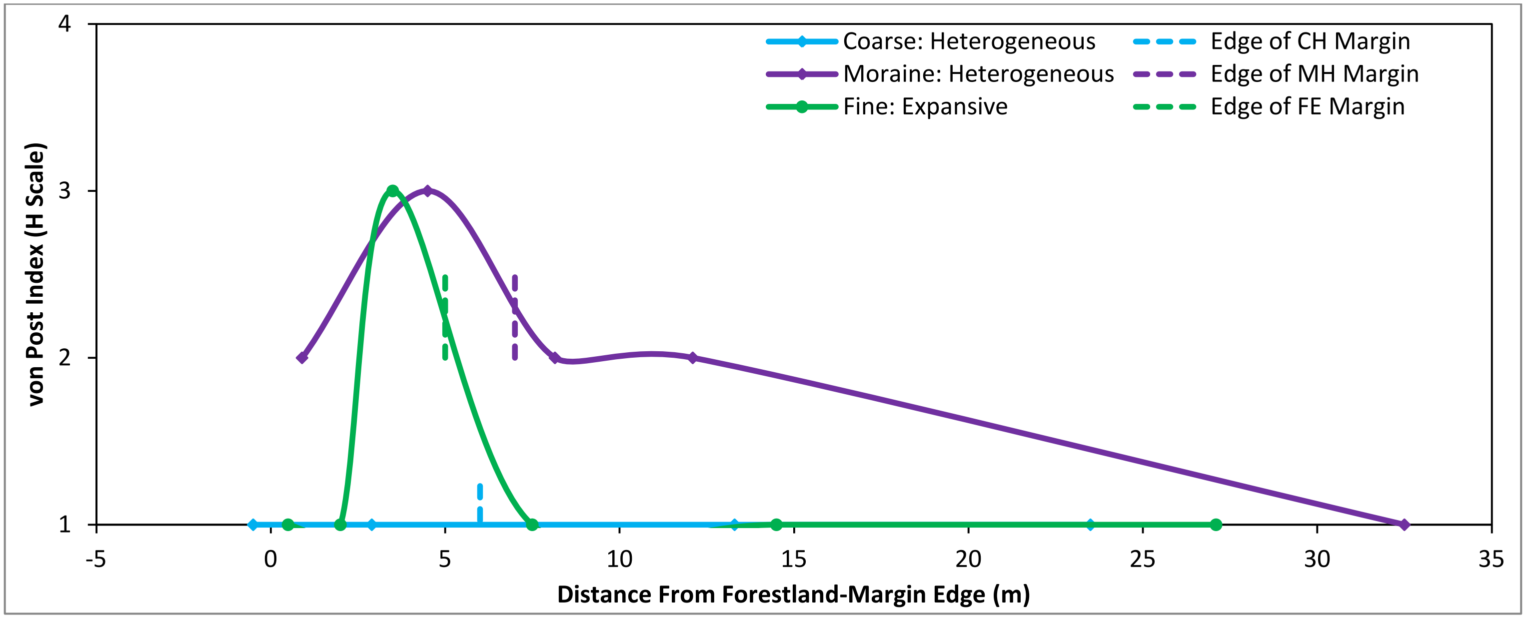

Figure 4: Observed level of decomposition (von Post) of peat observed at the ground surface along a transect from the forestland-margin edge (0 m) and into the peatland interior in three representative study sites. The inner boundary of the peatland margin is marked by a vertical line.

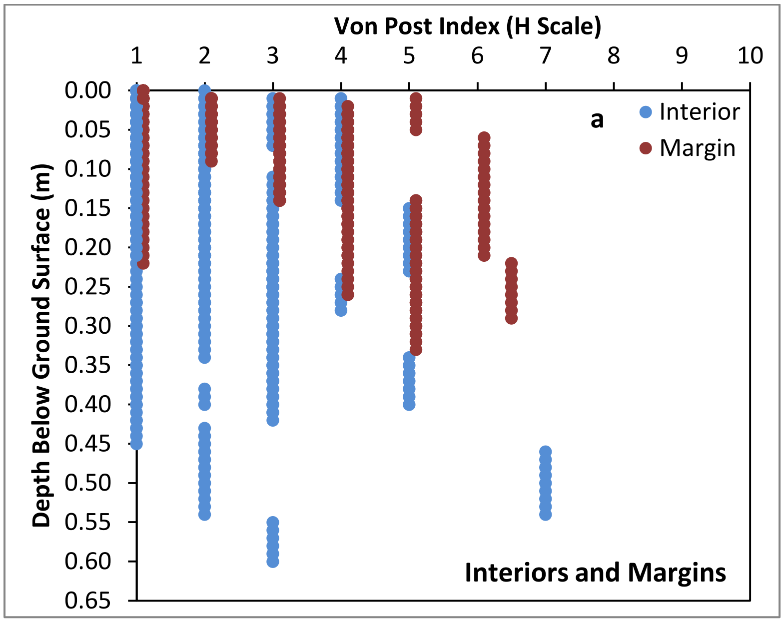

Figure 5a,b,c: Observed level of decomposition (von Post) of peat with depth above the uppermost charcoal layer at auger holes located furthest into the interior and in the middle of the margin. Differences in the increase in the level of decomposition of interior peat (blue) and margin peat (maroon) are visible in (a). Interior (b) and margin (c) data has also been formatted based on young (0-20 years since fire), medium (21-80 years), and old (>80 years) site age categories.

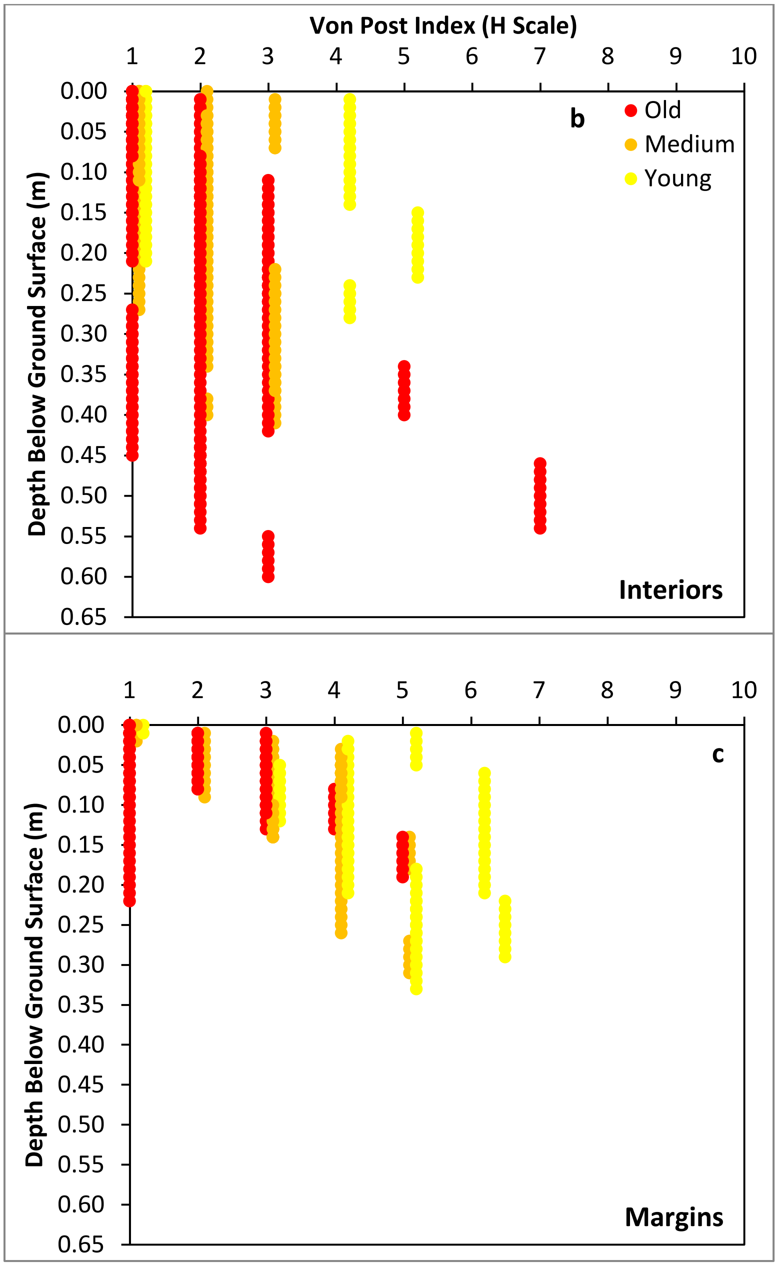

Figure 5a,b,c continued.

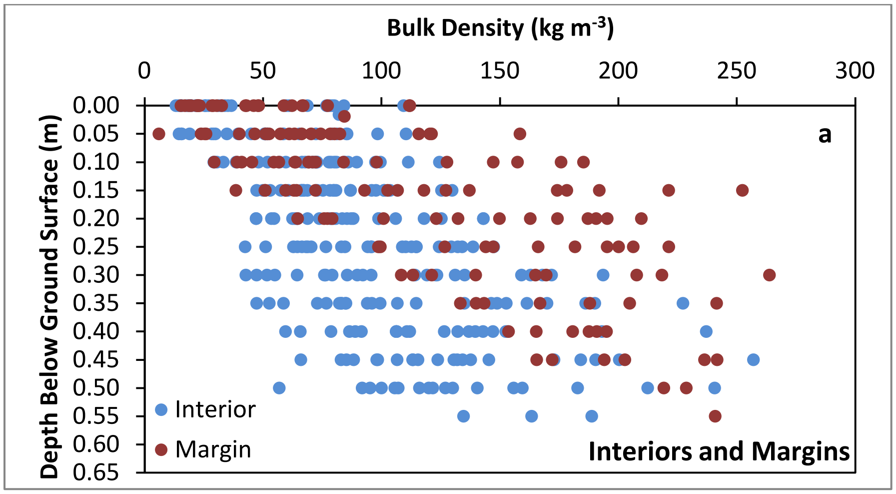

Figure 6a,b,c: Bulk density with depth below ground surface in peat cores removed from the interior and margin of each study site. Interior (blue) and margin (maroon) bulk densities are compared in (a), while (b) and (c) are formatted based on young (0-20 years since fire); medium (21-80 years); and old (>80 years) site age categories for the interior (b) and margin (c) cores.

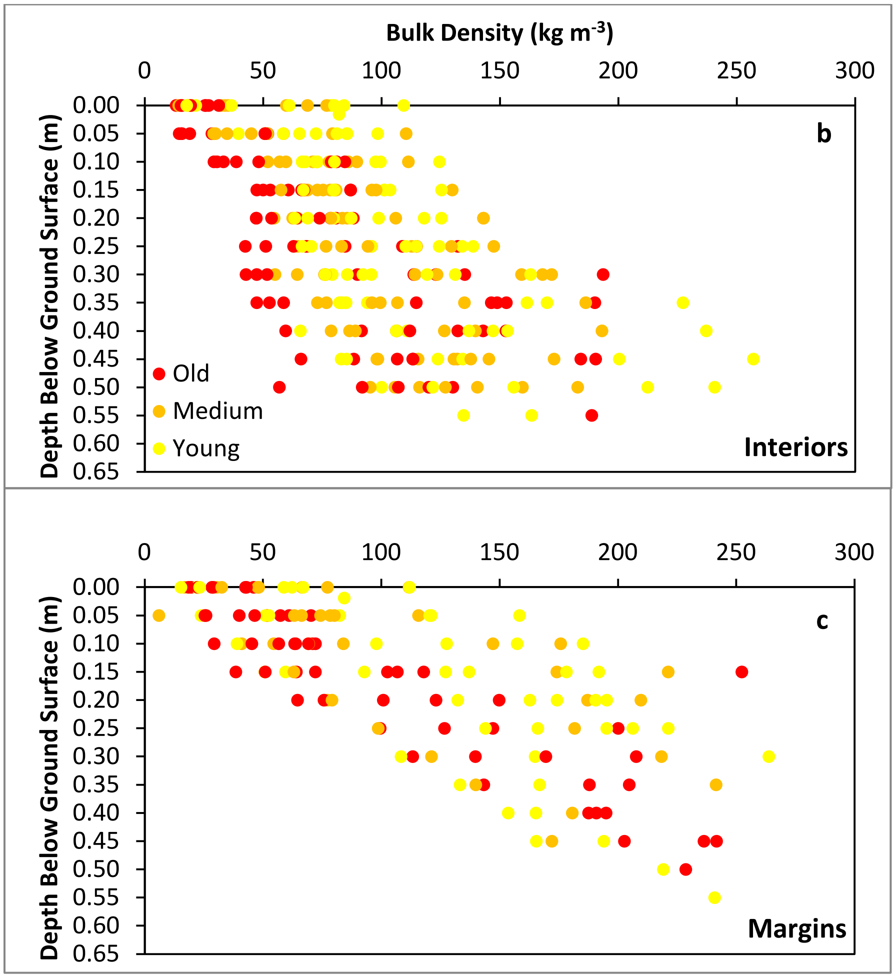

Figure 6a,b,c continued.

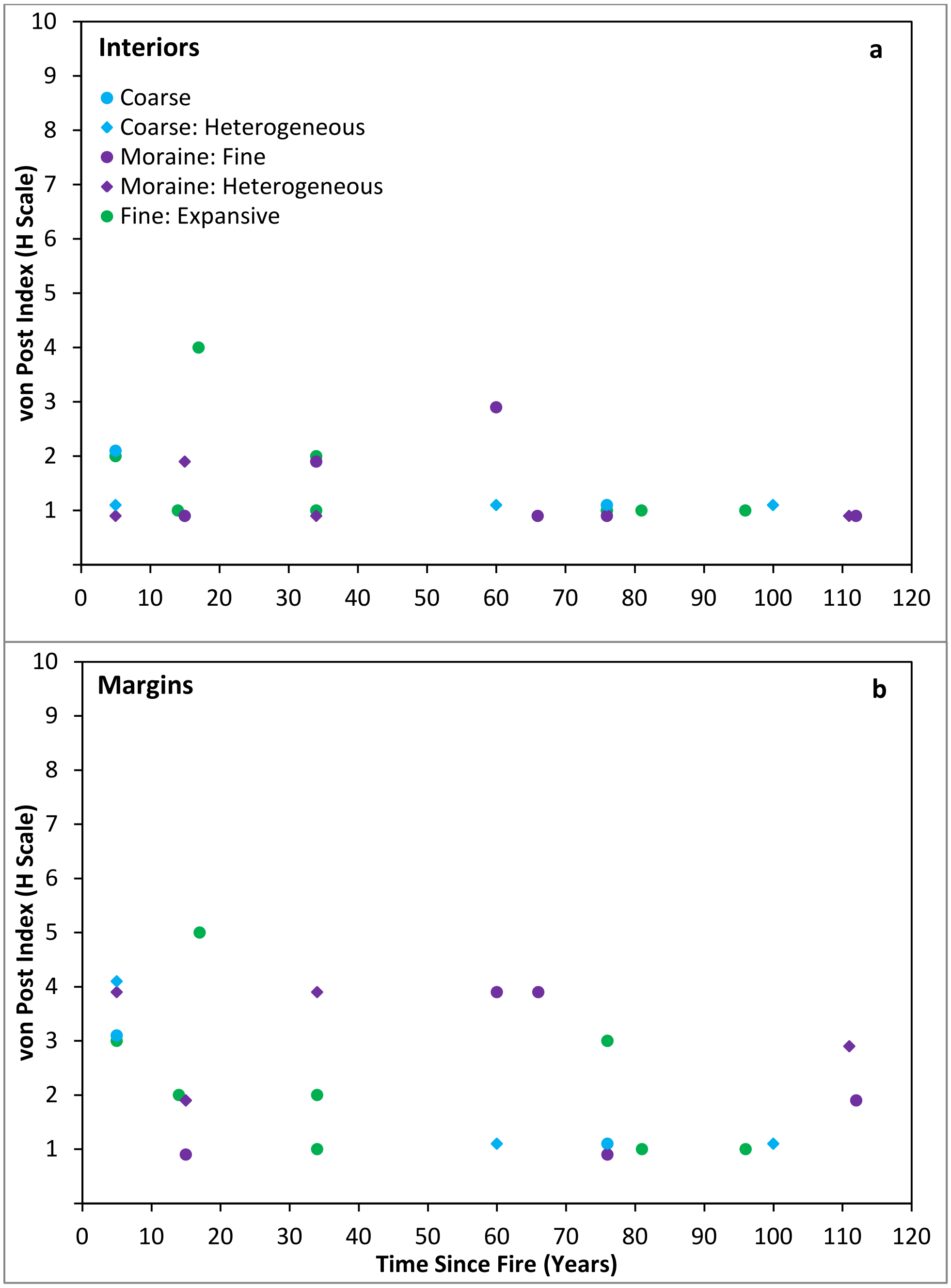

Figure 7a,b: Observed level of decomposition (von Post) of peat observed at the ground surface at the auger hole located furthest into the interior (a) and in the middle of the margin (b) of study sites plotted against time since fire. Coloured points indicate interpreted hydrogeological setting of each site.

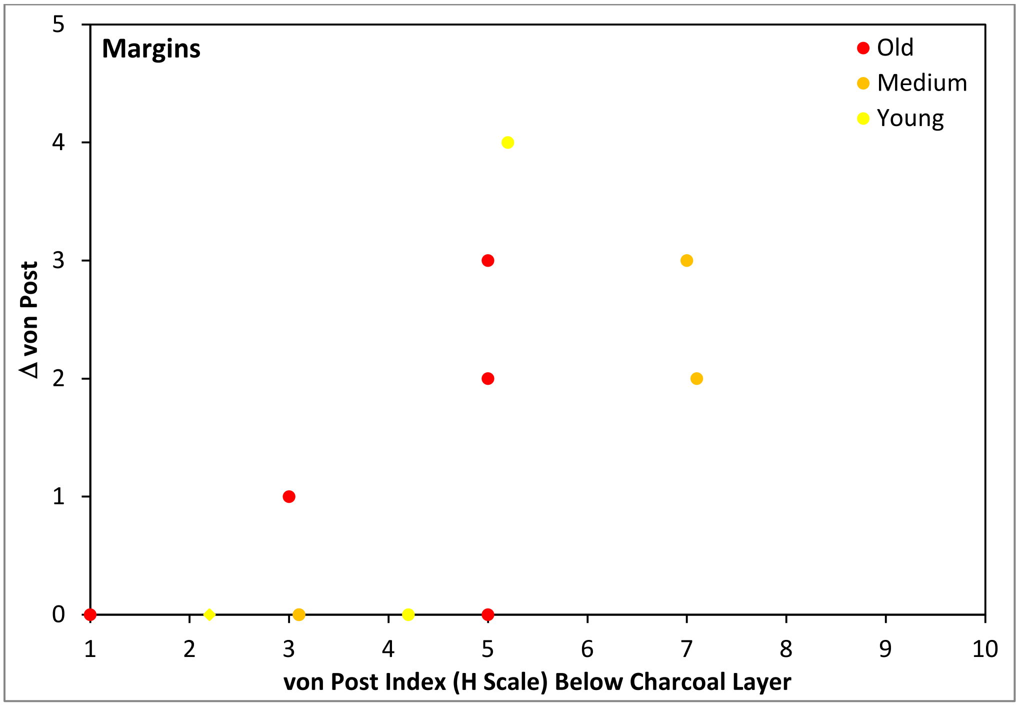

Figure 8: Change in level of decomposition (Δ von Post) of peat across the uppermost charcoal layer in the peat profile plotted against the level of decomposition (von Post) of the peat present below the charcoal layer. This is plotted using observations from an auger hole within the margin of each site where a charcoal layer was observed with peat present above and below the charcoal.

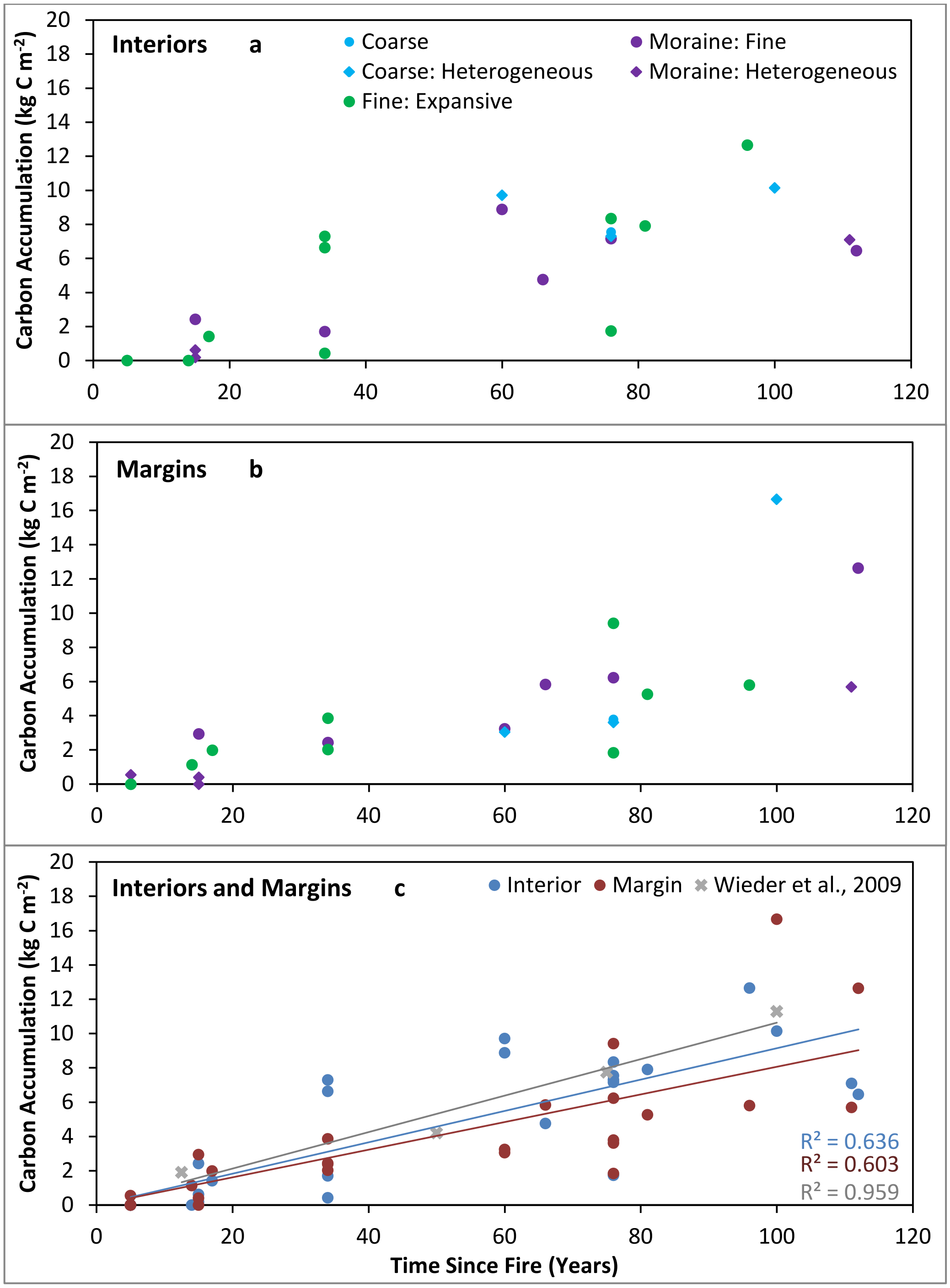

Figure 9a,b,c: Calculated organic soil carbon accumulation in the interior (a) and margin (b) of each study site, plotted against time since fire. Coloured points indicate interpreted hydrogeological setting. Comparison between all points, with trendlines showing the average rate of organic soil carbon accumulation within investigated peatlands across the Boreal Plains landscape is shown in (c).

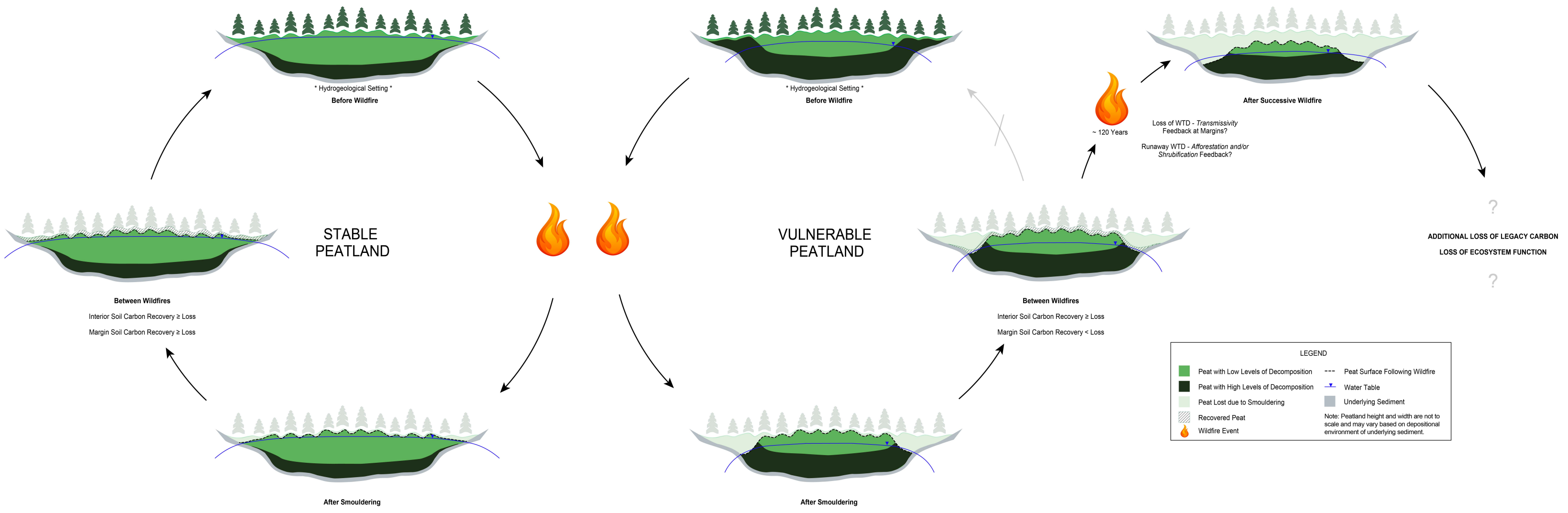

Figure 10: Conceptual model of peatland resilience following wildfire on the Western Boreal Plains of Alberta based on average organic soil carbon accumulation rates in peatland interiors and margins estimated in this thesis, combined with published values of organic soil carbon loss during wildfire (Hokanson *et al.*, 2016; Lukenbach *et al.*, 2015b). Peatlands which experience moderate depths of burn at the margins are expected to recover lost carbon within the fire return interval, and are therefore considered stable on the landscape under the current climate (Stable Peatland cycle). Conversely, peatlands which undergo severe smouldering at the margins during wildfire are unlikely to recover lost carbon at the margins before subsequent wildfire, resulting in permanent loss of legacy carbon and uncertain fate of the peatland system (Vulnerable Peatland cycle).

Table 1: List of chronosequence study sites with classifications based on time since fire and observed sedimentology. Sites are sorted based on hydrological response area (HRA) classifications. Continued on following page.

| **Site Name** | **Easting** | **Northing** | **Zone** | **Area* (ha)** | **Fire Year (~Approx)** | **Time Since Fire** (Years)** | **Age Category***** | **HRA Category***** |
|---|---|---|---|---|---|---|---|---|
| Loon1940 | 618032 | 6328292 | 11 | 6.9 | ~1940 | >76 | Old | Coarse |
| Utik2011C | 580739 | 6219560 | 11 | 0.5 | 2011 | 5 | Young | Coarse |
| Utik1916 | 593009 | 6214108 | 11 | 0.7 | ~1916 | >100 | Old | Coarse: Heterogeneous |
| Haig1940B | 553337 | 6308376 | 11 | 0.4 | ~1940 | >76 | Old | Coarse: Heterogeneous |
| Utik1956A | 595669 | 6211969 | 11 | 0.6 | 1956 | 60 | Medium | Coarse: Heterogeneous |
| Utik2011D | 598997 | 6220012 | 11 | 0.4 | 2011 | 5 | Young | Coarse: Heterogeneous |
| NWab1920 | 686086 | 6209980 | 11 | 34.1 | ~1920 | >96 | Old | Fine: Expansive |
| Utik1935 | 619549 | 6194079 | 11 | 35.7 | 1935 | 81 | Old | Fine: Expansive |
| SWab1940A | 335410 | 6199670 | 12 | 26.1 | 1940 | 76 | Medium | Fine: Expansive |
| SWab1940B | 333471 | 6200089 | 12 | 136.2 | 1940 | 76 | Medium | Fine: Expansive |
| NWab1982 | 682434 | 6214709 | 11 | 129.7 | 1982 | 34 | Medium | Fine: Expansive |
| RECr1982 | 605355 | 6249569 | 11 | 307.0 | 1982 | 34 | Medium | Fine: Expansive |
| Peli1999 | 352797 | 6186502 | 12 | 3.1 | 1999 | 17 | Young | Fine: Expansive |
| Loon2002 | 634588 | 6329101 | 11 | 6.6 | 2002 | 14 | Young | Fine: Expansive |
| Utik2011A | 614429 | 6205313 | 11 | 5.4 | 2011 | 5 | Young | Fine: Expansive |
| Utik1904 | 591471 | 6216082 | 11 | 0.4 | ~1904 | >112 | Old | Moraine: Fine |
| Haig1940A | 553240 | 6306764 | 11 | 1.0 | ~1940 | >76 | Old | Moraine: Fine |
| Peli1950 | 349205 | 6185797 | 12 | 0.7 | ~1950 | >66 | Medium | Moraine: Fine |
| Utik1956B | 595802 | 6210662 | 11 | 0.6 | 1956 | 60 | Medium | Moraine: Fine |

| Site Name | Easting | Northing | Zone | Area* (ha) | Fire Year (~Approx) | Time Since Fire** (Years) | Age Category*** | HRA Category*** |
|---|---|---|---|---|---|---|---|---|
| Ottr1982A | 568475 | 6269535 | 11 | 1.4 | 1982 | 34 | Medium | Moraine: Fine |
| Ottr2001B | 569649 | 6266860 | 11 | 0.4 | 2001 | 15 | Young | Moraine: Fine |
| Utik1905 | 592774 | 6214080 | 11 | 1.2 | ~1905 | >111 | Old | Moraine: Heterogeneous |
| Ottr1982B | 576971 | 6267292 | 11 | 0.2 | 1982 | 34 | Medium | Moraine: Heterogeneous |
| Ottr2001A | 570778 | 6266861 | 11 | 1.0 | 2001 | 15 | Young | Moraine: Heterogeneous |
| Ottr2001C | 569914 | 6266709 | 11 | 1.7 | 2001 | 15 | Young | Moraine: Heterogeneous |
| Utik2011B | 596223 | 6207777 | 11 | 1.1 | 2011 | 5 | Young | Moraine: Heterogeneous |

* For sites >5.0 ha in area, the peatlands are generally expansive systems and the mapped portion of the peatland generally underestimates total peatland area.

**Time Since Fire: Determined using the Canadian Forest Service National Fire Database (Natural Resources Canada, 2017) and aerial photographs, followed by tree age data in cases when Canadian Forest Service fire polygon data was unavailable (see Housman, 2017 for details). When the date is uncertain, the ">" symbol is used.

***Age Category: Assigned to sites based on time since fire, with Young consisting of 0-20 years, Medium as 21-80 years, and Old being >80 years since fire. Sites >76 years since fire are assumed to be Old.

*** Hydrological Response Area (HRA) Category: Classified based on observations of soil texture and landscape topography at each study site, used to interpret paleoenvironment of sediment deposition, sediment textural classes, and expected hydrogeological setting.

Table 2: Description of paleoenvironmental and textural classifications used to determine hydrological response areas (HRAs) of study sites based on observed sedimentology and topography. Continued on following page.

| **Paleo-environment** | **Textural Classification** | **Final HRA Categories** | **Relation to Devito *et al.* (2012, 2017) HRAs** | **General Properties** |
|---|---|---|---|---|
| Stagnant Ice Moraine | Mainly Fine | Moraine: Fine | Fine textured (2012)<br>Hummocky moraine (2017) | Sediments are heterogeneous, but mainly characterized by sandy clays (various densities, but in general, dense) containing pebbles of various sizes and levels of rounding.<br>Some sites contain sedimentological evidence of local glaciolacustrine influence, minor and major glaciofluvial influence.<br>Hummocky landscape topography. |
| | Heterogeneous, predominantly fine | Moraine: Heterogeneous | Fine textured (2012)<br>Hummocky moraine (2017) | |
| | Heterogeneous, predominantly coarse | Coarse: Heterogeneous | Possibly:<br>Veneer type (2012)<br>Hummocky moraine (2017) | |
| Glaciofluvial Outwash | Coarse | Coarse | Coarse textured (2012, 2017) | Sedimentology dominated by coarse grained sediments with minimal amounts of fine grains present.<br>Mainly hummocky landscape topography, some with minimal topographic change. |
| | Heterogeneous, predominantly coarse | Coarse: Heterogeneous | Possibly:<br>Veneer type (2012)<br>Hummocky moraine (2017) | |
| Glacio-lacustrine | Mainly Fine | Fine: Expansive | Fine textured (2012)<br>Clay-plain (2017) | Fine grained sediments, especially silty clay, dominate sedimentology.<br>Minimal landscape topography changes and low slope of sediment surface (for the majority of sites) leading to large and often expansive peatland areas. |

| **Paleo-environment** | **Textural Classification** | **Final HRA Categories** | **Relation to Devito *et al.* (2012, 2017) HRAs** | **General Properties** |
|---|---|---|---|---|
| Subglacial Till Sheet | Mainly Fine | Fine: Expansive | Fine textured (2012)<br>Clay-plain (2017) | Mainly dense sandy clays, but with areas of coarser sediments, including gravel lenses.<br>Minimal landscape topography changes and low slope of sediment surface (for the majority of sites) leading to large and often expansive peatland areas. |

Table 3: Description of statistical analysis methods employed, including brief details on the reasoning behind each method and the results of the analyses. Continued on following page.

| Purpose of Analysis | Test Employed | Data Used | Result |
|---|---|---|---|
| Investigate for normality of data distribution | Visual analysis of boxplot<br>Visual analysis of Normal Quantile-Quantile plot<br>Shapiro-Wilks test for normality | Total Soil Carbon Accumulation (Interiors and Margins)<br>Recovered Peat Depth (Interiors and Margins) | Total Soil Carbon Accumulation in Interiors and Margins are not normally distributed. Nor is accumulated peat depth in Interiors or Margins.<br>Transformation of data towards normality, or non-parametric analysis methods necessary. |
| Transform data towards normality | Rank Transformation | Total Soil Carbon Accumulation (Interior and Margins)<br>Recovered Peat Depth (Interiors and Margins) | Data distribution closer to normality.<br>Note: still outside of normality for total soil carbon accumulation in interiors, and recovered peat depth in interiors. |
| Test the effect of hydrogeological category and time since fire on recovery | ANCOVA<br>Analysis of Covariance | Ranked Total Soil Carbon Accumulation<br>HRA Categories<br>Time Since Fire | Time since fire has a significant effect on total soil carbon accumulation in the interior and margins; no significant effect of HRA observed. |
| Test if the mean of two paired samples are statistically different. Thus, test if the mean of soil carbon accumulation in the peatland margin is different from the interior | Paired t-test | Ranked Total Soil Carbon Accumulation | Weakly significant difference observed between margin and interior total soil carbon accumulation. |

| Purpose of Analysis | Test Employed | Data Used | Result |
|---|---|---|---|
| Test if recovered peat depth in the margins is significantly different from that in the interiors | Paired t-test | Ranked Recovered Peat Depth | There is a statistically significant difference between recovered peat depth in the margin and interior of sites. |
| Test for significant difference between measured interior soil carbon accumulation with time and Wieder *et al.* (2009) values | Full Factorial Analysis using Interior and Wieder *et al.* as factors to assess if the slope of carbon accumulation with time trendline depends on different factors (*i.e.*, measurement in this study or by Wieder *et al.*) | Total Soil Carbon Accumulation in Interiors<br>Understory Net Ecosystem Productivity from Wieder *et al.*, 2009 | No statistical difference between the slope of the linear regression line of carbon accumulation with time based on values measured in peatland interiors during this study, and those recorded in Wieder *et al.* (2009). |
| Determine if the decomposition of peat observed at the surface changes with time in interiors and margins | Mann-Kendall trend test | von Post measurements of surface peat from the innermost auger hole and from the middle of the margin at each site | Significant trend in surface von Post with time in Interiors, and weakly significant trend in surface von Post with time in Margins. |
| Test for significant trend in peat decomposition with depth | Mann-Kendall trend test | von Post measurements with depth in the innermost auger hole and middle of the margin | Significant trend in von Post with depth in 23 of 25 Interiors, and 19 of 25 Margins analyzed. |

Table 4: Detailed results of paired t-test, ANCOVA, full factorial analysis, and Mann-Kendall trend test used in analyses. Statistical significance of p-values are indicated by *** (strongly significant: $p < 0.01$), ** (significant: $0.01 < p < 0.05$), or * (weakly significant: $0.05 < p < 0.1$). Continued on following pages.

| Test | Data Used | p-value | Ratio value | Interpretation |
|---|---|---|---|---|
| Paired t-test | Margin and interior recovered peat depth | 0.004*** | t-Ratio = -3.158 | We reject the null hypothesis that the mean difference between interior and margin peat depth is zero. There is a strongly significant difference in the depth of peat recovered in the margin and interior following wildfire. |
| | Ranked interior and margin total soil carbon accumulation | 0.103* | t-Ratio = 1.691 | We reject the null hypothesis that the mean difference between peatland interior and margin values is zero. The soil carbon accumulation in interiors is weakly significantly different from that in the margins with a 90% confidence interval. |
| | Ranked interior and margin total soil carbon accumulation rate | 0.743 | t-Ratio = 0.331 | We do not reject the null hypothesis that the mean difference is zero. The soil carbon accumulation rates for the interior and margin at each study site are not significantly different. |

| Test | Data Used | p-value | Ratio value | Interpretation |
|---|---|---|---|---|
| ANCOVA | Ranked total soil carbon accumulation (Interior and Margin values assessed separately)<br>Factors: time, HRA categories (heterogeneous distinctions and summarized categories) | **Interior**<br>Time: <0.001***<br>HRA (all): 0.704<br>HRA (summarized): 0.450<br>**Margin**<br>Time: <0.001***<br>HRA (all): 0.259<br>HRA (summarized): 0.770 | F-Ratios<br>**Interior**<br>Time: 26.819 (all HRA considered)<br>HRA (all): 0.546<br>HRA(summarized): 0.829<br>**Margin**<br>Time: (all HRA considered) 60.210<br>HRA (all): 1.437<br>HRA(summarized): 0.265 | The effect of time since fire on total soil carbon accumulation is strongly significant in both the interiors and margins.<br>Hydrogeological categories (all five HRA categories including heterogeneous distinctions, and three summarized categories) do not significantly affect the amount of soil organic carbon which has accumulated post-fire. |
|  | Ranked soil carbon accumulation rate (Interior and Margin values assessed separately)<br>Factors: time, HRA categories (heterogeneous distinctions and summarized categories) | **Interior**<br>Time: 0.094*<br>HRA (all): 0.966<br>HRA (summarized): 0.992<br>**Margin**<br>Time: 0.430<br>HRA (all): 0.226<br>HRA (summarized): 0.266 | F-Ratios<br>**Interior**<br>Time: (all HRA considered) 3.094<br>HRA (all): 0.138<br>HRA summarized): 0.008<br>**Margin**<br>Time: (all HRA considered) 0.649<br>HRA (all): 1.550<br>HRA(summarized): 1.405 | Time since fire has a significant effect on the rate of carbon accumulation in the interior of study sites, but does not have a significant effect in the margins.<br>Hydrogeological setting did not have a significant effect on soil carbon accumulation rate in the studied peatlands. |

| Test | Data Used | p-value | Ratio value | Interpretation |
|---|---|---|---|---|
| Linear Regression of carbon accumulation against time with data from this study and from Wieder *et al.* (2009) as factors, full factorial to assess effects factors on the slope of the trendlines | Total Soil Carbon Accumulation in Interiors<br>Understory Net Ecosystem Productivity from Wieder *et al.* (2009) | 0.629 | 0.239 | Condition (this study or Wieder *et al.*) does not have a significant effect on carbon accumulation with time (*i.e.* There is no statistically significant difference between my results and the results of Wieder *et al.* (2009)). |
| Mann-Kendall trend test | von Post of surface peat with time since fire (Interior and Margin assessed separately) | **Interior**<br>0.033** (two-sided)<br>**Margin**<br>0.076* (two-sided) | **Interior**<br>τ = -0.347<br>**Margin**<br>τ = -0.279 | The null hypothesis, that no trend is present, is rejected for both interiors and margins. There is a significant trend in von Post with time in the interiors and a weakly significant trend in margins. |
| | von Post of peat with depth (Interior and Margin data from 25 peatlands all assessed separately) | **Interior**<br>Significant trend with depth in 23 of 25 sites analyzed; strongly significant in 22, significant in 1, no trend observed in 2.<br>**Margin**<br>Significant trend with depth in 19 of 25 sites analyzed; strongly significant in 15, significant in 4, not significant in 2, no trend observed in 4.<br>Note: p-values and τ not reported here due to quantity of analyses. | | |

## Appendix A: Sedimentological details used in paleoenvironmental and textural classification

Additional details regarding the sedimentology used in the interpretation of paleoenvironments and the textural classes found therein are presented below.

### *Stagnant Ice Moraine*

The observed sediments were heterogeneous, but mainly characterized by sandy clays containing pebbles of various sizes and levels of rounding. Sediment density varied, but was generally dense. Variations in classification categories within this paleoenvironment exist due to sediments interpreted to have been deposited through glaciolacustrine and glaciofluvial influence. One variation, *local glaciolacustrine influence* (via ponding in the depression during or following deglaciation), is interpreted based on the presence of silty clays in the peatland interior which were observed or assumed to be overlying sandy clays seen in the upland. *Local glaciofluvial influence*, a second variation, is based on the frequent observation of one auger hole at a site with a majority of coarse grained sediments, or multiple auger holes with a small amount of coarse sediments within the sediment profiles (not only at the top of the profile which could be due weathering). When the majority of sediments found during augering were coarse (*i.e.* several auger holes having thick sections of coarse sediments or very poor sediment recovery implying coarse sediments), but finer grained sediments than would be expected from an outwash area were also present along with hummocky topography, *larger scale glaciofluvial influence* is interpreted to have occurred.

Sediment textural classes within the stagnant ice moraine paleoenvironment include: *Mainly Fine; Heterogeneous, predominantly fine; and Heterogeneous, predominantly coarse*. These translate into the final hydrological response area (HRA) categories used in this thesis of *Moraine: Mainly Fine; Moraine: Heterogeneous*; and *Coarse: Heterogeneous* (see Table 2 for comparison of HRA categories used in this thesis with those from (Devito *et al.*, 2012 and 2017). Many SIM sites are dominated by fine sediments (clays and clay loams), thus given a *Moraine: Mainly Fine* classification. Sites were also placed into this category when small heterogeneities existed in their sedimentology (such as a very small quantity of coarser materials like sandy loam and sandy clay loam present and possibly due to weathering based on their location above sandy clay present in the upland), however they were still mainly fine grained. Several of the sites formed in a stagnant ice moraine paleoenvironment had a single auger hole which was dominated by coarse materials, or contained coarse material at several of the auger holes which may or may not have been adjacent. However, the coarse material was not the dominant material found at the site, was not likely to be continuous/connected, and/or was not present throughout the site. These sites were given a *Moraine: Heterogeneous* classification. The HRA category of *Coarse: Heterogeneous,* was given to sites where the majority of the sediment found when augering was coarse grained. These sites often had fine and coarse sediments layered at most of the auger holes, with the thicknesses and order of the sediment layers varying from one hole to the next. These sites were either observed to be confined by clays typical of a stagnant ice moraine area, or were assumed to be bound by fine grains outside of the depth augered based on the site's interpreted paleoenvironment (as per surficial geology mapping, air photo imagery and landscape topography).

### *Glaciolacustrine*

Sites were interpreted as having formed on sediments from this glacial paleoenvironment based on the presence of silty clays found when augering, combined with large, expansive peatland areas, minimal landscape topography changes, and low slope of the sediment surface (for the majority of sites). While smaller peatlands are present on the landscape in depressions within glaciolacustrine deposits that have a greater amount of topography change (even up to hummocky topography; Balzer *et al.*, 1995), expansive peatland systems were chosen in this paleoenvironment during site selection as they compose a large proportion of the Boreal Plains landscape in the study area. Some study sites had dense sandy clays (containing pebbles) present in the upland, overlain by silty clays in the peatland interior. This led to the creation of a *glaciolacustrine over subglacial till sheet* subcategory, with interpreted deposition of subglacial till sheet sediments which underwent flooding and deposition of silty clays during or following deglaciation.

The textural class for sediments deposited in a glaciolacustrine paleoenvironment is *Mainly Fine*, with an HRA classification of *Fine: Expansive*. The dominant sediment at these sites was very fine (usually silty clay), with some of the sites having an upland characterized by subglacial sediments (sandy clay, and occasionally some thin clay loams or even loams, possibly due to weathering).

### *Subglacial Till Sheet*

A few of the peatland sites were found to be located on dense sandy clays with areas of coarser sediments, including gravel lenses. These sites are large in area, formed on a landscape with minimal topography changes. Though the observed sedimentology was very similar to that found in stagnant ice moraine paleoenvironments, the topography was much more subdued than expected of and observed in stagnant ice moraine settings. Thus, these peatland sites were interpreted as having formed on top of subglacial sediments, but on a till sheet that was not dominated by stagnating ice blocks during deglaciation. It is worth noting that the subglacial till sheet deposits like those observed during this study are referred to in some surficial geology maps as "moraine" (e.g. Fenton *et al.*, 2013) and in some AGS reports as "ground moraine" (e.g. Henderson, 1959).

The textural and HRA classification for sites in this paleoenvironment are *Mainly Fine* and *Fine: Expansive.* Sites which have very low slopes from upland to peatland and are part of large, expansive systems were classified into this category along with glaciolacustrine sites. Though the sedimentology of these subglacial till sheet areas sometimes contains zones of coarse material and is more comparable to sites within the stagnant ice moraine category than the glaciolacustrine category, it is dominated by fine grains (clays), and the slope of the sediment surface; peat depth along the transect; and size of the peatlands are more comparable to the glaciolacustrine sites than the stagnant ice moraine sites. Thus, peatlands within the subglacial till sheet category are expected to behave more similarly to expansive glaciolacustrine sites than stagnant ice moraine sites (in terms of runoff response and water table drawdown due to upland aspen), and were grouped with the glaciolacustrine sites during textural and HRA classification.

### *Glaciofluvial Outwash*

Sites in this category are dominated by coarse grained sediments with minimal amounts of fine grains present. Regional topography is mainly hummocky, however one site exists in an area with minimal topographic change.

Textural classes for sites within this paleoenvironment include *Coarse* and *Heterogeneous, predominantly coarse*. These are translated into final HRA categories of *Coarse* and *Coarse: Heterogeneous*. The *Coarse* category contains two sites which had no or very little fine grains present; rather, sedimentology was dominated by sands. One of these sites is in an area of hummocky topography with a very steep sediment slope, while the other has a low sediment slope and is an expansive system. The remainder of the sites fall within the *Coarse: Heterogeneous* HRA category. Coarse sediments layered with finer sediments in varying orders and thickness characterized this textural class. Sites in this category are present in a landscape dominated by hummocky topography which implies melting ice blocks following burial by glaciofluvial sediments. Due to the implied presence of glacial ice, it is assumed that subglacial fine grained sediments ultimately underlie these sites. The paleoenvironment for these sites may include stagnant ice moraine influence, however sites were classified into a glaciofluvial/coarse category due to the predominance of coarse grained sediments and interpreted major influence of glaciofluvial processes.

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