EXAMINING ECOHYDROLOGICAL APPROACHES TO REDUCE PEAT SMOULDERING POTENTIAL IN BLACK SPRUCE PEATLANDS

EXAMINING ECOHYDROLOGICAL APPROACHES TO REDUCE PEAT SMOULDERING POTENTIAL IN BLACK SPRUCE PEATLANDS

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ABSTRACT

As wildfires increase in frequency, severity, and areal extent in western Canada's boreal region, wildfire managers are challenged with maintaining current levels of effectiveness. Review of recent wildfire events have identified a need for an improved understanding of vegetation management as a means to mitigate risk of future fires in the wildland-urban and wildland-industry interfaces. Peatlands cover 21% of the land area in continental western Canada; however, there is a lack of peatland-specific fuel modification strategies. The unique ecohydrological feedbacks that operate in these ecosystems provide an opportunity to implement novel peatland-specific treatments in these areas. This thesis examines the effectiveness of novel peatland-specific fuel modification treatments derived from seismic line analogs in reducing the smouldering potential of near-surface moss and peat.

An ecohydrological assessment of seismic lines bisecting bogs revealed that alterations to canopy structure and physical peat properties at the time of seismic line establishment leads to persistent changes to the ecohydrological structure and functioning of these systems, marked by limited regeneration of vegetation, dominance of *Sphagnum* groundcover, and greater near-surface volumetric water contents. Such traits are desirable in fuel modification strategies and therefore, we incorporated the seismic line framework into conventional fuel reduction approaches to create novel peatland-specific fuel modification treatments, involving alterations to canopy structure (thinning and clearing) and physical peat properties (compression). The short-term effects are compression-induced changes to hydrophysical properties including elevated mean near-surface volumetric water contents. Ecological and hydrological indicators of moss moisture stress suggest long-term effects likely include an expansion of *Sphagnum* moss ground cover within thinned and cleared areas. Ultimately, both short- and long-term effects contribute to the reduction of smouldering potential in near-surface moss and peat. We propose that these peatland-specific fuel modification treatments be incorporated into current FireSmart fuel strategies to reduce wildfire smouldering risk at the wildland-urban and wildland-industry interfaces.

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LIST OF ABBREVIATIONS

Net Primary Productivity	NPP
Photosynthetically Active Radiation	PAR
Photosystem Two	PSII
Polyvinyl Chloride	PVC
Saturated Hydraulic Conductivity	K_{sat}
Seismic Line	SL
Unsaturated Hydraulic Conductivity	K_{unsat}
Volumetric Water Content	VWC
Water Table	WT

DECLARATION OF ACADEMIC ACHIEVEMENT

The written material contained in this thesis dissertation has been prepared solely by this author. The research design is, however, a result of collaborative efforts of the McMaster Ecohydrology Lab and Alberta Agriculture and Forestry, notably Dave Schroeder, who coordinated work at the Pelican Mountain research site, the basis for Chapter 3 of this thesis. Contributions from this author include seismic line site selection and collection and analysis of field data and organic soil samples. Sophie Wilkinson contributed significantly to research design as well as assisting with fieldwork along with Greg Verkaik, Ryan Threndyle, the Alberta Fuels Inventory Crew, and the High Prairie Junior Forest Ranger Crew. Dr. Paul Moore contributed to research design and was instrumental in the analysis of canopy photographs.

CHAPTER 1: INTRODUCTION

1.1 Boreal Plains Peatlands

Peatlands, characterized as wetlands containing at least 0.4 m of organic material (National Wetlands Working Group, 1997), occupy approximately 21% of the land area in continental western Canada (Vitt et al., 2000). These ecosystems have developed throughout the Holocene to support a range of biodiversity (Whitehouse & Bayley, 2005), play an integral role in the landscape-scale water balance (Devito et al., 2012), and function as globally significant components of the carbon cycle (Gorham, 1991). Despite occupying only about 0.25% of the global land area, peatlands of Canada's Boreal Plains store approximately 48 Pg (1 Pg = 10^{15} g) of carbon in below ground stocks, equating to nearly 2.5% of all terrestrial carbon globally (Vitt et al., 2000). The spatial distribution of these peatlands is strongly controlled by climate and hydrogeological setting (Halsey et al., 1998). A sub-humid climate characterizes Canada's Boreal Plains ecozone, where mean annual precipitation (~480 mm) is generally exceeded by evapotranspiration (~520 mm) establishing a long-term water deficit (Devito et al., 2012; Ireson et al., 2015). Mean monthly temperatures range from 15.9 °C in the summer months to -18.7 °C in the winter months (Natural Regions Committee, 2006). The surficial geology is comprised of deep, heterogeneous glacial deposits, which can broadly be classified into one of three groups: coarse-textured outwash, fine-textured hummocky moraine, and lacustrine clay plains (Devito et al., 2012). The degree of hydrological connectivity is used to categorize peatlands in this region as predominantly minerotrophic fens or ombrotrophic bogs.

1.1.1 Peatland Mosses

Bryophytes are vital components in the ecohydrological functioning of peatlands on the Boreal Plains. Within black spruce (*Picea mariana*) dominated peatlands, bryophytes contribute to a significant portion of total peatland evapotranspiration (Bond-Lamberty et al., 2011) and their net primary productivity (NPP) has the ability to equal and even exceed that of overstory vegetation (Bisbee et al., 2001). *Sphagnum* and feather mosses are two bryophytes which dominate the ground cover in these ecosystems. The relative distribution of these mosses is controlled in part by the degree of canopy openness, which directly influences properties of the moss layer environment, including light availability (Bisbee et al., 2001). *Sphagnum* mosses commonly inhabit areas with high photosynthetically active radiation (PAR) transmittance, whereas feather mosses are commonly found in areas with lower PAR transmittance, especially when *Sphagnum* is also present (Bisbee et al., 2001). In bog ecosystems, the relative abundance of these moss types is tied to the wildfire regime. *Sphagnum* mosses typically dominate surface cover 20 years following a wildfire; however, tree growth reduces light availability at the surface level, thereby facilitating the succession to feather mosses between 60 – 80 years post-fire (Benscoter & Vitt, 2008). These groups of mosses are distinct both morphologically and physiologically and therefore, water and nutrient fluxes are dictated by the relative abundance of each moss type (Turetsky, 2003).

1.1.1.1 Sphagnum Mosses

Some species play the role of ecosystems engineers, where the functioning of these organisms acts to create, modify, and maintain the ecosystems which they inhabit (Jones et al. 2009). As a keystone peat-forming species (Rochefort, 2000) and the most abundant genus of surface vegetation in peat-forming ecosystems (Hayward & Clymo, 1982), *Sphagnum* mosses can be thought of as ecosystem engineers (van Breemen, 1995). *Sphagnum* has long been recognized for its ability to acidify the environment (Clymo & Hayward, 1982; Gorham & Janssens, 1992) exemplifying an ability to exclude vegetation that cannot tolerate such conditions. Decomposition rates in peatlands are limited by the cold, acidic environment induced by *Sphagnum* mosses, thereby promoting the accumulation of organic matter (Clymo & Hayward, 1982; Ise et al., 2008). The role of *Sphagnum* as an ecosystem engineer has been more recently conceptualized within the various autogenic feedback responses exhibited by peatlands (Waddington et al., 2015).

To better understand the role of *Sphagnum* mosses in peatland ecohydrology, one must first understand a bit about the structure and functioning of this genus. Bryophytes, such as *Sphagnum*, lack a vascular structure and therefore, must rely on alternative means of vertical water transport (Busby et al. 1978). In the case of *Sphagnum*, only about 10% of water content is actually stored internally (Proctor, 2000) while the remaining 90% is held externally between adjacent plant structures (Hayward & Clymo, 1982). Passive capillary forces to facilitate upward water movement from lower depths in the peat profile to the capitula at the moss surface to support physiological processes (Hayward & Clymo, 1982; Moore et al., 2015). As such, the factor limiting *Sphagnum* productivity and peat accumulation is often soil moisture (Hayward & Clymo, 1982; Williams & Flanagan, 1996). Pore-water pressure (ψ) is an important parameter connecting local hydrology and ecology in peatland systems (Thompson & Waddington, 2008). Pore-water pressure encompasses the water content in bryophytes both internally and externally, providing an advantageous approach when investigating ecosystem structure (e.g. spatial distribution of peatland mosses) or processes (e.g. nutrient fluxes) (Thompson & Waddington, 2008). Hayward and Clymo (1982) identified ψ = -100 hPa as the value lower than which hyaline cells, the water filled cells in *Sphagnum* mosses, begin to drain leading to desiccation. Ecological studies which use water table (WT) position as a means to explain the spatial distribution of bryophytes or water availability at the surface (e.g. Bisbee et al., 2001; Poulin et al., 2005) may undervalue the ability of some bryophytes to transport water to the moss surface via capillary action. For example, some hummock-forming *Sphagnum* mosses are able to obtain water up to 40 cm below the moss surface (Price & Whittington, 2010). Alternatively, soil moisture and pore-water pressure are two parameters shown to serve as better indicators of *Sphagnum* presence compared to WT position (Price & Whitehead, 2001). This is because the volumetric water content (VWC) and the gradient in pore-water pressure along with pore geometry influence the rate at which water is vertically transported to the moss surface via capillary action, commonly known as unsaturated hydraulic conductivity (K_{unsat}) (Hayward & Clymo, 1982; Price et al., 2008).

1.1.1.2 Feather Mosses

Feather mosses, such as *Pleurozium schreberi*, *Hylocomium splendens*, and *Ptilium crista-castrensis,* are also a common feature of peatlands on the Boreal Plains. Capillary water transport is less efficient in feather mosses compared to *Sphagnum* and as such, these mosses are reliant on precipitation events and dew formation as primary water sources (Busby et al., 1978; Longton & Greene, 1979). Due to this inconsistency in water supply, the NPP of feather mosses is generally significantly less than that of *Sphagnum* mosses (Bisbee et al., 2001). Moreover, feather mosses lack the density, structure, and mechanisms of *Sphagnum* mosses which allow them to retain water (Kettridge & Waddington, 2014; Thompson & Waddington, 2013; Waddington et al., 2015) and therefore, they must occupy environments where the evaporative demand is low. Such environments include those in which there is minimal exposure to incident radiation and wind (Skre et al., 1983). Additionally, less effective water retention capabilities increase the susceptibility of feather mosses to aerobic decomposition, which facilitates the production of greater density peat (Moore et al., 2007).

1.1.2 Hydrological Feedbacks

The ecohydrological functioning of peatlands as demonstrated through their development and by their role as globally significant carbon reserves has earned them the description of complex adaptive systems (Belyea & Baird, 2006). Justification for this description is perhaps best exemplified by the various autogenic feedbacks operating within these systems (Waddington et al., 2015). The long-term development of peat properties that has given rise to these autogenic feedbacks also facilitates the maximization of peatland water use efficiency in order to optimize ecohydrological functioning (Kettridge et al., 2016). Ecohydrological functioning in peatlands involves balancing carbon accumulation and water storage, while simultaneously minimizing vulnerability to disturbance (Kettridge et al., 2016).

1.2 Disturbance Regimes

1.2.1 Climate Change

Globally, the effects of climate change are becoming increasingly apparent and the Boreal Plains ecozone is no exception. Annual and decadal cycles of water availability control ecosystem functioning and hydrological responses to precipitation and disturbances (Devito et al., 2012). Ecosystem hydrology in this region is sensitive to change due to the long-term water deficit that exists as a result of the sub-humid climate (Thompson et al., 2017). Global temperatures have increased at an accelerating rate over the last century (IPCC, 2014). In the Boreal Plains annual temperatures have risen between 1 – 3 °C since 1948 and are expected to increase an addition 2 – 5 °C by 2050 (Barrow & Yu, 2005; Hengeveld et al., 2005; Lemmen et al., 2008). These warmer temperatures are expected to decrease the duration of the snow covered season (Beaubien & Freeland, 2000) and decrease the duration of soil in the frozen state (Smerdon & Mendoza, 2010). Such changes would consequently increase the likelihood of drought conditions through elevated evapotranspiration-mediated ecosystem water loss (Kettridge et al., 2017). Increases in precipitation are also projected under future climate scenarios; however, this increase in precipitation is insufficient to compensate for increases in evapotranspiration (Price et al., 2013). Increased evapotranspiration lowers peatland WT position and decreases near-surface water content (Roulet et al., 1992) resulting in greater aerobic decomposition and the degradation of peatland carbon stores (Ise et al., 2008; Tarnocai, 2006). A model examining peatland sensitivity to climate warming revealed that 60% of Canadian peatland area and 51% of the associated organic carbon mass is severely to extremely severely affected by climate change (Tarnocai, 2006).

1.2.2 Wildfire

The carbon stocks of peatlands in the Boreal Plains ecozone are intrinsically tied to the wildfire regime (Kasischke et al., 1995). Considering that the average fire return interval is 100 – 120 years (Turetsky et al., 2004), peatlands must accumulate more carbon within this timeframe than what is lost during a wildfire event to maintain their status as a net carbon sink. Peatlands that are able to regenerate lost carbon prior to a subsequent fire event can be thought of as resilient ecosystems, which can be defined as the ability of the ecosystem to maintain fundamental structure and functions in response to external pressures or disturbances (Gunderson, 2000).

The most important factor controlling wildland fire activity is temperature (Flannigan et al., 2005). This operates through a lowering of peatland WT position through enhanced evapotranspiration, increasing the frequency of lightning caused ignition events, and through an increased duration of the fire season (Flannigan et al., 2016). Increases in regional temperatures projected for the Boreal Plains ecozone are expected to not only increase drying of fuels (Wotton et al. 2010), but also increase lightning activity (Wotton et al. 2017). As such, the fire regime is expected to change accordingly, with increases in the frequency and intensity of wildfire (Flannigan et al., 2013; Flannigan & Wotton, 2001; Kasischke & Turetsky, 2006; Skinner et al. 1999). Within northern peatlands, wildfire accounts for greater than 97% of the total disturbed area, making it the largest disturbance within the Boreal Plains landscape (Turetsky et al., 2002). Further increases in the frequency and intensity of wildfire threatens the resiliency of northern peatlands (Gorham, 1991) and increases pressure on fire management agencies (Flannigan et al., 2009).

1.2.2.1 Ecohydrological Controls on Peat Combustion

The combustion of ground fuels, including peat, is the dominant source of ecosystem carbon loss in boreal wildfire events (Amiro et al., 2009). Due to the fuel packing ratio and the greater soil moisture typical of this fuel type, smouldering is the primary manner of peat combustion (Miyanishi & Johnson, 2002). Smouldering consists of a flameless form of combustion that steadily propagates within organic soils (Rein et al., 2008) and continues to do so as long as the heat transferred to the adjacent fuel at the combustion front exceeds the energy required for fuel combustion (Van Wagner, 1972). Thus, smouldering potential can be defined as the likelihood that a fuel will combust based on the ratio between the energy released upon fuel combustion and the energy required for combustion of an adjacent fuel (Benscoter et al., 2011). In this scenario, the adjacent fuel is likely to combust if the ratio exceeds a value of one; however, it is important to note that the energy generated during combustion is emitted in all directions by the fuel undergoing combustion. As such, the ratio may need to exceed a value (much) greater than 1 for combustion to occur as not all energy generated during combustion will be transferred to that adjacent fuel. In peatland fires smouldering combustion is not typically limited by fuel or oxygen availability, rather the hydrophysical properties of the peat (i.e. moisture content and bulk density) dictate the amount of energy required for fuel combustion (Benscoter et al., 2011; Frandsen, 1987; Miyanishi & Johnson, 2002; Van Wagner, 1972).

Moisture content is the primary factor controlling peat smouldering potential (Rein et al., 2008) and therefore, heterogeneity exists in the spatial distribution of burn severities associated with species-specific moisture retention properties under drought conditions (Benscoter & Wieder, 2003). In *Sphagnum*-dominated peatlands, intragenus variability exists in water retention capabilities correlating to microtopographic position – local variability in ground surface elevation – whereby the denser structure of hummock forming species (e.g. *Sphagnum fuscum*) improves the water retention capabilities of these mosses in relation to hollow species during periods of WT decline (Benscoter et al., 2011; Clymo & Hayward, 1982; Rydin & Mcdonald, 2014; Wagner & Titus, 1984). Similarly, even lower densities typical of feather mosses (Busby et al., 1978) suggest that this moss type is more susceptible to desiccation and smouldering under drought conditions. Moss species possessing greater water retention capabilities, and thus generally greater moisture contents under drought conditions, have been shown to have lower smouldering potential during wildfire events (Benscoter et al., 2011; Shetler et al., 2008).

In addition to water content, bulk density also exerts an important control on peat smouldering potential (Benscoter et al., 2011). Although greater bulk densities increase the water retention of moss and peat (Thompson & Waddington, 2013), they conversely act to increase fuel loading and increase the moisture threshold supporting peat combustion (Benscoter et al., 2011). The confounding effects between water retention and bulk density complicate their relationship with peat smouldering potential. Frandsen (1987) achieved combustion in *Sphagnum* peat with moisture contents up to 103% by dry mass; however, Benscoter et al. (2011) was able to achieve combustion at moisture contents up to 295%, nearly three times that observed by Frandsen (1987). The main discrepancy between these studies was Frandsen (1987) utilized fuel with uniform soil moisture profiles, whereas the fuels utilized by Benscoter et al. (2011) possessed a gradient in soil moisture with depth through the fuel. This suggests that peat ignition requires lower threshold moisture conditions relative to those required to sustain smouldering combustion. This may be a result of fuel drying due to heat energy released by the encroaching combustion front in a smouldering fire scenario.

1.3 Wildfire Management

Wildfire management is necessary in the fire-prone Boreal Plains landscape to protect human life, communities, watersheds, natural resources, and infrastructure. Wildfire management may take the form of suppression efforts in the event of a fire or proactive management practices such as fuel modification treatments, which reduce fire danger while simultaneously enhancing suppression efforts within treated areas. Most fire management agencies in North America have implemented some form of a proactive fuel management program intended to protect humans, properties, and resources from wildfire (Mooney, 2010). Canada has adopted a program known as FireSmart, which provides a set of guidelines for individuals and communities to assess the threat from wildfire and implement proactive risk reduction strategies.

1.3.1 Fuel Modification Treatments

Fuel modification treatments are designated areas within the wildland-urban interface and wildland-industry interface where anthropogenic modifications to ecosystem fuels have been conducted with the intention of protecting society from future wildfires. Depending on the nature of the treatment the intended results may include a reduction in fuel loading or, in the event of a wildfire, reducing fire intensity, rates of spread, crown fire development, and improving access for suppression resources. Currently, fuel modification treatments primarily involve the removal, reduction, or conversion of on-site fuels (Partners in Protection, 2003).

1.3.2 Wildfire Management within Peatland Environments

The ecosystem resiliency of peatlands and their associated carbon stocks are at risk from climate-mediated drought conditions and changes to the wildfire regime (Flannigan et al., 2005; Kasischke & Turetsky, 2006; Tarnocai, 2006). Peat fires also present significant human health concerns as a result of greater particulate and mercury emissions (Obrist et al., 2008; Turetsky et al., 2006). The smouldering combustion that is characteristic of peatland fires complicates fire suppression efforts. Smouldering is the most difficult form of combustion to extinguish (Rein, 2013). Compared to flaming combustion, smouldering requires significantly greater quantities of water (Hadden & Rein, 2011) and lower oxygen concentrations (Belcher & McElwain, 2008) to effectively extinguish. Failure to completely extinguish smouldering fires can result in the re-ignition of surface fuels (Frandsen, 1987). Additionally, the longer durations, resources and thus, financial commitments required to effectively extinguish these smouldering peat fires presents significant challenges to wildfire management agencies. With increased fire activity in the Boreal Plains landscape, there is doubt as to whether fire management agencies will be able to maintain their current levels of effectiveness (Flannigan et al., 2009). This emphasizes the need for adaptive wildfire management strategies aimed at reducing fire danger in the wildland-urban and wildland-industry interfaces.

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CHAPTER 2: SEISMIC LINES OF BOREAL TREED BOGS AS ANALOGS FOR FUEL MODIFICATION TREATMENTS

2.1 Introduction

A globally significant proportion of the world's oil reserves can be found in Alberta, the quantity of which ranks third to only Venezuela and Saudi Arabia (Alberta Energy, 2017). Geophysical assessments aimed at locating and quantifying these reserves involves the mechanical clearing of vegetation in a linear manner to permit the transmission and recording of seismic waves. A result of this exploratory process is a form of extensive linear disturbance, known as seismic lines, across Alberta's boreal region. As of 2001 over 1.5 million km of seismic lines covered the Albertan landscape (Timoney & Lee, 2001); however, continued exploration for oil reserves add an additional 2875 km of seismic lines annually (Komers & Stanojevic, 2013). The mean density of seismic lines in northeastern Alberta is 1.5 km km^{-2}, but can reach up to 10 km km^{-2} in some areas (Lee & Boutin, 2006). In comparison, the mean density of road networks in the developed agricultural zone of Alberta is 1.0 km km^{-2} (Lee & Boutin, 2006).

Vegetation recovery within seismic lines can be substantially delayed making this a persistent form of disturbance (Lee & Boutin, 2006; Van Rensen et al., 2015). A study conducted by Van Rensen et al. (2015) utilized LiDAR-derived data to model vegetation regeneration on seismic lines within the Central Mixedwood National Subregion of Alberta. Results from this study suggest that approximately one-third of existing seismic lines will fail to recover vegetation to a 3 m height following a 50-year post-disturbance period (Van Rensen et al., 2015). Van Rensen et al. (2015) attributed this delay in vegetation regeneration to (ranked from most to least influential): terrain wetness, line width, anthropogenic activity, and lowland ecosites. Due to the number of factors influencing vegetation regeneration within seismic lines, the rate of regeneration can be quite variable. Any alterations to vegetation structure will concurrently change radiation and energy balances and thus, local temperature and water fluxes; two variables which exert strong controls on the growth and distribution of vegetation (Holland & Steyn, 1975). Physical characteristics of seismic lines such as width and orientation, as well as alterations to physical soil characteristics are all contributing factors to the rate of vegetation regeneration.

Physical attributes of seismic lines such as width and orientation affect light availability (Revel et al., 1984) and thus, the vegetation composition and rates of regeneration. Wide seismic lines (5-10 m), also referred to as legacy seismic lines, were created prior to the early 1990s through the use of bulldozers (Lee & Boutin, 2006). The lack of shading in these legacy seismic lines results in large energy inputs which may inhibit the recovery of vegetation by reducing water availability and stomatal conductance (Abib et al., 2019). Efforts to reduce the environmental impacts of seismic lines has seen a reduction in line widths from legacy seismic lines to what are now referred to as low-impact seismic lines (~1.5-5 m) (Schneider & Dyer, 2006; Strack et al., 2019). Despite this reduction in line widths, there is little evidence that suggests vegetation regeneration rates have increased with disturbed areas (Schneider & Dyer, 2006; Van Rensen et al., 2015) and active restoration is still expected to be necessary to remediate low impact seismic lines (Lovitt et al., 2018). Seismic lines with an east-west orientation facilitate slightly faster vegetation recovery rates compared to lines with a north-south orientation, thought to be a result of greater shade within east-west lines hindering shade-intolerant vegetation, thereby reducing competition for regenerating trees (Van Rensen et al., 2015). In regards to terrain wetness, mesic sites tend to recover vegetation within a natural timeframe, whereas dry and particularly wet sites may experience substantial delays in regeneration (Van Rensen et al., 2015). Similar to wide seismic lines, moisture limited areas receiving greater quantities of solar radiation post-disturbance also experience delayed vegetation recovery as a result of decreased water availability (Abib et al., 2019; Van Rensen et al., 2015). In contrast, wetter areas, such as the lowland black spruce dominated peatlands covering much of Alberta’s boreal plains ecozone, experience delayed vegetation recovery as spruce are intolerant of flooding and water saturated conditions (Grossnickle, 2000) thought to be induced through seismic line construction. Significant signs of vegetation recovery are unlikely to be found after 35 years post-disturbance in bogs nor in fens 50 years post-disturbance (Bayne et al. 2011; Lee & Boutin, 2006; Revel et al., 1984). The delay in vegetation regeneration is thought to be greater in fens compared to bogs due to the hydrological connectivity of fens with surface and/or groundwater causing wetter conditions especially during snowmelt and precipitation events (Vitt, 1994).

In Alberta alone, at least 345,000 km of seismic lines intersect peatlands affecting an area of more than 1900 km^2 (Strack et al., 2019). In addition to the removal of vegetation, heavy machinery depresses the peatland surface and virtually eliminates microtopographic features (Lee & Boutin, 2006; Lovitt et al., 2018) such as *Sphagnum* hummocks, which are important sites for black spruce seedling establishment (Lee & Boutin, 2006). Mean ground surface elevations within seismic lines are lower than that of the undisturbed portion of the peatland, which coincides with a shallower WT and an increased likelihood of flooding events, hindering vegetation recovery (Grossnickle, 2000). Additionally, by depressing the peatland surface the operation of heavy machinery compresses peat soils causing an increase in near-surface bulk density (Severson-Baker, 2003) and concomitant increases in soil VWC and thermal conductivity (Braverman & Quinton, 2016). Increasing the bulk density of peat soils further hinders the regeneration of vegetation by decreasing soil aeration and restricting root penetration (Startsev & McNabb, 2009) allowing these disturbances to persist on the landscape.

While the persistence of seismic lines and their associated alterations to local ecosystems are generally perceived as negative, such changes within black spruce forested bogs may have utility in the context of wildfire management by representing analogs for novel fuel modification strategies aimed at reducing peat smouldering potential. Additionally, recent evidence has demonstrated that seismic lines within treed peatlands improve ecosystem resistance and resilience by serving as refugia for some plant and butterfly species during wildfire (Riva et al., 2019). The key feature of ombrotrophic bogs in comparison to other peatlands types (i.e. fens) is the abundance of *Sphagnum* mosses. Compared to other peatland mosses, particularly feather mosses, *Sphagnum* has greater moisture retention properties and typically has greater cellular water contents under field conditions (Clymo & Hayward, 1982; Waddington et al. 2011). Water content exerts a primary control on fuel combustion (Benscoter et al., 2011; Van Wagner, 1972), which suggests that greater *Sphagnum* ground cover would reduce near-surface smouldering potential. While competitively excluded by feather mosses under shaded conditions (Bisbee et al. 2001), it is likely that tree removal and delayed vegetation recovery induced through seismic line establishment unintentionally promotes suitable conditions for expansion of *Sphagnum* ground cover within seismic lines. Additionally, seismic lines intersecting bogs have lower flooding potential relative to those intersecting fens; such events are detrimental to the development of hummock-forming *Sphagnum* mosses (i.e. *Sphagnum fuscum*) (Van Rensen et al., 2015).

Given that seismic lines in bogs are resistant to wildfire (Riva et al., 2019), this research initiated ecohydrological assessments of six ombrotrophic bogs intersected by seismic lines within the Central Mixedwood Natural Subregion of Canada's Boreal Plains in order to identify environmental discrepancies influencing smouldering potential of near-surface moss and peat. We suggest that heavy machinery used in seismic line establishment likely resulted in persistent changes to physical peat properties, specifically elevated bulk density values, which serves as a proxy for compression of the peat soils (Golubev & Whittington, 2018). Moreover, the removal of trees during seismic line establishment in conjunction with limited vegetation regeneration in compressed seismic line peat soils (Startsev & McNabb, 2009) are expected to foster a greater proportion of *Sphagnum* mosses within the seismic line relative to the treed portions of the bog. We expect hummock-forming species of *Sphagnum* (e.g. *Sphagnum fuscum*) to occupy these open areas as facilitated by their capabilities for desiccation avoidance, drought tolerance, and rapid recovery following a period of drought (Hájek & Beckett, 2008). Hummock-forming *Sphagnum* mosses have greater bulk densities and therefore, greater vertical water transport and retention capabilities relative to feather mosses (Golubev & Whittington, 2018; Price & Whittington, 2010) and as such, we expect that near-surface (0 – 0.06 m) water contents at field capacity will be greater within the seismic line relative to the treed portions of the bog. The enhanced vertical water delivery of mosses within the seismic line are expected to sustain elevated levels of moss photosynthetic performance relative to those same species of moss in the portions of the treed bog adjacent the seismic line. Ultimately, we expect the aforementioned changes induced through seismic line establishment to generate a net decrease in smouldering potential of seismic line moss and near-surface peat compared to that of the adjacent treed portions of the bog, thus exemplifying the utility of seismic lines as analogs for novel fuel modification treatments.

2.2 Methods

2.2.1 Site Selection

All sites are located within the Central Mixedwood Natural Subregion of Canada's Boreal Plains, in proximity to Wabasca, Alberta. The landscape of this region consists of a mosaic of aspen, mixedwood, and white spruce forested upland regions surrounding abundant wetlands, predominantly bogs and fens (Natural Regions Committee, 2006). Within bog ecosites, black spruce (*Picea mariana*) is the dominant tree species and is commonly accompanied by various shrubs including Labrador tea (*Rhododendron groenlandicum*), bog cranberry (*Vaccinium vistas-idaea*), and small bog cranberry (*Vaccinium oxycoccos*). *Sphagnum* mosses, including *Sphagnum fuscum*, *Sphagnum capillifolium*, and *Sphagnum magellanicum*, often dominate the ground cover; however, feather mosses encroach over *Sphagnum* in later successional bogs (Benscoter & Vitt, 2008) and reach their maximum abundance at locations 30 cm above the local WT (Mulligan & Gignac, 2001). Ducks Unlimited Wetland Inventories were verified by ground truthing reports previously conducted by the McMaster Ecohydrology Lab (e.g. Mayner et al., 2018), which confirmed peatlands classified as bogs under the Boreal Plains Wetland Classification System (Smith et al., 2007). Potential research sites were identified using aerial imagery (Alberta Environment and Parks), which allowed us to locate peatlands intersected by seismic lines and the approximate the year of seismic line establishment. Additional ground truthing was conducted in May of 2018 to verify previous reports and six research sites were selected (Table 2.1) based on our ability to locate and access sites, as well as various safety considerations.

2.2.2 Transect-Based Approach to Field Data Collection

A transect-based approach to field data collection was employed at each of the six seismic line research sites. Three parallel transects, each 15 m in length, were established at research sites. One transect was established within the seismic line and the remaining two transects were established in the treed portions of the bog on opposite sides of the seismic line. Treed bog transects were located at least 4 m away from the edge of the seismic line in order to minimize edge effects. Ground layer vegetation plots were delineated using quadrats measuring 0.6 m by 0.6 m within which, ground cover, shrub presence, and degree of shrub shading were assessed at 1 m intervals along the transects. Canopy photographs were captured above each quadrat from a height of 0.5 m using a Sony Cyber-shot WX350 digital camera to evaluate canopy openness. Soil moisture (0 – 0.06 m) measurements were obtained for the most abundant ground cover type within each quadrat using an ML3 ThetaProbe (Delta-T Devices, Burwell, Cambridge, United Kingdom). At 3 m intervals along transects, a sample of the most abundant moss type within the quadrat was collected for moss productivity analysis using chlorophyll fluorometry (refer to section 2.2.4).

2.2.3 Field Sample Collection and Laboratory Analysis

At each research site field samples were collected for further analysis at the McMaster Ecohydrology Laboratory. Polyvinyl chloride (PVC) pipe (0.6 m in length by 0.076 m in diameter) was used in the extraction of two peat cores from each research site; one core was extracted from within the seismic line and the other was extracted from a randomly selected transect on either side of the seismic line before being sealed and shipped to McMaster University. Cores were collected from identical ground cover species to ensure comparable data.

Upon returning to McMaster, peat cores were frozen for preservation. Frozen cores were cut longitudinally into two equal halves to reveal the peat profile within the top 0.6 m at each site. Photographs were taken to compare and contrast these profiles (Figure 2.5). Cores were then dissected in 0.02 m intervals and dried at 85 °C until no change in sample mass was observed in order to calculate the sample bulk density. Samples were further dissected to quantify the dry weight of wood within each 0.02 m interval. Black spruce was the dominant tree species found at each research site and therefore, it was assumed that woody material within each sample was of black spruce origin. A known bulk density (0.44 g cm^{-3}) for dried black spruce was applied to calculate the volume of sample occupied by the woody material (Alberta, 2013). From here, calculations of peat volume, peat weight, and ultimately peat bulk density were conducted.

2.2.4 Chlorophyll Fluorometry

Chlorophyll fluorescence is a tool that allows for assessments plant photosynthetic performance in relation to a species-specific theoretical maximum value (0.78 – 0.89) in an unstressed state (Adams & Demmig-

Adams, 2004). Values lower than this maximum indicate external stress, typically in the form of insufficient water resources for bryophytes (Maxwell & Johnson, 2000). As light energy irradiates chlorophyll molecules, it is competitively distributed between photochemistry, heat dissipation, and light remission (i.e. chlorophyll fluorescence) within photosystem II (PSII). The competitive nature of this process allows measurements of chlorophyll fluorescence to provide information on the efficiency of heat dissipation and photochemistry. By irradiating a sample with light of a known wavelength and subsequently measuring the amount of light remitted at longer wavelengths, one can quantify the fluorescence yield. After a period of darkness, exposing a sample to light leads to progressive closure of PSII reaction centres, an effect known as fluorescence quenching. Chlorophyll fluorescence is greatest within the first couple seconds upon exposure to light, after which point fluorescence begins to decrease. A dark adaption period can be used to allow the samples to reach a steady state and mitigate the effects of fluorescence quenching. A portable OS-30p+ chlorophyll fluorometer (Opti-Sciences, Hudson, New Hampshire, U.S.A.) and a dark adaptation period of twenty minutes was implemented to quantify the maximum quantum yield of PSII (F_v/F_m) in bryophyte samples. Where sample fluorescence readings were below the minimum threshold for measurement by the chlorophyll fluorometer samples were assigned F_v/F_m values of zero. Quantifying F_v/F_m has been demonstrated to be a reliable indicator of plant photosynthetic performance (Baker & Oxborough, 2004; Hájek & Beckett, 2008; Leonard et al., 2017; Van Gaalen et al., 2007; Zarco-Tejada et al., 2002). In this study, F_v/F_m was used as an ecological indicator of moss moisture stress.

2.2.5 Canopy Openness

A MATLAB application was used to quantify canopy openness from canopy photos. To accomplish this, a function firstly classified canopy photographs based on RGB colour indexes to create a binary image, where white and black pixels correspond to vegetation and sky, respectively. The program utilizes default index thresholds which work reasonably well at distinguishing between vegetation and sky in a range of canopy photo imagery; however, the user has the option of modifying the default index thresholds to optimize software output based on light conditions at the time the photos were taken. A second function analyzes binary photos and calculates the proportion of black pixels within the image, corresponding to a canopy openness value. This method was used to derive canopy openness values from the canopy photos, and ultimately provide a mean canopy openness value for the seismic line and either side of the adjacent treed portions of the bog at each research site.

2.2.6 Smouldering Potential

In order to estimate the smouldering potential of near-surface (0 – 0.06 m) moss and peat, an energy balance model (Benscoter et al., 2011) was adapted to evaluate the relative likelihood that moss and near-surface peat within seismic lines and the adjacent treed portions of the bog would combust in the event of a wildfire. Other studies have successfully applied this approach to estimate and model peat vulnerability to ignition and smouldering combustion (Granath, Moore, Lukenbach, & Waddington, 2016; Lukenbach et al., 2015). Smouldering potential is estimated based on the ratio of energy released during combustion (H_{comb}) and the energy required to ignite (H_{ign}) adjacent fuels. The amount of energy released during peat combustion is defined by:

$$H_{comb(i)} = \rho_{b(i)} x_{(i)} E_{comb} \tag{1}$$

where ρ_b is the bulk density (g m^{-3}), x is the thickness of the fuel layer (0.06 m in this study), and E_{comb} (14 200 J g^{-1} for milled peat from Frandsen, 1991) is the low heat of combustion per unit mass of peat. The amount of energy required for ignition is defined by:

$$H'_{ign(i)} = h_{(i)} \rho_{b(i)} x_{(i)} \tag{2}$$

where h (J g^{-1} fuel) is the heat of ignition for the fuel horizon determined by:

$$h = mC_w(T_V - T_A) + L_V m + C_f(T_{comb} - T_A) + S \tag{3}$$

where m is the fuel gravimetric water content (g water g^{-1} of dry fuel), C_w is the heat capacity of water (4.186 J g^{-1} water °C^{-1}), T_V, T_A, and T_{comb} are the vapourization temperature of water (100°C), the ambient temperature (°C) (assumed to be 20°C), and the combustion temperature of duff (300°C from Van Wagner, 1972), respectively, L_V is the latent heat of vaporization of water (2250 J g^{-1} from Johnson, 1992), C_f is the specific heat of the dry fuel (1.92 J g^{-1} fuel °C^{-1} for peat from Oke, 1987), and S is the energy required to free water sorbed to peat (50.4 J g^{-1} fuel from Van Wagner, 1972). There is potential for combustion when $H_{comb}/H_{ign} > 1$; however, energy from fuel combustion is emitted in all directions, rather than a proportional transfer to an adjacent fuel and therefore, fuels likely require an H_{comb}/H_{ign} ratio greater than one to for combustion to occur.

While conducting surface vegetation surveys, near-surface (0 – 0.06 m) moisture readings were obtained from the most abundant moss type (*Sphagnum* or feather moss) within each quadrat. A bulk density value of 19.35 kg m^{-3} for 'seismic line peat' was determined by calculating the average peat bulk density (0 – 0.05 m) of seismic line peat cores (*n*=6). The same approach was used to determine standard bulk density values for non-seismic line peat for *Sphagnum* (16.40 kg m^{-3}, *n*=6) and feather moss (7.50 kg m^{-3}, *n*=3). It was assumed that these bulk density values calculated for the top 0.05 m of moss and peat are representative of bulk density values to a depth of 0.06 m. Measurements of VWC were converted to gravimetric water content (GWC) using:

$$m = \frac{VWC \cdot \rho_w}{\rho_b} \tag{4}$$

where VWC is the ratio of water volume to total volume and ρ_w is the density of water (g m^{-3}), assumed to be equal to one. These values were used to estimate smouldering potential of near-surface (0 – 0.06 m) moss and peat within each quadrat.

2.2.7 Statistical Analyses

All statistical analyses were performed using RStudio version 1.1.463 (RStudio Team, 2015). The three transects at each seismic line research site were compared for differences in canopy openness, *Sphagnum* ground cover composition, shrub cover, VWC, F_v/F_m, and smouldering potential (Table 2.4). No comparisons were conducted between sites. Normally distributed data was analyzed using parametric statistics. Tukey's test for multiple comparisons was employed using the function 'HSD.test' in the package 'agricolae' (de Mendiburu, 2019). Data that was not normally distributed was analyzed using non-parametric statistics. In this case, Kruskal-Wallis tests for multiple comparisons were coupled with Fisher's least significant difference (LSD) post hoc test using the function 'kruskal' also in the 'agricolae' package (de Mendiburu, 2019), however, the p-values output from this method were adjusted using Benjamini-Hochberg method to account for multiple comparisons by controlling for the false discovery rate, and thereby weakly controlling the family-wise error rate as well (Benjamini & Hochberg, 1995). The Benjamini-Hochberg method is preferred over widely used Bonferroni method as it has a lower risk of type II errors (Benjamini & Hochberg, 1995). Alternative statistical approaches were used to compare the mean peat bulk density by depth interval between bog and seismic line cores (Table 2.5). Two-sample t-tests for independent groups were used to analyze normally distributed data using the function ‘t.test’, where variance between means was quantified and accounted for in tests. Non-parametric statistics were applied to data that was not normally distributed in the form of Mann-Whitney U tests using the function ‘wilcox.test’. Both functions are from default statistics within RStudio.

2.3 Results

2.3.1 Canopy Openness

Kruskal-Wallis Tests were conducted to examine canopy openness between transects at each seismic line research site. Results from these tests indicate significant (α=0.05) differences in canopy openness at each site (Table 2.4). Figure 2.1 shows the results of Fisher’s LSD post hoc test corrected for multiple comparisons using the Benjamini-Hochberg method. At each site, canopy openness is greater in the seismic line compared to the adjacent treed portions of the bog. Notably, at five of the six sites assessed in this study, canopy openness is significantly different between treed portions of the bog on opposite sides of the seismic line (Figure 2.1).

2.3.2 Ground Layer Vegetation

Examination of Figure 2.2 demonstrates dominance of *Sphagnum* ground cover within seismic lines. Statistical analyses confirmed that there is a significant (α=0.01) difference in *Sphagnum* ground cover amongst transects at each research site (Table 2.4). Results of post hoc tests verified that *Sphagnum* ground cover is significantly greater in seismic lines relative to the treed portions of the bog (Figure 2.2). Shrub coverage did not vary significantly (α=0.05) between transects at four of the six research sites (Figure 2.3; Table 2.4). Only SL4 and SL5 showed significant differences in shrub cover between transects and in both cases, shrub coverage was greater in the seismic line relative to the treed portions of the bog. However, a Kruskal-Wallis test reveals a significant (α=0.01) difference in seismic line shrub cover between sites ($X^2(5) = 54.512$, $p = 1.645\text{x}10^{-10}$). Fisher's LSD post hoc test corrected for multiple comparisons using the Benjamini-Hochberg method identifies that SL1 and SL6, both north-south oriented sites, have significantly lower shrub cover percentages compared to other seismic line sites with different seismic line orientations (Figure 2.3).

2.3.3 Volumetric Water Content

Research sites showed significant (α=0.05) differences in near-surface (0 – 0.06 m) VWC between transect locations (Table 2.4). Results of Fisher's LSD post hoc test corrected for multiple comparisons using the Benjamini-Hochberg method are illustrated in Figure 2.4. Five of the six sites show significantly greater VWC within the seismic line relative to the adjacent treed portions of the bog, while the sixth site in this instance, SL6, shows only significant differences between the seismic line (15.6 ± 7.0%) and eastern portion (11.2 ± 10.1%), but not the western portion (11.5 ± 9.8%) of the bog (Figure 2.4). VWC was not significantly different between treed bog transects at five of the six sites. The exception, SL2, shows greater VWC in the northern portion (15.8% ± 6.2) relative to the southern portion (6.7% ± 8.5) of the treed bog.

2.3.4 Chlorophyll Fluorometry

Both parametric and non-parametric statistical methods were employed in the evaluation of F_v/F_m between transects at seismic line research sites based on the distribution of data at each site. Results from these tests show significant (α=0.05) differences in F_v/F_m at three of the six seismic line sites (Table 2.4). Notably, the three sites that showed statistical differences in F_v/F_m between transects had a north – south or northwest – southeast orientation, whereas sites that did not show significant differences had an east – west orientation. East – west oriented sites (SL2, SL3, and SL5) show no significant differences in F_v/F_m between the seismic line and the treed portions of the bog (Figure 2.5). At SL1, F_v/F_m within the seismic line (0.636 ± 0.062) is significantly greater than that of the adjacent treed portions of the bog, where the eastern portion (0.168 ± 0.302) had significantly greater F_v/F_m than the western portion (0.009 ± 0.013) of the bog. At SL4 and SL6, F_v/F_m of the western-most portions of the treed bogs were not significantly different than F_v/F_m of the seismic lines, but the eastern-most portions had significantly lower F_v/F_m values than the seismic lines.

2.3.5 Physical Peat Properties

Peat cores extracted from seismic line research sites were cut longitudinally to reveal the peat profile (0 – 60 m) at each site. Photos of the peat profile were captured and are documented in Figure 2.6. Observational evidence shows disconformities in seismic line cores compared to cores extracted from the adjacent treed portion of the bog, which are generally characterized by more gradual transitions from surface moss to increasing stages of decomposed peat. Peat bulk densities were quantified in 2 cm intervals and average seismic line and treed bog peat bulk densities were then calculated for each depth interval. Mean seismic line peat bulk density was then compared to mean treed bog peat bulk density for each depth interval (Figure 2.8; Table 2.5). Seismic line peat and adjacent treed bog peat were not found to have significant (α=0.05) differences from the surface to a depth of 14 cm; however, a subsequent layer between 14 – 22 cm below surface does show instances where seismic line peat is significantly greater than adjacent treed bog peat, although this is discontinuous. An underlying layer from 22 – 32 cm shows consistently greater average bulk density of seismic line peat compared to adjacent treed bog peat. All peat bulk densities below this depth, with the exception of 40 – 42 cm, are not significantly different between the seismic line and adjacent treed bog peat.

2.3.6 Smouldering Potential

The energy balance model developed by Benscoter et al. (2011) was adapted to calculate smouldering potential at each seismic line research site. Significant differences (α=0.05) in smouldering potential were detected within three of the six research sites (Table 2.4). No significant differences in smouldering potential were found at SL3, SL4, and SL6; coincidently, these sites happen to have the narrowest seismic lines (Table 2.1). For sites with wider seismic lines (SL1, SL2, and SL5), smouldering potential in the seismic line was significantly lower than that of the treed portions of the bog (Figure 2.9). No significant differences in smouldering potential were found between bog transects at SL1 and SL5; however, the smouldering potential of the south side of the treed bog (2.07 ± 1.42) at SL2 was significantly greater than that of the north side (0.63 ± 0.44). It is important to note that mean H_{ign}/H_{comb} ratios in all seismic lines assessed in this study are less than one, implying that seismic lines are generally resistant to combustion.

2.4 Discussion

2.4.1 Ecohydrological Discrepancies between Seismic Lines and the Adjacent Bog

The substantially greater canopy openness of seismic lines, particularly old, legacy seismic lines (e.g. SL1 and SL5), relative to the adjacent treed portions of the bog (Figure 2.1) confirm previous reports of delayed vegetation recovery in these areas (Lee & Boutin, 2006; Van Rensen et al., 2015) and exemplifies the persistence of these landscape features. Five of the six seismic line sites have significantly different canopy openness between the treed portions of the bog on opposite sides of the seismic line (Figure 2.1), which suggests that seismic lines may affect the hydrologic connectivity of bisected bogs. Peat compression induced through heavy machinery use in seismic line establishment may restrict lateral water movement across the seismic line, thereby creating a dam effect characterized by differential WT depth on opposite sides of a seismic line. Research has shown that a lowering of peatland WT position can alter canopy structure of peatlands through increasing afforestation (Dang & Lieffers, 1989; Linderholm & Leine, 2004), an effect that has since been characterized as the WT depth – afforestation and/or shrubification feedback (Waddington et al., 2015). However, statistical analysis of shrub cover data did not identify significant differences in shrub coverage on opposite sides of the seismic line at each site (Figure 2.3; Table 2.4). This does not dismiss the effect of seismic lines on proximal vegetation structure, an effect which has been documented in other studies (e.g. Abib et al., 2019). While little variation in shrub cover was found within sites, significant differences were found in seismic line shrub cover between sites. In north-south oriented seismic lines (SL1 and SL6) shrub cover in the seismic line itself is significantly lower than that of seismic lines with other orientations (Figure 2.3; Table 2.1). This finding corresponds to a previous study on vegetation regeneration in seismic lines, where east – west oriented lines facilitated greater rates of vegetation recovery compared to north-south lines (Van Rensen et al., 2015). Van Rensen et al (2015) hypothesized that greater shading in east – west lines facilitated faster tree recovery from reduced competition from shade intolerant shrubs and herbs; however, that hypothesis is refuted by our results which show greater shrub cover in east – west oriented seismic lines.

The persistent effects of seismic lines as demonstrated by the change to canopy structure (Figure 2.1) has also impacted ground layer vegetation. As predicted, seismic lines contain a greater percentage of *Sphagnum* ground cover relative to either side of the adjacent treed bog (Figure 2.2). The increased canopy openness and limited regeneration of vegetation in these areas is thought to have fostered this expansion in *Sphagnum* moss cover. Of all sites, *Sphagnum* ground cover is least dominant at SL3 (83.5 ± 15.6%), which also happens to be the site with the lowest seismic line canopy openness (94.9 ± 2.1%) and an east – west orientation, which typically receives less light at ground level than lines with a north-south orientation (Van Rensen et al., 2015). *Sphagnum fuscum* was the most abundant *Sphagnum* species inhabiting the open seismic line environment at all sites, which is thought to be due to the water conservation and management properties of this hummock forming species (Hájek & Beckett, 2008). Additionally, the dense structure of hummock-forming *Sphagnum* may be necessary in seismic lines to overcome a potential capillary barrier effect, which is often observed in cutover peatlands regenerating from previous peat harvesting operations (McCarter & Price, 2015).

Observational analysis of cores extracted from seismic line sites typically show greater disconformities in the peat profile of the seismic line compared to that of the adjacent treed bog (Figure 2.6). These disconformities are usually in the form of stark colour changes in successive peat layers (e.g. ~10 cm below surface in SL2, or ~20 cm below surface in SL1). The varying depth of this disconformity roughly correlates to the approximate date of seismic line establishment, where seismic lines that were established more recently (e.g. SL2 est. 1995 – 2000) show a disconformity closer to surface compared to seismic lines established longer ago (e.g. SL1 est. 1963 – 1970). Comparison of seismic line and adjacent treed bog peat bulk density by depth interval indicates no significant differences in the top 14 cm; however, instances of significantly greater seismic line peat bulk densities become apparent between 14 – 22 cm below surface, followed by a subsequent layer between 22 – 32 cm showing consistently greater bulk densities of seismic line peat compared to that of the adjacent bog. All peat below this depth, with the exception of 40 – 42 cm, is not significantly different between the seismic line and adjacent treed bog (Table 2.5). Based on this observational evidence of disconformities in the peat profile combined with the comparison of peat bulk densities between seismic line and adjacent bog peat, we hypothesize that these disconformities and layers of greater peat bulk densities correspond to the surface at the time of seismic line establishment and represent evidence for peat compression through heavy machinery use in seismic lines. The lighter coloured peat overlying the dark disconformity is thought to be new moss growth since seismic line establishment. These results also suggest that heavy machinery use primarily results in compression of unsaturated peat from the surface to a depth of about 10 cm; however, grouping of seismic line peat profiles from sites with a wide range of time since establishment may obscure statistical differences in peat bulk density by depth interval as evidenced by the layer of inconsistent significant differences (14 – 22 cm). Comparing sites with similar time since seismic line establishment would provide a better indication on the depth of peat affected by seismic line construction. The presence and/or contrast of disconformities as well as the peat bulk densities in seismic line peat profiles are inconsistent amongst sites. For example, SL5 does not show a distinct disconformity in the seismic line peat profile despite showing greater bulk density values compared to the adjacent bog (Figure 2.7). This inconsistency may be a result of varying degrees of compression of seismic line peat from various factors including quantity of fallen trees or tree roots, which would redistribute the weight of machinery over a larger area, or perhaps the depth of the snow pack or degree of frozen peat in winter operations (Strack et al., 2019).

We hypothesized that water content at field capacity would be greater in seismic lines relative to the adjacent treed portions of the bog, and this was largely the case, as five of the six research sites had significantly greater VWC in the seismic line (Figure 2.4). This increase in VWC in the seismic line is attributed to the abundance of *Sphagnum*, particularly hummock-forming *Sphagnum fuscum*, characterized by excellent vertical moisture transport and retention capabilities (Golubev & Whittington, 2018; Price & Whittington, 2010) (Figure 2.2). However, at SL6 the VWC in the seismic line (15.6% ± 7.0) was significantly greater than that of eastern portion of the treed bog (11.2% ± 10.1), but not the western portion (11.5% ± 9.8) (Figure 2.4). This may be a result of slightly greater *Sphagnum* cover in the western portion of the treed bog at SL6 (Figure 2.2).

While the greater VWC of near-surface seismic line peat did sustain high levels of moss productivity as expected, these levels generally were not significantly greater than those on either side of the treed bog at each site (Figure 2.5). Importantly, the high F_v/F_m values in the seismic lines indicate that despite the greater canopy openness (Figure 2.1), these mosses were not experiencing moisture stress (Figure 2.5). Feather mosses have an opportunistic water use strategy as demonstrated by a reliance on precipitation events and dew formation (Busby et al., 1978; Longton & Greene, 1979), whereas *Sphagnum* mosses have the ability exploit ground water up to 40 cm below the surface (Price & Whittington, 2010) to maintain physiological processes, meaning that the productivity of *Sphagnum* mosses does not respond as rapidly as feather mosses to rain-free periods. As such, it comes as no surprise that there is typically greater variability in F_v/F_m within treed bog transects, which contain greater diversity in ground cover compared to more homogenous seismic lines (Figure 2.2). The limited moss productivity data from each transect (*n*=5) also limits the robustness of this statistical analysis. Additional sampling may provide more insight into discrepancies in moss productivity and moisture stress between seismic line and adjacent treed bog transects.

Despite the significantly greater near-surface VWC of seismic line peat compared to that of adjacent treed bog peat at nearly all research sites (Figure 2.4), this effect was not reflected in smouldering potential. Only three (SL1, SL2, SL5) of the six sites showed significantly lower smouldering potential in the seismic line compared to either side of the adjacent treed bog (Figure 2.7). At the other three sites (SL3, SL4, and SL5), increased VWC of seismic line peat was insufficient to counter the effect of the increased bulk density on smouldering potential. Nonetheless, mean smouldering potential within each seismic line is still less than one, indicating that seismic lines are resistant to combustion. Interestingly, the three sites with lower smouldering potentials compared to adjacent treed bogs happened to be the widest of the six sites, suggesting a negative association between seismic line width and smouldering potential. Furthermore, as drought periods persist and become more common under future climatic scenarios (Price et al., 2013), the disparity in smouldering potential between seismic lines and adjacent treed bogs is expected to become more prevalent.

2.4.2 Applications in Wildfire Management

While not all seismic lines assessed in this study have a significantly lower smouldering potential compared to the adjacent treed portions of the bog, these findings still provide insight into the development of novel fuel modification treatments. The persistence of seismic lines within peatlands emphasizes the utility of heavy machinery in creating long-term fuel breaks, which act as barriers to fire spread and provide access for fire suppression resources. This research also identifies a framework for propagating *Sphagnum* mosses, which are less vulnerable to combustion as a result of greater water contents at field capacity and high desiccation resistance (Hájek & Beckett, 2008; Shetler et al., 2008). In the event that *Sphagnum*-dominated seismic lines or treatment lines ignite during a wildfire, these systems would likely decrease fire intensity and rates of spread, aiding in suppression efforts. Fire managers looking to implement fuel modification strategies based on seismic line analogs should consider following two additional guidelines to optimize effectiveness: (1) Create wide (≥8 m) treatment lines, and (2) implement north – south oriented treatment lines where possible. While intuitively, one may assume that widening fuel breaks would reduce the likelihood that fire would cross from one side to the other, results indicate that the smouldering potential of near-surface moss and peat is also reduced in wider seismic lines. Additionally, implementing north – south oriented treatment lines may reduce shrub coverage, thereby reducing the likelihood that fire crosses seismic lines via combustion of above ground biomass.

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Table 2.1: Overview of bog research sites intersected by seismic lines.

Site	Established	Orientation	Width (m)	Latitude	Longitude
SL1	1963-1970	N-S	16[a]	55.71062	-113.5766
SL2	1995-2000	W-E	8[b]	55.91799	-113.6797
SL3	1977-1980	W-E	6	56.03263	-114.0359
SL4	1977-1980	NW-SE	5[c]	55.99314	-114.0117
SL5	1950-1963	W-E	8	55.79353	-113.3875
SL6	1992-1994	N-S	7	55.79252	-113.4030

[a] original seismic line (7-12 m) recently widened.

[b] two parallel seismic lines separated by treed ridge (4 m) with open *Sphagnum* plateau on far side (total width 27 m).

[c] two parallel seismic lines separated by treed ridge (7 m) (total width 19 m)

Table 2.2: Position of transects at research sites in relation to location of seismic line.

Site	Transect	Location relative to Seismic Line
SL1	A	West
	SL	-
	B	East
SL2	A	North
	SL	-
	B	South
SL3	A	North
	SL	-
	B	South
SL4	A	Northeast
	SL	-
	B	Southwest
SL5	A	North
	SL	-
	B	South
SL6	A	West
	SL	-
	B	East

Table 2.3: Ground cover composition (percent) at each seismic line research site. See Table 2.2 for transect positions relative to seismic line.

	Site																	
Surface Cover Type	**SL1**			**SL2**			**SL3**			**SL4**			**SL5**			**SL6**		
	A	**SL**	**B**	**A**	**SL**	**B**	**A**	**SL**	**B**	**A**	**SL**	**B**	**A**	**SL**	**B**	**A**	**SL**	**B**
Sphagnum spp.	7	98	4	66	99	32	13	84	24	2	94	7	5	91	18	16	97	18
Feather Mosses	78	0	82	17	0	53	76	0	23	87	0	80	83	0	57	65	0	66
Polytrichum spp.	0	2	0	0	0	0	0	2	0	0	1	0	0	0	0	0	1	0
Dicranum sp.	0	0	0	0	0	0	0	0	2	1	0	0	0	1	0	0	0	0
Aulacomium sp.	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0
Mylia sp.	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Cladina spp.	3	0	0	8	0	7	1	5	0	0	0	1	1	0	15	4	0	1
Tree	4	0	3	0	0	1	1	0	1	1	0	2	2	1	1	2	0	2
Litter	9	1	11	8	1	8	10	9	44	9	5	9	8	8	8	13	2	12

Table 2.4: Summary of Chapter Two statistics. Statistical significance for each test is indicated using an asterisk (*) following the p-value.

Multiple Comparisons (Kruskal-Wallis / ANOVA)				
Figure	**Description**	**Site**	**Test Statistic**	**Significance**
2.1	Comparison of canopy openness between transects	SL1	$X^2(2) = 45.514$	$p = 1.309\text{x}10^{-10}$*
		SL2	$X^2(2) = 33.754$	$p = 4.682\text{x}10^{-8}$*
		SL3	$X^2(2) = 34.482$	$p = 3.253\text{x}10^{-8}$*
		SL4	$X^2(2) = 29.363$	$p = 4.205\text{x}10^{-7}$*
		SL5	$X^2(2) = 27.956$	$p = 8.498\text{x}10^{-7}$*
		SL6	$X^2(2) = 31.480$	$p = 1.459\text{x}10^{-7}$*
2.2	Comparison of *Sphagnum* ground cover percentage between transects	SL1	$X^2(2) = 47.121$	$p = 5.856\text{x}10^{-11}$*
		SL2	$X^2(2) = 27.244$	$p = 1.213\text{x}10^{-6}$*
		SL3	$X^2(2) = 28.807$	$p = 7.961\text{x}10^{-7}$*
		SL4	$X^2(2) = 31.664$	$p = 1.331\text{x}10^{-7}$*
		SL5	$X^2(2) = 29.505$	$p = 3.917\text{x}10^{-7}$*
		SL6	$X^2(2) = 29.754$	$p = 3.459\text{x}10^{-7}$*
2.2	Comparison of shrub cover between transects	SL1	$X^2(2) = 3.190$	$p = 0.203$
		SL2	$X^2(2) = 3.725$	$p = 0.155$
		SL3	$X^2(2) = 3.137$	$p = 0.208$
		SL4	$X^2(2) = 12.413$	$p = 0.002$*
		SL5	$X^2(2) = 14.919$	$p = 5.76\text{x}10^{-4}$*
		SL6	$X^2(2) = 4.669$	$p = 0.097$
2.3	Comparison of VWC between transects	SL1	$X^2(2) = 44.319$	$p = 2.38\text{x}10^{-10}$*
		SL2	$X^2(2) = 33.539$	$p = 5.21\text{x}10^{-8}$*
		SL3	$X^2(2) = 19.686$	$p = 5.31\text{x}10^{-5}$*
		SL4	$X^2(2) = 23.490$	$p = 7.93\text{x}10^{-6}$*
		SL5	$X^2(2) = 17.213$	$p = 1.83\text{x}10^{-4}$*
		SL6	$X^2(2) = 7.297$	$p = 0.026$*
2.4	Comparison of F_v/F_m between transects	SL1	$X^2(2) = 11.469$	$p = 0.003$*
		SL2	$X^2(2) = 0.287$	$p = 0.867$
		SL3	$F(2, 12) = 0.107$	$p = 0.899$
		SL4	$F(2,12) = 5.452$	$p = 0.021$*
		SL5	$X^2(2) = 1.833$	$p = 0.400$
		SL6	$X^2(2) = 7.151$	$p = 0.028$*
2.7	Comparison of smouldering potential between transects	SL1	$X^2(2) = 38.167$	$p = 5.154\text{x}10^{-9}$*
		SL2	$X^2(2) = 33.880$	$p = 4.395\text{x}10^{-8}$*
		SL3	$X^2(2) = 5.569$	$p = 0.0618$
		SL4	$X^2(2) = 4.212$	$p = 0.1217$
		SL5	$X^2(2) = 9.899$	$p = 0.0071$*
		SL6	$X^2(2) = 0.665$	$p = 0.7173$

Table 2.5: Statistical analysis of mean peat bulk density of treed bog (*n*=6) and seismic line (*n*=6) cores by depth intervals. Statistical significance for each test is indicated using an asterisk (*) following the p-value.

Depth Interval (cm)	**Mean Peat ρ_b (g cm^{-3})**		**Test Statistic**	**Significance**
	Treed Bog	**Seismic Line**		
0 – 2	0.0140	0.0158	$t(10) = -0.596$	$p = 0.564$
2 – 4	0.0159	0.0204	$W = 14$	$p = 0.589$
4 – 6	0.0195	0.0218	$t(10) = -0.544$	$p = 0.599$
6 – 8	0.0195	0.0215	$W = 21$	$p = 0.699$
8 – 10	0.0203	0.0241	$t(10) = -0.859$	$p = 0.423$
10 – 12	0.0216	0.0378	$W = 11.5$	$p = 0.336$
12 – 14	0.0213	0.0469	$W = 9$	$p = 0.180$
14 – 16	0.0221	0.0552	$W = 5$	$p = 0.041$*
16 – 18	0.0231	0.0540	$W = 14$	$p = 0.589$
18 – 20	0.0250	0.0546	$W = 3$	$p = 0.015$*
20 – 22	0.0288	0.0679	$W = 6$	$p = 0.065$
22 – 24	0.0354	0.0812	$t(10) = -2.534$	$p = 0.030$*
24 – 26	0.0368	0.0844	$t(10) = -3.342$	$p = 0.007$*
26 – 28	0.0407	0.0760	$t(10) = -3.241$	$p = 0.009$*
28 – 30	0.0504	0.1005	$t(10) = -2.861$	$p = 0.017$*
30 – 32	0.0515	0.0968	$t(10) = -2.369$	$p = 0.039$*
32 – 34	0.0522	0.0889	$t(10) = -1.963$	$p = 0.078$
34 – 36	0.0515	0.0763	$t(10) = -1.769$	$p = 0.107$
36 – 38	0.0609	0.0892	$t(10) = -1.792$	$p = 0.103$
38 – 40	00573	0.0923	$W = 8$	$p = 0.132$
40 – 42	0.0534	0.0905	$t(10) = -3.620$	$p = 0.005$*
42 – 44	0.0618	0.1001	$t(10) = -1.949$	$p = 0.080$
44 – 46	0.0648	0.0923	$t(10) = -1.597$	$p = 0.141$
46 – 48	0.0760	0.1010	$t(10) = -1.602$	$p = 0.140$
48 – 50	0.0853	0.1123	$t(9) = -1.128$	$p = 0.289$
50 – 52	0.0825	0.1054	$t(9) = -0.926$	$p = 0.379$
52 – 54	0.0598	0.0902	$W = 3$	$p = 0.059$
54 – 56	0.0630	0.0835	$t(8) = -0.833$	$p = 0.429$
56 – 58	0.0567	0.0904	$t(6) = -1.522$	$p = 0.179$

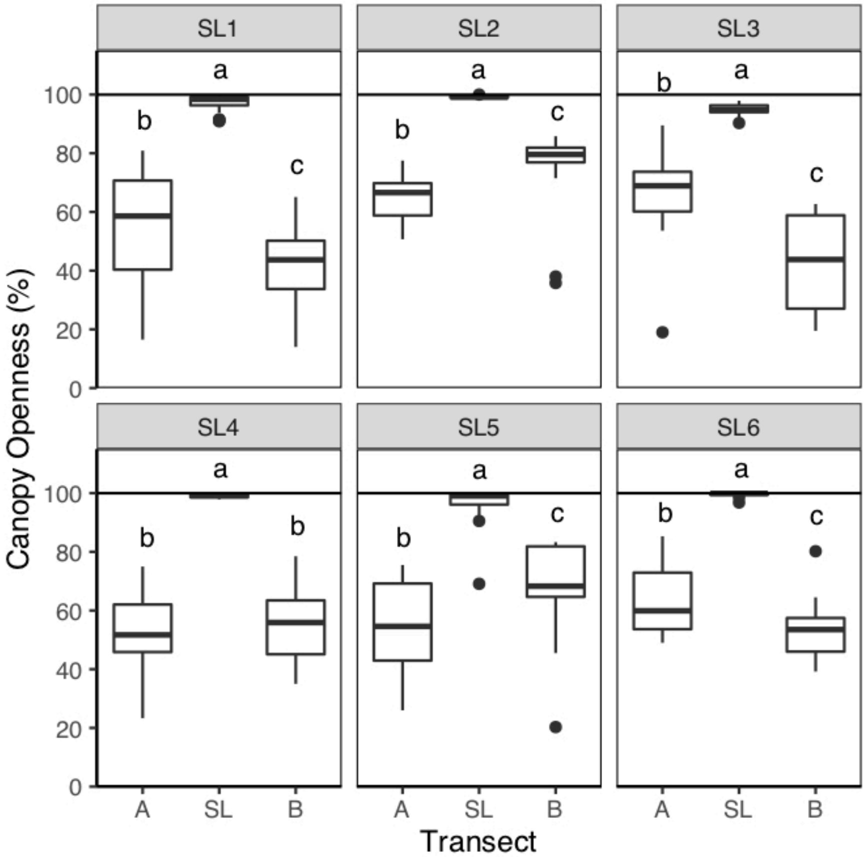

Figure 2.1: Boxplots of canopy openness as calculated from canopy photos (*n*=45) captured at each seismic line research site. Transects 'A' and 'B' are located in the treed portions of the bog on opposite sides of seismic line containing the 'SL' transect. See Table 2.2 for more on relative positions of transects. Alphabetical notation identifies significant (α = 0.01) differences in canopy openness between transects at each site, no comparison amongst sites.

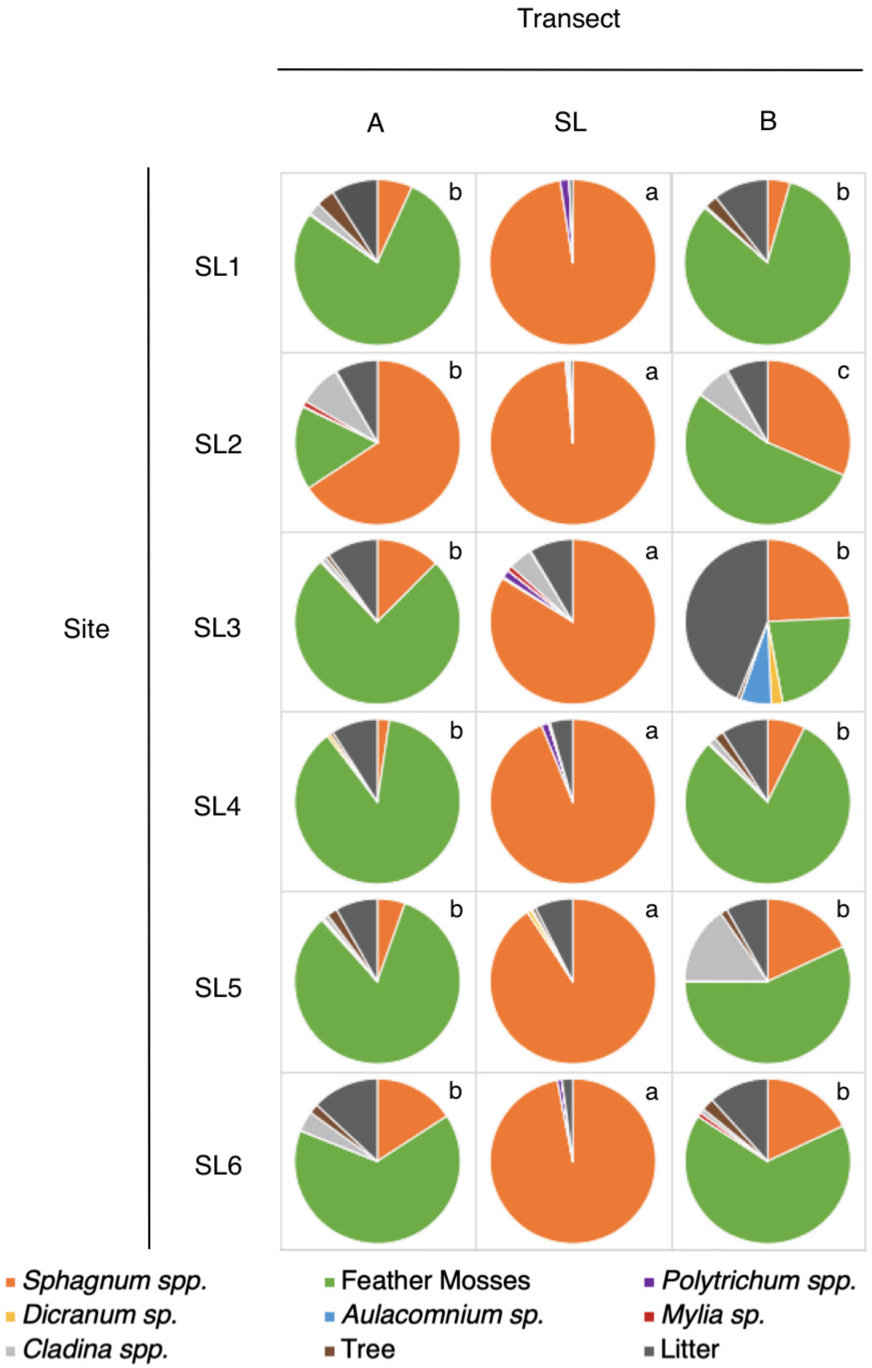

Figure 2.2: Percent ground cover composition in quadrats (*n*=45) at each seismic line site. Transects 'A' and 'B' are located in the treed portions of the bog on opposite sides of the seismic line containing the 'SL' transect. See Table 2.2 for relative position of transects. Alphabetical notation identifies significant (α = 0.01) differences in *Sphagnum* ground cover percentage between transects at each site, no comparison amongst sites.

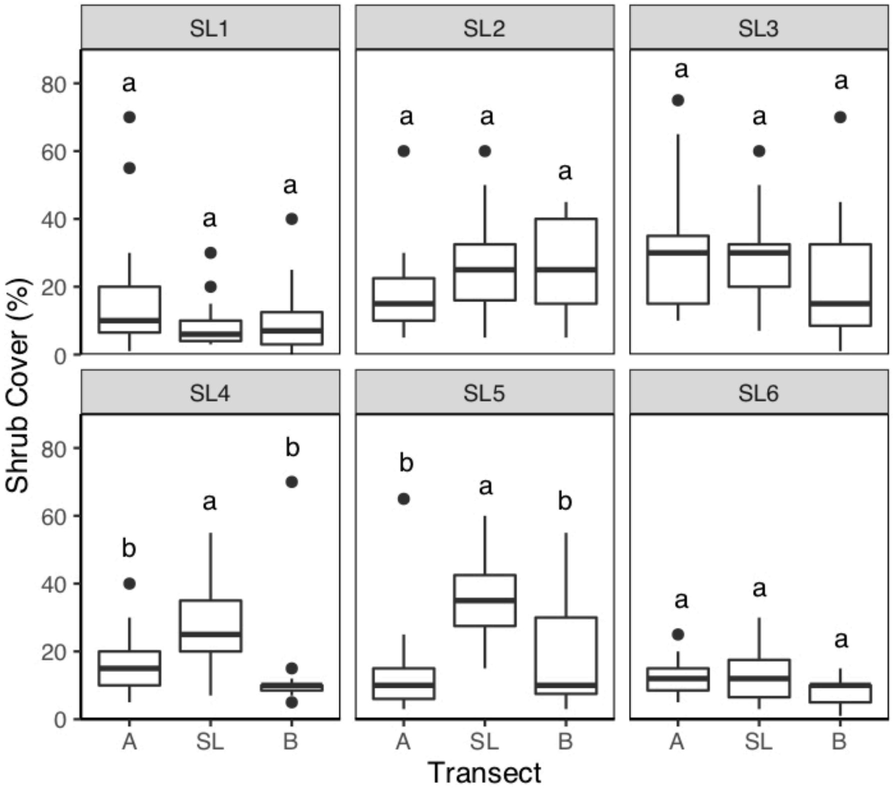

Figure 2.3: Percent shrub coverage within quadrats (*n*=45) at each seismic line research site. Transects 'A' and 'B' are located in the treed portions of the bog on opposite sides of the seismic line containing the 'SL' transect. See Table 2.2 for more on relative position of transects. Alphabetical notation identifies significant (α = 0.05) differences in shrub cover percentage between transects at each site, no comparison amongst sites.

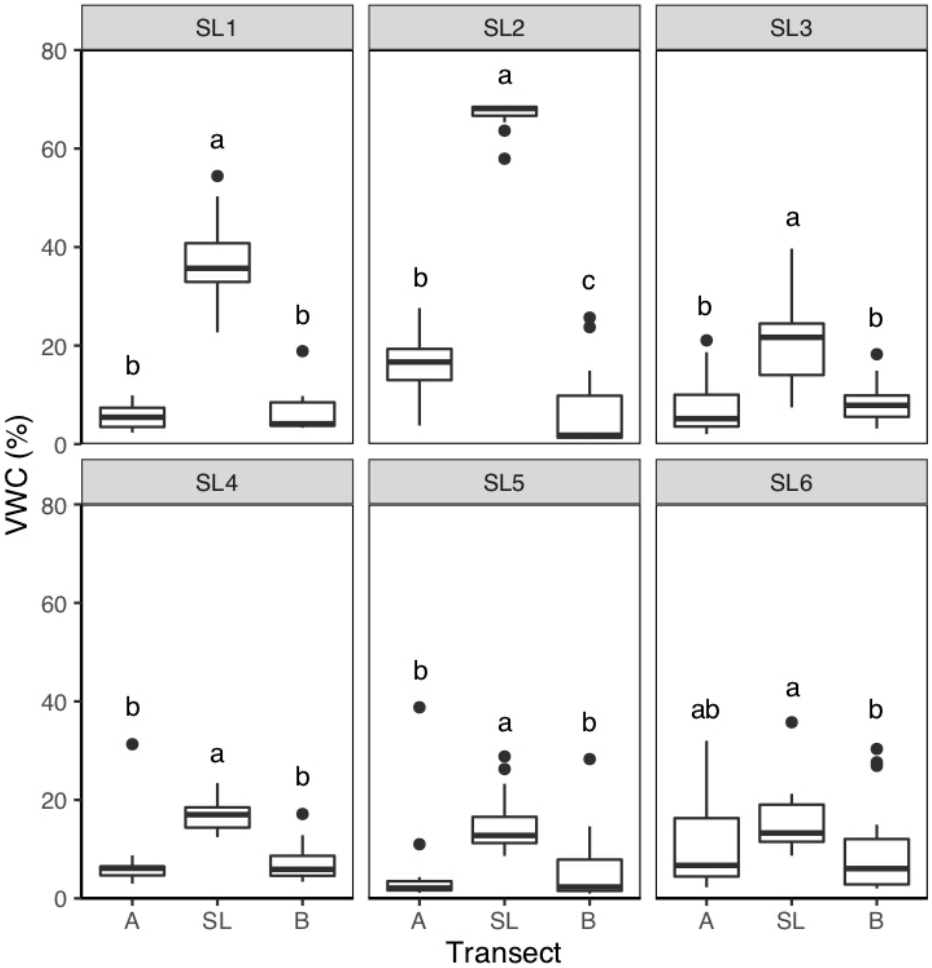

Figure 2.4: Near-surface (0 – 0.06 m) volumetric water content as measured in quadrats (*n*=45) at each seismic line research site. Transects 'A' and 'B' are located in the treed portion of the bog on opposite sides of the seismic line containing the 'SL' transect. See Table 2.2 for more on relative positions of transects. Alphabetical notation identifies significant (α = 0.05) differences in volumetric water content between transects at each site, no comparison amongst sites.

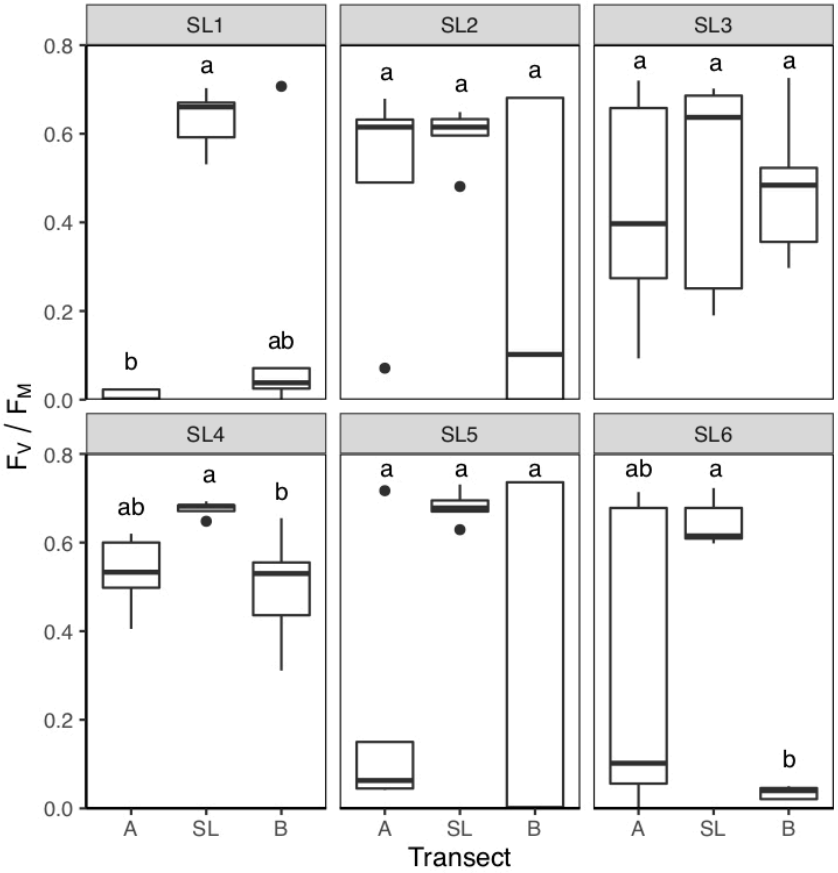

Figure 2.5: Maximum quantum yield of PSII (F_v/F_m) of most abundant moss species within each quadrat (*n*=45) at each seismic line research site. Transects 'A' and 'B' are located in the treed portion of the bog on opposite sides of the seismic line containing the 'SL' transect. See Table 2.2 for more on relative positions of transects. Alphabetical notation identifies significant (α = 0.05) differences in F_v/F_m between transects at each site, no comparison amongst sites.

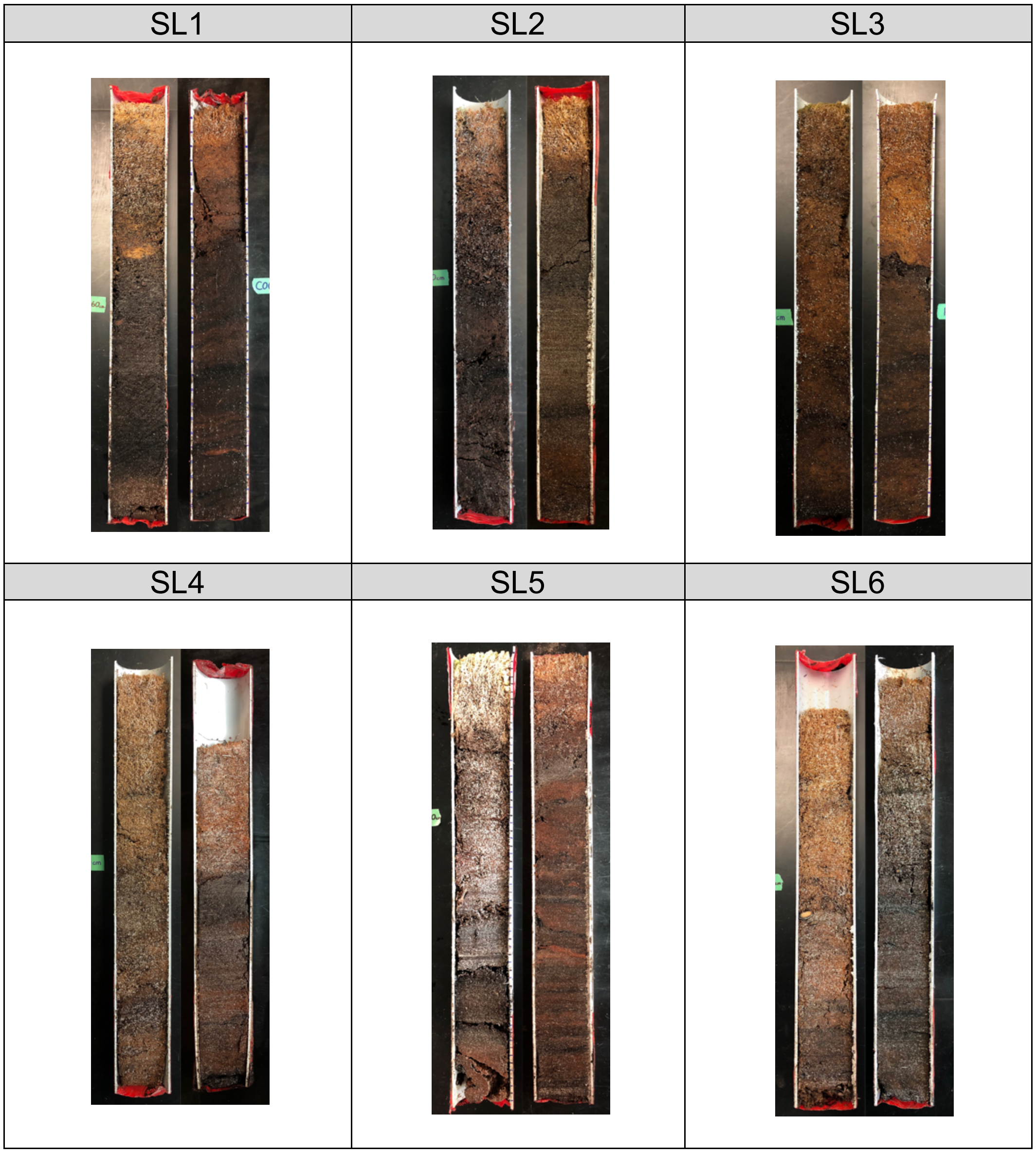

Figure 2.6: Peat profiles of the treed portion of the bog (left) and the intersecting seismic line (right) at each research site.

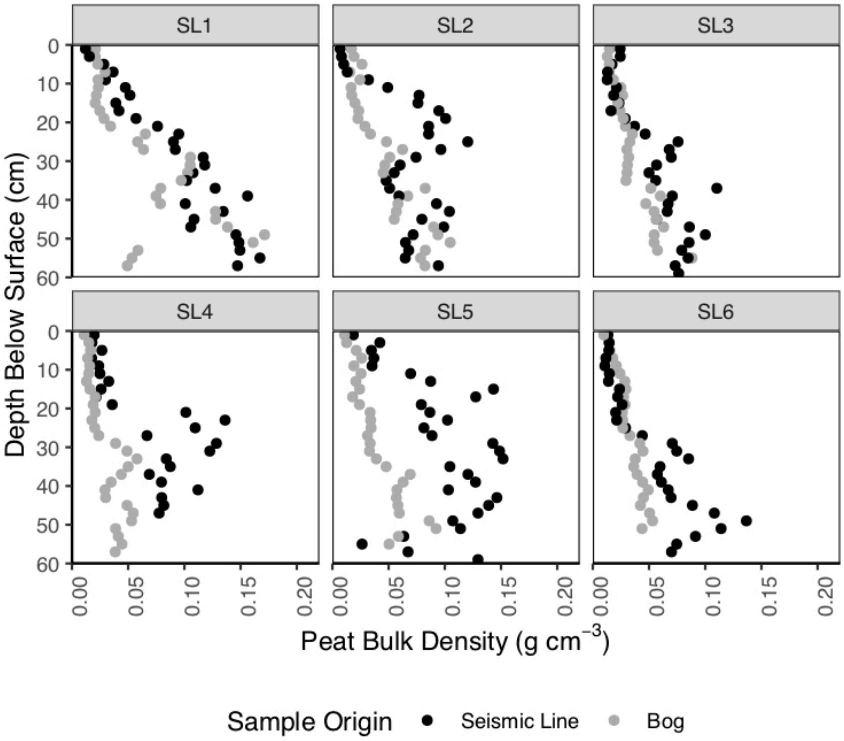

Figure 2.7: Peat bulk densities (2 cm intervals) of the core extracted from seismic line (*n*=1) and the core extracted from the adjacent treed portion of the bog (*n*=1) at each seismic line research site.

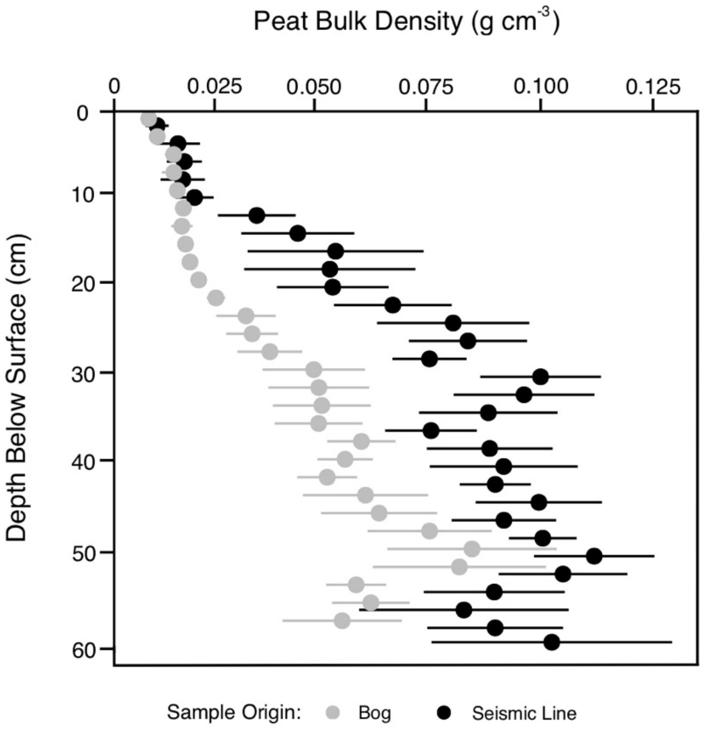

Figure 2.8: Peat bulk density averaged by 2 cm depth intervals for seismic line (*n*=6) and adjacent treed bog (*n*=6) cores.

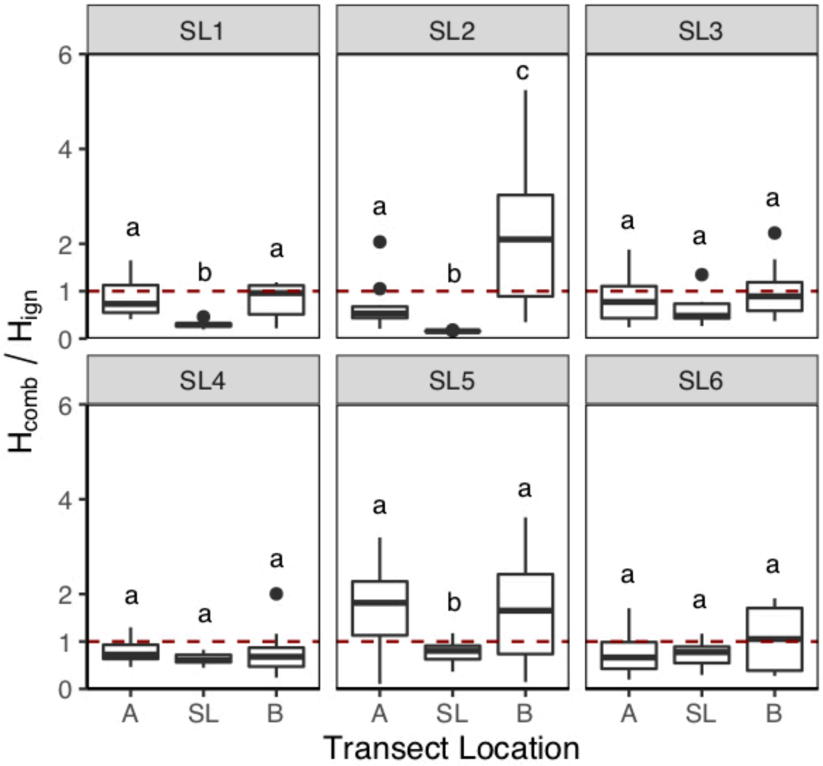

Figure 2.9: Smouldering potential of near-surface (0 – 0.06 m) moss and peat as calculated using an energy balance model (Benscoter et al., 2011) within each quadrat (*n*=45) at seismic line research sites. Where $H_{comb}/H_{ign}>1$ indicates potential for smouldering combustion. Transects 'A' and 'B' are located in the bog on opposite sides of the seismic line containing the 'SL' transect. See Table 2.2 for more on relative positions of transects. Alphabetical notation identifies significant (α = 0.05) differences in H_{comb}/H_{ign} between transects at each site, no comparison amongst sites.

CHAPTER 3: ASSESSING THE EFFECTIVENESS OF FUEL MODIFICATION TREATMENTS IN REDUCING PEAT SMOULDERING POTENTIAL IN A BLACK SPRUCE PEATLAND

3.1 Introduction

Projections for Canada’s boreal region indicate that the aerial extent and severity of wildfire will increase under future climate scenarios (Flannigan et al., 2013; Flannigan et al., 2005) to the point where fire managers may struggle to maintain their current level of effectiveness (Flannigan et al., 2009). Fuel modification treatments are a proactive approach to address this issue in the expanding wildland-urban and wildland-industry interfaces. However, increases in fire behaviour emphasize the need for enhancement of current strategies beyond conventional fuel reduction approaches (Flat Top Complex Wildfire Review Committee, 2012). Peatlands comprise 21% of the land area in western continental Canada (Vitt et al., 2000), but ecosystem-specific approaches to fuel management are lacking in these areas. Seismic lines intersecting treed bogs have shown promise as analogs for peatland-specific fuel modification treatments (refer to Chapter 2). Here we propose novel peatland-specific fuel modification treatments that incorporate the two principle components of seismic line construction: 1) manipulation of canopy structure (thinning and clearing) and 2) manipulation of hydrophysical peat properties (surface compression).

3.1.1 Modifications to Black Spruce Canopy

The non-vascular structure of bryophytes means that their abundance and spatial distribution is strongly controlled by environmental factors influencing local water dynamics (Busby et al., 1978). Feather mosses, which depend on precipitation events and dew formation as primary water sources, occupy shaded areas where evaporative demands are low (Bisbee et al., 2001). In contrast, *Sphagnum* mosses tend to occupy areas with greater PAR transmittance (Bisbee et al., 2001), which is accredited to the structure of these mosses, particularly hummock-forming species (e.g. *Sphagnum fuscum*), which are able to access water up to 40 cm below surface via capillary action (Hayward & Clymo, 1982; McCarter & Price, 2014; Price & Whittington, 2010). The contrast in environment requirements between these moss types suggest that by increasing the canopy openness (i.e. increasing PAR transmittance) more favourable conditions for the expansion of *Sphagnum* ground cover is created, as feather mosses would likely experience radiation damage and desiccation from increased evaporative stress (Bisbee et al., 2001; Busby et al., 1978). This would have a profound effect on peatland water and carbon balances as the NPP of *Sphagnum* mosses are over three times greater than that of feather mosses (Bisbee et al., 2001), leading to increases in peatland carbon stores and increased evaporation (Kettridge et al., 2013). *Sphagnum* mosses also retain more moisture than feather mosses, thereby reducing the quantity of greater density peat typically produced through the aerobic decomposition feather mosses (Moore et al., 2007).

Leonard et al. (2017) examined medium-term responses of moss species composition within the transitional period following increased canopy openness within northern forested peatlands. Their study aimed to isolate the effects of increasing canopy openness while avoiding confounding factors such as the effects of machinery which are often used in large-scale timber clearances. Despite what the correlations between PAR transmittance and moss type may suggest, it was found that there were no significant differences in moss species composition following a four-year post-treatment period (Leonard et al., 2017). This result contrasts strongly with the responses observed in similar studies on mineral soils, in which *Sphagnum* ground cover increased in the years following disturbance (Fenton & Bergeron, 2007) and feather mosses were either absent (Shields et al., 2007) or significantly reduced (Fenton et al., 2003). The discrepancy between these studies may be influenced by the physical differences in soil substrates; however, it is thought that the aforementioned study by Leonard et al. (2017) may have overlooked a key component of the treatment process: the effect of large machinery operation on the moss surface and underlying peat.

3.1.2 Modification of Physical Peat Properties

Operating large machinery within peatland environments would no doubt have a major impact on the moss surface and the hydrophysical properties of the underlying peat. Studies conducted on mineral soils (Fenton & Bergeron, 2007; Fenton et al., 2003; Shields et al., 2007) document the use of large equipment or machinery in tree removal and the associated compression of the ground surface. Compared to mineral soils, peat soils have a significantly greater porosity and typically have a greater water content which allows for soil volume changes to be up to ten times greater in these environments (Hobbs, 1986). The enhanced compressibility of peat has the potential to substantially alter hydraulic parameters and their relationships within peatlands (Schlotzhauer & Price, 1999; Waddington et al., 2010). Not only would the operation of large machinery compress the peat, but the destructive nature of this method would also eliminate ground cover species which may otherwise competitively exclude *Sphagnum* from expanding within that area.

Volume changes in peat do not arise exclusively from anthropogenic intervention; in fact, volume changes occur naturally as an autogenic peatland response to periods varying water availability, known as the WT depth – peat deformation feedback (Waddington et al., 2015). As the WT rises during times of high water availability, pores fill with water and the pore water pressure increases causing the bog surface to rise as both the volume of the peat matrix and water storage capacity increase (Howie & Hebda, 2018). This increase in water storage capacity acts to sustain moss physiological processes during periods of drought. As drought persists, the WT declines and the bog surface falls. Air enters pores that were previously saturated causing an increase in effective stress on the saturated zone from the greater weight of unsaturated peat above, compressing and reducing the volume of the saturated peat matrix (Howie & Hebda, 2018; Schlotzhauer & Price, 1999; Schothorst, 1977). In the unsaturated zone, peat undergoes aerobic decomposition and shrinkage caused by the collapse of pores, thereby decreasing peat volume (Howie & Hebda, 2018; Price & Whittington, 2010; Price et al., 2008). Large pores are first to collapse in these scenarios, increasing the relative proportion of smaller pore spaces and increasing the bulk density of the peat (Price, 2003; Schlotzhauer & Price, 1999). This alteration of physical peat properties initiates a negative feedback response in which the increased bulk density causes reductions in both the permeability and saturated hydraulic conductivity (K_{sat}) of the peat matrix (Schlotzhauer & Price, 1999; Whittington & Price, 2006), thereby constraining lateral water loss and minimizing further WT declines (Van Seters & Price, 2002; Waddington et al., 2015). In unsaturated soils, compression promotes hydrological connectivity by reducing the proportion of air-filled pore space (Price &

Whittington, 2010) leading to increases in both the VWC and the unsaturated hydraulic conductivity (Golubev & Whittington, 2018). Therefore, the compression of the peat profile facilitates water delivery to the capitula at the moss surface. Additionally, compressed (i.e. greater bulk density) peat also experiences greater soil matric suctions (Schlotzhauer & Price, 1999), which promotes water retention (Golubev & Whittington, 2018; Price & Whittington, 2010).

3.1.3 Conceptual Model of Proposed Fuel Modification Strategy

The proposed fuel modification treatments (canopy thinning/removal and peat compression) have both a short-term and a long-term component which are presented here as a conceptual model to demonstrate the interconnectedness of the processes, interactions and feedbacks (see Figure 3.1). It is anticipated that short-term effects would be marked by an adjustment to the hydrological functioning of the bog through compression-induced changes to hydrophysical peat properties. Immediate effects of mechanical compression would likely result in a depression of the bog surface, resulting in a decrease in WT depth, as well as increases in peat bulk density; effects which are evident from the study of seismic lines (Lee & Boutin, 2006; Lovitt et al., 2018). The decrease in WT depth concurrently decreases the vertical hydraulic gradient in the unsaturated zone, thereby increasing near-surface VWC (Waddington et al., 2015). Mixed effects result from the greater bulk density of peat following the surface compression treatment. Enhanced moisture retention and unsaturated hydraulic conductivity of compressed peat function to increase near-surface VWC (Golubev & Whittington, 2018; Price & Whittington, 2010; Schlotzhauer & Price, 1999), thereby decreasing smouldering potential (Rein et al., 2008); however, the increase in peat bulk density in itself increases smouldering potential (Benscoter et al., 2011).

The long-term component of this proposed fuel modification strategy involves facilitating an ecological shift in ground vegetation composition as a result of alteration to canopy structure and physical peat properties (Figure 3.1). *Sphagnum* hummocks, which are sites for black spruce seeding establishment, may be greatly impacted and even eliminated through surface compression treatments (Lee & Boutin, 2006), while compressed soils and shallow WT positions reduce soil aeration and restrict root penetration (Startsev & McNabb, 2009) hindering vegetation regeneration. Less above ground biomass contributes to the maintenance of a shallow WT position by reducing water loss through transpiration as well as decreasing interception during precipitation events. In shaded areas with a low evaporative demand feather mosses begin to encroach over *Sphagnum*, a scenario that is typical of later successional bogs (Benscoter & Vitt, 2008; Skre et al., 1983). Surface resistance to evaporation is significantly greater in feather mosses relative to that of *Sphagnum* (Brown et al, 2010; Kettridge et al., 2013) and therefore, as these later successional bogs transition to systems with a greater proportion of feather moss ground cover, ecosystem evaporation rates decrease. This affect is characterized in the WT depth – afforestation feedback (Waddington et al., 2015). *Sphagnum* mosses dominate the ground cover in seismic lines of boreal bogs (refer to Chapter 2). It is thought that by implementing these modifications to canopy structure and physical peat properties one can create ecohydrological conditions that resemble those found in seismic lines, thereby initiating a new trajectory for peatland ground cover consisting primarily of *Sphagnum*. Ultimately, it is expected that the cumulative effects of these fuel modification treatments will decrease the smouldering potential of near-surface moss and peat in both the short- and long-term by increasing near-surface water contents (Figure 3.1).

The proposed fuel modification treatments are also expected to have a range of effects on the ecohydrological functioning of bog ecosystems. As canopy openness increases across treatment types, forest floor evaporation rates are expected to increase concurrently as a result of exposure to wind and increased solar radiation. These conditions are expected to induce moss moisture stress in feather mosses, which are not physiologically equipped to survive within these open areas (Busby et al., 1978; Skre et al., 1983). Mulch treatments are an exception to the canopy openness –

evaporation hypothesis, as the woody-mulch covering the surface is expected to function as an evaporative cap on underlying moss, thereby substantially reducing evaporation rates in this area. As such, it is thought that VWC in the mulch treatment will be dependent on mulch depth and therefore, be quite variable across this treatment type. The presence of a thick woody-mulch layer may result in lower VWC measurements; however, a thinner layer of woody-mulch may allow the soil moisture probe to enter wet, underlying peat resulting in higher VWC readings. In the other treatments, VWC is expected to be greater in *Sphagnum* compared to feather moss and be lower in treatments with a greater canopy openness; however, moss type is expected to exert a stronger control on VWC compared to treatment type. Soil water pressure, which is dependent on near-surface VWC, is expected to follow a similar trend. The thin, wiry structure of feather mosses and the reliance of these mosses on precipitation and dew formation as water sources (Busby et al., 1978; Longton & Greene, 1979) suggests that they will dry out more readily than *Sphagnum*, which is anticipated to be observed as greater soil water pressures in this moss type. Surface compression treatments are expected to increase bulk density of near-surface moss and peat, thereby increasing vertical unsaturated hydraulic conductivity in compressed areas (Golubev & Whittington, 2018), which is expected to increase near-surface VWC, decrease soil water pressure, and increase evaporation. Since moisture content exerts a primary control on combustion (Rein et al., 2008), we expect smouldering potential to follow a similar trend to that of VWC where smouldering potential is lower in *Sphagnum* compared to feather moss, and also lower in areas with greater canopy closure. The increase in VWC associated with compression is expected to offset concomitant increase in bulk density, leading to a net decrease in smouldering potential in compressed areas.

3.2 Methods

3.2.1 Site Description

In response to the disastrous fires of 2011 that burned into the communities of the Lesser Slave Lake area of Alberta, the Alberta Wildfire Management branch commissioned an external review of the wildfires and response efforts. The review identified a need for a better understanding of vegetation management as a means to mitigate impacts of future fire (Flat Top Complex Wildfire Review Committee, 2012). As part of the response to this issue, the Pelican Mountain FireSmart Fuel Management Research Site was established in 2015 with intent to examine the effectiveness of fuel management strategies at (1) decreasing head fire intensity and (2) limiting initiation of crown fire, thereby aiding or enabling direct suppression efforts as well as (3) providing a location for the testing of novel fuel modification strategies (Schroeder, 2018). The Pelican Mountain site (55.701636, -

113.578543) is located just north of kilometre 123 on the Alpac C Road, approximately 11 km west of Highway 813 near the community of Sandy Lake, Alberta. Results from a previous prescribed fire near the hamlet of Red Earth Creek, AB emphasized the effectiveness of *Sphagnum* mosses, particularly hummock-forming species (Wilkinson et al., 2018), in reducing burn severity and emphasized the potential utility of increasing the proportion of *Sphagnum* ground cover as part of a FireSmart fuel treatment (Hvenegaard et al., 2016). As such, a six-hectare area of peatland at Pelican Mountain was dedicated to optimizing black spruce fuel treatments to promote *Sphagnum* ground cover.

3.2.2 Fuel Modification Treatments

A six-hectare area at Pelican Mountain was separated into twelve, 0.5 ha blocks designated for FireSmart treatments (Figure 3.2). Treatments were implemented in triplicate and include control, thin, clearfell, and mulch treatment blocks. Control blocks provide an undisturbed stand and peatland surface to serve as analogs of pre-treatment conditions within adjacent treated blocks. Stand density has been reduced in thin blocks and ladder fuels have been removed. The tree stand is completely removed in clearfell and mulch blocks; however, the moss surface remains untreated in the former whereas in the latter the trees have been mulched and the woody remains now cover the surface. These treatments were conducted in January and February of 2018 when winter conditions and frozen ground minimize soil disturbance (Strack et al., 2019). In August 2018, one half of each treatment block underwent a surface compression treatment. In search for a universal method of surface compression within all stand treatments working with limitations imposed by the high stand densities of control blocks which restricted equipment access, the most feasible method entailed systematic gridding of designated areas with a group of people actively compressing near-surface moss and peat with body weight. Gridding was repetitively performed in a multidirectional manner to ensure comprehensive coverage of designed areas.

3.2.3 Transect-Based Approach to Field Data Collection

As part of the ecohydrological characterization and evaluation of fuel modification treatments, transects, 40 m in length, were established within each treatment block (Figure 3.2). These transects bisect treatment blocks in a direction parallel to the bank of the nearby pond in order to mitigate the effect of proximity to open water on transect data. In control and thin treatment blocks, canopy photos were captured at 1 m intervals along transects from a height of 0.5 m in and later used in the calculation of canopy openness (refer to Section 2.2.5). No photos were captured in clearfell and mulch treatment blocks as canopy openness was assumed to equal 100% in these areas. Prior to the surface compression treatment, relative elevation measurements were recorded at 1 m intervals along each transect using a Smart Leveler (Digital Leveling Systems, Smyrna, Tennessee, USA) and a location with low compressibility was noted in the non-compressed portion of each treatment block to serve as the reference point. Relative elevation measurements were repeated following surface compression treatments and used to quantify the change in height at each location. To quantify compression in each treatment block, the height relative to the reference point was first calculated for each position along the transect. Next, the change in height was calculated between subsequent measurements prior to and following surface compression treatments. The mean change in height was then calculated for the compressed and non-compressed halves of each transect. Finally, a compression value was determined by subtracting the mean change in height of the non-compressed portion of the treatment block from the mean change in height of the compressed portion of the block (Table 3.1). This approach ensured accuracy in compression measurements by accounting for variability in the non-compressed portion of the block between subsequent measurements.

3.2.4 Plot-Based Approach to Field Data Collection

A plot-based approach was taken to evaluate differential responses of *Sphagnum* and feather mosses to fuel modification treatments. Within each treatment block twelve plot locations were established, six of which were *Sphagnum* hummocks and six were feather moss hummocks. Mulch blocks no longer possessed a visible or intact moss surface, instead plots were divided between locations with woody-mulch and moss-mulch mix. Ecohydrological assessments involved temporally pairing measurements of VWC, F_v/F_m, soil water pressure, and evaporation. Soil water pressure was quantified through the use of tensiometers (Soil Measurement Systems, Huntington Beach, California, U.S.A.) installed at a depth of 5 cm below the surface, with measurements recorded following a rain-free period of at least four days. To quantify evaporation, a small area (~180 cm^2) of each plot location was first cleared of above ground biomass. A small, cylindrical plexiglass chamber (15.2 cm tall by 15.2 cm in diameter) was then slightly embedded in the shrub free portion of the moss. This chamber contained a small fan for air circulation, powered by a 12-volt battery, and a Hygrochron™ iButton® DS1923 (Maxim Integrated, San Jose, California, U.S.A.), which logged measurements of temperature and relative humidity (accurate to 0.6 % RH, 0.5°C) at two-second intervals. A measurement cycle consisted of a two-minute measurement period followed by a one-minute non-measurement period, during which the chamber was held in the air to allow the air inside to return to ambient conditions prior to subsequent measurements. To quantify the evaporation rate, saturation vapour pressure was firstly was calculated as a function of temperature and then relative humidity was used to determine actual vapour pressure in the chamber. Given actual vapour pressure in a fixed volume, the ideal gas law was applied to determine the number of mols of water in the chamber. The molar mass of water and an assumed constant density (1 g cm^{-3}) yielded a volume of water, which was divided by the surface area of the chamber base to yield a depth of water. Lastly, the change in water depth over the measurement period provided the evaporation rate at each plot location.

3.2.5 Organic Soil Sample Collection and Analysis

Two *Sphagnum* peat samples were collected in PVC pipe (0.6 m in length by 0.1 m diameter) from each treatment block: one from the compressed half and the other from the non-compressed half of each block. These cores were sealed and shipped to McMaster University, where upon arrival, they were frozen for preservation awaiting laboratory analysis. In the laboratory, cores were cut laterally into 0.05 m increments, volume measurements were recorded, and samples were placed in an oven to dry at 85 °C until no change in mass was measured. Bulk density of each sample was then calculated.

3.2.6 Smouldering Potential

An energy balance model (Benscoter et al., 2011) was applied to evaluate smouldering potential at plot locations amongst fuel modification treatments (refer to section 2.2.6). Feather moss samples were collected from the research site, half of which underwent a compression treatment, and using the protocol outlined above (section 3.2.4) and a near-surface (0 – 0.05 m) bulk density value was derived for feather moss (7.50 kg m^{-3}, *n*=3) and compressed feather moss (8.70 kg m^{-3}, *n*=3). Bulk density values for *Sphagnum* (26.39 kg m^{-3}, *n*=9) and compressed *Sphagnum* (36.12 kg m^{-3}, *n*=9) were obtained from averaging near-surface bulk densities of cores collected from non-compressed and compressed halves of each control, thin, and clearfell treatment block. The same approach was used to obtain near-surface bulk density values for moss-mulch mix and woody-mulch (71.77 kg m^{-3}, *n*=3) and compressed moss-mulch mix and woody-mulch (89.53 kg m^{-3}, *n*=3); however, due to a lack of samples, it was assumed that there was no distinction between moss-mulch mix and woody-mulch samples. It was also assumed that bulk density values of the top 0.05 m of samples are representative of bulk density values to a depth of 0.06 m. VWC measurements were collected from plots located in treatment replicates A and B and converted to GWC using the method outlined in Section 2.2.6. This allowed for the calculation of smouldering potential in replicates A and B of each treatment type.

3.3 Results

3.3.1 Canopy Openness

Canopy openness percentage was compared amongst control and thin treatment blocks. It was assumed that canopy openness in clearfell and mulch blocks is equal to 100% and thus, they were not included in this analysis. A Kruskal-Wallis test identified significant ($\alpha = 0.05$) differences in canopy openness between treatment blocks (Table 3.2). Results from Fisher's LSD post hoc test corrected for multiple comparisons with the Benjamini-Hochberg method are shown in Figure 3.3. Canopy openness of thin blocks (79.4 ± 10.1%) was significantly greater than that of control blocks (38.4 ± 20.1%); however, significant differences were also identified within treatment replicates for both control and thin treatments.

3.3.2 Ecohydrological Measurements

Ecohydrological variables (VWC, F_v/F_m, soil water pressure, and evaporation) measured at plot locations were compared within and between treatments. Data for these variables are not normally distributed and therefore, nonparametric Kruskal-Wallis tests and post hoc Fisher's LSD tests with p-values adjusted with the Benjamini-Hochberg method were used in the multiple comparisons of these data sets (Table 3.2).

A general trend in mean VWC for plot types was identified across control, thin, and clearfell treatments, whereby the greatest mean VWC were found in compressed *Sphagnum* followed by *Sphagnum*, compressed feather moss and lastly feather moss (Figure 3.4). This suggests that compression increases VWC in both *Sphagnum* and feather moss; however, this effect is only significant ($\alpha = 0.05$) in thin treatments and for feather moss in clearfell treatments (Figure 3.4). Similar plot types do not have significantly different VWCs across treatment types. In mulch treatments, mean VWC was greatest in compressed moss-mulch mix, intermediate in compressed woody mulch, and lowest non-compressed plots. In reference to other treatments, VWC of compressed moss-mulch mix is most comparable to compressed *Sphagnum*, whereas compressed woody-mulch, moss-mulch mix, and woody mulch are all most comparable to compressed feather moss.

Results of statistical analysis of chlorophyll fluorometry data show significant ($\alpha = 0.05$) differences both within and between sites (Figure 3.5; Table 3.2). Mean F_v/F_m for all plot types decreases with greater canopy openness. *Sphagnum* in control blocks had the greatest mean F_v/F_m and was significantly greater than that of compressed *Sphagnum*. Mean F_v/F_m of feather moss in control blocks was not significantly different than either *Sphagnum* nor compressed *Sphagnum*, but it was significantly greater than compressed feather moss. In both the thin and clearfell treatments, compression did not significantly affect F_v/F_m in either *Sphagnum* or feather moss, but *Sphagnum* plots did have significantly higher F_v/F_m than feather moss in both treatment types.

Statistical analysis of soil water pressure data indicates significant ($\alpha = 0.05$) differences amongst plot and treatment types (Figure 3.6; Table 3.2). Across all treatments *Sphagnum* and compressed *Sphagnum* were above the -100 hPa threshold below which *Sphagnum* mosses begin to desiccate (Hayward & Clymo, 1982). Soil water pressure of *Sphagnum* and compressed *Sphagnum* were not significantly different in the control treatment; however, compressed Sphagnum had significantly greater soil water pressure that that of *Sphagnum* in thin and clearfell treatments. Mean soil water pressure in feather moss was below the -100 hPa threshold in all treatment types. This was also the case for compressed feather moss in the control treatment, but not the thin or clearfell treatments. In general, compression appears to increase (less negative) the soil water pressure of both *Sphagnum* and feather moss; however, this effect was only significant in thin and clearfell treatments for *Sphagnum,* and thin treatments for feather moss. In the mulch treatment, woody-mulch was the only plot type showing mean soil water pressure below the -100 hPa threshold. Soil water pressure was not significantly different between moss-mulch mix, compressed moss-mulch mix, and compressed woody-mulch, nor was it significantly different between compressed moss-mulch mix and woody-mulch. To compare the mulch treatment to the other treatment types, soil water pressure of moss-mulch mix and compressed moss-mulch mix were most comparable to that of *Sphagnum*, soil water pressure in compressed woody-mulch was most comparable to that of compressed *Sphagnum*, and soil water pressure in woody-mulch was most comparable to that of feather moss.

A Kruskal-Wallis test revealed significant (α = 0.05) differences in evaporation amongst treatment blocks (Table 3.2) and results of post hoc tests are illustrated in Figure 3.7. Only the mulched treatment showed significant differences between block replicates, evaporation rate amongst replicates of other treatment types was otherwise non-significant. In general, evaporation rates were lowest in the control treatment and greatest in the clearfell treatment, with thin and mulch treatments having more intermediate evaporation rates. Examining evaporation rates within treatments reveals no significant (α = 0.05) effect of plot type on evaporation rate in control and thinned treatments (Figure 3.8; Table 3.3). The mulch treatment showed mixed effects, with no significant differences amongst plots in Mulch A, but in Mulch B the evaporation rate of woody mulch was significantly lower than that of moss-mulch mix and compressed moss-mulch mix. The biggest discrepancies were found in the clearfell treatment, where mean evaporation rates were greatest in *Sphagnum,* slightly lower in compressed *Sphagnum*, and much lower in feather moss and compressed feather moss. Compression does not significantly affect evaporation rate in either *Sphagnum* or feather moss in any treatment type.

3.3.3 Smouldering Potential

Smouldering potential was evaluated within and between treatment types using a Kruskal-Wallis test, which identified significant (α = 0.05) differences

(Table 3.2) and was therefore, followed up with Fisher's LSD post hoc test corrected for multiple comparisons using the Benjamini-Hochberg method (Figure 3.10). Mean H_{comb}/H_{ign} ratios were less than one for *Sphagnum* and compressed *Sphagnum* across all treatment types indicating that these plots did not have potential for smouldering. Conversely, feather moss had potential for smouldering in all treatments given mean H_{comb}/H_{ign} ratios were greater than one. Compressed feather moss showed mixed effects, where H_{comb}/H_{ign} ratios spanned across the threshold for smouldering combustion. Moss-mulch mix, woody-mulch, and compressed woody-mulch showed similar effects to feather moss, where H_{comb}/H_{ign} ratios span across the combustion threshold. Compressed moss-mulch mix showed similar H_{comb}/H_{ign} ratios to compressed *Sphagnum* and therefore, did not show potential for smouldering combustion. Plot types do not show significant differences in smouldering potential across treatment types; however, mean smouldering potential in feather moss increases with greater canopy openness. Compression decreases mean smouldering potential in all plot types, however, this effect is only significant in *Sphagnum* in the thin treatment*,* feather moss in the clearfell treatment, and moss-mulch mix.

3.4 Discussion

3.4.1 Ecohydrological Effects of Fuel Modification Treatments

Visually, the most apparent difference amongst these fuel modification treatments is the progressive reduction in above-ground fuel load between treatment types. Less apparent are the changes to the moss layer environment and hydrophysical peat properties; however, these changes at the near-surface level greatly impact ecohydrological functioning within this bog ecosystem. Feather mosses are generally able to outcompete *Sphagnum* when canopy openness falls below 20% (Bisbee et al., 2001). As a result of the thinning treatment, we see canopy openness percentages approximately double in thin treatments (79.4 ± 10.1%) compared to that of control stands (38.4 ± 20.1%), reducing the proportion of the treatment area below this 20% canopy openness threshold (Figure 3.3). Chlorophyll fluorometry was used as an ecological indicator of moss moisture stress, where mosses in control blocks represent mosses in the unstressed state. When comparing F_v/F_m amongst treatment types, we found that mean F_v/F_m decreased with increasing canopy openness at all plot locations (Figure 3.5). Compared to control blocks, F_v/F_m in the thin treatment was significantly lower for all plot types. While *Sphagnum* and compressed *Sphagnum* were able to maintain mean F_v/F_m values that are 81% and 87% of that in the unstressed state, respectively, mean F_v/F_m for feather moss and compressed feather moss were near zero. This suggests that feather mosses are experiencing significant moisture stress in thin treatments and are not likely to persist in the open environment. Meanwhile, *Sphagnum* and compressed *Sphagnum* showed little indication of moisture stress in thin treatments or even the more open clearfell treatments, where F_v/F_m was not significantly different than that of the thinned treatment for either moss type. This demonstrates the ability of *Sphagnum* mosses to outcompete feather moss and thrive in the open environment of these treated areas.

To complement chlorophyll fluorometry data, soil water pressure served as a hydrologic metric to assess moisture stress between and within treatment types. One advantage of using soil water pressure versus chlorophyll fluorometry is that it allows for the assessment of moisture stress with mulch treatments. Additionally, we can compare soil water pressure to a known threshold of -100 hPa where *Sphagnum* hyaline cells begin to drain, leading to desiccation (Hayward & Clymo, 1982). Contrary to fluorometry results, however, plot types did not show significant differences in soil water pressure across treatment types (Figure 3.6). Chlorophyll fluorometry quantifies fluorescence of living moss directly at the surface and therefore, is likely to be more sensitive to the differences in light conditions across treatment types. Soil water pressure on the other hand was quantified at a depth of 0.05 m below the moss surface, and while it may not be as sensitive to changing light conditions, it can provide important information regarding hydrological processes. For example, compressed mosses in all treatment types showed greater mean soil water pressure than that of non-compressed analogs. This effect is attributed to the increased bulk density in compressed plots enhancing vertical unsaturated hydraulic conductivity to increase near-surface VWC (Golubev & Whittington, 2018). This theory is supported by greater mean VWC in compressed mosses relative to non-compressed analogs (Figure 3.4).

Examination of near-surface VWC shows that there is not a significant change in VWC across treatment types as anticipated (Figure 3.4). Perhaps these differences would emerge following a longer duration of a rain-free period. Additionally, this study area was part of a larger peatland complex (178.4 ha), which may buffer against substantial WT fluctuations, thereby maintaining low hydraulic gradients in the unsaturated zone.

With the caveat that the approach used to measure evaporation is generally used to assess relative differences between sites (i.e., high versus low or near-zero) (see Kettridge et al., 2019), evaporation rates appear to be linked to canopy openness, as mean evaporation rates are greatest in clearfell treatments, intermediate in thin treatments, and lowest in control treatments (Figure 3.7). However, comparison within treatment blocks shows surprisingly little variation between plot types (Figure 3.8). Compression treatments were expected to increase evaporation rates in both *Sphagnum* and feather moss, but no significant ($\alpha = 0.05$) differences were identified in this regard. Additionally, evaporation rates in mulch treatments were greater than anticipated. It was thought that mulch cover would act as an evaporative cap, greatly reducing evaporation rates in these treatment blocks; however, Mulch A showed a mean evaporation rate comparable to that of clearfell treatments and Mulch B showed a mean evaporation rate comparable to that of control blocks (Figure 3.7). The variation in evaporation rates both within and between mulch treatments speaks to the heterogeneity of surface cover in these blocks, possibly due to the inconsistency of the mulching treatment itself.

Modification of hydrophysical peat properties through the manual surface compression treatment did not influence ecohydrological variables to the degree that was expected. There was a lack of consistent statistically significant differences amongst variables in compressed plots compared to non-compressed analogs. This is attributed to the low compression values as a result of the manual surface compression method (Table 3.1). Methods for surface compression were limited by the stand density imposed by control blocks and the search for a consistent compression method across all treatment types. The manual surface compression method implemented in this study would not likely have the same magnitude of impact as mechanical compression methods that were used in the establishment of seismic line sites.

3.4.2 Evaluating Effectiveness of Fuel Modification Treatments

Smouldering potential was compared both within and between treatment types (Figure 3.10; Table 3.2). Treatment type has no significant effect on smouldering potential as indicated by plot types, which are not significantly ($\alpha = 0.05$) different across treatments. Despite the results of the statistical analysis, there is large variability in mean H_{comb}/H_{ign} ratios of feather moss amongst control (1.54 ± 0.48), thin (2.64 ± 0.78), and clearfell (3.45 ± 1.30) treatments. When developing fuel modification strategies, the objective is to maintain H_{comb}/H_{ign} ratios less than one within treated areas. Findings indicate that only *Sphagnum* and compressed *Sphagnum* consistently showed H_{comb}/H_{ign} ratios below the threshold for smouldering combustion.

Chlorophyll fluorometry results indicated feather mosses were experiencing substantial moisture stress in both thin and clearfell treatments in response to increased canopy openness (Figure 3.5), suggesting that these areas may experience a shift in ground cover composition to mosses better suited to open environments (i.e. *Sphagnum*) (Bisbee et al., 2001). Expansion of *Sphagnum* mosses in treated areas will likely be a slow process; meanwhile, moisture-stressed and desiccated feather mosses characterized by high smouldering potential will likely cover the ground surface. One solution to this issue would be to manually remove feather mosses from treated areas to facilitate the expansion of *Sphagnum* ground cover; however, this approach would be both time- and labour-intensive.

Instead, it is proposed that the method of surface compression treatments be altered from a manual approach, as conducted in this study, to a mechanical approach similar to that of seismic line establishment. This could involve a mulcher simultaneously churning up and compressing near-surface moss and peat, to produce a surface cover similar to that of compressed moss-mulch mix plots, characterized by similar VWC to that of compressed *Sphagnum* (Figure 3.4), relatively low near-surface soil water pressure (Figure 3.6), lower mean evaporation rate (0.021 ± 0.006 mm h^{-1}) than that of *Sphagnum* (0.043 ± 0.010 mm h^{-1}) or compressed *Sphagnum* (0.033 ± 0.006 mm h^{-1}) in open areas, and importantly, low smouldering potential that is not significantly different from that of compressed *Sphagnum*. It is thought that such conditions will promote the regeneration of *Sphagnum* in treated areas, similar to that of seismic lines, while not compromising smouldering potential in the short-term like the manual compression method tested in this research.

3.5 References

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Table 3.1: Average surface compression within each treatment block. Refer to Section 3.2.3 for method.

Surface Compression	
Block ID	**Mean (Standard Deviation) (cm)**
CONTROL A	11.3 (2.6)
CONTROL B	8.5 (6.7)
CONTROL C	6.5 (6.2)
THIN A	8.7 (6.9)
THIN B	6.5 (5.8)
THIN C	9.2 (6.8)
CLEARFELL A	8.1 (5.1)
CLEARFELL B	6.0 (4.0)
CLEARFELL C	5.2 (4.4)
MULCH B	5.5 (3.5)
MULCH B	5.8 (3.7)
MULCH B	3.1 (3.0)

Table 3.2: Summary of Chapter Three Statistics. Statistical significance for each test is indicated using an asterisk (*) following the p-value.

Multiple Comparison (Kruskal-Wallis Test)			
Figure	**Description**	**Test Statistic**	**Significance**
3.3	Comparison of canopy openness between treatment blocks	$X^2(5) = 163.04$	$p = 2.20\text{x}10^{-16}$*
3.4	Comparison of VWC within and between treatment blocks	$X^2(15) = 71.69$	$p = 2.23\text{x}10^{-9}$*
3.5	Comparison of F_v/F_m within and between treatment blocks	$X^2(11) = 82.97$	$p = 3.92\text{x}10^{-13}$*
3.6	Comparison of soil water pressure within and between treatment blocks	$X^2(15) = 35.05$	$p = 2.42\text{x}10^{-3}$*
3.7	Comparison of evaporation rate between treatment blocks	$X^2(7) = 37.29$	$p = 4.14\text{x}10^{-6}$*
3.10	Comparison of smouldering potential within and between treatment types	$X^2(15) = 71.69$	$p = 2.23\text{x}10^{-9}$*

Table 3.3: Results of statistical comparative analysis of evaporation rate within each treatment block. Statistical significance for each test is indicated using an asterisk (*) following the p-value.

Multiple Comparisons (Kruskal-Wallis / ANOVA)		
Block ID	**Test Statistic**	**Significance**
CONTROL A	$F(3, 8) = 0.759$	$p = 0.548$
CONTROL B	$F(3, 8) = \mathit{3.764}$	$p = 5.94\text{x}10^{-2}$
THIN A	$F(3, 8) = 0.406$	$p = 0.753$
THIN B	$F(3, 8) = 0.715$	$p = 0.570$
CLEARFELL A	$F(3, 8) = 8.264$	$p = 7.82\text{x}10^{-3*}$
CLEARFELL B	$F(3, 8) = 10.57$	$p = 3.71\text{x}10^{-3*}$
MULCH A	$F(3, 8) = 3.276$	$p = 7.98\text{x}10\text{x}10^{-2}$
MULCH B	$F(3, 8) = 7.099$	$p = 1.21\text{x}10^{-2*}$

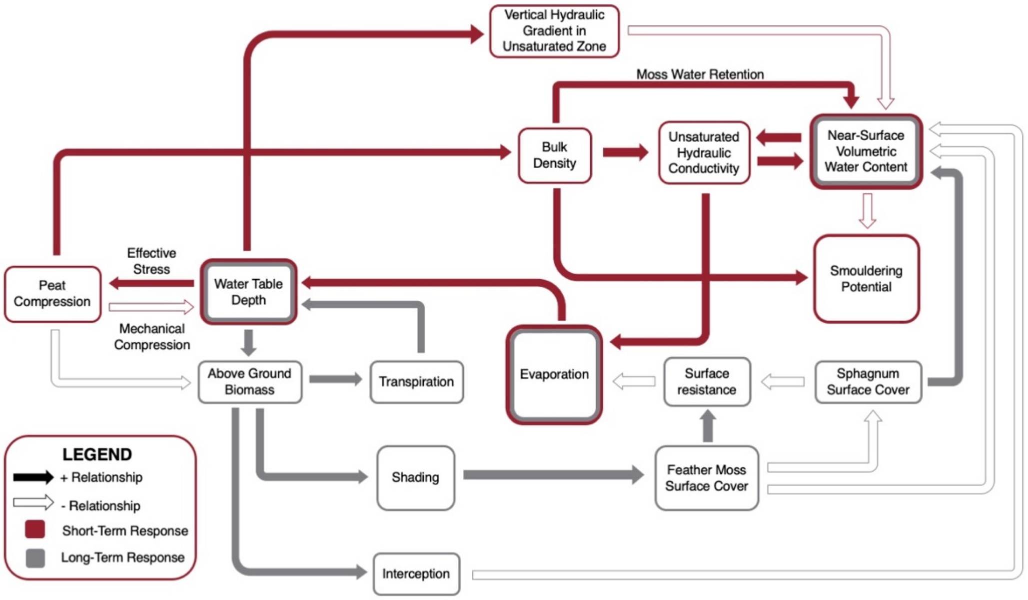

Figure 3.1: Conceptual understanding of the effects of mechanical compression on the ecohydrological structure and functioning of a black spruce forested bog within the Boreal Plains ecozone. Solid and outline arrows represent positive and negative relationships, respectively. Maroon colouring represents short-term responses to mechanical compression, whereas grey colouring indicates longer-term responses.

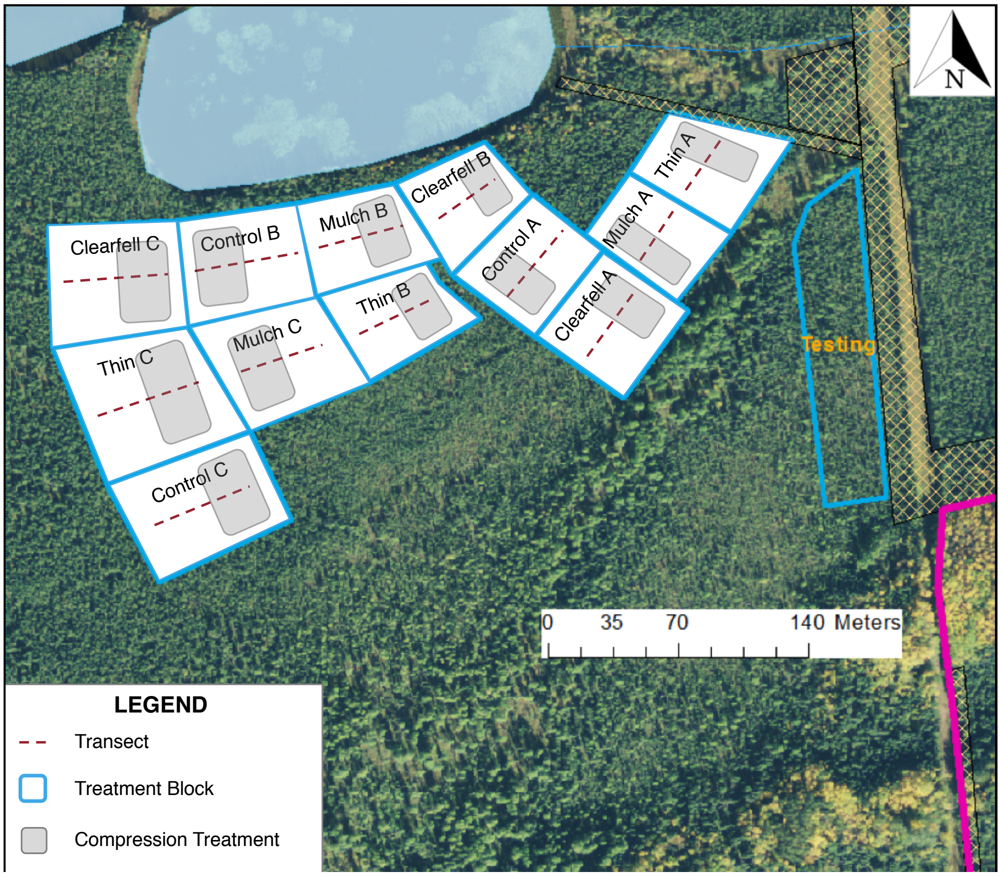

Figure 3.2: Overview of the Pelican Mountain research site depicting the twelve treatment blocks, transect locations, and areas that underwent surface compression treatment.

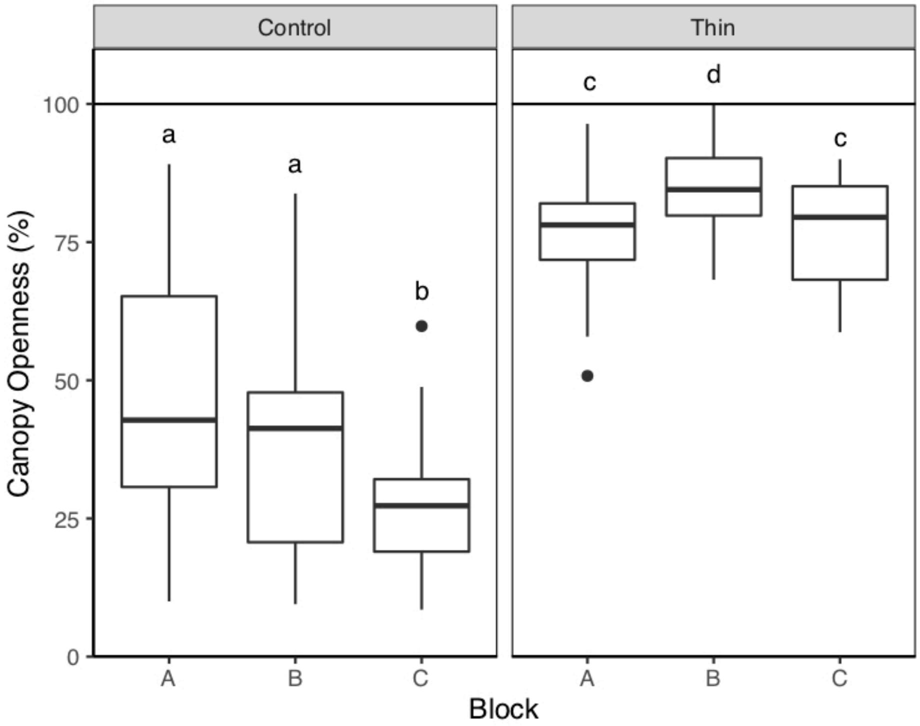

Figure 3.3: Boxplots of canopy openness in control and thin treatment blocks as calculated from canopy photographs (*n*=240). Canopy openness assumed to be 100% in clearfell and mulch blocks and therefore, not shown in this figure. See Figure 3.2 for locations of treatment blocks. Alphabetical notation identifies significant (α = 0.05) differences in canopy openness between blocks.

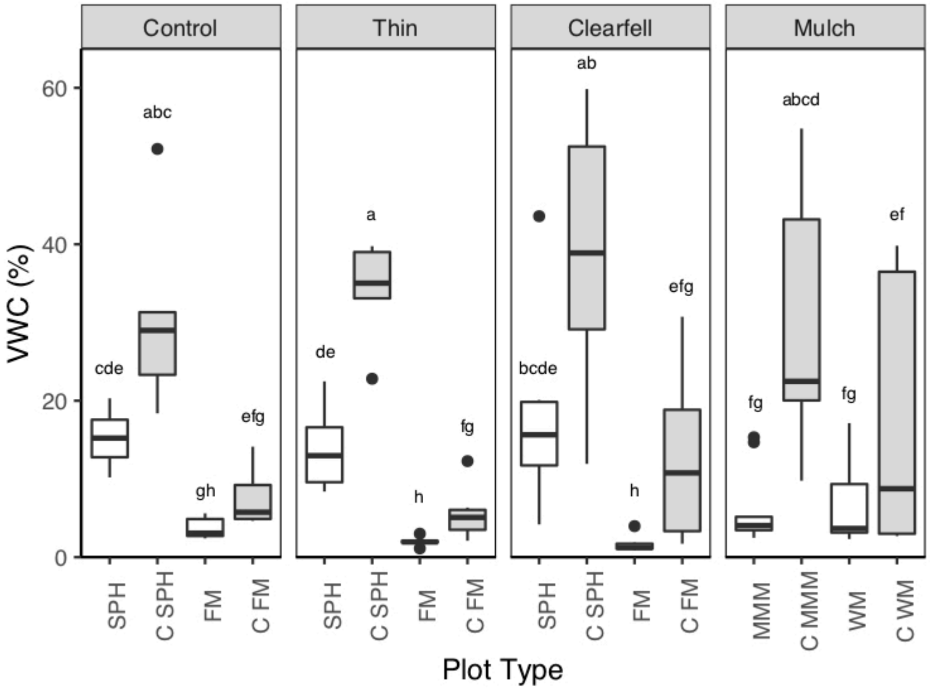

Figure 3.4: Near-surface (0 – 0.06 m) volumetric water content as measured at plot locations (*n*=108) within study area. Plot types include *Sphagnum* (SPH), feather moss (FM), moss-mulch mix (MMM), and woody-mulch (WM), with a 'C' prefix and grey boxplots indicating plots that underwent a surface compression treatment. Alphabetical notation identifies significant (α = 0.05) differences in volumetric water content between plot types.

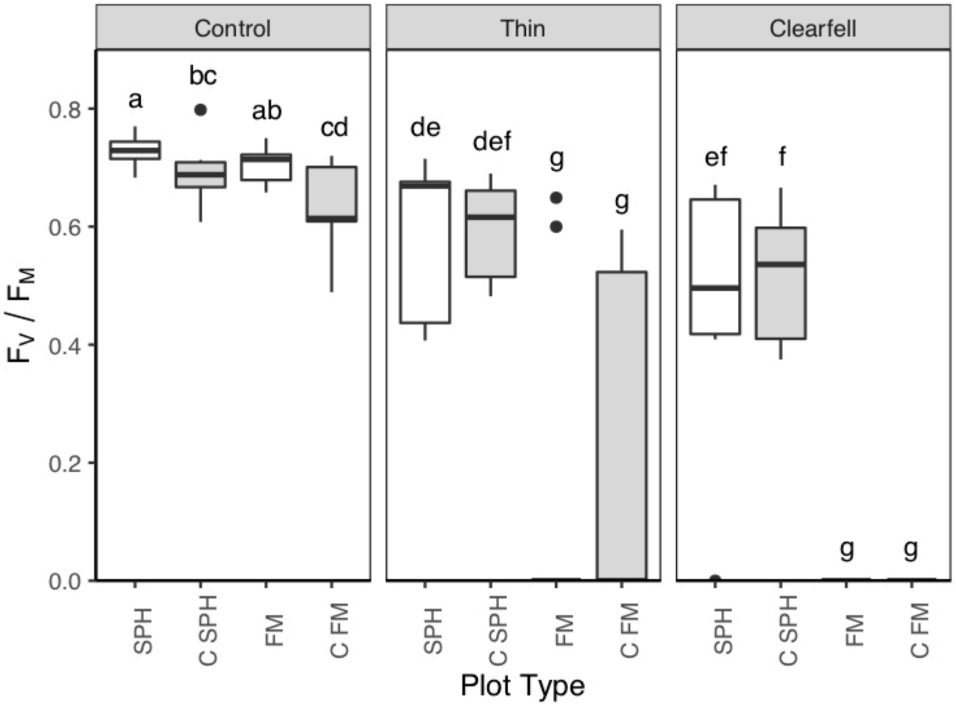

Figure 3.5: F_v/F_m of surface mosses as measured at plot locations (*n*=108) amongst treatment blocks following surface compression treatment. Plot types include *Sphagnum* mosses (SPH) and feather mosses (FM), with a 'C' prefix and grey boxplots indicating plots that underwent a surface compression treatment. Alphabetical notation identifies significant (α = 0.05) differences in F_v/F_m between plot types.

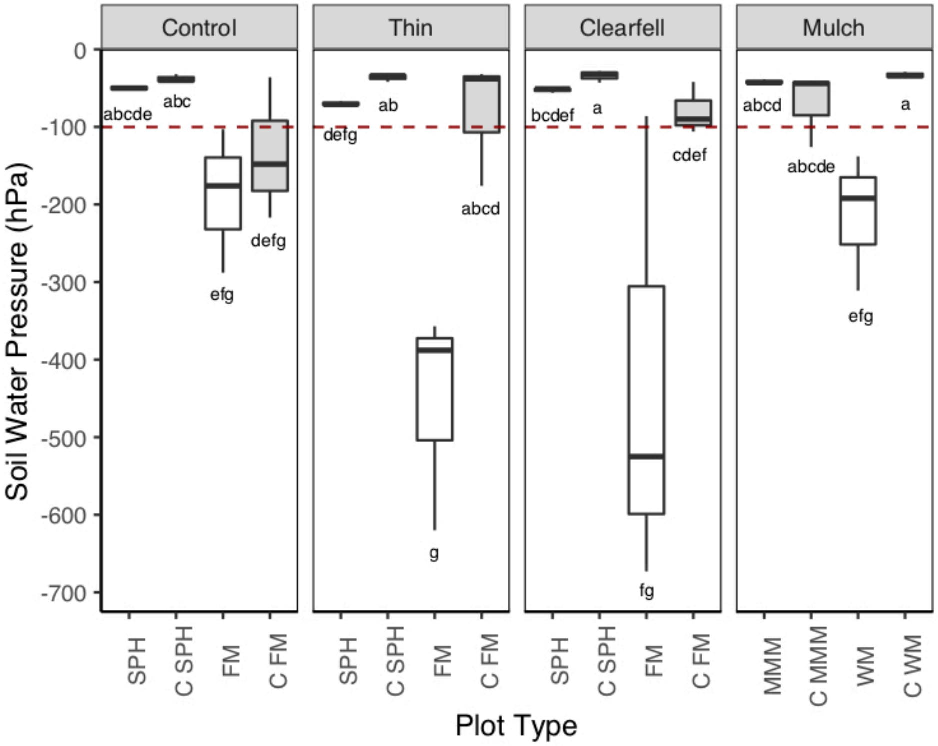

Figure 3.6: Soil water pressure measured at a depth of 0.05 m at plot locations (n=48) amongst treatment blocks. Plot types include *Sphagnum* (SPH), feather moss (FM), moss-mulch mix (MMM), and woody-mulch (WM), with a 'C' prefix and grey boxplots indicating plots that underwent a surface compression treatment. The maroon dashed line indicates the -100 hPa threshold below which *Sphagnum* mosses begin to desiccate (Hayward & Clymo, 1982). Alphabetical notation identifies significant (α = 0.05) differences in between plot types amongst block treatments.

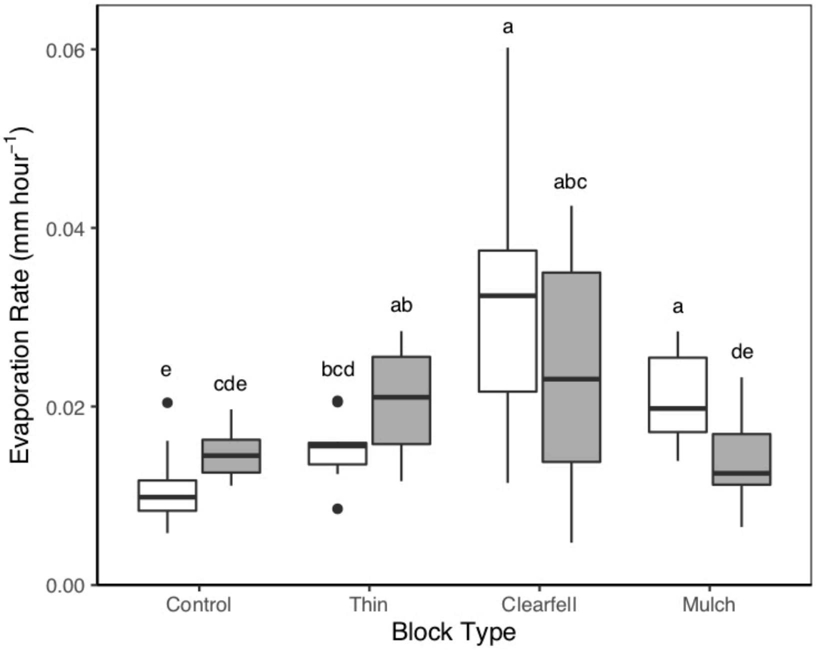

Figure 3.7: Evaporation rate within treatment blocks as measured at plot locations (*n*=96). White and grey boxplots represent A and B replicates of each block type, respectively. See Figure 3.2 for locations of treatment blocks. Alphabetical notation identifies significant (α = 0.05) differences in between plot types amongst treatment blocks.

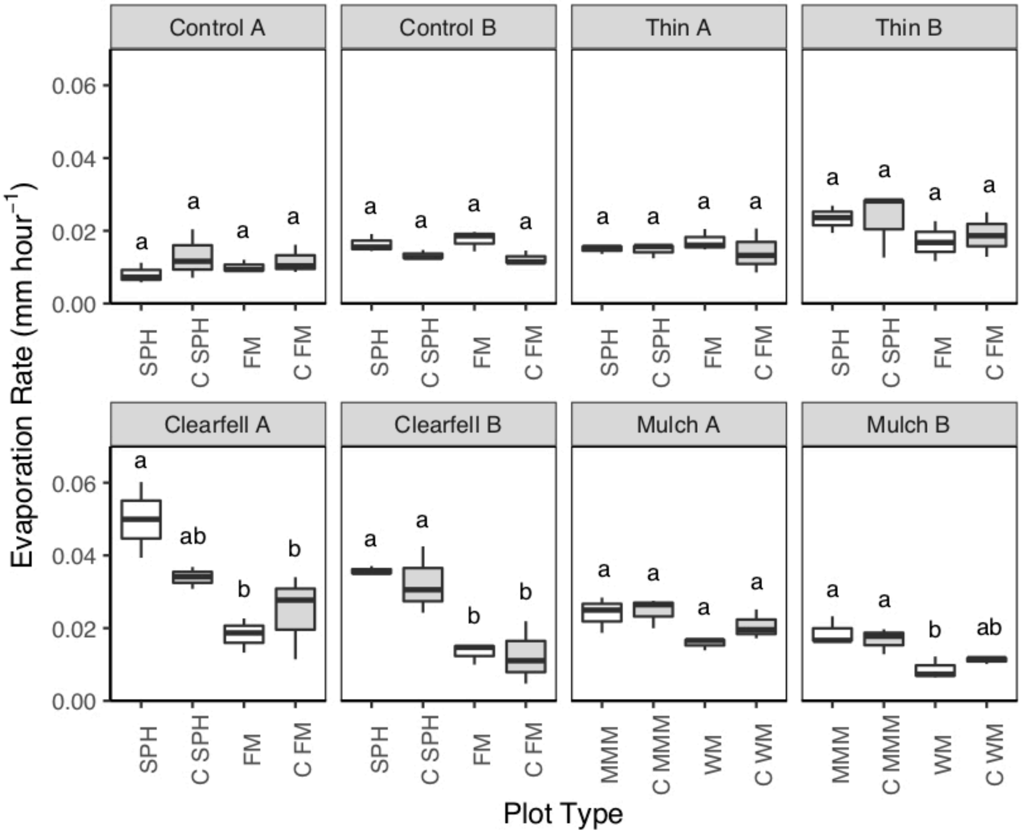

Figure 3.8: Evaporation rate at plot locations (*n*=96) amongst treatment blocks. Plot types include *Sphagnum* (SPH), feather moss (FM), moss-mulch mix (MMM) and woody-mulch (WM), with a 'C' prefix and grey boxplots indicating plots that underwent a surface compression treatment. See Figure 3.2 for locations of treatment blocks. Alphabetical notation identifies significant (α = 0.05) differences between plot types, no comparison between treatment blocks.

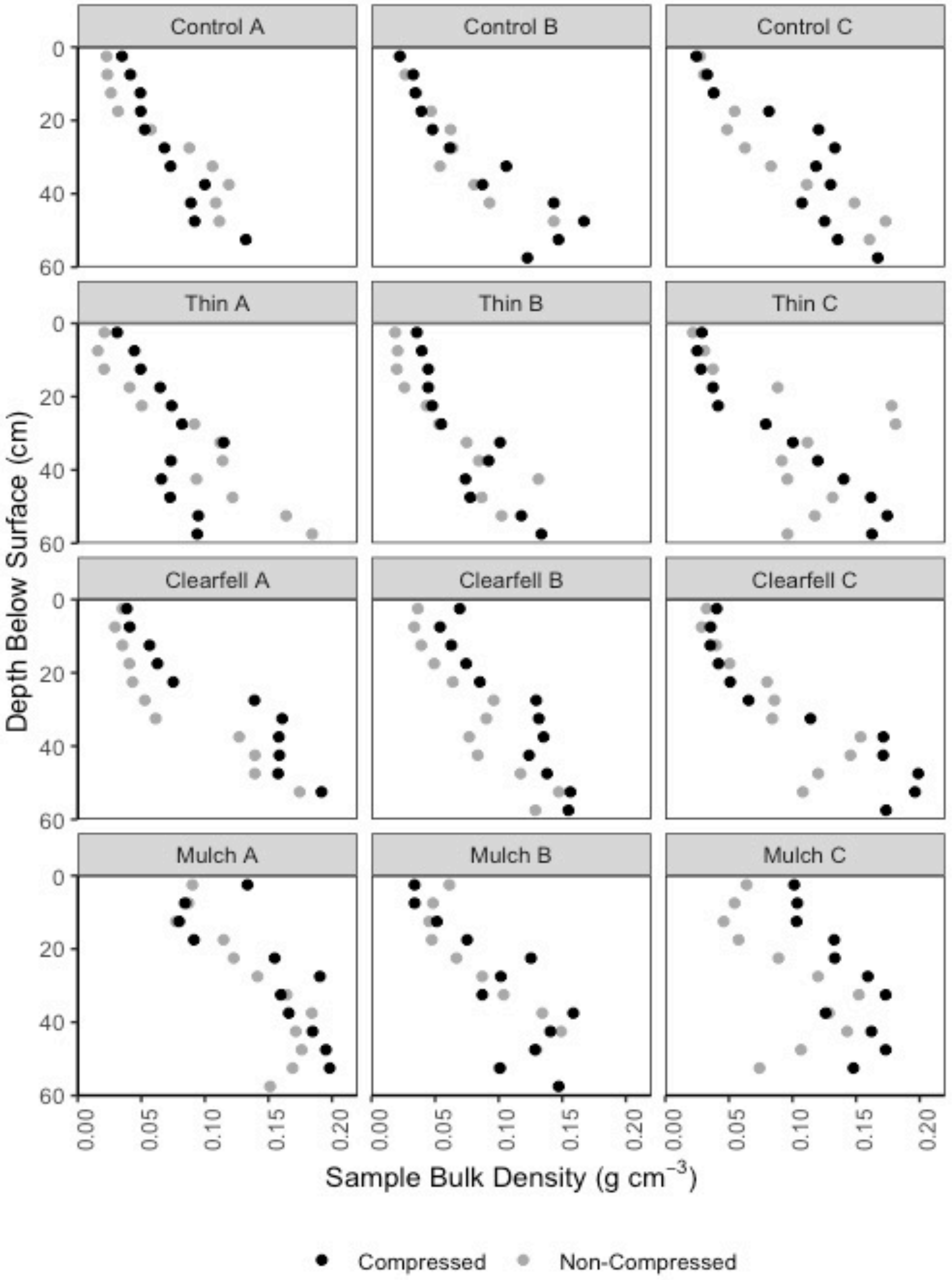

Figure 3.9: Sample bulk density (0.05 m intervals) of the peat profile amongst treatment blocks. Grey and black points represent non-compressed and compressed samples, respectively. See Figure 3.2 for locations of treatment blocks.

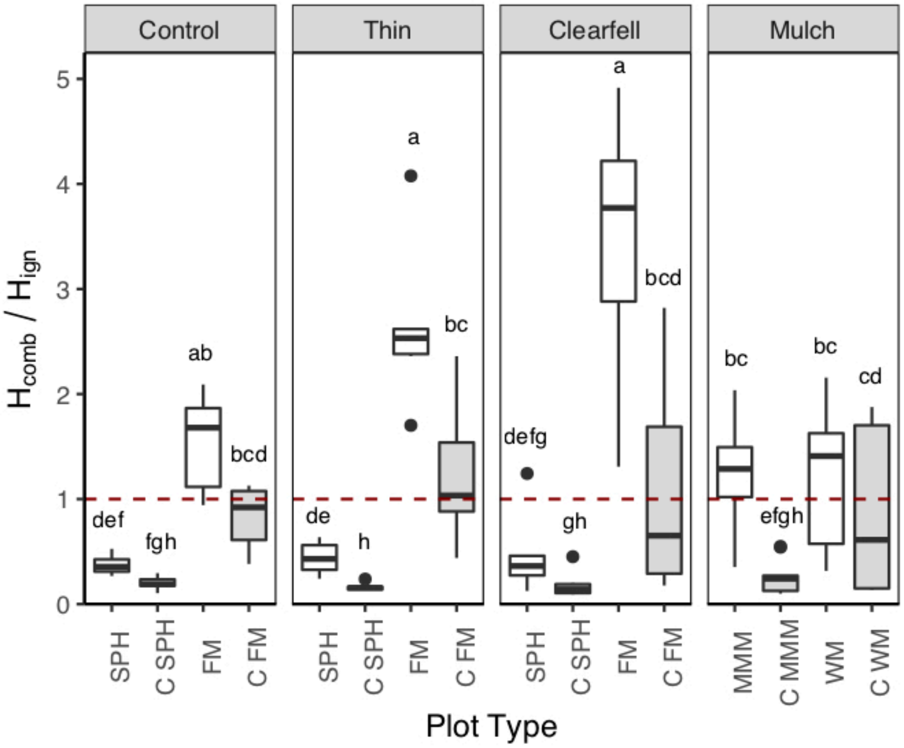

Figure 3.10: Smouldering potential calculated using an energy balance model (Benscoter et al., 2011) at plot locations (*n*=108) at the Pelican Mountain research site. Where $H_{comb}/H_{ign}>1$ indicates potential for smouldering combustion. Plot types include *Sphagnum* (SPH), feather moss (FM), moss-mulch mix (MMM) and woody-mulch (WM), with a 'C' prefix and grey boxplots indicating plots that underwent a surface compression treatment. Alphabetical notation identifies significant ($\alpha = 0.05$) differences between plot types amongst treatment blocks.

CHAPTER 4: CONCLUSION

Wildfire is the largest disturbance in the Boreal Plains landscape (Turetsky, 2002) and wildfires are only expected to increase in frequency, severity, and aerial extent under future climate projections (Flannigan et al., 2013, 2005, 2016). These changes to the wildfire regime may exceed current resource capabilities of wildfire management agencies, leading to an increased rate of escaped fires, thereby further increasing the area burned (Flannigan et al., 2009; Wotton et al., 2005). This emphasizes the need for proactive FireSmart fuel management strategies to mitigate impacts of wildfire in the wildland-urban and wildland-industry interfaces (Mooney, 2010; Partners in Protection, 2003). Despite making up a large portion of these interfaces (Vitt et al., 2000), peatlands lack ecosystem-specific fuel modification treatments. We propose that the unique ecohydrological functioning of peatlands (Waddington et al., 2015) provide an opportunity for fire managers to apply novel peatland-specific fuel modification treatments that go beyond conventional fuel reduction approaches by increasing water content of near-surface moss and peat.

In Chapter 2, we conducted ecohydrological assessments of six ombrotrophic bogs intersected by seismic lines to examine the utility of these landscape features as analogs for novel peatland-specific fuel modification treatments. Canopy openness within seismic lines was significantly greater than that of the adjacent treed portions of the bog, up to 70 years following initial seismic line establishment (Figure 2.1), confirming previous reports of the persistence of these landscape features (Bayne et al., 2011; Revel et al., 1984; Van Rensen et al., 2015). The persistent nature of seismic lines has utility in the context of fuel modification treatments by creating long-term fuel breaks, which reduce the likelihood of fire spread while also providing access for fire suppression resources. Analysis of ground level vegetation revealed that shrub cover in seismic lines is influenced by line orientation. North – south oriented seismic lines have significantly lower shrub cover compared to that of east – west lines, suggesting that fire managers should utilize north – south where possible to reduce the likelihood that fire crosses fuel breaks by way of above ground biomass combustion. *Sphagnum* mosses are a prominent feature in the open seismic line environment of these bogs, where they dominate the ground cover composition (Figure 2.2). *Sphagnum* is a desirable feature of fuel modification treatments as these mosses, particularly the hummock-forming species found in seismic lines, are able to maintain high near-surface VWC (Figure 2.4), thereby subduing fire behaviour and limiting fuel consumption (Hvenegaard et al., 2016; Shetler et al., 2008). Our findings indicate that an alteration of physical peat properties occurred though mechanical compression of the bog surface at the time of seismic line establishment. This is evident by disconformities in seismic line peat profiles

(Figure 2.6) corresponding to a layer of significantly greater bulk densities in these profiles compared to that of the adjacent bogs (Figure 2.8; Table 2.5). The alterations to canopy structure and physical peat properties during of seismic line establishment modified the ecohydrological structure and functioning of these systems. Ultimately, none of the seismic lines assessed in this study showed potential for smouldering (Figure 2.9), demonstrating the utility of seismic lines in serving as analogs for novel peatland-specific fuel modification treatments.

In Chapter 3, novel fuel modification treatments (derived from seismic line analogs) were evaluated for relative effectiveness in reducing smouldering potential of near-surface moss and peat. These novel fuel modification treatments include alterations to canopy structure through conventional fuel reduction/conversion approaches (thin, clearfell, and mulch treatments) and alterations to hydrophysical peat properties through manual surface compression treatments. Results from these treatments show that greater canopy openness in thin and clearfell areas are sufficient to invoke significant moisture stress in feather mosses, whereas *Sphagnum* mosses are able to maintain relatively high productivity levels in these open areas (Figure 3.5). This is supported by the analysis of soil water pressure data, which shows *Sphagnum* (compressed and non-compressed) across all treatments are above the -100 hPa threshold below which desiccation occurs (Hayward & Clymo, 1982) (Figure 3.6). These findings suggest that over time, *Sphagnum* ground cover percentage will likely increase in both the thin and clearfell treatments. Effects of manual surface compression treatment did not consistently show significant effects across plot types; however, mean VWC and mean soil water pressure appear to increase in both *Sphagnum* and feather moss following the compression treatment. It is thought that a mechanical compression approach such as that used in seismic line establishment would yield significantly higher VWC in near-surface moss and peat. Nonetheless, the manual compression method implemented here was sufficient to reduce mean smouldering potential in all plot types (Figure 3.10).

Overall, seismic lines show great promise as analogs for novel fuel modification treatments. The framework identified through this research and summarized in the conceptual model (Figure 3.1) can be successfully applied to reduce smouldering potential of near-surface moss and peat in boreal treed bogs. We propose that these peatland-specific fuel modification treatments be incorporated into current FireSmart fuel strategies to reduce wildfire smouldering risk at the wildland-urban and wildland-industry interfaces.

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