12-11-2013 12:00 AM

Mitigating permafrost degradation due to linear disturbances in sub-arctic peatlands

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A thesis submitted in partial fulfillment of the requirements for the Master of Science degree in Geology

MITIGATING PERMAFROST DEGRADATION DUE TO LINEAR DISTURBANCES IN SUB-ARCTIC PEATLANDS

(Thesis format: Integrated Article)

by

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Graduate Program in Geology

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science

The School of Graduate and Postdoctoral Studies
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Abstract

The presence or absence of permafrost significantly influences the hydrology and ecology of northern watersheds. Linear disturbances resulting from tree canopy removal have led to widespread permafrost degradation in northern peatlands. Seismic lines resulting from oil and gas exploration now account for large portions of the drainage density of sub-arctic basins, and affect the region's water and energy balances. As these peatlands represent some of the most sensitive ecosystems to climate and human disturbances, the ability to simulate perturbations to natural systems in a controlled lab environment is particularly important. This study presents a method that is able to simulate realistic freeze-thaw and permafrost conditions on a large variably-saturated peatland monolith, housed in a two level biome. The design was able to replicate realistic thermal boundary conditions and enabled field scale rates of active-layer freezing and thawing. The climate chamber and experimental design allows for the complete control of certain hydrological processes related to heat and water movement in permafrost environments without scaling requirements; and presents a path forward for the large-scale experimental study of frozen ground processes.

Mulching over seismic lines, upon completion of surveys, has been proposed as a best management practice to help reduce its environmental impact. The new experimental set-up enabled field-scale remediation techniques to be tested, and was used to investigate the effects of using mulch of the removed tree canopy on thermally mitigating permafrost thaw. Freeze-thaw cycles with and without the mulch enabled its effects to be tested. The data were assimilated into a coupled heat and water transport numerical model, which allowed quantification of the key physical parameters. An analysis was conducted on the combined effects of mulch thickness, antecedent moisture conditions and meteorological interactions. The mulch had beneficial effects on slowing thaw, by decoupling the subsurface from meteorological forcing and impeding heat conduction. Results indicate that mulching is an effective technique to reduce permafrost degradation and provides a scientific basis to assess the mitigation measure. This study will provide guidance in ensuring that northern exploration is performed in a more environmentally sustainable manner.

Keywords

Linear disturbance; coupled heat and water movement; permafrost; peat; climate chamber; ecohydrology

Co-Authorship Statement

In accordance with the guidelines of the University of Western Ontario's School of Graduate and Postdoctoral Studies, I declare that I am the sole author of this thesis except where noted. This thesis consists of four chapters, including two independent manuscripts (Chapters 2 and 3) for submission to peer-review journals, along with introduction (Chapter 1) and conclusion (Chapter 4) chapters. I would like to acknowledge the following co-authors: Dr. Robert Schincariol, Dr. William (Bill) Quinton, Dr. Ranjeet Nagare and Dr. Gerald Flerchinger.

Dr. Schincariol provided guidance on conduction of the research, as well as on the analysis, interpretation and presentation of the results. He reviewed all the articles in this thesis, and provided numerous invaluable recommendations and meticulous remarks.

Dr. Quinton provided field data obtained by his research group at Scotty Creek, NWT Canada and contributed to manuscript development through discussions, editing and providing intellectual comments and guidance on drafts of work.

Dr. Nagare provided guidance on direction of the research, analysis and interpretation of results and contributed to edits, intellectual comments and guidance on drafts of work.

Dr. Flerchinger developed the SHAW model, provided technical guidance on performing simulations and calibrations, and corresponded with me on what processes were important and how to incorporate them into the model to fit the purposes of this work.

Acknowledgments

This research would not be possible without the financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canadian foundation for innovation (CFI), the Canadian Space Agency's (CSA) Capacity Building in SS&T Cluster Pilot grant and the UWO academic development fund.

Firstly, I would like to sincerely thank and extend my appreciation to my supervisor, Dr. Rob Schincariol for this opportunity. His guidance, insight, patience, financial support and, what seemed to me at times, surprising confidence in my ability to successfully complete this undertaking were all vital to the completion of this thesis. Rob, your mentorship has considerably strengthened my expertise and passion as a scientist; you're ability to intuitively analyze processes within hydrogeological environments has been inspiring. Thanks for being a great supervisor and mentor Rob; I will always be indebted to you. I'd also like to thank Dr. Bill Quinton from the Cold Regions Research Centre at Wilfred Laurier University, for allowing me access to his archive of field data from Scotty Creek, and for his stimulating discussions and enthusiastic comments that contributed to improving this thesis. I'd also like to thank Drs. Steve Hicock, Brian Branfireun and Hugh Henry for taking the time to review my thesis and agreeing to be on my committee.

I must extend a special thank you to Dr. Ranjeet Nagare at WorleyParsons, Canada for his support throughout this journey. His technical advice and friendship were an invaluable part of this experience. My research was largely built upon his, thus his input was crucial to developing the direction and details of this project. Dr. Gerald Flerchinger, from the USDA Agriculture Research Center, provided technical guidance with the SHAW model. He answered my many long emails, checked my input and output files and corresponded with me what processes were important and how to incorporate them into the model to fit the purposes of this work. I'm very grateful for his invaluable assistance. Thank you to all those that aided with the design and construction of the soil column used in this work: Roger Peters, Jon Jacobs, Steve Bartlett and Marc Schincariol. The subsequent experiments carried out would not have possible had it not been for their assistance.

On to all my friends and colleagues who've I shared the last couple years with here during grad school at Western. To Jeff Blaylock, Phil Spencer, Greg Munro, Tom Ulanowski, Emad Dehkordi and all my other friends, there are too many of you to all name individually but you know yourselves: thanks for the all the camaraderie, advice and friendship over the last few years.

Finally I would like to acknowledge the people to whom I am most indebted to, my amazing parents: Noreen and Jameel, and I would be remiss if I didn't mention my grandmother Yvonne and brother Tariq. Thank you for all the support through every milestone of my life. Your unyielding affection, support, sacrifices, life lessons, guidance, and unconditional love have allowed me to find my passions and pursue my dreams. This thesis is dedicated to you Mom and Dad, as will any other achievement in my life.

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Chapter 1

1 General introduction

1.1 Background

Permafrost, defined as any geologic media that remains below 0 °C for more than two consecutive years, currently underlies approximately a quarter of the earth's surface (Nelson *et al*., 2002). Classified based on its areal continuity, permafrost distribution is divided into 3 main zones: continuous, discontinuous and sporadic, shown in Figure 1-1. This classification varies slightly in the literature but the most accepted definition classifies the zones as areas where 90%, 50 to 90% and less than 50% of the surface are underlain by permafrost, respectively (Brown *et al*., 1997). When present, the spatial characteristics of permafrost controls watershed hydrology by creating barriers and channels in the subsurface, directing water movement during summer months and modulating the ground's temperatures and energy balance (Woo, 1986). Although climate is the main parameter affecting permafrost presence, it is also governed by factors such as vegetation, soil conditions, topography and presence of water (Shur and Jorgenson, 2007). These factors are readily apparent as permafrost spanning the northern hemisphere occurs in areas of vastly differing landscapes and vegetation type: from tundra and steppe terrain, boreal forests and shrub lands to extensive wetlands blanketed by peat soils. Recent evidence suggest that decreases in permafrost's geographic extent and increases in active layer thickness (portion of ground that undergoes seasonal freezing and thawing) can trigger changes to the hydrology, ecology and carbon flux dynamics of northern landscapes (Smith *et al*., 2005; Anisimov and Reneva, 2006; Zimov *et al*., 2006; Shur *et al*., 2008; Osterkamp *et al*., 2009). These permafrost degradation patterns play a significant role in hydrological and ecological processes on local scales which may have regional impacts to water and forest quality and resources (Hinzman *et al*., 2005).

Observational data regarding the response of permafrost to temperature changes have become much more extensive in recent years. Observations from Alaska (Jorgenson *et* *al*., 2001; Osterkamp, 2007), Canada (Camill, 2005; Y. Zhang *et al*., 2008), China (Cheng and Wu, 2007) and Russia (T. Zhang *et al*., 2005; Anisimov and Reneva, 2006) all indicate that permafrost temperatures have increased in several locations during the later portion of the 20th century, and will likely increase through the 21st century (Lawrence and Slater, 2005). Permafrost loss and increasing active layer thickness have caused significant changes to sub-arctic and polar regions' hydrological and topographical conditions (Osterkamp *et al*., 2009). Studies predict that the largest impact to the hydrology of areas underlain by permafrost in the next century will be as a result of thawing and disappearance of permafrost (Hinzman *et al*., 2005; Rowland *et al*., 2011). Significant changes in the hydrologic regime of the river basins throughout the northern hemisphere have been attributed to increased permafrost thaw leading to changes in drainage characteristics (Serreze *et al*., 2002; Yang *et al*., 2002; Quinton *et al*., 2003; Hinzman *et al*., 2005). However, there still are some discrepancies as some high-latitude areas show no change in active layer thickness or ground temperature in response to increased air temperatures (Anisimov and Reneva, 2006). Also, permafrost in the discontinuous zone can be present or absent in regions of similar climate, highlighting the importance of other local environmental factors (Beilman and Robinson, 2003; Shur and Jorgenson, 2007).

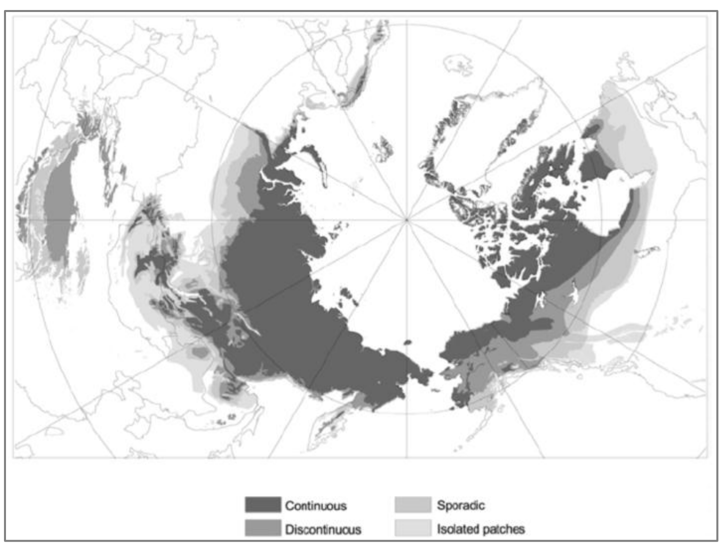

Figure 1-1. Zonation map of permafrost distribution in the Northern Hemisphere (Nelson *et al*., 2002).

1.2 Introduction

Climate change and human disturbances in wetland dominated basins within the zone of discontinuous permafrost have resulted in significant permafrost thaw in recent years (Quinton and Hayashi, 2005). Permafrost processes, to a large extent, control the basin hydrology of these cold regions (Woo, 1986; Woo and Winter, 1993). In peatlands of the Lower Liard River valley, Northwest Territories, Canada, permafrost occurs as ice cored peat plateaus while bogs and fens are only subject to seasonal frost (Wright *et al*., 2008). The mixture of channel fens, flat bogs and permafrost plateaus are very important to the cycling and storage of water and energy in northern watersheds (Hayashi *et al*., 2004). This research project is aimed at mitigating the environmental impacts of anthropogenic disturbances resulting from tree-canopy clearing in these permafrost regions. The main types of disturbances are termed linear disturbances which take the form of winter roads, pipelines and seismic lines. Linear disturbances have led to wide spread permafrost loss in wetland dominated regions of the Canadian sub-arctic. The most common type of linear disturbance is the seismic line or cutline. These cutlines are essentially linear tracts where vegetation is removed for geophysical surveys for oil and gas exploration. When the canopy is removed along the cut lines, the permafrost below thaws; connecting areas that were previously hydrologically isolated. Permafrost peat plateaus serve a distinct hydrologic purpose; they generate large amounts of run-off for stream flow (Wright *et al*., 2008). In fact, Quinton *et al*. (2003) found that watersheds with a greater density of peat plateaus have higher total annual run-offs than basins with a smaller density. These cut lines therefore can have a significant impact on water drainage, run-off and soil-water storage within catchments. The density of linear disturbances can in some cases be substantially greater than the natural drainage density (Quinton *et al*., 2009) and thus may greatly alter the water and energy dynamics of the area.

1.3 Study region

Temperature and soil conditions simulated in this study are based on field studies conducted at Scotty Creek, NWT, Canada located near Fort Simpson shown in Figure 1-2.

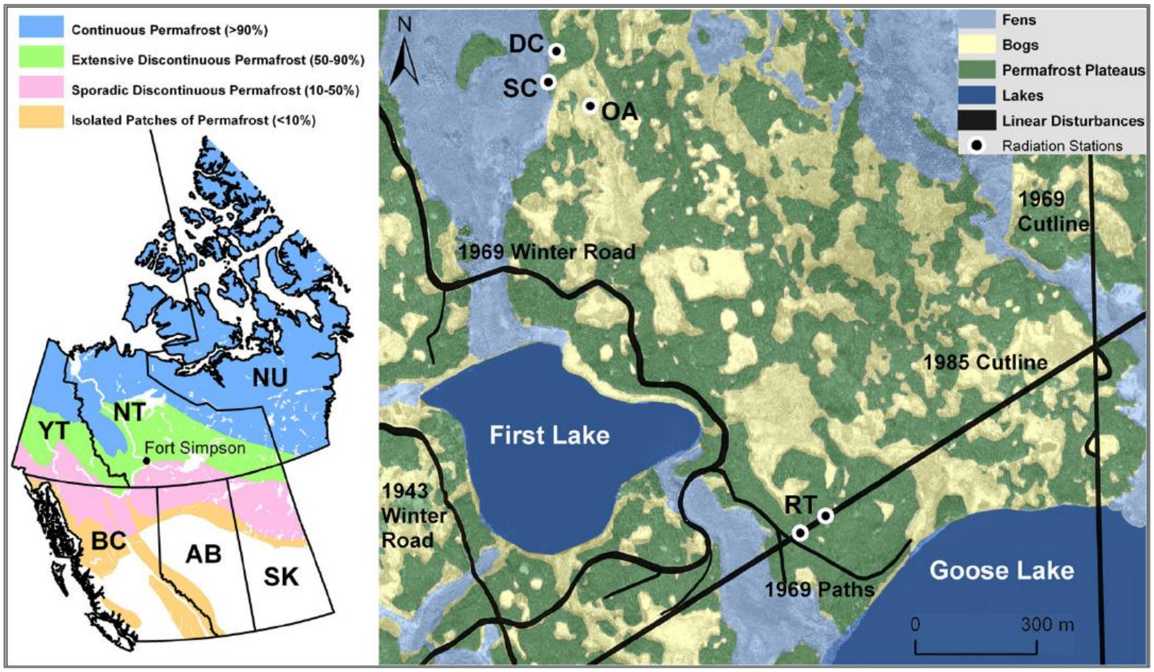

Figure 1-2. Left: study site Scotty Creek, loacted within the zone of discontinuous permafrost in the Lower Liard Valley just south of Fort Simpson. Right: plan view of the patterned peatland complex of Scotty Creek (Williams and Quinton, 2013). DC, SC, OA and RT represent radiation stations.

Scotty Creek is a 152 km^2 basin located in the lower Liard River valley in the central part of the Mackenzie River basin, and is characteristic of wetland dominated basins found within the zone of discontinuous permafrost (Wright *et al*., 2008). This region is located close to the southern limit of the discontinuous permafrost zone and represents one of the ecosystems most vulnerable to climate warming and human disturbances (Quinton and Baltzer, 2012). Soil characteristics and temperature regimes at Scotty Creek were used as a surrogate for a typical peat-covered permafrost landscape. Figure 1-2 shows a plan view of the general type of patterned landscape characteristic of discontinuous permafrost peatlands. The different landforms all have a distinct role in the basin hydrological cycle of these watersheds (Hayashi *et al*., 2004). Peat plateaus are the only areas where permafrost is present; the volumetric expansion of ice has allowed these plateaus to gain approximately 1 m of relief compared to the low lying wetland bogs and channel fens (Wright *et al*., 2009). These plateaus generate most of the run-off that contributes to stream flow (Wright *et al*., 2008). Bogs mainly store water and provide hydraulic connectivity between different landforms and channel fens act as conduits that direct drainage and run-off to stream discharge (Hayashi *et al*., 2004), Figure 1-3 illustrates this conceptual model.

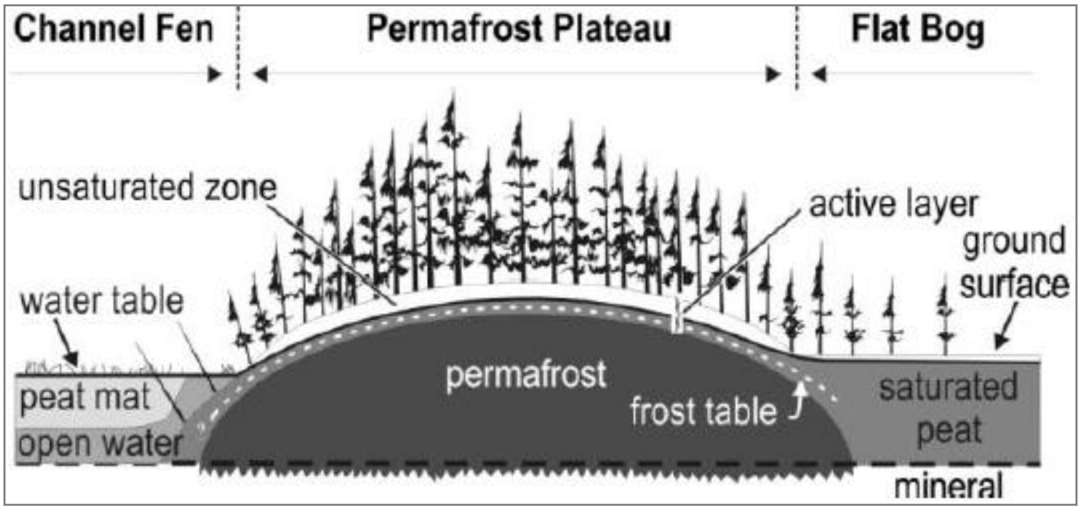

Figure 1-3. Conceptual schematic cross-section of a permafrost plateau flanked by a flat bog and channel fen (Quinton et al., 2009).

1.4 Linear disturbances

Linear disturbances range from 5 to 15 meters in width, depending on the type of disturbance (CAPP, 2004; AECOM 2009). As mentioned above, the most common types of disturbance are seismic lines or cutlines. These are a result of seismic surveys done during oil and gas exploration, which is increasing at an unprecedented rate in the north (Quinton and Hayashi, 2005). The net result is a network of tree-less corridors shown in Figure 1-4, having a significant spatial footprint on the landscape. The density of these cutlines at Scotty Creek is now more than 5 times the natural drainage density of the watershed (Quinton *et al*., 2009). Where these disturbances exist the permafrost has since been lost, illustrated in Figure 1-4, which results in subsidence of ground surface due to thaw of the ice-rich permafrost. Loss of trees coupled with new topographic lows created from subsidence redirects water flow, resulting in conversion of forest to wetland systems through the creation of collapse fens or bogs, depending on local conditions (Williams *et* *al*., 2013). The increased thawing and discontinuity of permafrost, resulting in new landforms and changes in vegetation, may significantly alter the hydrology of the area, modifying the landscape due to changes in local and regional flow patterns. These changes in hydrological response and relief will have subsequent impacts on vegetation and ecosystem processes further complicating matters regarding the region's response to degrading permafrost.

The number of cutlines and the fact that they result in complete permafrost loss has raised concern and questions regarding their impacts on the hydrologic cycle and permafrost distribution and extent in the region (Quinton *et al*., 2009). Figure 1-5 is an example of a mature linear disturbance where not only has the permafrost below the cutline thawed but now, additional ground heating is spreading and causing lateral thaw. The loss of ice rich permafrost lowers the bearing capacity of ground to support trees, causing these trees to bend and ultimately collapse (Williams *et al*., 2013). Where permafrost has been lost, there is very little evidence of tree re-growth. This ecosystem is home to Caribou populations which are a primary food source for local populations (Williams, 2012) and thus local agencies are trying to find ways to reduce the environmental damage resulting from these seismic lines.

One promising and relatively simple mitigation measure is the application of the mulch of the removed tree canopy to the cutlines once seismic surveys are complete. This is based on reports from the field that woody debris when piled and spread over the ground has been observed to preserve permafrost below it (Williams, 2012). The large geographic area of these cutlines and their possibility to affect people's livelihoods, underscores the need for the method to be assessed in a controlled manner to define the scientific basis for such a large-scale measure. This will require an analysis of the thermal and hydrological factors affecting permafrost thaw in peat-covered permafrost regions as well as the quantification of the subsequent effects of the mulch on heat and water transport in the underlying soil profile.

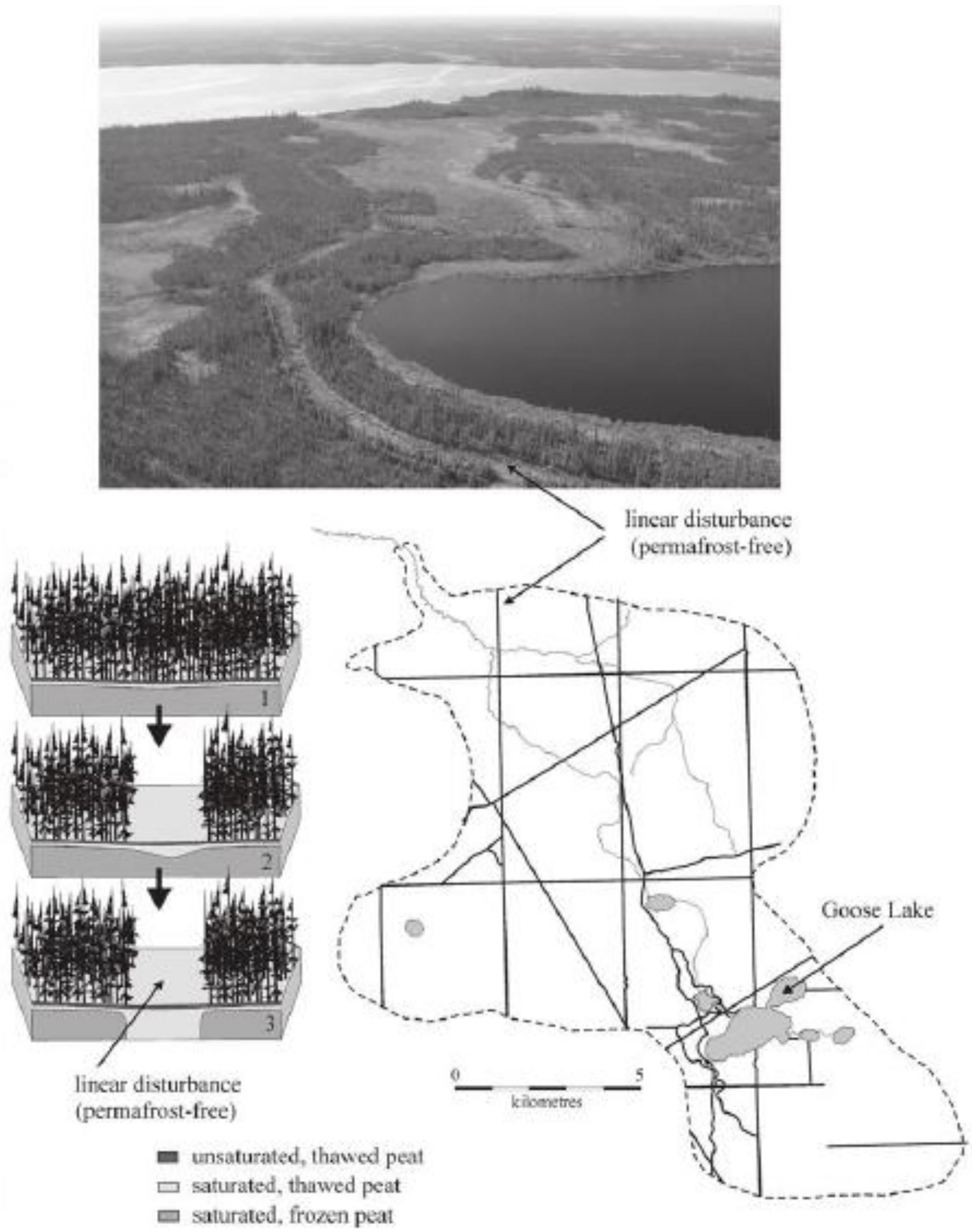

Figure 1-4. Plan schematic and picture of linear disturbances at Scotty Creek along with a conceptual diagram of permafrost thaw once the tree canopy has been removed (Quinton *et al*., 2009).

Figure 1-5. Picture showing a winter road cleared in 1943 west of Goose Lake in Scotty Creek. Surrounding trres are beginning to lean due to a loss of load bearing capacity as a result of permafrost thaw (Williams, 2013).

1.5 Process controlling permafrost thaw in sub-arctic peatlands

The main process governing permafrost and active layer freezing and thawing is heat transport. The source of this heat is the Sun's radiant energy and the site's energy balance determines how that heat is partitioned for different surface and subsurface processes. The energy balance at the ground surface is expressed as (Wright, 2009):

$$\boldsymbol{Q^{*} = H_S + LE + q_h} \tag{1. 1}$$

where the terms represent net all-wave radiation (Q^*), ground heat flux (q_h), surface latent heat flux via evaporation (LE) and surface sensible heat flux (H_S), respectively. All terms have units of W m^{-2} (Watts per square meter). Active layer thaw depths in organic-covered permafrost terrains have been shown to be regulated by ground heat flux (Quinton and Marsh, 1999; Wright *et al*., 2008). The primary mechanism controlling ground heat flux through the shallow subsurface to the frost table is thermal conduction (Hayashi *et al*., 2007). Because temperature forcing is primarily top-down from ground surface temperatures, thermal gradients and thus heat transport is effectively one dimensional (1D). Heat is conducted along temperature gradients between the ground surface and underlying permafrost table (Hayashi *et al*., 2007), and can be described by Fourier's law (Mckenzie *et al*., 2007):

$$\boldsymbol{q_h = -k_m(\theta)\frac{dT}{dz}} \qquad (1.\ 2)$$

where k_m is the thermal conductivity of the composite porous medium (soil matrix, water, air, ice). θ is the volumetric water content, T is temperature, and z is the vertical distance. In variable saturated media, thermal conductivity is a function of water content. Peatlands exhibit a layered stratigraphy due to the degradation and consolidation processes characteristic of the terrain type. As such the transition from fibrous to decomposed peat translates to a depth-wise change in its physical, hydraulic and thus thermal properties (Quinton *et al*., 2000).

Heat transport is tightly coupled with water movement, which can move in response to a combination of matric (pore-water pressure) and temperature gradients (Harlan, 1973). Flowing water carries heat by advection and leads to changes in thermal properties of soils (Philip and de Vries, 1957). In many organic-covered permafrost landforms, water tables are near the ground surface and consist of a shallow unsaturated zone between the ground surface and underlying water table (Quinton *et al*., 2003; Hayashi *et al*., 2004). The upper horizons of the peat profile can have bulk densities as low as 50 kg/m^3 and porosities as high 96% by volume. This means that soil moisture content and the subsequent volumetric fraction of air, liquid water and ice strongly affects the thermal state of permafrost and rates of freezing and thawing in the active layer. Because of the water-ice phase change in these environments, latent energy transfer modulates the thermal regime for long periods of time as soil temperatures remain at freezing point temperatures until the phase change has completed (Nagare *et al*., 2012a). This effect is even more pronounced in peatlands, as opposed to mineral soils, due to their higher porosities and total water contents. As a result of this tight coupling and the non-linear nature of these transfer processes, problems related to mass and heat transport are often difficult to study in the field and can benefit from controlled laboratory work where the important climatic and physical properties can be isolated and investigated (Zhou *et al.*, 2006).

1.6 Research objectives

This thesis presents the results of an integrated laboratory and computer modeling study to better understand the transport of subsurface water and heat in peat-covered permafrost regions. Motivation for this research stems from a need to understand the effect of linear disturbances on the thermal and hydrological regimes of peatlands within zones of discontinuous permafrost. Understanding the thermal regime of these peatlands is critical to predicting and mitigating the effect of anthropogenic disturbances. The primary objective is to investigate the effectiveness of mulching on mitigating permafrost thaw due to linear disturbances in organic-covered permafrost terrains. This was achieved via a combination of laboratory and numerical simulations of the seasonal freezing and thawing of a soil column that represented a natural peatland profile underlain by permafrost. This experiment was conducted in a two-level climate chamber specifically designed to realistically represent permafrost environments (Nagare *et al.*, 2012b). A novel soil column set-up, designed to mirror field conditions where appropriate, was able to simulate field-scale soil freeze-thaw processes. Representation of transient thermal conditions produced ground thawing on time scales similar to observed in field studies, i.e. months. This enables studies investigating the field scale hydrological implications of freezing and thawing, on samples which allow for the establishment of natural thermal and moisture gradients.

This method then allowed the key thermal and hydrological processes related to permafrost thaw as a result of canopy removal to be investigated. The active layer thaw regime was the critical field scenario that had to be well represented in the soil column. The experimental set-up and design enables field application techniques to slow thaw propagation to be tested. The study tested the effect of the wood mulch of the removed canopy (Black Spruce, *Picea Mariana*) on insulating the ground surface and impeding heat conduction through the subsurface. This was done by running freeze-thaw simulations with and without the mulch surface layer.

The initial freeze/thaw cycle without the mulch applied to the column served two distinct purposes. The first was to test the design of the monolith on how well the thermal regime of soil column compared to field conditions. Once this was established, the initial data served as a base case scenario of a natural peatland profile that has had its canopy removed for seismic exploration. A second freeze thaw cycle was then initiated, with the thaw run only differing by the addition of 20 cm thick Black Spruce (*Picea Mariana*) mulch on the soil surface.

Numerical simulations of laboratory experiments were conducted using the SHAW (Simultaneous Heat and Water) Model (Flerchinger and Saxton, 1989). The model was utilized to perform an analysis on the combined effects of mulch thickness, moisture conditions and surface water- soil moisture interactions (snowmelt and precipitation) on heat transport within the soil profile. Incorporating these data into the model and using the laboratory experiment to validate the model allowed the key physical, hydrological and thermal properties important to simulating the effect of the mulch observed in the laboratory experiment. The model was parameterized with measured values for most driving variables, which were ground surface and permafrost temperatures, physical characteristics and saturated hydraulic conductivity in the soil column needed to be represented in the model. Parameters that had to be estimated were used to calibrate the model, specifically hydraulic retention parameters. Once calibrated and validated, the 1D model was then used to investigate and assess the effectiveness of mitigation measures under typical field conditions.

1.7 Thesis organization and role of co-authors

This thesis consists of four chapters, including two independent manuscripts (Chapters 2 and 3) for submission to peer-review journals, along with introduction (Chapter 1) and conclusion (Chapter 4) chapters. The manuscripts are submitted in a format consistent with the University of Western Ontario's thesis requirements. In accordance with the

School of Graduate and Postdoctoral Studies guidelines, I declare that the research presented in these papers is work of my own conception and execution under the guidance of the listed co-authors. Chapters 2 and 3 include enough necessary background information that they can be read independently of this thesis. Brief descriptions of the chapter content and roles of the co-authors are listed below.

Chapter 2 is a modified version of a manuscript that will be submitted to *Vadose Zone Journal* as a technical note for peer-review. The Manuscript is titled 'Mohammed, A.A., Schincariol, R.A., Nagare, R.M., and Quinton, W.L. Reproducing field scale active-layer thaw in the lab. Dr. Rob Schincariol provided guidance on conduction of the research, as well as on the analysis, interpretation and presentation of the results. He reviewed all the articles and this thesis, and provided numerous invaluable recommendations and meticulous remarks. Dr. Bill Quinton provided field data obtained by his research group at Scotty Creek, NWT Canada. Drs. Nagare and Quinton contributed to paper development through discussions with me, edited and provided intellectual comments and guidance on drafts of the paper.

Chapter 3 will be extended upon to form a manuscript that will be submitted to *Ecological Engineering* for peer-review. The manuscript is titled 'Mohammed, A.A., Schincariol, R.A., Quinton, W.L., Nagare, R.M., and Flerchinger, G.N. On the use of mulching to mitigate permafrost degradation due to linear disturbances in sub-arctic peatlands'. The major difference will be the completeness of the experimental thaw data set with the mulch. Dr. Rob Schincariol provided guidance on conduction of the research, as well as on the analysis, interpretation and presentation of the results. He reviewed all the articles and this thesis, and provided numerous invaluable recommendations and meticulous remarks. Dr. Bill Quinton provided field data obtained by his research group at Scotty Creek, NWT Canada. Dr. Flerchinger developed the SHAW model and provided crucial guidance on performing simulations and calibrations. Drs. Nagare and Quinton contributed to paper development through discussions with me, edited and provided intellectual comments and guidance on drafts of the paper.

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Chapter 2

2 Reproducing field-scale active layer thaw in the lab

2.1 Introduction

Permafrost and active layer processes occur over approximately 25% of the earth's surface (Williams and Smith, 1989) and play a vital role in the hydrological functioning of northern watersheds (Woo and Winter, 1993). Layered peat deposits underlain by permafrost are geographically extensive, and pervade large areas of arctic, sub-arctic and boreal environments (Woo and Winter, 1993). High latitude warming trends and increased anthropogenic activities stress the need for a comprehensive understanding of the mechanisms responsible for permafrost sustainability in these sensitive ecosystems. Because peat hydraulic conductivity decreases by several orders of magnitude with depth (Quinton *et al*., 2000), active-layer thicknesses strongly influence the basin hydrology of these northern landscapes (Wright *et al*., 2009). In many organic-covered permafrost landforms, water tables are typically near the ground surface, exhibiting a shallow vadose zone. For example, Quinton *et al*. (2003) and Hayashi *et al*. (2004) found the depth to the water table varied from 10 - 50 cm over a peat plateau in Northern Canada. However, the dryer ground surface in these elevated areas, because of the large change in thermal conductivity with degree of saturation, is significant enough to insulate the soil beneath it such that permafrost and tree-canopy presence is dependent on it (Wright *et al*., 2009; Williams and Quinton, 2013). Active layer thickness is controlled by heat and water transfer between the ground surface and the underlying permafrost table (Hayashi *et al*., 2007). The freezing and thawing of soils induces both water and heat movement (Harlan, 1973; Nagare *et al*, 2012a). These processes are not independent as water flows under matric and thermal gradients, while moving water transports energy and affects soil thermal properties (Hoekstra, 1966; Dirksen and Miller, 1966). In variably saturated media, because frozen soil retains water, freezing temperatures perturb the soil pressure-saturation equilibrium, resulting in steep gradients that redistribute water from warmer to colder zones (Dirksen and Miller, 1966). As a result of this tight coupling and non-linear nature, problems related to water and heat transport are often difficult to study in the field and can benefit from controlled laboratory work where the important climatic and physical properties can be isolated and investigated (Zhou *et al*., 2006). When conducted carefully, soil column experiments can increase our understanding of heat and water transport in frozen ground processes.

The primary mechanism controlling ground heat flux through the shallow subsurface to the frost table is heat conduction (Hayashi *et al*., 2007; McKenzie *et al*., 2007). In order to represent this effect it is important to realistically simulate the field conditions that control it. In a natural terrestrial environment, any arbitrary soil column will be radially insulated by soil around it, so temperature forcing is primarily top-down from ground surface temperatures. This means that thermal gradients and heat conduction are effectively vertical and one dimensional (1D) (Hayashi *et al*., 2007). Creating an experimental setup that can simulate 1D vertical heat flow is critical to being able to adequately replicate field conditions. For example both Zhou *et al*. (2006) and Nagare *et al*. (2012b) stress the importance of minimizing ambient temperature interference in their coupled heat and water movement laboratory studies. The interference creates lateral temperature gradients which make maintaining 1D thermal gradients challenging (Prunty and Horton, 1994). This often results in studies using sample volumes that may be too small to capture field-scale processes and limits the use of field instrumentation within the sample. Work done by others to reduce ambient temperature interference use passive insulation methods, the most effective of which have been presented by Zhou *et al*. (2006) and Heitman *et al*. (2007) for experiments without freezing conditions. These authors used insulated soil cells with a concentric layer of the same soil at similar moisture conditions. This method is very effective for experiments of short duration (96 hours), but fails for longer periods of time. For studies investigating the field scale hydrological implications of freezing and thawing, larger samples which allow for the establishment of realistic thermal and moisture gradients, over long periods of time (i.e. months) are required. Such experiments therefore require careful instrumentation and alternative approaches to reduce ambient temperature interference and validate field-scale conditions (Henry, 2007; Lewis and Sjöstrom, 2010).

This paper presents a novel experimental method which reduces radial temperature gradients at a scale, and under boundary conditions, which replicate coupled heat and water movement in permafrost environments. We make use of the two-level climate chamber presented by Nagare *et al*. (2012b) designed for large scale study of active layer-permafrost systems. The use of large mesocosm-type soil column experiments is being recognized as a necessary tool to better understand the complex interactions between biological, geological and climate systems. A key example of this is the Bioklima project, which is in the process of designing large-scale 'Ecotrons' to study the effects of climate change on natural and agriculture environments (French and Olsen, 2012). The experiment described in Nagare *et al*. (2012b) and a subsequent study in Nagare *et al*. (2012a), highlight the effect of freezing on the active layer hydrology of permafrost peatlands. The experiment presented herein highlights a new soil column designed to maintain 1D thermal gradients under longer term, field-rate freezing and thawing conditions. The previous experimental set-up was only able to sustain 1D thermal gradients under less demanding freezing conditions for shorter periods of time. It is easier to maintain 1D thermal gradients in the lab during freezing conditions because of the permafrost boundary condition; freezing occurs from both ends. This means that the soil column reaches the freezing point relatively quickly, due to two freezing fronts and the entire active layer remains under the zero degree curtain for a long period of time (Carey and Woo, 2005). Once the active layer is completely frozen, there is less temperature variation in the vertical direction of the soil profile as it changes gradually with depth. Thawing, however, occurs only from the top-down and this creates a stark temperature difference between the thawing front and the soil profile above it (Quinton and Hayashi, 2008). Establishing realistic ground thaw conditions in a controlled environment can give insight into parameters controlling the thermal regime of the active layer during thawing. This is important as active layer thaw regimes significantly affect run-off and drainage characteristics of permafrost basins (Wright *et al*., 2009). In fact, Zhang *et al*. (2010) concluded in a study of infiltration into peat covered permafrost soils, that the single most important factor controlling infiltration is ground thaw depth.

The goal of the design was to limit ambient temperature interference by placing the soil column concentrically within another larger container and radially insulate the soil by circulating air within the cavity between the two containers. Our hypothesis was that while being exposed to transient temperature boundary conditions over the ends of the column, we could actively manipulate the temperature within the cavity to reflect the average temperature in the active layer portion of the soil column, and reduce lateral thermal gradients. The airspace and the outer volume of soil are expected to buffer the 30 cm diameter core, where the instrumentation is housed. This set-up enables ambient temperature interference to be minimized while the soil column is exposed to a range of transient temperatures associated with freezing and thawing. We provide data highlighting the column's ability to maintain 1D freezing and thawing front movement.

2.2 Materials and methods

2.2.1 Climate chamber

The climate chamber used is that presented by Nagare *et al*. (2012b); a two level biome capable of simulating large scale subsurface environments (Figure 2-1). The chamber consists of an upper and lower level allowing for soil monoliths to be placed between the two levels and separated by an adjustable insulated floor as shown in Figure 2-2. Both levels of the chamber are capable of simulating a temperature range from +40 °C to -40 °C. Additional climatic controls in the upper level include light intensity, relative humidity, wind, rain and CO_2 concentrations. Situating part of a monolith in the lower chamber allows for the simulation of the permafrost condition common to sub-arctic peatlands: a saturated base layer that remains frozen while the rest of the column in the upper level can be exposed to a variety of climatic conditions. This proxy permafrost is crucial to simulating the upward redistribution of water during freezing, which is not possible with a combination of cold plates and heat exchangers used in other studies (Nagare *et al*., 2012b). A full description of the climate chamber and its capabilities can be found in Nagare *et al*. (2012b).

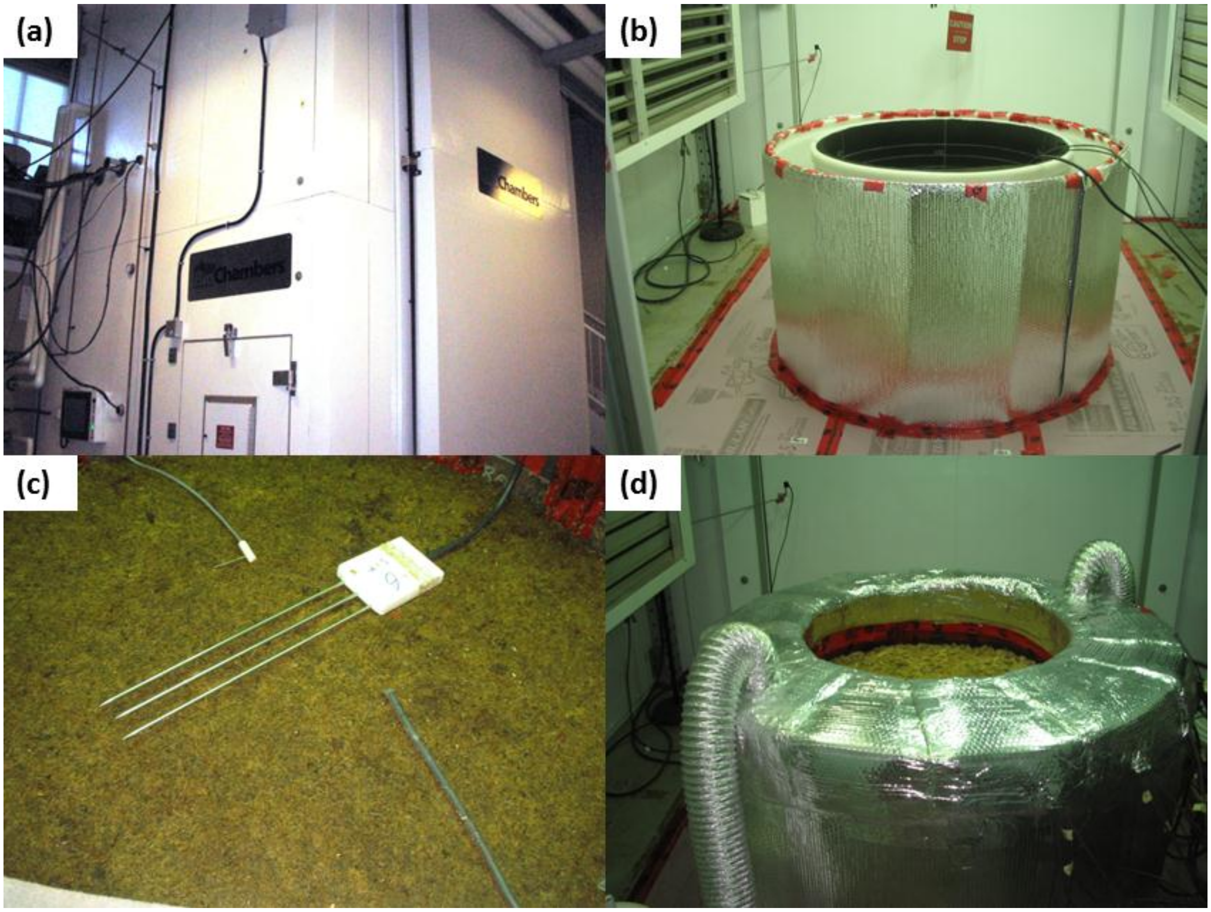

Figure 2-1. (a) Two level climate chamber. Dimensions (W x D x H): exterior 3 m x 3 x 5.5 m, and interior 2.8 m x 2.8 x 4.8 m. (b) 2-column design to create air-filled cavity. (c) Placement of field sensors. (d) Final instrumented soil column.

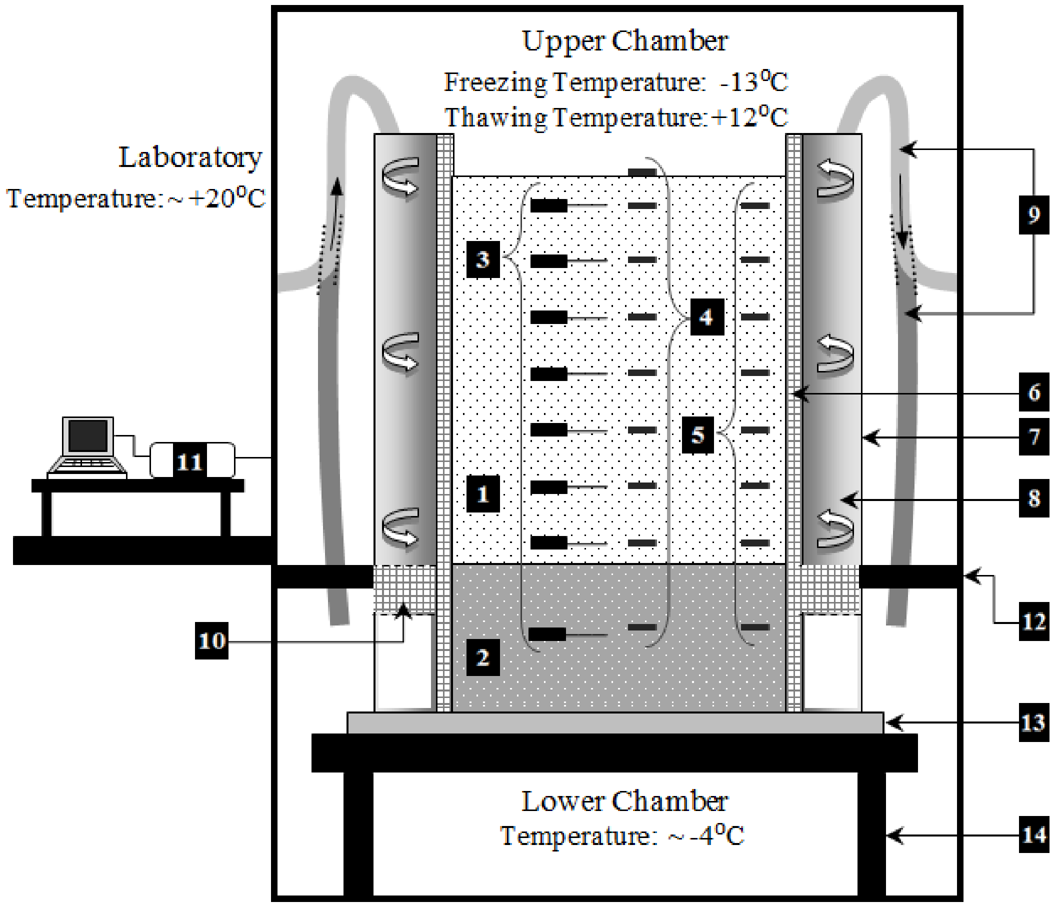

Figure 2-2. Diagram showing experimental setup (not drawn to scale): 1. 65 cm deep active-layer, 2. 40 cm bottom frozen layer, 3. TDR probes, 4. Thermistor probes (centre), 5. Thermistor probes (edge), 6. Inner LDPE container lined with neoprene foam, 7. Outer LDPE container insulated with Reflectix© from outside, 8. Cavity in which air is circulated, 9. Ducting through which air is circulated into/out the cavity, 10. 15cm thick Neoprene band separating airspace from lower chamber, 11. Multiplexers and data-logger connected to a personal computer, 12. Adjustable insulated floor separating upper and lower chamber, 13. Weighing scale, 14. Frame to support monolith.

2.2.2 Experimental setup

Temperature and soil conditions simulated in this experiment are based on field studies conducted at Scotty Creek, NWT, Canada. Scotty Creek is a 152 km^2 basin located in the lower Liard River valley in the central part of the Mackenzie River basin, and is characteristic of wetland dominated basins found within the zone of discontinuous permafrost (Wright *et al.*, 2008). This region is located close to the southern limit of the discontinuous permafrost zone and represents one of the permafrost ecosystems most vulnerable to climate warming and human disturbances (Quinton and Baltzer, 2012).

Temperature settings in the upper and lower levels of the climate chamber provide the vertical boundary conditions of the soil monolith, i.e. permafrost and ground surface temperatures. To ensure one-dimensional heat transport and the reduction of lateral thermal gradients, a number of new design measures were undertaken.

The monolith setup consists of two low density polyethylene cylindrical containers (LDPE) (U.S. Plastic Corp., Lima, OH), one placed inside the other. The inner and outer containers have internal diameters of approximately 90 cm and 120 cm respectively, both are 120 cm in depth. The inner container houses the soil and instrumentation as described in the following section. Placing it in the second container creates an airspace isolating the sides of the soil column from the conditions in the upper level of the climate chamber. This creates a cavity where air can be circulated to reduce the lateral gradients imposed by the temperature setting of the upper chamber. The temperature of the airspace can then be adjusted manually to reflect the average temperature of the active layer. What this effectively does is dampen the temperature that the sides of soil column are exposed to, while giving the ability to actively manipulate temperatures in the cavity as the thermal regime of the active layer changes during freezing and thawing.

Seasonal fluctuations in air and ground surface temperature decrease in amplitude with depth because of the thermal buffering capacity of soil. This creates a time lag in response to changes in surface temperature and results in active layer temperatures being warmer than the surface in winter and cooler in summer. For laboratory simulations, this means that during freezing warmer air is needed to warm the cavity and during thawing, cooler air is needed to cool it. Figure 2-2 illustrates how this was achieved. The airspace was sealed off from the upper chamber environment with the exception of two 4 inch diameter ports where insulated aluminum ducting was attached to provide an inlet and outlet for air to be circulated within the cavity. The system makes use of the differences in ambient temperatures of the upper chamber, lower chamber and room temperature of the lab the chamber is located in. Air which is warmer or cooler (depending on whether freezing or thawing) is vented into the cavity through the inlet with the outlet maintaining circulation. The two ducting configurations are shown in Figure 2-2 and illustrate the port differences for freezing and thawing cycles. When the active layer is undergoing freezing, lab air which is at approximately 20 °C is circulated in the cavity. This incoming air is cooled by the ambient temperature of the upper chamber (-13 °C) creating a blended air temperature that can be manipulated to match the average temperature of the active layer. During thawing where cooler air is needed in the cavity, air is vented from the lower chamber (-4 °C) such that the blended temperature reflects the thermal regime of the active layer. For both configurations, the outlet vents back to the inlet source of air.

To control the airflow and temperature within the cavity, a muffin fan (24 VDC, Sanyo Denki Inc.) was attached in-line to the inlet ducting. The fan was connected to a proportional controller with an integral temperature control (System 350™ A350P, Johnson Controls Inc.). A temperature sensor was placed within the cavity and attached to the controller. The integral temperature control regulates the fan speed based on the temperature the controller is set to. Fan speed is adjusted to achieve the desired temperature in the cavity.

In addition to the temperature controlled air circulated through the cavity, the inner container was lined with 2.54 cm thick closed-cell neoprene foam. This provided additional insulation and ensured a tight seal between the peat and container (Nagare *et al.*, 2012b). The outer container was insulated with two layers of reflective bubble wrap (Reflectix©, Inc., Markleville, IN). The portion of the cavity that is situated in the lower chamber was partitioned from that in the upper chamber by a 15 cm thick layer of neoprene foam. This ensured that the air is only circulated within the active layer of the soil column, keeping the soil in the lower chamber frozen and under a stable temperature regime.

2.2.3 Soil column and instrumentation

The soil column was constructed using re-packed peat in an effort to simulate a natural peatland profile characteristic of those found in the zone of discontinuous permafrost, while allowing us to reduce the effect of small-scale heterogeneities such as macro-pores and rooting zones. Although these small-scale heterogeneities can affect thaw development by processes such as infiltration (Kane *et al*., 2001), they are not representative of the thermal properties of the bulk soil matrix, which is what controls thaw at the basin scale due to conduction (Hayashi *et al*., 2007). Peatlands exhibit a layered stratigraphy due to the degradation and consolidation of the organic matter that comprises the soil type. As such the transition from fibric to well decomposed humic peat translates to a depth-wise change in its physical and hydraulic properties (Quinton *et al*., 2000). The base of the soil column consists of a 40 cm layer packed with unprocessed humified peat to a bulk density of 250 kg m^{-3}. Once packed, this layer was saturated and allowed to freeze in order to represent the ice-rich saturated permafrost. A 65 cm active layer was packed above this using sphagnum moss matching the density profile at Scotty Creek documented by Hayashi *et al*. (2007); see Figure 2-3 (a) and (b). Time-domain reflectometry (TDR) probes (CS10 with SDMX multiplexers connected to a TDR100, Campbell Scientific Inc., Logan, UT) were used to measure unfrozen water content. Additional instrumentation includes temperature sensors (107BAM multiplexed using an AM16/32B, Campbell Scientific Inc.) placed in the centre and edge of all instrumented depths; see Figure 2-1(c) and Figure 2-2. Calibration of the TDR probes utilized Maxwell-De Loor's four phase mixing model, details of which can be found in Nagare *et al*. (2011). Porosity values at different depths used in the mixing model were determined using small samples of the same peat used in the monolith, packed to the same bulk densities. All instrumentation was connected to data loggers (CR1000, Campbell Scientific Inc.) and values were measured and recorded every 15 minutes.

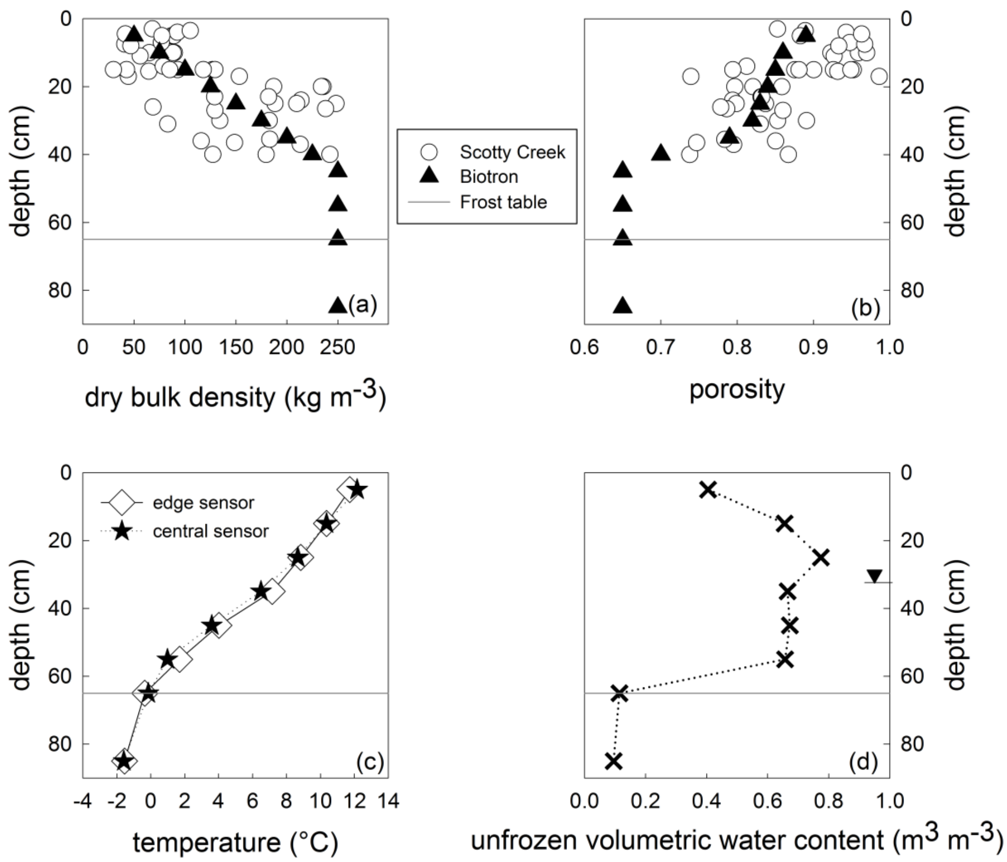

Figure 2-3. (a) and (b) show the density and porosity profiles, Scotty Creek values obtained from Hayashi *et al*.(2007). (c) and (d) show initial temperature and water content profiles of soil column, water table depth is indicated by the inverted triangle symbol at 35 cm. Frost table depths on all plots are for the Biotron experiment.

2.2.4 Experimental conditions

Upper and lower temperatures were initially held at 20 °C and -4 °C to establish stable temperature and water content profiles. At the onset of the freezing cycle, the water table was maintained at approximately 35 cm below the soil surface. Upper level temperature (a proxy for air temperature) was then sequentially dropped to -13 °C over a period of 36 days to simulate winter conditions; -13 °C is the average winter ground surface temperature at Scotty Creek (Wright *et al*., 2009). Once the column was completely frozen and the temperature profile stable, the upper level temperature was sequentially increased from -13 °C to 12 °C (average ground surface temperature at Scotty Creek when air temperatures are consistently above 0 °C), allowing 45 cm of the active-layer to undergo thawing. Initial liquid water content and temperature distributions are shown in Figure 2-3(c) and (d).

2.3 Results

2.3.1 Radial temperature differences and temperature distribution

A key objective of the experiment was to replicate freeze-thaw processes at a scale that allows for the realistic representation of coupled heat and water transport in permafrost environments. Thus the degree to which 1D freezing and thawing front propagation was maintained has to be taken in context with the accuracy of typical field sensors also used in the experiment. While studies on smaller soil cells, such as Zhou *et al*. (2006), achieved better minimization of radial temperature gradients, such techniques are not applicable at the scales simulated here.

Lateral temperature gradients, measured by radial differences between thermistors in the centre and edge of the monolith, were used as one way to examine the influence of ambient temperature interference. The temperature time series in Figure 2-4 shows that the design, as expected, was better able to maintain 1D conditions during the freezing cycle than the thawing cycle. The greatest radial temperature differences are evident in the upper-most measurement depth (5 cm) with thaw differences of ≤3.0 °C. The differences diminish with depth to ≤1.0 °C; results below 5cm are comparable to the work of others (Zhou *et al*., 2006; Heitman *et al*., 2007).

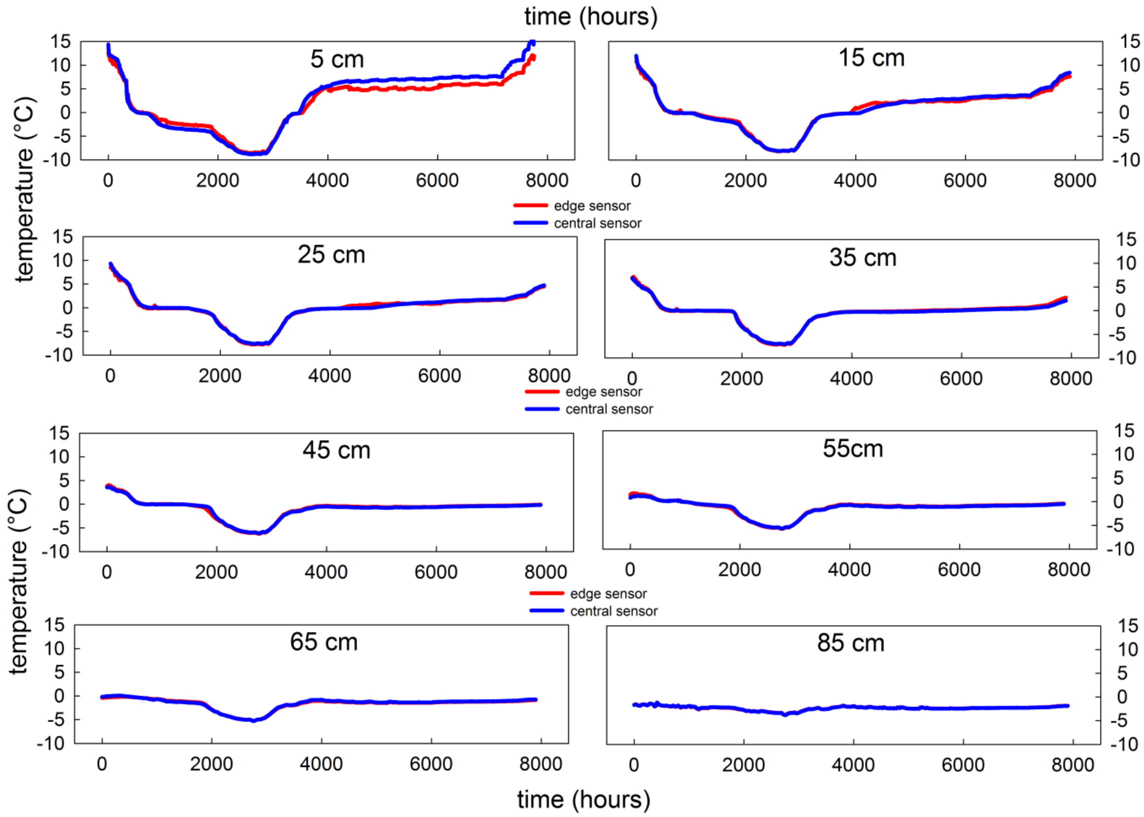

Figure 2-4. Temperature time series for all instrumented depths (5 to 85 cm) in the soil column. Depths of each time series are listed in each graph. Central and edge sensors nearly completely overly each other and thus edge sensor cannot be seen for 45 cm and deeper.

The difficulty in maintaining 1D thermal conditions during thaw arises from the permafrost boundary condition. Freezing occurs from both ends, which means that the soil column reaches the freezing temperature relatively quickly and the entire active layer remains under the zero degree curtain for a significant period of time. As can be seen in Figure 2-5, this makes minimizing lateral temperature gradients easier, because the cavity air temperature (providing the radial temperature boundary) is more representative of the soil temperatures. However, thawing occurs only from the top-down; during thaw, the phase changes (and thus zero-degree curtain effect) with depth occurs over a longer period of time. The result is that the thaw front propagates downward slower than the distance covered by two bi-directional freezing fronts. This creates a large temperature contrast between the thawing front and the thawed soil profile above it, such that soil temperatures within the column cover a wider range than during freezing. For example as shown in Figure 2-5, at Day 119, temperatures in the soil profile range from approximately -3 to -9°C while during thawing at Day 256 temperatures ranged from approximately -2.5 to 14°C. The observation that temperature gradients are largest during thaw is well supported by field studies such as Carey and Woo (2001) and Quinton and Hayashi (2008). Freezing and thawing front progression is also slower in peat than in mineral soils because latent heat effects become more dominant within peat soils which have high volumetric water contents. Thus the portion of the soil column most affected by ambient temperature interference was the uppermost 5 cm which had the highest porosity (Figure 2-3(b)). Peat exhibits much higher porosities than most soils, suggesting that results with this design should be even better for mineral soils.

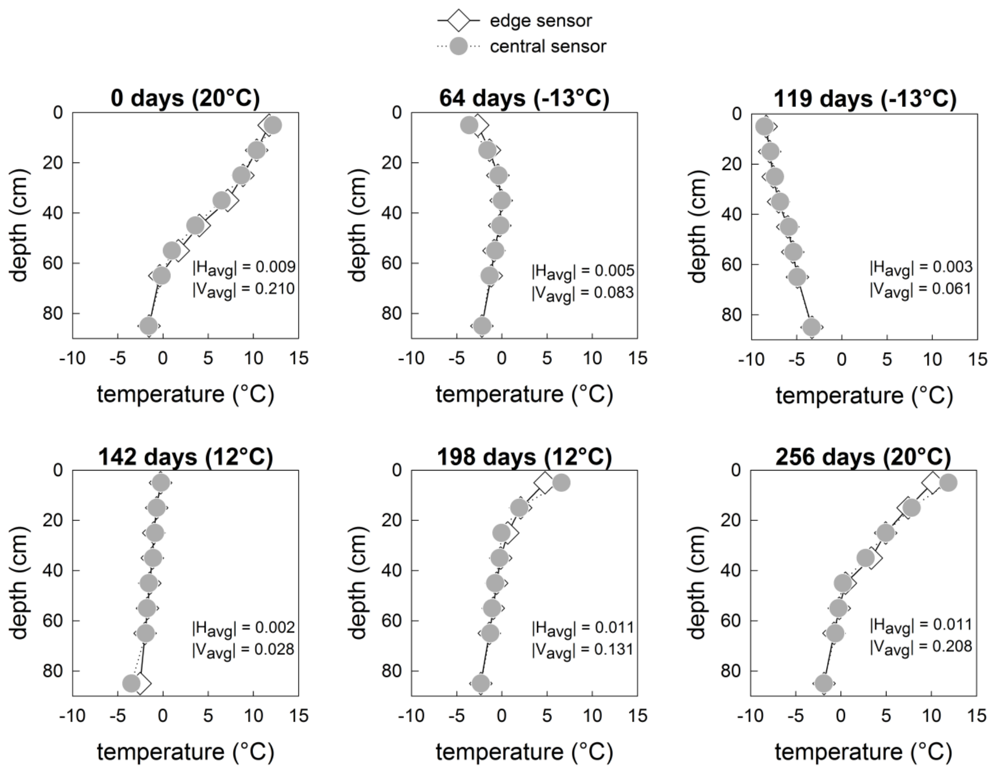

Figure 2-5. Temperature distribution profiles at different time periods for centre and edge thermistors. Upper chamber temperature settings are shown in brackets next to each time period. Numbers shown on the right of each graph are the calculated values of average horizontal ($|H_{avg}|$) and vertical ($|V_{avg}|$) gradients in °C cm^{-1} for the 65 cm active layer.

2.3.2 Freezing and thawing curves

During periods of phase change, ground heat flux is dominated by latent energy exchange to freeze or thaw the active layer (Roulet and Woo, 1986), and temperature remains at the freezing point at discrete depths until the end of phase change. In the field this period of phase change extends from the time the ground becomes snow-free in the spring, until late-summer when the frost table reaches the bottom of the active layer. The relationship between liquid water content and temperature during this process is illustrated by soil freezing and thawing characteristic curves (Figure 2-6).

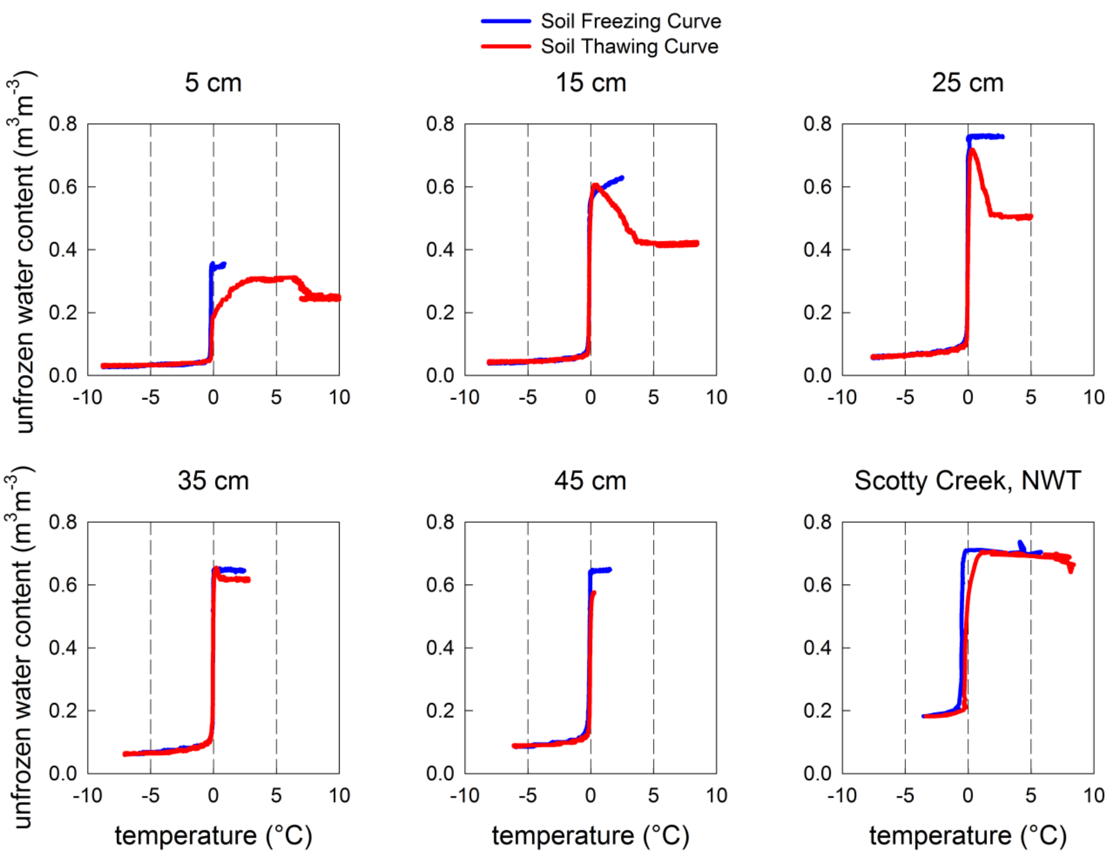

Figure 2-6. Soil freezing and thawing curves for 5 to 45 cm depths of the laboratory soil column and from the 30 cm depth of an instrumented soil pit at Scotty Creek from 2002-2003 field season, obtained from Quinton and Hayashi (2008).

If heat transport is assumed to be 1-D vertically, then one of the fundamental requirements when generating freeze-thaw curves is that measurements of temperature and unfrozen moisture content in a time series are made at the same depth and lie on the same spatial plane (perpendicular to heat flow). Significant lateral temperature gradients, and thus non-1D freezing/thawing front movement over the core's 30 cm diameter, can be interpreted from the freezing/thawing curves in Figure 2-6. Lateral freezing and thawing is evident as a deviation of the curve from vertical over the zero-degree curtain period, indicating a temperature increase or decrease from the freezing point before all phase change has occurred and the liquid moisture content has stabilized. This deviation is clearly present in the upper-most 5 cm layer of the soil column over the late periods of thawing; it can be seen that before the maximum liquid water content (approximately 0.3) is reached, temperatures begin to rise indicating energy is being utilized by sensible heat. This significantly diminishes in deeper layers as the other freezing and thawing curves almost completely overlap each other during freezing and thawing periods. However, deviations in the surface layers are expected not to be important because under field conditions snowmelt infiltration results in advective heat transfer and thus non-uniform freeze-thaw processes. The decrease in moisture upon thaw completion in the 5-25 cm depths is due to evaporation at positive temperatures. A good illustration of the freeze-thaw curves in the relative absence of other processes is the 35 cm depth curves, where both prior to and after phase-change, moisture content is relatively stable. Overall the freeze-thaw curves compare well with those reported for the field as reported by Quinton and Hayashi (2008) and also shown in Figure 2-6. The Scotty Creek curves exhibit some hysteresis between freezing and thawing cycles. This is illustrated as the thawing curve deviated slightly from the general freezing temperature towards the end of phase change. This slight hysteresis may be attributed to 1) non-vertical heat movement and the effect of lateral heat transfer as was evident in the 5 cm depth of this study or, 2) differences in pore-scale interfacial tension-temperature relations for different pore sizes depending on whether undergoing freezing and thawing (Smerdon and Mendoza, 2010). The latter will be expected to be more evident in peat with higher porosity and thus shallower depths, however, results here show that it is not strongly correlated to depth as porosity certainly is; porosity decreases with depth due to increased consolidation (Figure 2-3 (a) and (b)).

Our results indicate that in the absence of lateral heat transfer, hysteresis is tremendously diminished. This is very interesting to note as recently there have been divergent theories on the cause of thermal hysteresis in freezing soils from field and laboratory data (Smerdon and Mendoza, 2010; Parkin at al., 2013; Kurylyk and Watanabe, 2013). This may mean that it is other heat transfer effects, not taken into account in conceptual models, rather than the osmotic and matric potential differences proposed by some researchers (e.g. Smerdon and Mendoza, 2010).

2.3.3 Thermal regime and thaw time

A very important simulation parameter is the length of time taken to thaw the active-layer. The thaw time in this study was approximately 200 days which compares relatively well with the 156 days thawing period observed at the field site by Wright, 2009. Also, a comparison of the thermal regimes in the soil column and at Scotty Creek clearly shows the experiment's ability to reproduce the full range of temperature distributions observed in the field (Figure 2-7).

Thawing was halted at a depth of 45 cm (256 days, Figure 2-7) to begin preparing the column for a subsequent freezing cycle. The possible reasons for a longer thaw time than observed in the field are: 1) the experiment did not simulate the effect of precipitation and snowpack and thus lacked an external source of water (and its associated energy), and 2) thawing temperature was held at 12°C which represents the average thawing period temperature at Scotty Creek, and not the higher temperatures experienced in late summer which is when maximum thaw depths are reached (Wright *et al*., 2009). While simulating precipitation and a snowpack is possible in the climate chamber the purpose of this study was to simply validate the design and ability to simulate 1D heat transport. The infiltration of snowmelt water affects the thaw process because the thermal conductivity of soil increases with increasing moisture content; the thermal conductivity of water is approximately 22 times that of air (Hillel, 1998). In addition, the absence of a snowpack in this study resulted in evaporation beginning earlier in the thawing period than it would in the field. Decreases in moisture content and energy from the active layer due to evaporation, decreases the rate of heat conduction and slows thaw front progression.

Because temperature was maintained at 12 °C, combined with the decreased thermal conductivity from evaporative water loss, thawing towards the latter end of the run slowed and started to approach steady state as the thermal regime stabilized under the temperature boundary conditions. This stabilization required that the temperature in the upper chamber be increased to 20 °C towards the end of the thawing cycle for the 45cm depth to completely thaw as can be seen in Figure 2-4.

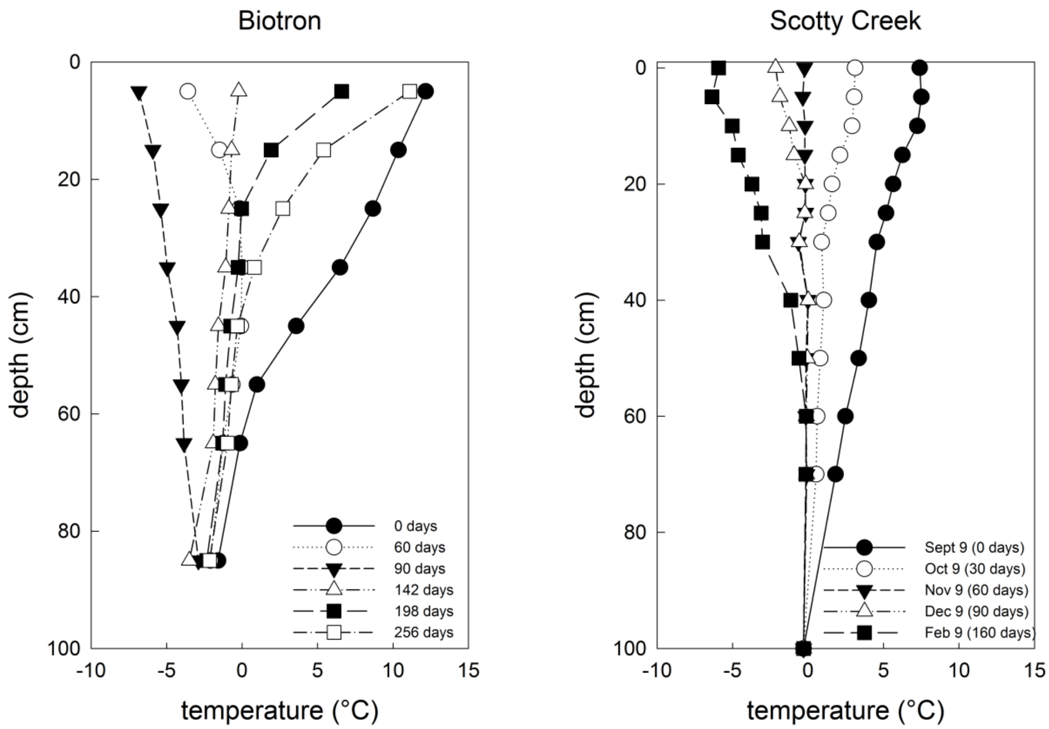

Figure 2-7. Thermal regime over entire freeze-thaw cycle for soil column experiment and Scotty Creek field site (November 2001-Feburary 2002). The temperature at 100 cm depth for Scotty Creek is approximated from the Norman Wells pipeline (Smith *et al.*, 2004.

2.4 Discussion and conclusions

This study was able to simulate field-scale heat and water transfer in a soil column through an experiment that reduced lateral thermal gradients, while a unique two-level biome maintained permafrost and surface temperatures at the vertical ends of a soil column. The active-layer portion of the monolith consists of an inner peat column insulated by an air-filled cavity. Temperature controlled air is circulated within the cavity that represents the average temperature of the active layer, and acts as a buffer from the ambient temperature of the climate chamber. Results show the experimental design was successful in minimizing lateral temperature gradients to a reasonable degree of accuracy given the large scale of the soil column. The minimization of these gradients allows for the physical simulation of one-dimensional active-layer thawing, which is what occurs in nature. The thaw rate observed here was validated by field observations.

Other experimental studies aimed at reducing ambient temperature interference have all used passive methods of insulation (e.g., soil, insulation materials). As no insulation is perfect, this limits the time scale of experiments and the range of freezing and thawing temperatures that soil cells can be exposed to. However an active method, like that used here, allows the temperature in the insulation air space to be adjusted to accommodate active layer freeze-thaw thermal regime changes. This in turn enables the use of a larger range of temperatures that more closely resemble field conditions. Realistic thermal regimes are required to study the impact of climate changes on hydrological and ecological processes. Although a very sophisticated climate chamber was used in this study, the methodology employed here is transferable to simpler, or more complex, climate chambers and can be down or up-scaled. Thus the described methodology could improve studies using hot/cold plates or heat exchangers (Dirksen and Miller, 1966; Hoekstra, 1966; Fukada *et al*., 1980; Staehli and Stadler, 1997) to more complex studies as proposed by French and Olsen (2012). It is simply the application of a transient radial temperature boundary condition.

The methodology proposed and validated here provides a path forward for the large scale experimental study of coupled heat and water transport on frozen soils. In particular, for the apparatus and climate chamber discussed, the effect of complex surface variables such as vegetation, snowpack and winter snowmelt events can now be studied. Such laboratory studies, when coupled with field studies to constrain and validate parameters, are critical to understanding the effects of environmental stressors on the hydrological cycles of sensitive permafrost ecosystems. This is a major issue in cold region studies due to the tight coupling of heat and water movement, and non-linear feedbacks that control the thermal, hydrological and ultimately ecological functioning of these landscapes.

2.5 Acknowledgements

We wish to acknowledge the financial support of the Natural Science and Engineering Research Council of Canada (NSERC) and BioChambers Inc. (MB, Canada) through a NSERC-CRD award, NSERC Strategic Projects grant, and the Canadian Space Agency (CSA) through a Capacity Building in SS&T Cluster Pilot grant. We also thank Roger Peters, Steve Bartlett, Jon Jacobs and Marc Schincariol for their assistance in the laboratory.

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Chapter 3

3 On the use of mulching to mitigate permafrost degradation due to linear disturbances in sub-arctic peatlands

3.1 Introduction

Hydrological and ecological processes in northern latitudes are strongly coupled, and significantly influenced by the distribution of permafrost and peatlands (Woo and Winter, 1993). Peatlands cover approximately 12% of Canada's land surface (Tarnocai, 2006), of which approximately 30% is underlain by permafrost (Aylsworth *et al*., 1993; Zoltai, 1993). Exploration practices resulting in tree canopy removal have led to widespread permafrost degradation in northern peatlands (Quinton *et al*., 2009; Williams *et al*., 2013). Linear disturbances are increasing occurrences in northern Canada; pipelines, winter roads and seismic lines now account for large portions of the drainage density of watersheds in the Canadian sub-arctic (Quinton *et al*., 2011). The most common types of linear disturbances are seismic lines, created during oil and gas exploration. In the zone of discontinuous permafrost, these disturbances have led to a suite of environmental impacts on the hydrologic and ecological functioning of these sensitive ecosystems. Impacts include changes in the basin hydrology, vegetation growth, habitat destruction and entire land-cover change (Beilman and Robinson, 2003; Williams *et al*., 2013). These mentioned changes, however, are secondary and a direct result of the main impact of linear disturbances, which is permafrost thaw (Jorgenson *et al*., 2010; Williams *et al*., 2013). In large areas, seismic lines have caused the loss of permafrost in sub-arctic and boreal peatlands, where the tree canopy along with the unsaturated zone in the soil horizon insulates the ground surface (Wright *et al*., 2009). Peat covered terrains in discontinuous permafrost are largely found in wetland dominated regions where permafrost occurs as ice cored peat plateaus while bogs and fens are only subject to seasonal frost (Wright *et al*., 2008). The volumetric expansion of ice has allowed plateaus to gain 0.5 to 2 m of relief compared to the lower lying wetland bogs and fens. Average water-table depths are approximately 50 cm below the ground surface, creating a shallow relatively dryer unsaturated zone (Wright *et al*., 2009). Permafrost distribution strongly controls the basin hydrology of these cold regions where the ratio of channel fens, flat bogs and permafrost plateaus are very important to the cycling and storage of water and energy (Hayashi *et al*., 2004). Plateaus are hydrologically important, as they generate large amounts of run-off for stream flow (Wright *et al*., 2008). In fact, Quinton *et al*. (2003) found that watersheds with a greater density of peat plateaus have higher total annual run-offs than basins with a smaller density. These disturbances, therefore, can have a significant impact on water drainage, storage, run-off, and ultimately, may alter the water and energy dynamics within catchments.

In most ecosystems, permafrost's presence and distribution are dependent on climate and are correlated to mean annual air temperatures (MAAT) (Shur and Jorgenson, 2007). Permafrost thaw along peat plateaus has been initiated by regional climate perturbations (Camill, 2005; Quinton *et al*., 2009), but it is complex and is also influenced by other local factors (Beilman and Robinson, 2003; Shur and Jorgenson, 2007). The timing, extent and distribution of thaw can be controlled by local meteorological and hydrological factors such as soil moisture, relief, incoming radiation and its effect on ground surface temperatures, and is not as strongly correlated to MAAT fluctuations (Beilman and Robinson, 2003; Williams and Quinton, 2013). Beilman and Robinson (2003) studied permafrost degradation at four peat plateaus and concluded that thaw did not correlate to MAAT differences at the sites.

Conventional seismic surveys conducted during petroleum exploration effectively clears the tree canopy, creating linear tree-less corridors called seismic lines or cutlines (Quinton *et al*., 2009). Traditional seismic exploration practices create 6-8 m wide cutlines, usually resulting in ground compaction and subsidence due to use of heavy machinery. Typically when the canopy is removed the underlying permafrost thaws. The loss of ground ice, which can constitute up to 80% of the plateau's volume, results in significant topographical changes (Wright, 2009). Thus, once permafrost thaws completely below these disturbances, they adopt completely new thermal, hydrological and ecological (vegetation) regimes (Williams *et al*., 2013).

Woody debris from the removed trees, when mulched into small pieces and spread out over the disturbed land, has been reported to preserve permafrost under the mulch (Williams, 2012). Adopting best management practices is crucial to reducing impacts in areas of discontinuous permafrost where MAATs are closer to 0 °C and ground thermal regimes are more vulnerable to disturbance (Burgess and Smith, 2000; Williams and Quinton, 2013). While the ability of mulch to preserve permafrost has been observed, the method has not been rigorously assessed in a controlled manner to define the scientific basis for such a mitigation strategy. As such, research is needed to understand its effects.

This study is aimed at investigating the effectiveness of mulching on thermally mitigating permafrost degradation in organic covered permafrost regions. This was achieved via a combination of laboratory and numerical model simulations of the seasonal freezing and thawing of a natural peatland based soil monolith. Laboratory experiments involved a novel soil column set-up, designed to investigate the key thermal and hydrological processes related to permafrost thaw. This experiment was conducted in a two-level climate chamber specifically designed to realistically represent permafrost environments (Nagare *et al*., 2012). The study specifically tested the effect of mulch, of the removed canopy, on slowing thaw progression by insulating the ground surface and impeding ground heat flux. This was done by running freeze-thaw cycles with and without the mulch surface layer. The data was assimilated into the one-dimensional coupled soil water-energy transport model, SHAW (Simultaneous Heat and Water) (Flerchinger and Saxton, 1989). Incorporating this data into the SHAW model allowed for key physical parameters important to simulating the process observed in the laboratory to be determined. This enabled the effect of the mulch to be tested and quantified. The model, once calibrated and validated, was used to conduct a sensitivity analysis on the combined effects of mulch thickness, moisture conditions and meteorological interactions (snowmelt and precipitation). This provided a basis to assess the effectiveness of the mitigation measure on its ability to slow permafrost thaw and for permafrost stabilization at disturbed areas.

3.2 Experimental description

3.2.1 Study region and linear disturbances

Temperature and soil conditions simulated in this study, used as a surrogate for a typical permafrost affected peatland profile, are based on field studies conducted at Scotty Creek, NWT (Figure 3-1): a watershed characteristic of wetland dominated basins found within the zone of discontinuous permafrost (Wright *et al*., 2008). This region is located close to the southern limit of the discontinuous permafrost zone and represents one of the ecosystems most vulnerable to climate and anthropogenic disturbances (Quinton and Baltzer, 2012). The different landforms comprising this patterned landscape are shown in Figure 3-1. Subsurface flow through the seasonally thawed active layer on plateaus is the main run-off mechanism, and generates most of the run-off within basins (Wright *et al*., 2008). Bogs mainly store water and provide hydraulic connectivity between the different landform types and channel fens convey drainage and run-off towards the basin outlet, ultimately for stream flow (Hayashi *et al*., 2004). Studies have indicated that plateau drainage follows a 'fill and spill' concept (Wright *et al*., 2009; Williams *et al*., 2013), which is controlled by the frost table topography. Because of degradation and consolidation of organic soils, peatlands exhibit a layered stratigraphy. The transition from fibric to well decomposed peat means hydraulic conductivity decreases exponentially with depth (Quinton *et al*., 2000). Therefore, the magnitude and timing of run-off is coupled with ground thaw depth (Quinton and Marsh, 1999; Hayashi *et al*., 2007).

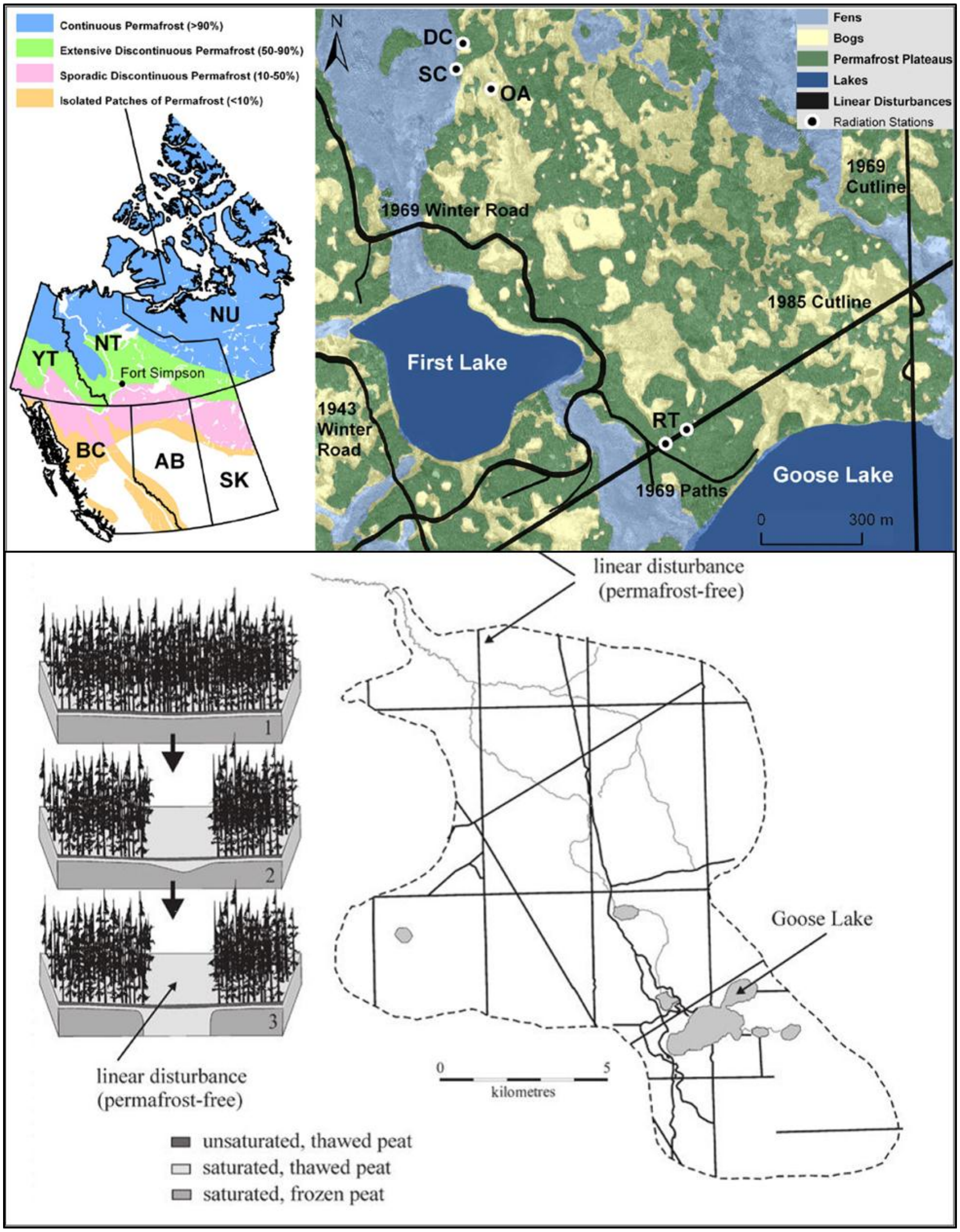

Figure 3-1. Location of Scotty Creek near Fort Simpson, Northwest Territories within the zone of discontinuous permafrost and a plan view of the patterned peatland landscape (GSC, 2002). Lower images show plan schematic of linear disturbances at Scotty Creek along with a conceptual of permafrost thaw once the tree canopy has been removed (adapted from Quinton *et al*., 2009 and Williams and Quinton, 2013).

Active-layer thaw occurs as a result of ground heat flux, which is the fraction of the site's energy balance that is transferred into to the subsurface (Woo and Xia, 1996). The main mechanism controlling ground heat flux is thermal conduction (Hayashi *et al.*, 2007), although advective heat transfer can result due to processes such as snowmelt infiltration (Kane *et al.*, 2001). Forcing is primarily top-down as heat is conducted along temperature gradients between the ground surface and underlying permafrost table. While air temperatures do affect ground thaw evolution, ground surface temperature (GST) controls the magnitude of the thermal gradient and its subsequent effect on subsurface temperatures, and air temperatures are only a proxy for radiation's effects on GST (Kurylyk *et al.*, 2013). Heat transport is tightly coupled with water movement, as the rate of ground thaw depends not only on the energy input at the surface but also on the thermal properties of the soil, which is strongly affected by soil moisture (Hayashi *et al.*, 2007).

Linear disturbances range from 5 to 15 m in width, depending on the type of disturbance (CAPP, 2004; AECOM 2009). As mentioned above, the most common types of disturbance are seismic lines. These are a result of seismic surveys done during petroleum exploration, which is increasing at an unprecedented rate in northern latitudes (Quinton and Hayashi, 2005). The large network of disturbances has a substantial footprint on the landscape (Figure 3-1). Satellite image analysis by Quinton *et al*. (2011) of Scotty Creek revealed 133 km of linear disturbances (seismic lines and winter roads) within the 152 km^2 basin. This drainage density of 0.875 km km^{-2} is about five times the natural drainage density of the basin, 0.161 km km^{-2} (Williams *et al*., 2013). Where these disturbances exist the permafrost has since thawed (Figure 3-1). The large number of these cutlines and resulting permafrost loss raises concerns regarding their impacts on the hydrologic cycle and sustainability of permafrost in the region (Quinton *et al*., 2009). Where permafrost has been lost, there is very little evidence of tree re-growth, thus the ecology of the area is also affected. The oldest disturbances, winter roads built in 1943, have shown extensive land subsidence as a result of permafrost thaw (Williams *et al*., 2013). In addition to the largely unknown changes to water resources in the region brought about by these disturbances, the region is also home to Caribou populations that are a primary food source for local populations (Williams, 2012). Concerns of habitat disruption have motivated local agencies to try to find ways to reduce the environmental damage resulting from these seismic lines.

3.2.2 On the use of mulching

One promising and relatively cost-effective mitigation measure is the application of mulch of the removed tree canopy, mainly black spruce (*Picea Mariana),* to cutlines once seismic surveys are complete. This is based on reports that woody debris, when piled and spread over the ground, has been observed to preserve permafrost below it (Williams, 2012). Williams and Quinton (2013) performed a study on the relative contributions of increasing incoming solar radiation and increases in soil moisture to permafrost thaw at linear disturbances at Scotty Creek. The authors concluded that the increase in incoming radiation at the ground surface is secondary compared to the increase in soil moisture on its effect on increasing ground heat flux to thaw underlying permafrost. This means that it is effectively the vadose zone's lower moisture content that acts to insulate the subsurface from atmospheric forcing that sustains the permafrost (Wright *et al*., 2009). This hypothesis which is supported by field observations at Scotty Creek, forms the basis of our study. Further evidence includes observations of bogs of slightly elevated relief and dryer ground conditions, where new growth black spruce and possible permafrost regeneration has been observed. There exists frozen ground at a depth of around 60 cm beneath the new growth trees, approximately 5-20 cm thick and a few meters wide, that has been present year round (Williams, 2012). This supports the paradigm that peat plateaus were formed from bogs through the development of sphagnum mounds that, as they grew vertically, sustained ground-ice perennially and became stable enough to support trees (Quinton *et al*., 2009).

Mulching is appealing as a potential mitigation measure because mulch (in this case wood chips), lacks the capillarity to exhibit significant matric potential and creates a dryer ground surface with higher albedo (Oke, 1987). Reduced water retention capability and a low thermal conductivity enable the mulch to act as a thermal buffer: a well aerated, low thermal conductivity layer insulating the permafrost below while also reflecting some solar radiation. However, due to the large geographic areas affected by cutlines, and concerns on how mitigation measures may affect the local hydrology, carefully controlled scientific studies are required. This will require an analysis of the effects of mulch on heat and water transport in the underlying soil profile and quantification of the thermal and hydrological factors affecting the mulch. Mulching has long been used to modulate soil temperatures, but influences on moisture and thermal regimes are complex being affected by mulch properties as well as local metrological and hydrological factors (Hillel, 1998).

Traditional agricultural mulches are usually applied in thin layers (≤ 10 cm) where their micro-topography, resistance to vapor transfer, and albedo play a dominant role in energy transfer (Oke, 1987; Sui *et al*., 1992; Fuchs *et al*., 2011). Heat transfer through these mulches is a mixture of thermal conduction through the wood particles and air convection in voids. However, the application of wood chips over permafrost, involves much thicker and denser layers that are better represented as a shallow variably-saturated porous media layer (Sui *et al*., 1992). Thus air flow is minimized in these layers with thermal conduction being the prominent heat transport mechanism in pore-spaces in the absence of flowing water. When moving water is present, e.g. infiltration, heat will also be transferred by advection. In peatlands, which are much wetter than most agricultural environments, the mulch may be subject to the water table moving in and out of the layer, and as such its wetting/drying characteristics are again better simulated as a porous media layer.

3.2.3 Climate chamber and soil column experiment

The climate chamber in which the soil column experiment was conducted is a two level biome capable of simulating large-scale subsurface environments (Nagare *et al*., 2012a). The chamber consists of an upper and lower level allowing for soil columns to be placed between the two levels and separated by an adjustable insulated floor (Figure 3-2). Situating part of the soil column in the lower chamber allows for the simulation of a saturated layer that remains frozen while the rest of the column in the upper chamber can be exposed to different climatic conditions. A full description of the climate chamber and its capabilities is described in Nagare *et al*. (2012a).

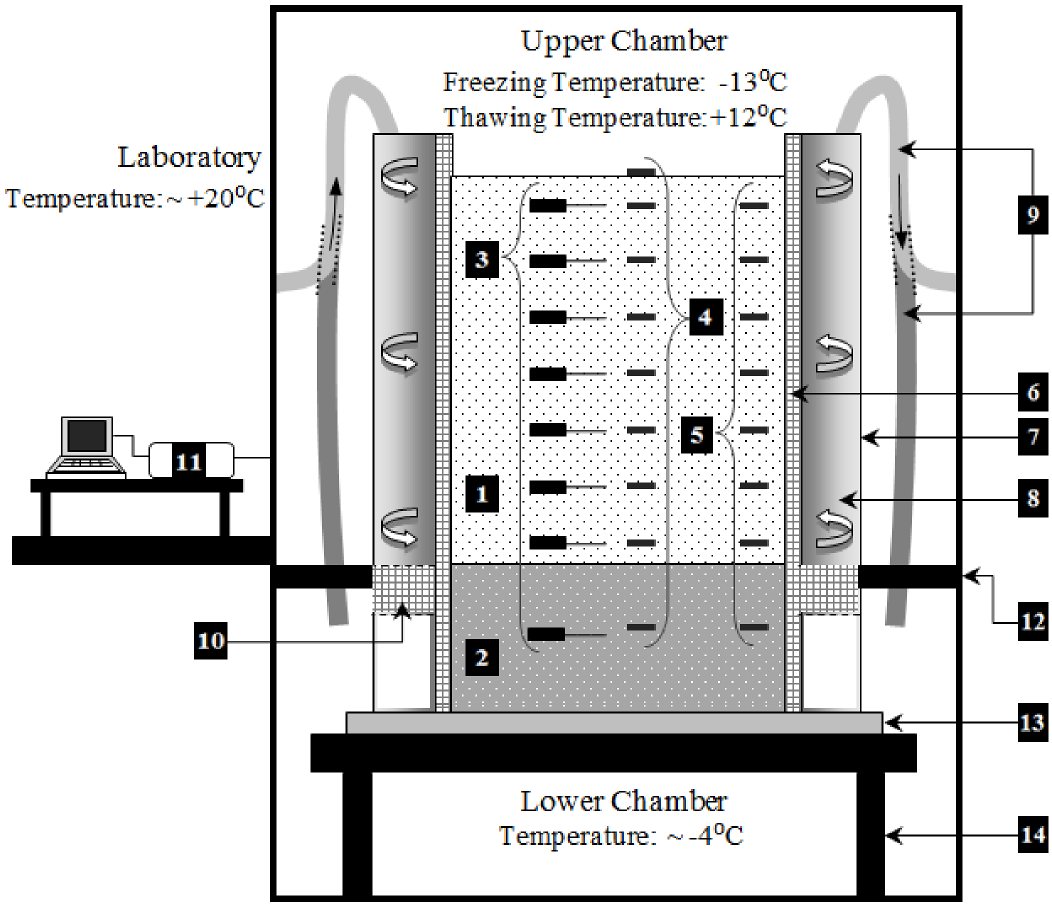

Figure 3-2. Diagram showing experimental setup (not drawn to scale): 1. 65 cm deep active-layer, 2. 40 cm bottom frozen layer, 3. TDR probes, 4. Thermistor probes (centre), 5. Thermistor probes (edge), 6. Inner LDPE container lined with neoprene foam, 7. Outer LDPE container insulated with Reflectix© from outside, 8. Cavity in which air is circulated, 9. Ducting through which air is circulated into/out the cavity, 10. 15cm thick Neoprene band separating airspace from lower chamber, 11. Multiplexers and data-logger connected to a personal computer, 12. Adjustable insulated floor separating upper and lower chamber, 13. Weighing scale, 14. Frame to support monolith.

The soil column used in conjunction with the climate chamber utilized a column design that was able to simulate realistic vertical and lateral thermal boundary conditions on a variably-saturated peat monolith. The upper and lower chamber maintained permafrost and ground surface temperatures at the vertical ends of the soil column, while the active-layer portion of the soil column is insulated by an air-filled cavity. Temperature controlled air is circulated within the cavity matching the average temperature of the active layer as it underwent freezing and thawing, enabled through the active manipulation of the radial temperature boundary. This design facilitated a controlled environment in which certain hydrological processes related to heat and water transfer in permafrost environments can be isolated and investigated without scaling requirements. A full description of the soil column design is discussed in Chapter 2.

The soil column was re-packed according to bulk density profiles from Scotty Creek in an effort to simulate a natural peatland profile characteristic of those found in the zone of discontinuous permafrost, while allowing us to reduce the effect of small-scale heterogeneities such as macro-pores and rooting zones. Although these heterogeneities can affect thaw regimes, they are not representative of the bulk thermal properties of the soil matrix, which is what controls thaw at the basin scale (Hayashi *et al*., 2007), and thus should be an acceptable assumption given the scale of the problem under investigation. Bulk density and porosity profiles from Scotty Creek and the monolith are shown in Figure 3-3. From the porosity profile it is evident that porosities measured on the re-packed samples fall on the lower end of the ranges measured in the field. This may be advantageous for this study as one of the impacts of seismic exploration is ground compaction which would likely lower porosities, thus the set-up captures the important hydrological and thermal properties of peatland profile beneath a linear disturbance.

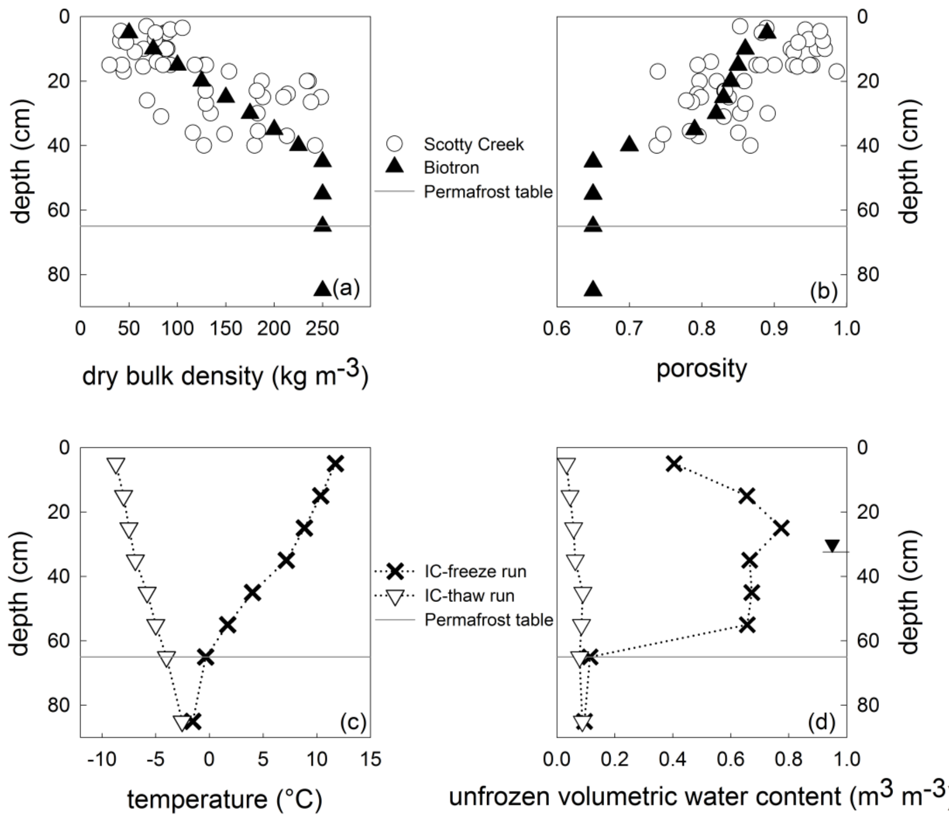

Figure 3-3. (a) and (b) show the density and porosity profiles, Scotty Creek values obtained from Hayashi *et al*.(2007). (c) shows initial temperature profiles of soil column prior to the beginning of a freezing run and thawing run, denoted as IC (initial conditions) -freeze and IC-thaw. (d) shows initial water content profile of soil column for IC-freeze and IC-thaw runs; water table depth in the soil Biotron experiment is indicated by the inverted triangle symbol at 35 cm. Permafrost table depths on all plots are for the Biotron experiment.

Temperatures were initially maintained at 20 °C and -4 °C in the upper and lower chambers respectively, to establish stable temperature and water content profiles. The freezing cycle was then initiated, lowering the upper chamber temperature to -13 °C to simulate winter conditions. Once the column was completely frozen and the temperature profile relatively stable, the upper level temperature was sequentially increased from -13 °C to 12 °C, allowing 45cm of the active-layer to undergo thawing. Freezing and thawing temperatures in this study represent approximately the average ground surface temperatures for the freezing and thawing periods at Scotty Creek (Wright *et al*., 2009). Initial water content and temperature distributions are shown in Figure 3-3.

On completion of the first experimental cycle, the soil column was adjusted such that it matched the initial cycle's moisture and temperature conditions, and a second freeze-thaw run was then initiated. The only difference being the addition of a 20 cm layer of black spruce wood chip mulch. Rationalization for realistic mulch thicknesses were based on the volume of mulch available from chipping operations and its associated particle size distribution (Figure 3-4). Scotty Creek supports an open mainly black spruce canopy of about 1 stem m^{-2}, with average heights and diameters being 3-5 m and 0.15 m, respectively (Wright *et al*., 2008; Williams *et al*., 2013). Using these numbers, and taking into account the porosity of the mulch (80%) when applied in the climate chamber, a maximum thickness of approximately 30 cm was calculated: thus 20 cm was deemed a conservative estimate.

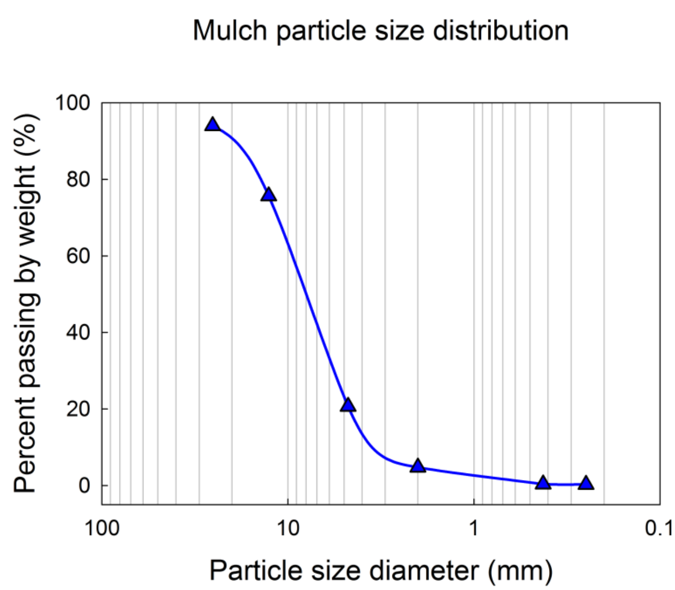

Figure 3-4. Average particle distribution of black spruce mulch used in Biotron experiment.

3.2.4 The SHAW model

Computer modeling is widely used to investigate the response of hydrological systems to stresses due to climate and anthropogenic disturbances (Painter *et al*., 2013). However, natural hydrologic systems are complex and the isolation of key driving parameters can be difficult from field studies and the numerical models that are designed to represent them. The laboratory experiment discussed here was specifically designed to simulate the primary physical mechanism governing frost table progression – thermal conduction. It also represents the water and energy dynamics of a typical field system: variably saturated with water-ice phase change. In the field, isolating the influence of parameters on observations is difficult due to the simultaneous forcing from different hydrological and meteorological variables. Thus data collected in the controlled laboratory experiment contains much less noise than present in field studies. This enables the quantification of the singular effect of the mulch on impeding heat conduction, and allows the simulation of a system that represents the key physical process governing ground thaw depths in these environments. Isolating the effect of the mulch on ground heat flux and incorporating other driving meteorological variables via modeling is beneficial as relationships between parameters may not be intuitively obvious given the complexities, and number of driving parameters involved in permafrost thaw. Modeling can then play a vital role in understanding processes that may possibly include complex feedback mechanisms (Painter *et al*., 2013). Because of the tightly coupled nature of these environments, these feedbacks can, and have been shown to, determine hydrological, thermal and ultimately landscape evolution (Smith *et al*., 2005; Quinton *et al*., 2011; Painter *et al*., 2013).

The SHAW model was chosen for this study because of its strong physical basis for simulating surface water and energy fluxes, and coupled heat and water transfer through a 1-dimensional soil profile (Flerchinger and Saxton, 1989). It integrates the detailed physics of energy and water transfer within a plant canopy, snowpack, residue and soil profile including soil freezing and thawing. We present the fundamental equations and descriptions relevant to the modeling in this study below. All variables used in the equations are defined in Table 3-1. A detailed description of all physical processes represented in the model can be found in the technical documentation (Flerchinger, 2000). Heat flux within the soil matrix is defined by:

$$\boldsymbol{C_s \frac{\partial T}{\partial t} - \rho_i L_f \frac{\partial \theta_i}{\partial t} = \frac{\partial}{\partial z}\left[k_s \frac{\partial T}{\partial z}\right] - \rho_l c_l \frac{\partial q_l T}{\partial z} - L_v \left(\frac{\partial q_v}{\partial z} + \frac{\partial q_v}{\partial t}\right)} \tag{3.1}$$

where the terms on the right side represent the change in temperature and latent energy required to freeze water. The terms on the left describe Fourier's law of heat conduction with the addition of advective heat transfer by infiltrating water and latent heat of evaporation, respectively. Thermal conductivity of the soil matrix is calculated by the de Vries (1963) equation:

$$\boldsymbol{k_s = \frac{\Sigma m_j k_j \theta_j}{\Sigma m_j \theta_j}} \tag{3.2}$$

where the thermal conductivity is a weighted composite value taking into account the different volumetric fraction of the soil-water matrix. The temperature at which freezing begins, and latent heat dominates energy transfer, is represented by a form of the Clausius-Clapeyron equation (Fuchs *et al*., 1978), which relates the total water potential (matric plus osmotic) when ice is present to the vapor pressure over ice. The temperature-water potential equilibrium relation is defined by:

$$\boldsymbol{\varphi = \pi + \psi = \frac{L_f}{g}\left(\frac{T}{T_K}\right)} \tag{3.3}$$

Water flux within the soil is governed by a version of the Richards equation (Richards, 1931):

$$\boldsymbol{\frac{\partial \theta_l}{\partial t} + \frac{\rho_i}{\rho_l}\frac{\partial \theta_i}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial \psi}{\partial z} + 1\right)\right] + \frac{1}{\rho_l}\frac{\partial q_v}{\partial z} + U} \tag{3.4}$$

where the terms on the left side of the equation represent the change in volumetric liquid water and ice content, respectively. The terms on the right side represent the net liquid influx in a layer, net vapor influx, and a source/sink term accounting for the water extraction by plants, respectively. Water flux is calculated as the product of the hydraulic conductivity times the soil matric potential gradient. The unsaturated hydraulic conductivity is calculated in the SHAW model using the equation of Campbell (1974):

$$\boldsymbol{K = K_s\left(\frac{\theta_l}{\theta_s}\right)^{(2b+3)}} \tag{3.5}$$

and the Campbell (1974) equation is used to relate the soil moisture content to matric potential as:

$$\boldsymbol{\psi = \psi_e \left(\frac{\theta_l}{\theta_s}\right)^{(-b)}} \qquad (3.6)$$

Table 3-1. Definition and units for all variables used in equations (3.1) – (3.6).

Symbol	Definition and Respective Units
b	pore-size distribution parameter
c_l	specific heat capacity of water (4,200 J kg^{-1} °C^{-1})
C_s	volumetric heat capacity of soil (J m^{-3} °C^{-1}
g	acceleration due to gravity (9.81 m s^{-2})
k_j	thermal conductivity of jth soil constituent (W m^{-1} °C^{-1})
k_l	thermal conductivity of liquid water (0.57 W m^{-1} °C^{-1})
k_s	thermal conductivity of porous medium (W m^{-1} °C^{-1})
K	unsaturated hydraulic conductivity (m s^{-1})
K_s	saturated hydraulic conductivity (m s^{-1})
L_f	latent heat of fusion (335,000 J kg^{-1})
L_v	latent heat of vaporization (2,500,000 J kg^{-1})
m_j	weighting factor for thermal conductivity of jth soil
M_w	molecular weight of water (0.018 kg mole^{-1})
q_l	liquid water flux (m s^{-1})
q_v	water vapor flux (kg m^{-2} s^{-1})
t	time (s)
T	temperature (°C)
T_{frz}	freezing point of water based on water potential of soil
T_K	temperature (Kelvin)
U	source/sink term for water flux equation (m^3 m^{-3} s^{-1}).
θ_i	volumetric ice content of soil layer (m^3 m^{-3})
θ_j	volumetric fraction for jth soil constituent (m^3 m^{-3})
θ_l	volumetric liquid water content of soil layer (m^3 m^{-3})
π	osmotic potential of soil solution (m)
ρ_i	density of ice (920 kg m^{-3})
ρ_l	density of water (1,000 kg m^{-3})
ρ_v	vapor density of air space (kg m^{-3})
ρ_{vs}	saturated vapor density (kg m^{-3})
ρ_{rs}	vapor density at an exchange surface (kg m^{-3})
φ	total water potential (m)
ψ	soil water potential (m)
ψ_e	soil air-entry potential (m)
R	universal gas constant (8.3143 J K^{-1} mole^{-1})

3.2.5 Modeling procedure

Inputs used in the model included: initial conditions for soil temperature and water content profiles (Figure 3-3-IC_thaw), hourly ground surface temperatures (GST), permafrost boundary temperatures (PBT), relative humidity and physical characteristics of the soil and mulch. The model was developed to simulate the freeze-thaw cycle and associated heat and water transfer within the soil column experiment presented in Chapter 2. The model was parameterized with measured values for most driving variables, that is, the physical characteristics of the soil needed to be represented in the model. Parameters that had to be estimated were used to calibrate the model, specifically the hydraulic retention parameters: air entry pressure ($\psi_{\boldsymbol{e}}$) and Campbell pore-size distribution index (b). Simulations were forced with ground surface temperatures (GST) and permafrost temperatures measured in experiments at ends of the soil column. The freezing period data was used to calibrate the model. The estimated parameters at the end of the calibration period were then used to validate the model against the thawing data.

Once the model was calibrated, and then validated such that it represented reasonably well the rate of ground thaw in the lab, the addition of the black spruce mulch (measured properties in Table 3-2 and Figure 3-4), was simulated. The model was used to assess the effect of the mulch on impeding frost table progression, while being exposed to additional variables not simulated in the climate chamber. This was achieved by using available meteorological data measured at Scotty Creek to drive the calibrated model. Seismic best practice guidelines recommend that seismic surveys be conducted when the ground is still frozen. Thus the modeling efforts were directed at replicating the effect of the mulch on a soil profile that captures initial conditions upon completion of a survey. The simulations replicate initial conditions prior to snow melt and were run from January 1st to August 1st (until time when peak average air temperatures are reached) for a period of 210 days. The driving variables included hourly values of air temperature (used as GST was unavailable), precipitation, relative humidity, wind speed and solar radiation measured at Scotty Creek (Figure 3-5). In addition to investigating the response of the mulch to typical meteorological conditions, initial soil moisture distributions were varied as well in the simulations. Realistic wet and dry ground conditions were simulated, by initializing water tables depths with values representative of a disturbed and undisturbed peat plateau (Table 3-3); this was done because soil moisture has a significant effect on the hydraulic and thermal properties of peat, and may consequently affect the evolution of the active-layer (Nagare *et al*., 2012b). Finally, the effects of differing mulch thicknesses were explored under the meteorological and soil moisture scenarios.

Wood is hygroscopic, meaning it attracts and retains moisture (Tsoumis, 1991). Thus the mulch's water transmission ability will vary with moisture content within matrix pores and also with the amount of moisture in the wood chips. Consequently, laboratory analyses were conducted to obtain moisture characteristics of the mulch at both saturated and unsaturated hygrometric conditions, through tension infiltrometer experiments on samples packed to the same density used in the climate chamber. The infiltrometer results were assimilated into a MATLAB program developed by Mollerup *et al*. (2008) which combines the Philip (1957, 1958) solution for 1D infiltration with a numerical inversion scheme to obtain the Campbell (1974) hydraulic retention parameters for the mulch. As sub-arctic peatlands are mostly wetland-dominated environments, we believe it reasonable to assume that the 'wet' mulch is the more realistic of the hygrometric extremes, and were the parameters used in the SHAW model, shown in Table 3-2.

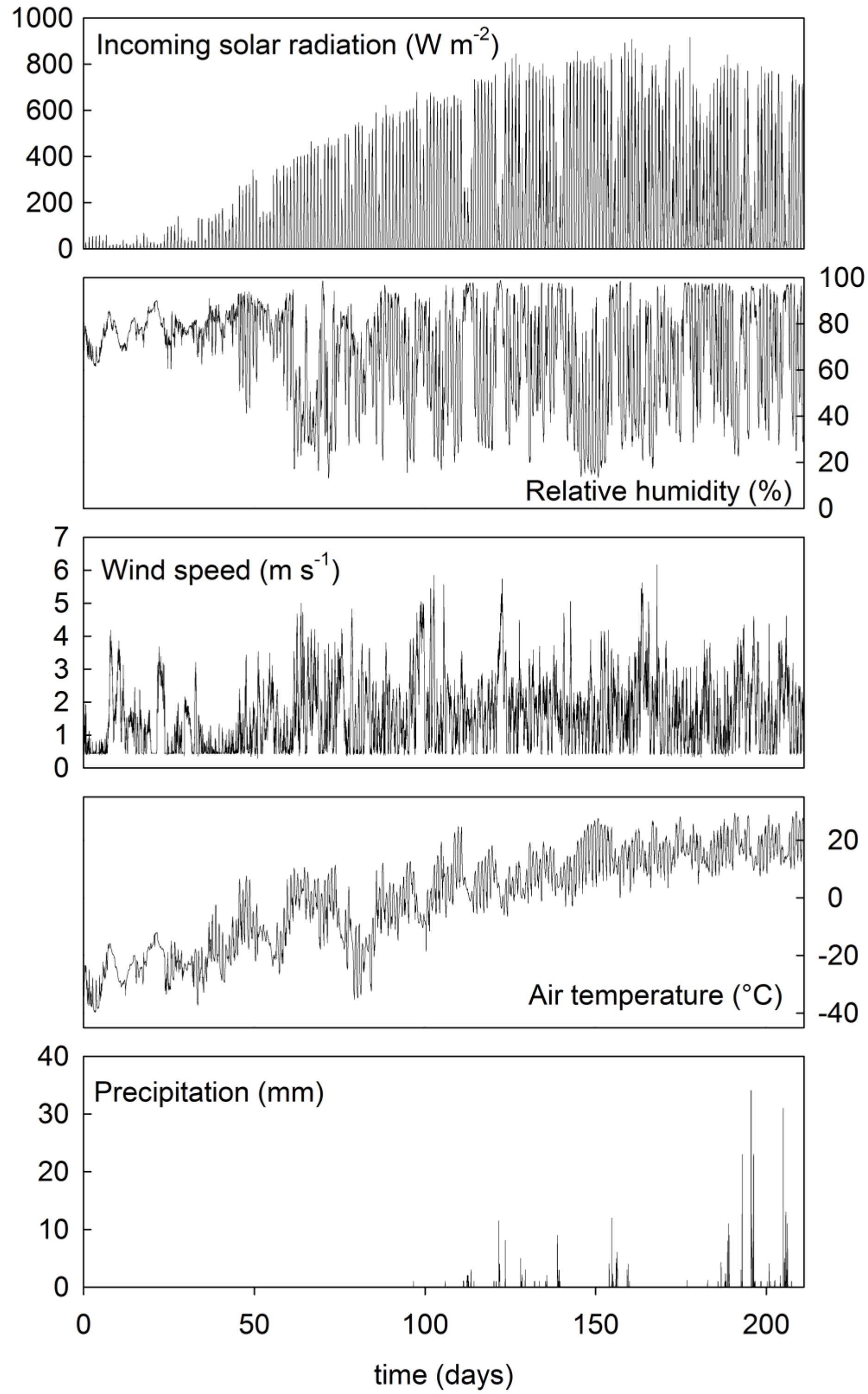

Figure 3-5. Meteorological variables measured at Scotty Creek from January 1st, 2010 to August 1st, 2010, used to drive the calibrated SHAW model.

3.3 Results and Discussion

3.3.1 Experimental results

The thermal regime of the monolith over the first freeze/thaw cycle without the mulch is shown in Figure 3-6. Temperature time series (Figuren3-7) highlight the experiment's ability to simulate one-dimensional heat transfer, which is discussed and validated in Chapter 2. A comparison of the temperature distributions produced in the soil column and at Scotty Creek clearly highlights the experiment's ability to reproduce the ground temperature conditions observed in the field (Figure 3-6).

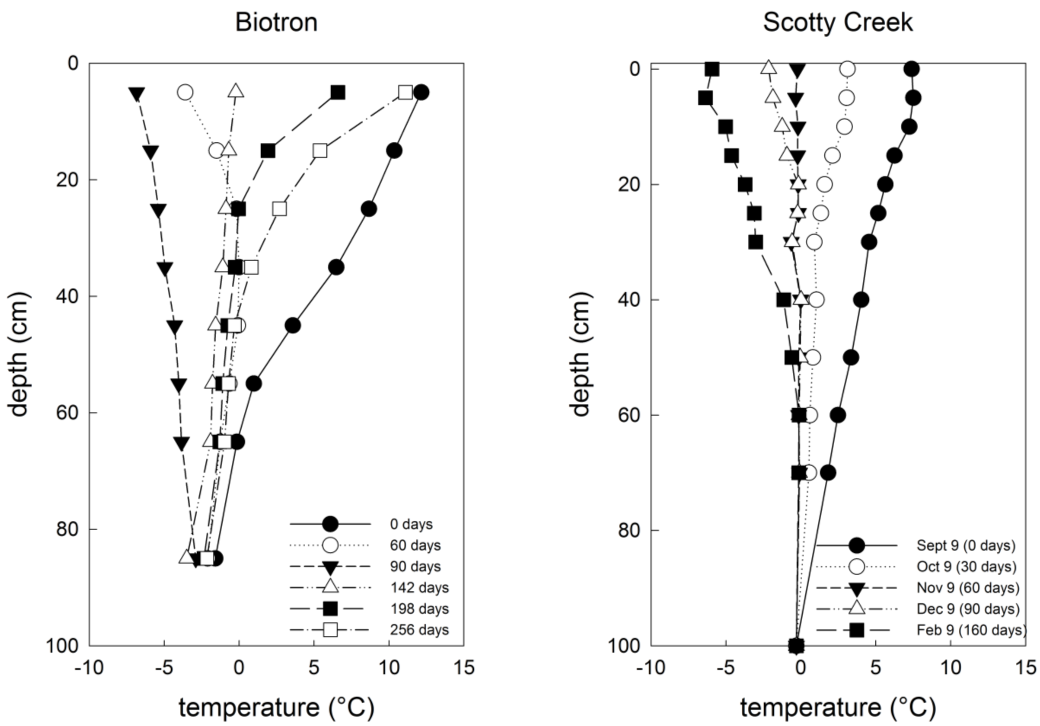

Figure 3-6. Thermal regime over entire freeze-thaw cycle for soil column experiment and Scotty Creek field site (November 2001-Feburary 2002). The temperature at 100 cm depth for Scotty Creek is approximated from the Norman Wells pipeline (Smith *et al*., 2004).

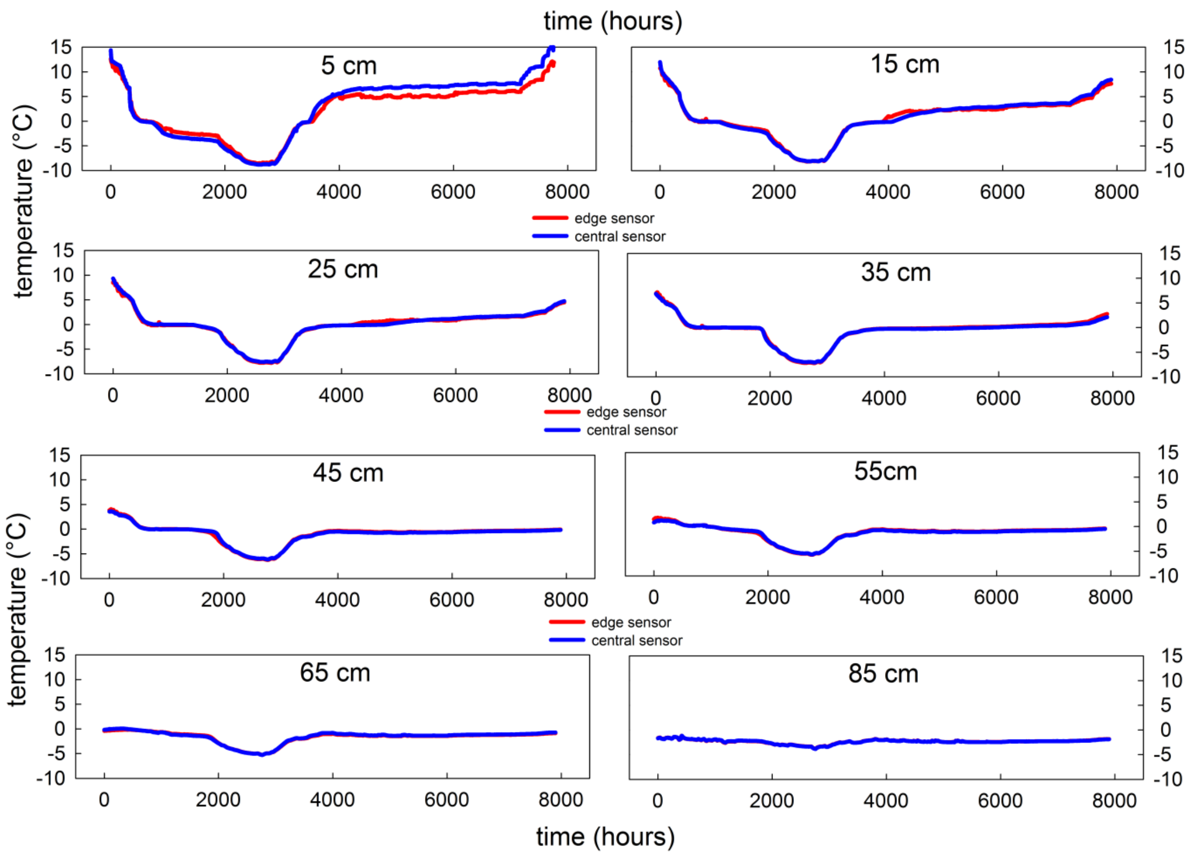

Figure 3-7. Temperature time series for all instrumented depths (5 to 85 cm) in the soil column during the experimental cycle without the mulch. Depths of each time series are listed in each graph. Central and edge sensors nearly completely overly each other and thus edge sensor cannot be seen for 45 cm and deeper.

The thaw time in this study was approximately 200 days, comparing relatively well with the 156 days thawing period observed at the field site by Wright *et al*. (2009). Reasons for a longer thaw time are discussed in Chapter 2 but in summary, are likely due to: 1) the absence of external sources of water (and thus energy) as the experiment did not simulate precipitation and snowpack, 2) the thawing temperature was held at 12°C which represents the average thawing period temperature at Scotty Creek, and not the higher temperatures experienced in late summer which is when maximum thaw depths are reached (Wright *et al*., 2009), and, 3) the absence of a snowpack in this study resulted in evaporation beginning earlier in the thawing period than it would in the field. Decreases in moisture content and energy from the active layer due to evaporation, decreases the rate of heat conduction and slows thaw front progression.

Initial time-series data comparing the thermal evolution of the active layer for 55 days are shown in Figure 3-8. The run with the mulch layer is still in its early stages of its thaw cycle, but it is clearly having an insulating effect on the soil’s temperatures and significantly slowing thaw progression. The run with the mulch will continue for at least another 150 days. However, very encouraging observations can be measured and quantified thus far.

Ground thaw, for the purposes of this study, is defined as the zero-degree isotherm. Ground thaw for the no-mulch run began 13 days after the upper-level air temperatures increased and stabilized at 12 °C. In comparison the mulched-surface run shows thaw began, comparably, after 27 days; a 14 day extension of the frozen ground period. Temperature time series comparisons at different depths also show slower warming rates in the upper most depths (Figure 3-8).

By removing the variability and its inherent uncertainty of field data, the controlled mesocosm environment ensures that the only difference was the addition of the mulch. This verifies the expected thermal insulation ability of the mulch. However, implications on mulching based solely on these experiments are limited due the absence of important meteorological processes not simulated, e.g. precipitation and snowpack. External sources of water (and thus energy), snowpack dynamics, and mid-winter thaw events can be very important mechanisms for active layer warming. Parameterized and validated with experimental data, incorporating these meteorological processes via numerical modeling enables effect of variables not simulated in the lab to be considered.

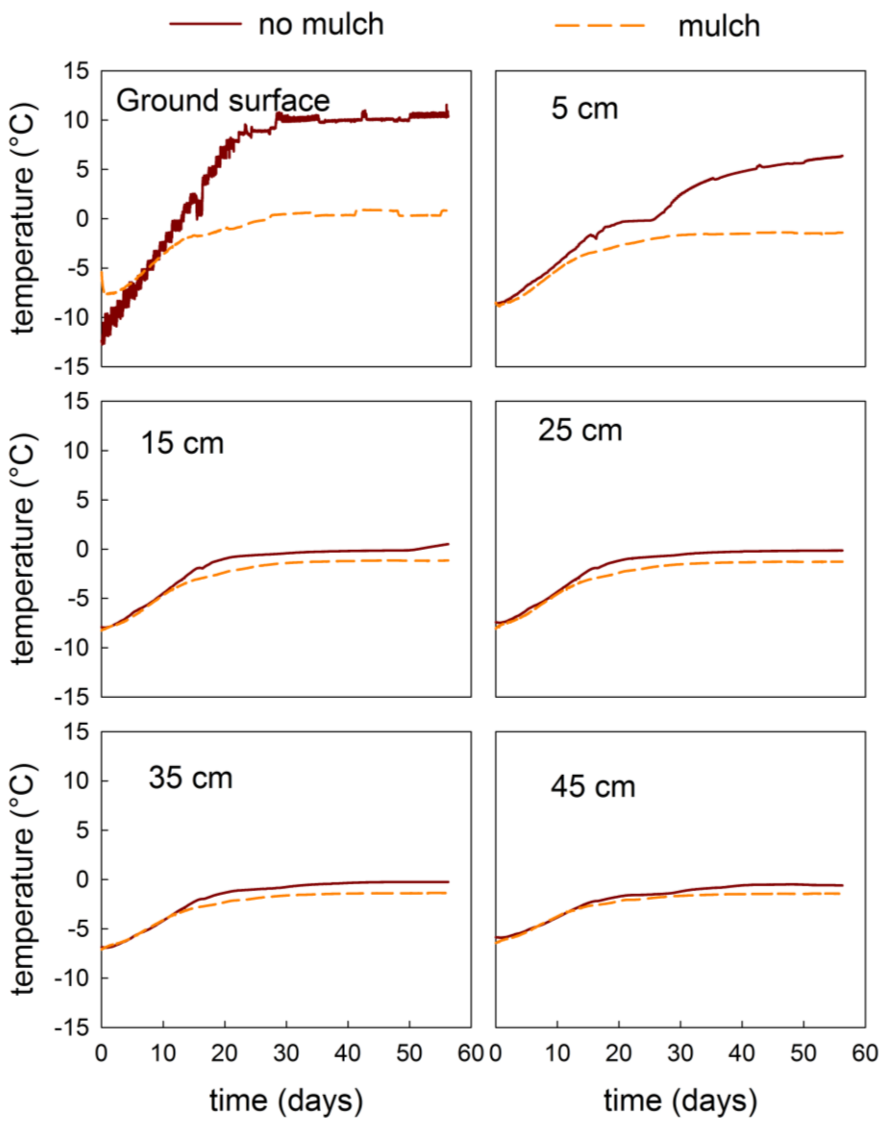

Figure 3-8. Time series comparison of ground temperatures for all instrumented depths within the active-layer of the soil column during the first 55 days of the thaw period of the second experimental cycle with the added 20 cm mulch layer.

3.3.2 Model evaluation

The initial experimental cycle without the mulch was used as part of the model evaluation process. The soil column model was calibrated using the freezing period data, and then evaluated against the thaw observations to validate it. Table 3-2 summarizes the parameters used to calibrate the model; values were typical of other SHAW modeling studies in organic covered permafrost soils, including Scotty Creek (Zhang *et al*., 2008, 2010).

Table 3-2. Soil texture and hydraulic parameters used in the SHAW model developed for this study.

Parameter	**Values used at soil nodes in the SHAW Model**								
Depth (m)	**+0.05 - +0.30**	**0.00 - 0.05**	**0.05 - 0.15**	**0.15 - 0.25**	**0.25 - 0.35**	**0.35 - 0.45**	**0.45 - 0.55**	**0.55 - 0.65**	**0.65 - 0.85**
Texture	mulch	peat	peat	peat	peat	peat	peat	peat	peat
Sand	0	0	0	0	0	0	0	0	0
Silt	0	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Clay	0	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Organic	1.00	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
ρ_b(kg m^{-3})	140	50	100	150	200	250	250	250	250
θ_s(m^3 m^{-3})	0.8	0.9	0.89	0.85	0.76	0.70	0.65	0.65	0.60
ψ_0(m)	0.02	0.01	0.03	0.05	0.05	0.05	0.05	0.05	0.05
b	22.8	3.5	3.6	3.9	4.2	4.5	4.5	4.5	4.5
K_S(m s^{-1})	2.2×10^{-5}	3.5×10^{-5}	3.5×10^{-6}	3.0×10^{-7}	2.3×10^{-7}	2.3×10^{-7}	2.3×10^{-7}	2.3×10^{-7}	2.3×10^{-7}
albedo	0.40	0.25	-	-	-	-	-	-	-

The calibration was based on the temperatures and moisture content time series measured at each depth in the soil column during the freezing portion of the cycle. It was only necessary to optimize hydraulic parameters in the simulations since the other main factors affecting heat transport (GST, PBT, soil texture and density) were directly measured or determined. The accurate representation of water retention was critical to representing the ground heat flux due to the change in thermal conductivity with water content. The model was then used to simulate the thawing period without the mulch; Figures 3-9 and 3-10 shows the comparison between modelled and measured temperatures and frost table progression, respectively. The largest discrepancies occur at the 15 cm and 25 cm depths and during the latter stages of the thawing period. The overestimation of temperatures towards the latter end of the thawing period could be due to the possibility that the imposed temperature range in the climate chamber approached upper limits of the current experimental set-up's ability to maintain 1D thermal forcing: in effect, small lateral temperature gradients in the soil column at higher temperatures. The greatest vertical range of temperatures within the active layer of the soil column is experienced during the thaw cycle at the warmest temperatures. Portions of the soil column nearest the surface were then slighter cooler near the column edges because the air cavity temperature has to be less than higher soil temperatures to match the average temperature of the entire 65 cm column profile. Thus, it is reasonable to assume that those small lateral thermal gradients had a modulating influence on the vertical thermal gradient in the soil column (decreased slightly), which wasn't picked up by the ground surface thermistor that provided the upper boundary for the model simulations. These deviations, from otherwise little or no difference in measured and modeled ground temperatures (Figure 3-9), occurred when upper chamber temperature was increased to 20 °C to perturb the approaching steady state thermal condition before ground thaw reached the desired 45 cm depth. The opposite is true, although to a much lesser degree for the freezing temperatures in the simulation, where there was a slight warming influence in the opposite direction. Despite these differences the model was still able to represent reasonably well the thaw progression in the active-layer (Figure 3-10). Figures 3-11 illustrates results on 1:1 plots of measured versus simulated temperatures for all depths (39487 total data points) over the 5640 hour simulation period and measured versus simulated thaw progression times over the same time interval. Also shown in both figures are values for average root-mean squared residuals, which lie within range presented in other studies (Daanen *et al*., 2007; McKenzie *et al*., 2007). Thus given these results it is reasonable to assume that the calibrated model is able to serve as a realistic analogue for heat transport in the soil column.

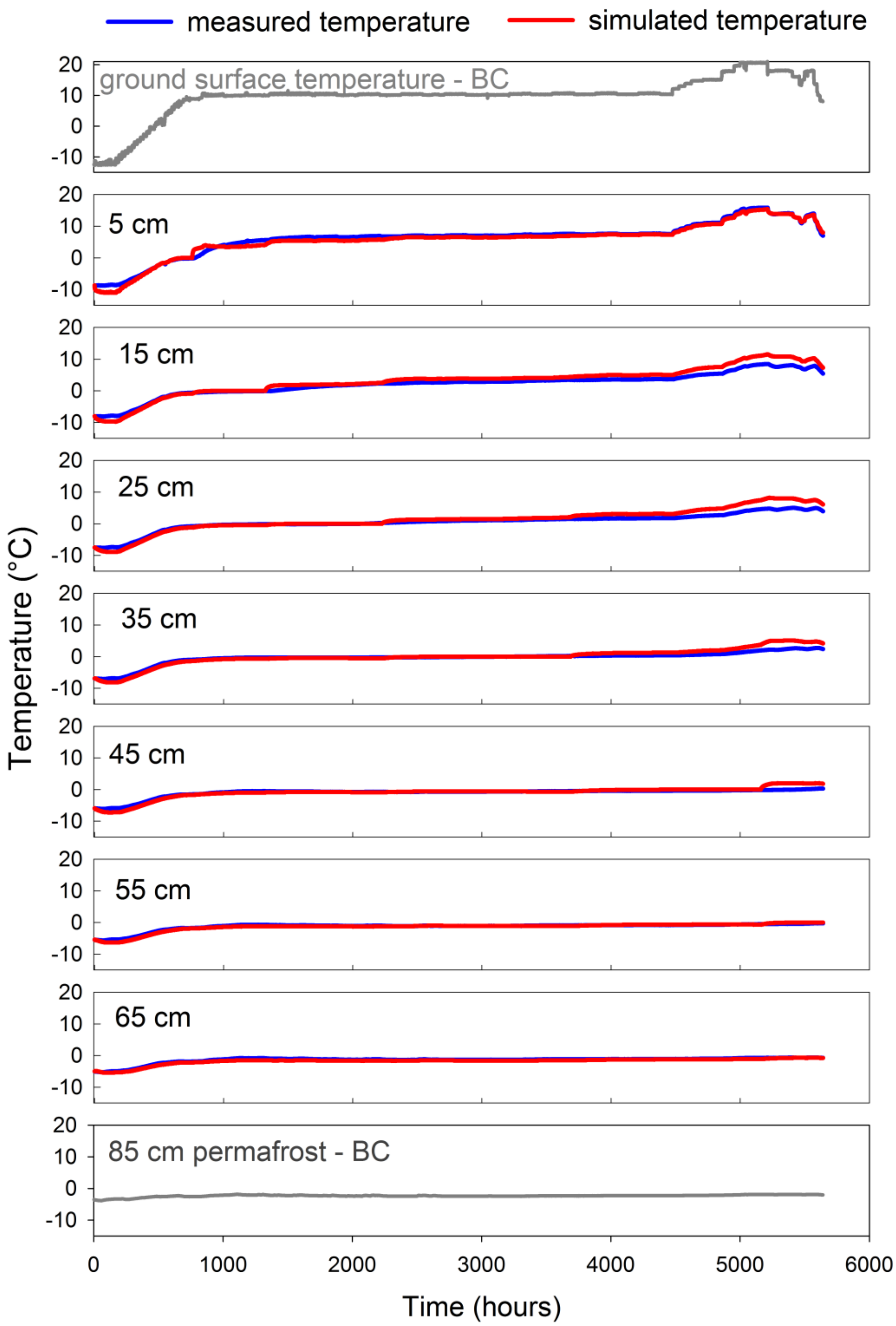

Figure 3-9. Time series comparison of simulated vs. measured temperatures for all instrumented depths within the active-layer of the soil column during the thaw period of the first experimental cycle without added mulch. Temperature boundary conditions used in the model: ground surface temperatures and permafrost temperatures are shown in grey.

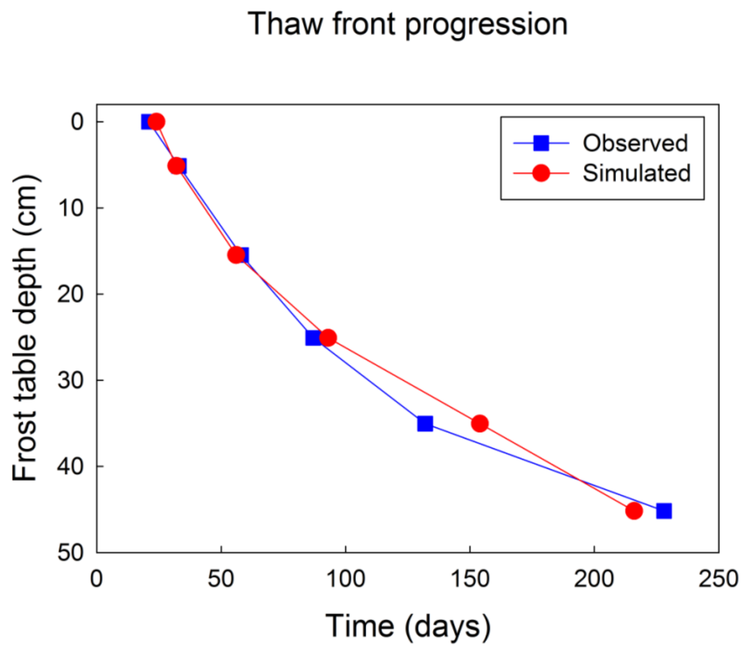

Figure 3-10. Comparison of simulated vs. measured thaw progression in soil column.

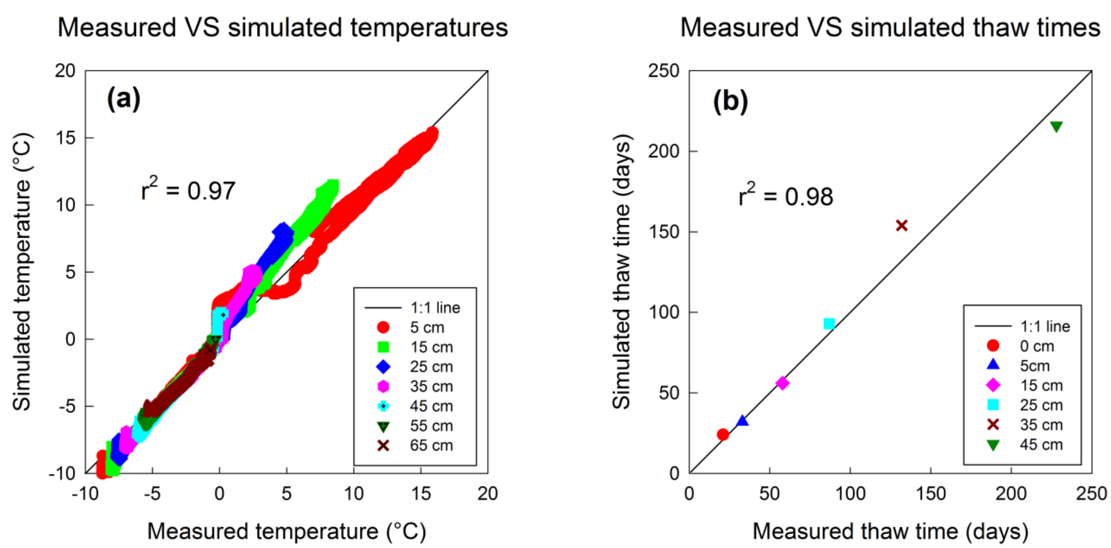

Figure 3-11. a) Scatter plot of simulated versus measured temperature values for all depths within the active-layer of the soil column. (b) Scatter plot of simulated versus measured thaw progression times for all depths within the active-layer of the soil column.

3.3.3 Effect of mulch on ground thermal regime

Table 3-3 summarizes the different scenarios simulated to quantify the effect of the mulch on ground heat flux, thaw depth and soil temperature. The no-mulch scenario represents a generic peatland profile underlying a seismic line. Because the model's lower temperature boundary condition is kept as the PBT in the soil column experiment, complete permafrost loss is not possible as temperatures are always < 0 °C. Thus, while the lower boundary condition in the field will be affected by thaw, this is a conservative measure as the PBT essentially constrains the amount of possible thaw. As such it should be emphasized that the simulations are not exact predictions of how much the ground thaw will be advanced under the cut lines; they are a tool to explore the relative contributions of different mulch thicknesses under typical field conditions on ground thaw reduction. Figure 3-12 illustrates the impact of the different mulch thicknesses on cumulative net ground heat flux, frost table progression and soil temperature distributions, respectively, for both dry and wet ground scenarios.

Table 3-3. Summary of soil moisture and mulch combinations used in model analysis under the meteorological forcing data from Scotty Creek.

Scenario	**No Mulch**		**Mulch**	
Soil moisture	Dry	Wet	Dry	Wet
Water table depth (m)	-0.55	-0.05	-0.55	-0.05
Mulch thickness (m)	0	0	0.10 – 0.30	0.10 – 0.30

Ground heat flux is calculated as the residual of the surface energy balance in the SHAW model. Under both dry and wet soil conditions, the mulch acts to slow cumulative net heat flux and reduces the amount of energy being partitioned to thaw and warm the underlying soil over the thawing period. Closer inspection reveals that under all mulch scenarios the cumulative net flux is actually reversed compared to the no-mulch scenarios until approximately Days 124, 139, and 150 for the 10, 20 and 30 cm mulch thicknesses respectively. Negative cumulative net heat flux is indicative of heat being lost to the atmosphere as opposed to heat being conducted through the ground. For both wet and dry scenarios, 10 and 20 cm thicknesses show similar trends in regards to reducing heat flux: 10 cm mulch decreases heat flux by 25 and 26 %, and doubling mulch thickness to 20 cm produced a 32 and 33 % heat flux reduction, for respective conditions. While a slightly larger change is seen with the 30 cm mulch under the wet scenario (45%), there is a significant divergence later in time for the dry soil profile and a much larger reduction results (62%). Overall, this net reduction of energy input into the subsurface can be attributed to 1) the higher albedo of the woods chips compared to a bare soil surface, and 2) the low thermal conductivity of the mulch which slows the rate at which heat can be conducted from the ground surface to the underlying soil. Less cumulative net heat flux is the first step in reducing permafrost thaw as it will ensure cooler thermal regimes, provided other energy sources not simulated in this study (e.g. advection by laterally flowing water) remain the same.

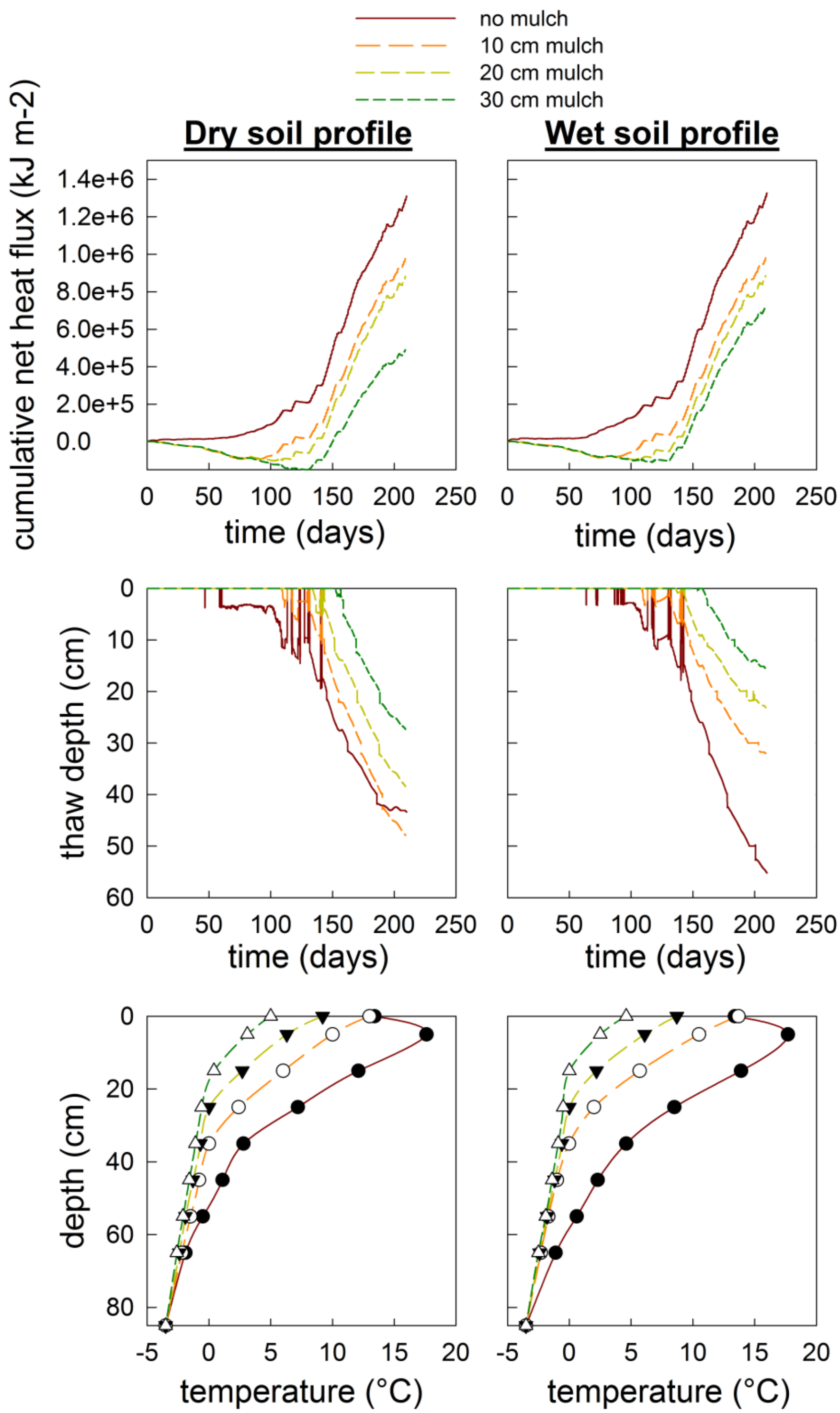

Figure 3-12. Cumulative net ground heat flux, ground thaw progression and soil column temperature distributions during the simulated thawing period or dry (left column) and wet soil (right column) scenarios under 0 – 30 cm of mulch.

The first major effect on ground thaw evident from mulching is the prolonged period of time the ground remains frozen during positive air temperatures. Under the two no-mulch scenarios, ground thaw began when the ground surface became snow free at approximately Day 47 and 53 for dry and wet ground conditions, respectively. However, the 10, 20 and 30 cm mulch thicknesses delayed ground thaw until approximately Days 110, 143 and 155 for both scenarios, respectively. This coincides closely to the periods when net heat flux becomes positive during the thaw period and is expected as energy must be supplied for thaw to begin. Thaw depth fluctuations for short periods of time, most evident under the no-mulch scenarios, are a result of temperatures decreasing to below freezing during approximately Days 111 and 140 (Figure 3-12). This time is long enough for ground refreezing to occur before thaw is re-initiated. Under both scenarios, the mulch reduces the ability of surface temperature perturbations to penetrate the ground, which is evident as oscillations in thaw depth diminish with increasing mulch thicknesses. Under dry conditions, up until approximately Day 180, the 10 cm, 20 cm, and 30 cm depth reductions are similar, i.e. the thaw rates (slope and difference between the plot lines) are similar. The dry ground-10 cm mulch scenario only shows reduced thaw until Day 180. The thaw depth goes deeper in later times when the no-mulch scenario begins to stabilize and the 10 cm-mulch performs worse as thaw continues its downward progression. The lack of thaw reduction under the 10 cm mulch is probably because of the re-freezing of thawed ground for the short periods of between Days 111 and 140 (Figure 3-12). Refreezing influence was diminished because of the thermal buffering capacity of the mulch. This resulted in the thawing front under the 10 cm mulch being deeper at times just after the re-freezing events, evident when the 10 cm mulch thaw front dips below the no mulch thaw front in Figure 3-12. Since thaw rates were similar after the initial ground thaw delay, more incoming heat had to be spent thawing the re-frozen water, resulting in less energy for ground thaw. The 20 and 30 cm thicknesses show reduced thaw for the entire period. Doubling the mulch thickness from 10 cm to 20 cm negates the effect seen with the 10 cm mulch, resulting in a 12% reduction in thaw depth. Increasing it again by 50% (i.e. 30 cm) results in a further 37% reduction.

Under the wet soil scenario all simulated mulch thicknesses showed reduced thaw. Again, similar to the dry ground conditions, the application of the mulch insulates the underlying soil and delays thaw initiation. However, in the wet ground scenario, because of the larger amount of water present compared to the dry scenario, the soil column requires more latent heat to melt ground ice. The reduction of available heat flux and the thermal buffering capacity of the mulch, combined with the larger amount of ice, extends the zero-degree curtain period and increases the time to thaw soil layers. Because of this, thaw reduction is larger than dry ground scenarios, resulting in 42, 58 and 71% reduction for the 10, 20 and 30 cm mulch thicknesses, respectively.

For both scenarios, the prolonged soil thawing period also resulted in the mulch subsurface temperature remaining cooler compared to no-mulch scenarios (Figure 3-12). This again is linked to the combined effects of lower cumulative heat flux and insulation, both attributed to the addition of the mulch. The diminished energy input means that upon thaw, less sensible heat is available for warming and thus ground temperatures remain cooler with the mulch layer.

In general, the application of the mulch insulates the underlying soil, which delays thaw initiation by slowing the input of energy to the subsurface. This effect prolongs the period of time the ground remains frozen during positive air temperatures. Similar reductions are seen in thaw depth and heat flux as they show comparable trends in thaw reduction percentage (Figure 3-13). Ground thaw begins at similar times to when positive net heat flux occurs, delayed slightly by the latent energy exchange to initiate thawing. A notable difference between thaw depth and heat flux result trends is that under dry ground conditions there is quite a difference in late periods between 20 and 30 cm mulches. However, this difference in heat flux is not represented in the thaw depth differences, as the difference in thaw depth is similar for each increase in mulch thickness (Figure 3-12).

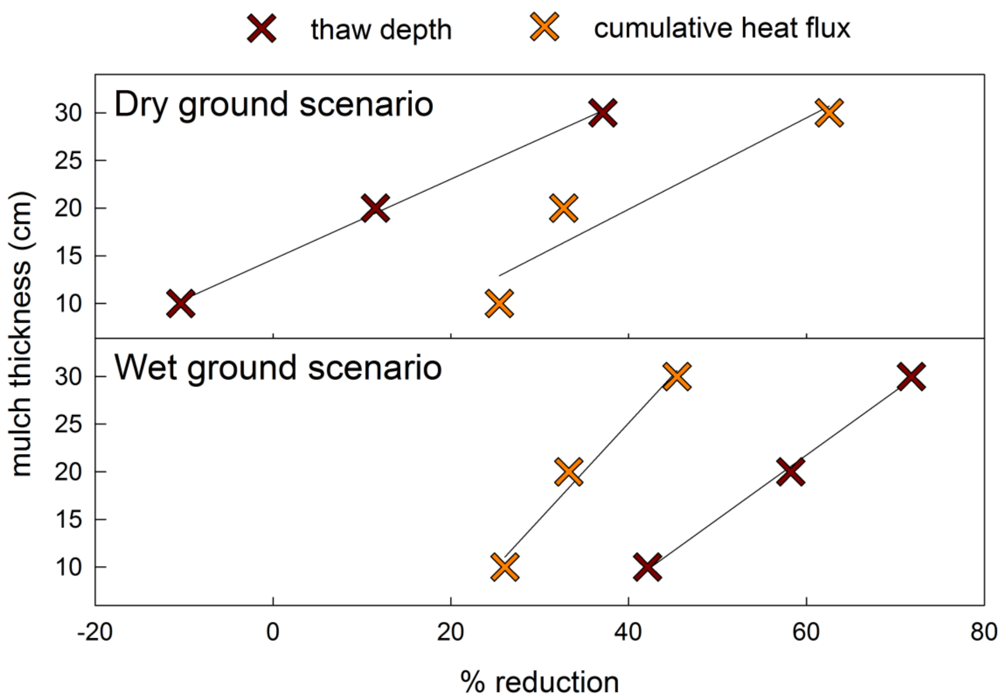

Figure 3-13. Mulch thickness versus % reduction for cumulative heat flux and thaw depth reduction, illustrating the effect of increasing mulch thickness on cumulative net heat flux and ground thaw reduction for dry and wet ground scenarios.

3.4 Conclusions

Mulching over seismic lines has been proposed as a best management practice to reduce the impact of linear disturbances on permafrost degradation in the sub-arctic peatlands of Northern Canada. A soil monolith-climate chamber experiment was utilized to investigate the effects of using mulch of the removed tree canopy on thermally mitigating permafrost thaw. Running freeze-thaw simulations with and without the mulch enabled its effect on impeding ground heat flux to be tested. The data were assimilated into a coupled heat and water transport model, allowing the quantification of important parameters controlling the process observed in the lab. Using meteorological data measured at Scotty Creek to drive the model, simulations investigated the combined effects of mulch thickness, antecedent moisture conditions and meteorological interactions. This provided a basis to assess the mitigation measure on its ability to slow permafrost thaw. Results demonstrate the ability of the mulch to decouple the subsurface thermal regime from meteorological forcing by impeding ground heat flux. This is due to the drier unsaturated conditions produced by the layer, and also its increased albedo. The mulch acts to insulate the ground surface, prolonging the period of time the ground remains frozen and delaying thaw initiation. The experimental cycle with the mulch is still in its early stages of thaw but it is clearly having an insulating effect on soil temperatures, and is significantly slowing thaw progression.

The numerical modeling efforts were aimed at replicating the effect of the mulch on a soil profile that replicated field initial conditions. Simulations that were initialized during the winter period show that, upon positive air temperatures, the mulch insulates the soil profile and actually prolongs the time before ground thaw begins. Results indicate that different mulch thicknesses show similar thaw reducing ability except under specific conditions and during certain time periods. Under dry conditions, a mulch thickness of 10 cm did not have a positive effect on reducing ground thaw as the mulch dampens ground surface temperature fluctuations and kept the ground warmer when air temperatures dipped below freezing briefly. During these re-freezing events in the thawing period, depths of re-freezing were reduced, keeping the ground warmer than the no-mulch scenario. Under wet conditions, however, all simulated mulch depths showed reduced thaw. Aside from the dry ground-10 cm mulch scenario, thaw reduction ranged from 12 to 71 %, with the wet ground-30 cm mulch scenario achieving the maximum thaw depth reduction. Mulching also resulted in the subsurface temperature remaining cooler compared to no-mulch scenarios. The consequence of linear disturbances most detrimental to permafrost thaw is the increase in soil moisture (Williams and Quinton, 2013). Thus the wet scenario, where the soil layers 5 cm below the ground surface were saturated, represents a potentially ‘worst case’ situation. Under this scenario, all mulch thicknesses were still able to reduce ground thaw and maintain cooler thermal regimes. The overall result of its application is less energy being partitioned into ground heat flux by decreasing the rate of heat conduction to the frost table, reducing energy available for permafrost thaw and thus slowing thaw front progression. Results indicate an overall positive relationship between mulch depth and reduced thaw.

While results validate the insulative ability of the mulch, the above analyses do have some limitations. There remain uncertainties regarding the persistence and evolution of the mulch properties over time. Degradation of the mulch will likely affect its physical characteristics, for example aging mulch may lower its albedo, and as such these changes will have effects on the mulch's capability. Subsurface run-off within the mulch was not simulated as SHAW is only a 1D model. As shallow subsurface flow is the main run-off mechanism on plateaus, and when frost table depths are shallow early in the thaw season, run-off will likely be within the mulch at some point. The effects of different relief and laterally flowing pore-water through the mulch remain unknown.

Due to these data limitations and assumptions in this study, results are difficult to extend beyond the scenarios described. However, the ability of the mulch to limit the initial disturbance to the ground thermal regime and subsequently conserve permafrost is very encouraging. It is the sustained additional energy being supplied over linear disturbances for ground heat flux over many years that contributes to complete permafrost loss and its associated hydrological and ecological impacts. Climate-chamber and numerical experiments investigating the mulch's effect on ground heat flux indicate reduced ground thaw and cooler subsurface temperatures, which should reduce the impact of the disturbances. As such, mulching should be an effective technique to reduce permafrost degradation in sub-arctic peatland regions. This is a major issue in cold region studies due to the tight coupling of heat and water movement, and non-linear feedbacks that control the hydrological and ecological cycles of these environments. This lab and modeling study, coupled with field data to constrain and validate parameters, provides a scientific basis to the resource management practice of mulching over seismic lines, and will aid in ensuring that the inevitability of increased northern exploration is performed in a more environmentally conscious and sustainable manner.

3.5 Acknowledgements

The authors wish to acknowledge the financial support of the Natural Science and Engineering Research Council of Canada (NSERC) and BioChambers Inc. (MB, Canada) through a NSERC-CRD award, NSERC Strategic Projects grant, and the Canadian Space Agency (CSA) through a Capacity Building in SS&T Cluster Pilot grant. We also thank Roger Peters, Steve Bartlett, Jon Jacobs and Marc Schincariol for their assistance in the laboratory.

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Chapter 4

4 Conclusions and future recommendations

4.1 General conclusions

The ability to understand and predict coupled heat and water movement in permafrost affected organic soils is critical to mitigating climate and human induced changes, currently being observed in northern latitudes (Hinzman *et al*., 2005). Controlled laboratory experiments can improve the ability to study and understand the closely connected thermal and moisture regimes of permafrost environments. Results and discussions presented in this thesis clearly show how controlled and carefully designed laboratory methods can validate the accuracy of the interpretations of physical processes from field studies. Insight gained from these types of laboratory experiments compliments field work and can help promote more accurate and purposeful investigations. This is particularly true of cold region studies, where resources are expensive and access is often limited.

The ability to simulate and isolate the main heat transport mechanism governing permafrost depths in sub-arctic peatlands (thermal conduction), enables the effects of different perturbations to its thermal regime to be investigated. The unique experimental design allowed for the testing of how ground surface conditions affect heat and water transfer in the underlying soil and permafrost. Seismic surveys in permafrost peatlands remove the tree canopy and compact the ground surface, changing the surface energy balance. The net result is more heat being transmitted though the ground to warm and thaw the underlying permafrost. Mulching the removed trees and applying it over seismic lines has been observed to preserve permafrost below. The scientific premise lies in the mulch’s ability to restore some of the pre-disturbance topographic relief while also promoting dryer ground surface conditions. The low thermal conductivity of the mulch should slow net heat flux into the soil. The new experimental design, once it ability to reproduce realistic active layer thaw was validated, was utilized to study the effect of the mulch layer on heat transfer in the soil profile.

In summary the research presented in this thesis makes the following original contributions in peat soils active layer heat transport:

(1) This unique experimental design provides a method that allows for the isolated study of certain thermal and hydrological processes related to coupled heat and water movement in soils underlain by permafrost. The method is one that enables the control of the radial temperature boundary on soil cells. It can be applied to large or small samples, depending on the apparatus used and scale needed to be represented. The lab experiment was very carefully conceived, and successfully linked to on-going field research, and has advanced the understanding of active layer thermal processes. In particular the experiment design was able to minimize radial temperature gradients and simulate one-dimensional active-layer thawing on time scales similar to those observed in field studies. Representation of realistic spatial and transient thermal regimes is required to study the impact of temperature changes on hydrological and ecological processes (e.g. infiltration into partially frozen soil, nutrient cycling rates).

(2) Another result of particular interest is the lack of observed thermal hysteresis observed in the absence of significant lateral temperature gradients. This result is contrary to the interpretations of some researchers who present a different view on the controls of freeze-thaw characteristics of northern peatlands, for example Smerdon and Mendoza (2010). They proposed that the degree of hysteresis was dependent on initial total water content prior to freezing. The also suggested super-cooling and osmotic freezing point depression due to solute exclusion effects, during the freezing process may have played a role in their observed thermal hysteresis. However, most studies of the soil freezing based on the thermodynamic equilibrium assumption of the relation between soil temperature and pressure, have all concluded that residual unfrozen water content (while it is temperature dependent) is not dependent on the initial total water content (Kurylyk and Watanabe, 2013). Parkin *et al*. (2013) has also noted that thermal hysteresis is 'more apparent than mechanistically real'. This essentially means that we do indeed observe hysteresis; but in the absence of other driving parameters than can affect soil moisture and temperature, hysteresis will be much less under the sole influence of thermal conduction, than what has been observed in previously reported studies (Quinton and

Hayashi, 2008; Quinton and Baltzer, 2012). The observed hysteresis may then be due to the influence of other heat and water transfer mechanisms not taken into account in the mathematical conceptualization of the soil freezing process. This makes sense intuitively if one considers that in any terrestrial environment during times of freezing or thawing, there will be a number of hydrological processes occurring simultaneously (e.g. evapotranspiration, snowmelt, infiltration, subsurface run-off and uneven thermal properties due to soil heterogeneity). This study adds to the discussion that it is other heat transfer effects that control freezing characteristics of cold region peatlands, not taken into account in conceptual models, rather than the soil water potential differences suggested (e.g. Smerdon and Mendoza, 2010).

(3) The mesocosm-modeling study explored the effects of the mulch layer on heat transport and active-layer thaw. Laboratory experiments physically simulated a natural peatland soil profile which was exposed to two freeze thaw cycles, varying only by the addition of a 20 cm layer of black spruce mulch on the soil surface of the second thaw run. Numerical modeling of the climate-chamber experiments explored the effect of meteorological variables not simulated in the lab study. Parameterized and validated with experimental data, the modeling results indicate that mulching is a potentially effective measure to combat the ecological consequences of linear disturbances. The mitigative ability lies in the mulch's physical and hydraulic properties. The high porosity-high permeability layer of low thermal conductivity organic material restores some of the pre-disturbance ground conditions, which are crucial to sustaining permafrost. The mulch reduces the cumulative ground heat flux. The net result is a slower cumulative heat flux rate and reduction in subsurface temperatures. This combined effect extended the period of time the ground remained frozen and slowing the progression of the frost table.

4.2 Future recommendations

(1) Further improvement of the soil column design to better maintain 1D thermal gradients during thawing can still be achieved. As noted in Chapter 2 the largest lateral thermal gradients were present at the warmest temperatures near the end of the thawing period, indicating that the design has upper limits on the magnitude of positive temperatures that the column can be exposed to, whilst still maintaining vertical heat

transport. The column design presented here consisted of an air-filled cavity where temperature controlled air was circulated within it that matched the average vertical temperature profile of the active layer. The addition of a second cavity, between the instrumented soil column and air-cavity, filled with soil at similar moisture conditions, may further control the ability to simulate 1-D temperature gradients. This may seem very similar to the current design, as there was an outer radius of soil in the column that insulated the instrumented core. But the addition of a second cavity will further isolate the instrumented soil cell as the discontinuity provided by the second cavity wall will reduce ATI and also prevent temperature induced lateral moisture flow. As water, a heat carrying mass, moves in response to thermal gradients (Harlan, 1973), the coupled nature of moisture and temperature distributions in freezing soils for this type of lab work means that ATI has to be taken in context of the processes it affects. Thus limiting the effects of ATI on moisture flow is also important when studying heat movement. Maintaining 1D moisture gradients will reduce radial temperature distributions, thus improving 1D heat flow and vice versa. This modification will further increase the range of temperatures the experiments can be exposed to and provide an even more controlled environment. The further refinement of experimental techniques is needed in the study of heat and mass transfer in soils to elucidate the mechanisms controlling the process affecting hydro-ecological function of cold region environments.

(2) For the apparatus and climate chamber discussed, the effect of surface variables such as vegetation, snowpack and winter snowmelt events can now be studied. Regarding subsurface phenomena, a growing concern is the transport of contaminants, particularly those resulting from pipeline leaks or spills in permafrost soils, present over extensive arctic and sub-arctic regions. The thermal state of soils will significantly affect its flow and transport characteristics, as the presence of ice and temperature induced water re-distribution affects permeability and hydraulic conductivity relationships. As temperature controls rates of biological processes, e.g. decay and degradation, thermal conditions will also affect any bioremediation efforts (Van Stempvoort and Grande, 2006). This apparatus, with its ability to house field equipment (piezometers, TDRs, thermistors) is an ideal set-up to investigate both theoretical and empirical non-isothermal relative

saturation-permeability relationships among different types of contaminants (e.g. oil, oil-sand affected water). This will aid in the design of mitigation and remediation techniques for subsurface industrial contamination.

Another very important issue in northern watersheds is the wetland reconstruction currently being pursued and tested by researchers such as Price *et al*. (2010) and Devito *et al*. (2012). Increased resource activity in these landscapes means that reconstructed peatlands need to be able to replicate their natural counterparts' hydrologic functioning such that coupled water and energy cycles continue to support their ecosystems. Our experimental set-up presents a controlled environment in which the effect of different hydrologic influences can be tested on a soil column mirroring field conditions. The design is very conducive to testing the functioning reconstructed peatland soil monoliths in climatic range of conditions they would be exposed to.

(3) Bolstered by encouraging initial results, further field studies on mulching as a best management practice to reduce permafrost loss due to linear disturbances are warranted. A paired plot experiment would test the mulch's ability under direct field conditions and constrain the uncertainty. Paired plot experiments can examine issues unable to be recreated in the lab. As subsurface flow through the active-layer is the dominant run-off mechanism in discontinuous permafrost peatlands, the effects of mulching in relation to topographical setting and the effect of lateral heat flow should be studied. The effect of mulch degradation on its insulation capacity also remains uncertain. Identifying these uncertainties will help to further characterize the effect of the mulching technique at the basin scale, and its persistence over time.

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