2016

Seasonal Evolution of Active Layer Formation in Subarctic Peat Plateaux and Implications for Dissolved Organic Matter Composition and Transfer

Jennifer L. Hickman
Wilfrid Laurier University, hick3620@mylaurier.ca

Recommended Citation

Hickman, Jennifer L., "Seasonal Evolution of Active Layer Formation in Subarctic Peat Plateaux and Implications for Dissolved Organic Matter Composition and Transfer" (2016). *Theses and Dissertations (Comprehensive)*. 1780.
https://scholars.wlu.ca/etd/1780

Seasonal Evolution of Active Layer Formation in Subarctic Peat Plateaux and Implications for Dissolved Organic Matter Composition and Transfer

by

Jennifer Lee Hickman

Honours BA in Environmental Studies, Wilfrid Laurier University, 2012

THESIS

Submitted to the Department of Geography and Environmental Studies

in partial fulfillment of the requirements for

Master of Science

in

Physical Geography

Abstract

Peat-accumulating wetlands are ecosystems whose rate of photosynthetic production of organic matter is greater than that of its decomposition, resulting in a build up of soil organic matter that may take centuries to fully decompose. Carbon (C) stocks within these ecosystems are a function of inputs from photosynthesis, and losses from heterotrophic decomposition. Due to the short growing season and overall cold climate of boreal and tundra regions, C has been accumulating within these landscapes, mostly in soil organic matter, since the last glaciation. Climate change, predicted to result in rising temperatures and increased precipitation, has begun to degrade the underlying permafrost of peat plateaux. Hydrologically, permafrost below the active layer acts as an impermeable layer, similar to bedrock, limiting the movement and storage of groundwater to the seasonally thawed active layer. The presence of seasonal ice in the active layer reduces the hydraulic conductivity and available storage capacity, significantly reducing water infiltration, and potentially increasing the occurrence of surface ponding. Accumulated water in surface pools maintains soil moisture levels for longer periods of time, and are often the locations of the deepest thaw depth due to the downward transfer of latent heat aided by the increased thermal conductivity of the peat in the presence of water. Understanding the linkages between the hydrology, the energy balance, and chemical release into surface and groundwater is essential to predicting the response of these landscapes to future climate change.

To examine how Northern peatlands are responding to recent warming, two study sites (62° 27’ N, 114° 31’ W; 62° 33’ N, 114° 00’ W) outside of Yellowknife, NT, were instrumented between October 2012-October 2013 to monitor groundwater carbon chemistry, ground thermal and moisture regimes, organic matter decomposition rates, and active layer development over an entire summer period. An integral precursor to site-wide degradation, surface microtopography has been identified as a major determinant in the future evolution of peat plateaux into permafrost-free, bog-like environments. A Biochambers laboratory peat monolith experiment replicating the climatic conditions of a hummock and a depression in the natural system revealed that during the spring freshet while the ground remains frozen, the largely ice-free hummocks function as water contributors to ice-rich depressions, acting as water catchments. This transfer of water aids in the mobilization of DOM from hummocks into depressions, where it potentially accumulates over long time periods and is susceptible to export as the peat plateaux degrade. The accumulation of water in depressions prevents complete freeze-back of the active layer in the winter, allowing microbial activity and DOC production to occur year-round. The formation of supra-permafrost taliks has also been observed as an outcome of trapped heat beneath the seasonally frozen active layer and above the permafrost table, which, over time, may form interconnected subsurface flowpathways for DOM export. As warming commences over time, it is thought that the physical and carbon chemistry characteristics of the degraded portion of the plateaux may act as a proxy for future landscape change.

Acknowledgements

First, I would like to give a huge thank you to Mike English, not only for believing in me and the work that I've done, but for supporting me through my master's thesis despite living across the country! Not only have you introduced me to the North, you've shared a great deal of wisdom with me and I'll appreciate that always. You've made the past three years really enjoyable, even when it was – 50 °C and we were crazy enough to core lakes or later on munching down on some 'gourmet' dinner. Thanks Mike!

Thank you to my committee members, Dr. Sherry Schiff, Dr. Chris Spence, and Dr. Igor Lehnherr, who took the time to read my thesis and provide me with valuable comments and suggestions to make this a better piece of writing.

Alex MacLean, Steve Kokelj, and Pam Schaus, your help along the way has made my thesis a much better piece of research, and I appreciate that hugely!

A big thanks to Pieter Aukes, who taught me most everything I know about the intricate world of DOM characterization. You're a joy to work with and always so positive, thanks for continuously making time to answer my questions and share ideas. It would have been so much more difficult without you!

I'm very grateful for the financial support provided by the Cumulative Impact Monitoring Program of the GNWT Government.

Most of all, I'd like to thank my sisters, grandparents, and especially my parents. Mom and Dad, you've supported me through two degrees and I hope one day I can do something meaningful enough to repay this profound gift you've given me. I hope you know how much you've helped me through every stage of life and education, this thesis being no exception. Thank you!

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction to Subarctic Peatlands and Dissolved Organic Matter

1.1 Introduction

Ongoing permafrost thaw in the Canadian subarctic is largely attributed to the changing global climate (Schuur et al., 2015), with both temperature and precipitation increases resulting in major landscape change in this fragile southern zone of discontinuous permafrost. As one of the most rapidly warming regions on Earth (Johannessen et al., 2004; Quinton & Baltzer, 2012), subarctic Canada has experienced an unprecedented loss of permafrost during the past century, causing rapid and widespread landscape degradation. With 30 – 65% of permafrost in the southern discontinuous zone having degraded over the past 100 – 150 years (Beilman & Robinson, 2003), subarctic peatlands remain particularly sensitive to the effects of a warming climate. Peat plateaux, underlain by permafrost and elevated above surrounding permafrost free wetlands, are often characterized by a hummocky surface terrain and substantial organic matter accumulation (Moore & Basiliko, 2006). As permafrost within the peatland thaws, ground surface subsidence occurs, altering the hydrological and thermal functioning of the system, and ultimately inducing a positive feedback for continued thaw.

As permafrost thaws and ground surface subsidence progresses, the microtopographical variations of the peatland may become more pronounced. Hummocky surface terrain is a prominent surficial feature of many subarctic peatlands, with large mounds rising from the peat alternating with lower, flatter and often wetter depressions (Quinton & Marsh, 1999). These mounds, called hummocks, maintain permafrost beneath them and typically support healthy vegetation growth. Conversely, depressions are low-lying areas where water frequently pools, with degrading permafrost beneath and little-to-no healthy vegetation growth. Due to its ability to influence water movement, the microtopographical structure of the peatland *i.e.* the ratio of hummocks to depressions surface area, is a key controlling factor for potential future degradation. Similar to the edge effects observed in subsiding Boreal forests bordering wetlands (Baltzer et al., 2014), hummocks and depressions behave on a micro-scale similarly to how peatlands and wetlands behave on a macro-scale.

Characterized by substantial accumulations of organic matter, boreal peatlands are second only to tropical forests in terms of the amount of carbon (C) they store (Baltzer et al., 2014; Gorham, 1991). With typical peat accumulation rates of 0.31 mm/year (Gorham, 1991), peatlands store humified organic debris containing C that is centuries, if not millennia old. As permafrost thaws, it incorporates legacy C into the present day C cycle, potentially exporting it to surface water bodies as dissolved organic matter (DOM) or re-entering the atmosphere as carbon dioxide (CO_2).

DOM is a term encompassing organic compounds dissolved in water and comprised of carbon, oxygen, nitrogen, and hydrogen (Aukes, 2012), and is derived from the microbial degradation of organic material. The difficulty associated with measuring this group of heterogeneous molecules means that the concentration of dissolved organic carbon (DOC) is often used as a proxy measurement for the concentration of DOM, as DOC comprises approximately 50% of total DOM.

Although DOM occupies an integral role in the ecosystem by acting as a source of energy, it also acts as a transporting device, mobilizing contaminants, organic pollutants, and heavy metals, making it a major concern for overall water quality (Aukes, 2012). Importantly, it has been observed that DOM reacts during the chlorination process of drinking water, forming carcinogenic disinfection by-products (Marhaba & Van, 2000). In addition, increased loading of DOM into lake and river systems may potentially alter the thermal structure of the water column and hinder the availability of light necessary for photosynthesis but also protecting aquatic organisms from ultraviolet (UV) subjection (Aukes, 2012; Schindler et al., 1996). As such, it is essential to establish the quantity, quality and lability of C sequestered in present day peatlands, and determine the mechanisms responsible for C release into surface water bodies. In doing so, the highly complex network of processes acting in unison to produce DOM will be examined, making it possible to isolate the most influential factors driving the production and export of C from peatlands.

The highest concentrations of DOC (> 50 mg/L) are often found in organic soil porewaters and freshwaters draining wetlands and peatlands, particularly where runoff is low (Evans et al., 2004). As the subarctic climate warms and precipitation regimes shift (Spence et al., 2011), the potential for heightened DOC production and export amidst thawing permafrost is unquestionable. While the quality of the organic matter is a large contributor to the production and export of DOC (Laiho, 2006), numerous studies (Moore & Dalva, 2001; Reynolds & Fenner, 2001; Fenner, 2002; Evans et al., 2004; Moore & Basiliko, 2006; DeConto et al.,

2012) have highlighted the positive relationship between increasing soil temperature and DOC concentration, while other studies (Schiff et al., 1998; Blodau et al., 2001; Evans at al., 2004; Laiho et al, 2006; Lyon et al., 2010) have indicated a strong link between the hydrological functioning of various ecosystems and the DOC dynamics within those ecosystems. Identified as two of the most influential physical drivers behind peatland degradation, the thermal and hydrological functioning of these systems may also play a prominent role in the regulation of DOM dynamics.

1.2 Study Site Descriptions

Two peatland study sites were selected in the Yellowknife, Northwest Territories, Canada region, both of which border a wetland, lake and/or pond, and show signs of a degrading forest-wetland transition zone extending from the wetland boundaries into the forested peat plateaux. While sites were partially selected based on proximity to the Yellowknife region and ease of accessibility, landscapes representing typical subarctic peat plateaux in the southern region of discontinuous permafrost were necessary in order to evaluate the study results on a broader, regional scale. Both sites have variable canopy cover and surface topography, and a transition zone exists where the peat plateau is degrading due to either disturbance (Pontoon Lake), or flooding (Airport site). Wetlands form the boundaries of both peat plateaux, where ground surface subsidence occurs along plateau edges and degradation is present. Surface microtopographical variability was initially the most prominent feature identified at both sites, with significant differences observed between hummocks and depressions including large variability in frost table depth, vegetation, elevation, and degree of saturation. With the nature of the study focusing on physical and chemical changes in the midst of landscape degradation and permafrost loss, each site appeared to represent a gradation of climate induced landscape change from heavily degraded, permafrost free plateau edges and depressions to stable permafrost in the absence of peat degradation.

1.2.1 Airport Site

The Airport site (62°27 N, 114°31 W) is located on the Taiga Shield ~ 5km outside of Yellowknife, NWT along the southern fringe of the sporadic discontinuous permafrost zone. The mean annual air temperature of the Yellowknife region (class 'A' meteorological station, Environment Canada) is -4.9 °C (1945-2010) (Figure 1.1) with a mean annual total precipitation of 299 mm. Throughout the 2013 study period, daily mean air temperatures measured at the Airport Site were largely above the long term average, particularly in early April and during the months of May – June and September – October (Table 1.1, Figure 1.1). Warmer conditions during these hydrologically critical time periods can accelerate snowmelt in the spring, leading to earlier ground thaw, and delay freeze-back during the winter. Long-term records for both annual precipitation and air temperature show increasing trends for the Yellowknife region since 1945.

Table 1.1: Mean monthly air temperatures in 2013 compared to the monthly mean long-term (1945-2010) temperatures for April, May, June, September, and October.

Month	Mean Temperature 2013	Mean Long-term (1945-2010) Temperature
April	-8.5	-6.4
May	7.5	4.7
June	16.1	13.0

September	9.4	7.1
October	1.0	-1.4

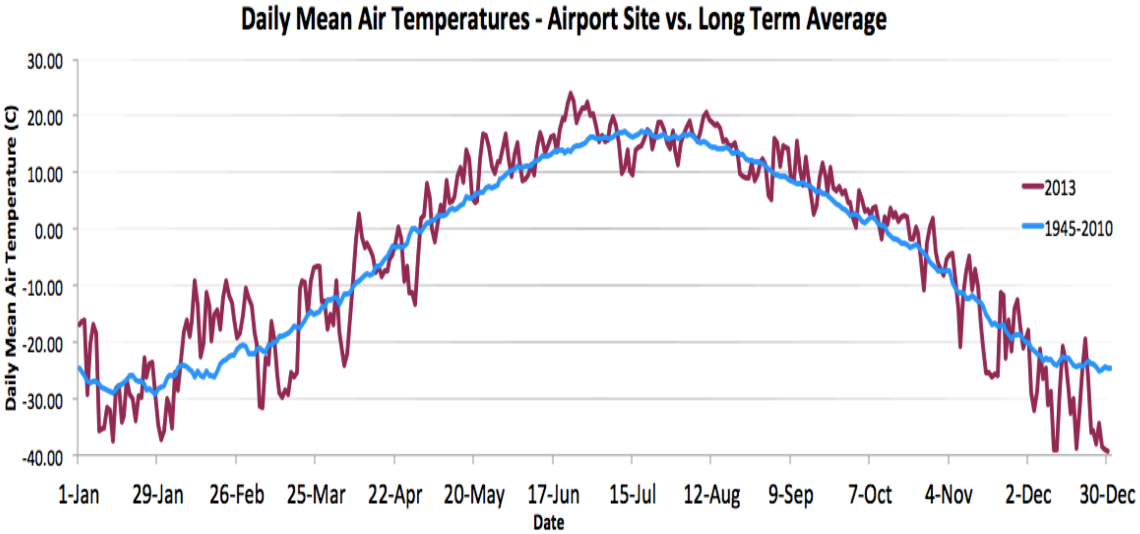


Figure 1.1: A comparison of daily mean air temperatures recorded at the Airport site over the course of 2013 vs. the long-term mean daily air temperatures recorded by Environment Canada between 1945-2010.

As is typical of this zone, the Airport site is a peatland environment with ~ 5 m thick organic layer underlain by mineral soil (Dr. S. Kokelj, *personal communication,* 2012). The northern portion of the site is raised ~ 1 m above the bog and pond located on the southern edge of the peat plateau where active degradation and gradual subsidence is occurring (Figure 1.2, Figure 1.4). The northern end of the site supports a thin black spruce (*Picea mariana*) canopy, which becomes sparse and eventually open towards the southern degrading edge. The plateau also supports the widespread growth of Labrador tea (*Ledum groenlandicum*), lichens (*Cladina* spp. and *Cladonia* spp.), cloudberry (*Rubus chamaemorus*), and mosses (*Sphagnum* spp.). Near the southern degraded edge sporadic stands of Tamarack (*Larix laricina*) and cotton grass (*Eriophorum angustifolium*) also exist. The sparse tree canopy typically has an average height of

5-7 m at the northern end of the site, and 2-4 m towards the middle and southern edge of the plateau.

The Airport site was chosen as a proxy site for the largely inaccessible peat plateaus of the region, and as such, many physical characteristics are shared between the chosen site and the numerous surrounding peat plateaus of the subarctic discontinuous permafrost zone (Dr. S. Kokelj, *personal communication,* 2012). An exposed Precambrian bedrock outcrop borders the western edge of the study site. Lichen covers approximately 80% of this outcrop, with small stands of jack pine (*Pinus banksiana*) and black spruce (*Picea mariana*) growing in depressions where sediment and organic matter have accumulated over time. Within bedrock fracture apertures and depressed areas of the outcrop, mosses (*Sphagnum* spp.) can also be found (Spence, 2006).

The topographic structure of the peat plateau is characterized by randomly distributed hummocky terrain alternating with flatter, wetter depressions (Figure 1.2, Figure 1.4). There is a great deal of variability in the size of individual hummocks and depressions, each ranging from < .5 m^2 to 1.5 m^2. Depressions are often saturated or near saturation, and are frequently the locations of surface ponding following the spring freshet. They support very little plant growth, with the exception of some mosses (*Sphagnum* spp.) and have active layers that can exceed 1.5 m at their deepest. In some cases, depressions may not freeze back fully, with a perennially unfrozen layer existing 1 -1.5 m beneath the annually frozen active layer. In contrast, hummocks rise above depressions, and can range from ~ 0.5 m – 1 m in height with active layers generally reaching a maximum of 50 – 65 cm in depth.

They support the growth of Labrador tea, black spruce, lichens, and mosses, and often have moisture contents ranging between 10 – 30%.

The site can be classified into two scales: site-scale and micro-scale. On the site-scale, the non-degraded “cold” portion of the plateau exists in the northern 1/3 of the peatland, while the degraded “warm” portion comprises the remaining southern 2/3 of the site. This general classification of the site indicates predominantly cold and warm areas, however some exceptions apply to individual hummocks and depressions. On the micro-scale, degradation occurs within individual depressions, both in the cold and warm areas of the site. Hummocks in the cold, non-degrading area of the site remain with stable active layers, which can also be found in some cases in the warm, degrading area of the site. Degradation within the site is defined as an area frequently inundated with water, having little-to-no living vegetation cover, with a humified surface layer and very little recognizable organic material (*i.e.* roots, needles, leaves), warmer ground temperatures than surrounding hummocks, an active layer that may not fully freeze-back during the winter, and a frost table depth that largely exceeds that of a stable hummock during the thaw season. The term non-degrading is defined as an area that supports healthy vegetation growth, particularly of black spruce and Labrador tea, has a surface layer comprised of easily recognizable litter with living material in the top 10 cm, is relatively dry, freezes back fully during winter, and has a stable active layer *i.e.* the active layer thaws and freezes back fully to the same approximate depth year after year.

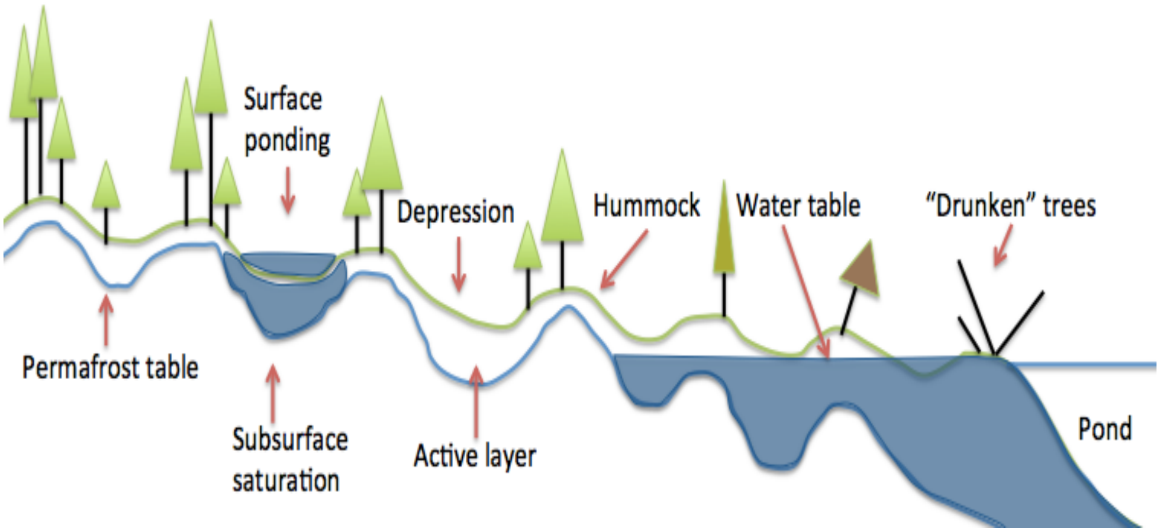


Figure 1.2: Representation of the Airport site physical setting including variable surface microtopography sloping toward the pond, vegetation differences across the site, subsurface saturation below depressions, surface ponding within depressions, and a highly variable frost table. A drunken forest where saturation has caused tree death is also shown, and represents the transition zone between the peat plateau and the pond.

The thawing of permafrost plateaus often occurs horizontally along their edges, resulting in ground surface subsidence, causing the development of a "drunken forest" or trees that have become waterlogged and died (Williams, 2012; Baltzer et al., 2014). This is the case along the southern edge of the Airport site, where the peatland meets a saturated permafrost free bog encircling a small pond (Figure 1.2, Figure 1.3). Along this juncture, the plateau has been thermally impacted by elevated water levels seeping into the peat, potentially as a result of beavers damning a nearby stream, causing gradual subsidence and waterlogging, resulting in tree death.

Figure 1.3: Top image: transition zone between the subsided peat plateau and the bog encircling the pond. A drunken forest is observed, along with surface ponding and a shift in vegetation species. Bottom image: Transect A near the degraded plateau – bog transition zone. Dead trees are observed at the pond edge.

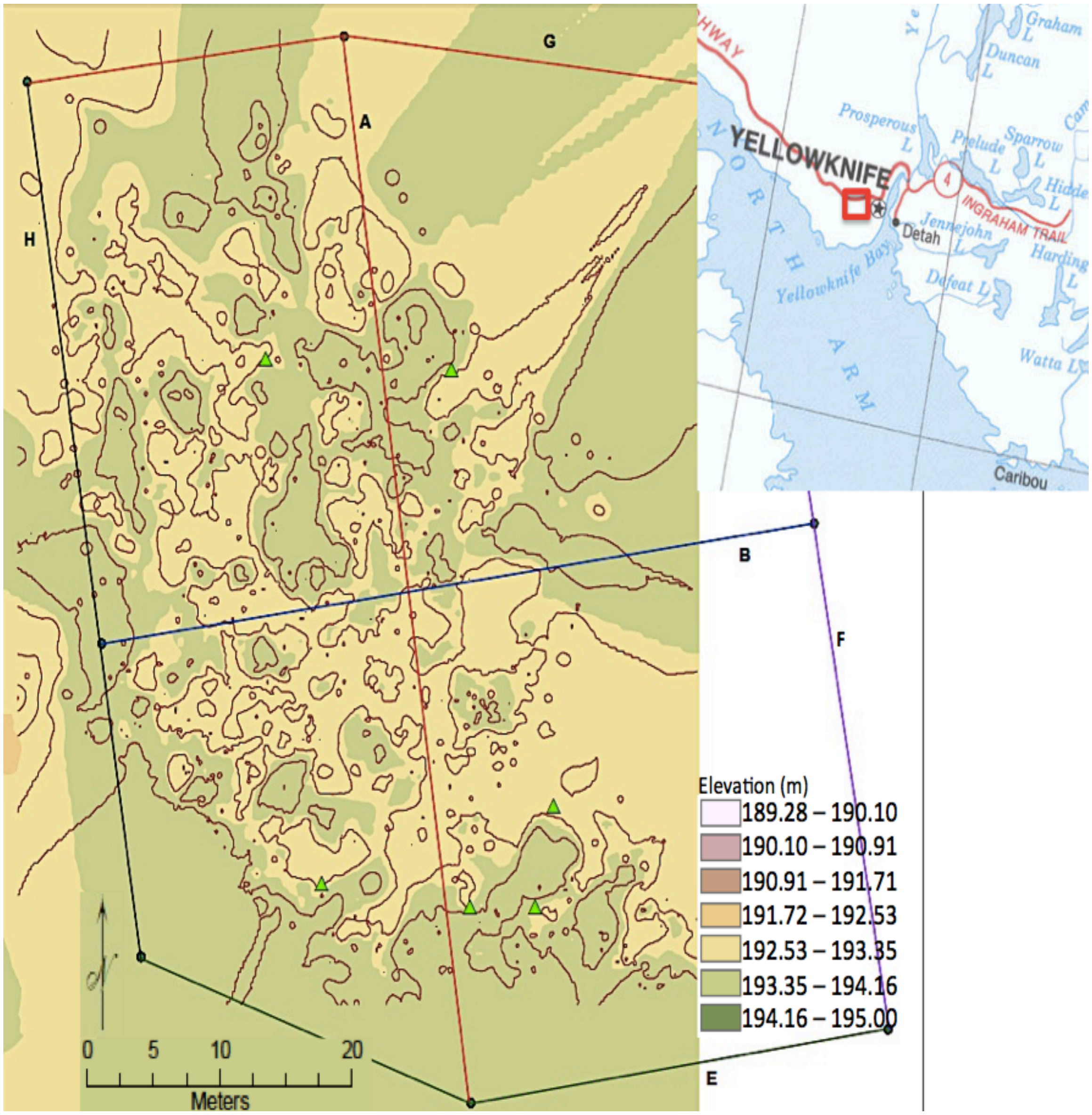


Figure 1.4: Topographic map of the Airport site with superimposed transect locations created using data collected from a Leica differential GPS survey.

1.2.2 Pontoon Lake

The site named 'Pontoon Lake' (62°33 N, 114°00 W) is a peatland environment located ~ 28 km northeast of Yellowknife on an unnamed lake ~ 1 km^2 adjacent and northeast of Pontoon Lake. The northern end of the site is bordered by the Ingraham Trail, a highway connecting Yellowknife with the ice roads leading to the diamond mines to the northeast. Separating the road from the site is a Precambrian bedrock outcrop, sloping downward ~ 6 m from the road into a dense black spruce (*Picea mariana*) forest. The canopy thins and becomes open towards the middle of the site, before developing a medium canopy cover along the southern edge of the peatland (Figure 1.5), which borders the unnamed lake. The site also supports the widespread growth of lichen (*Cladina* spp. and *Cladonia* spp.), particularly *Cladonia stellaris*, Labrador tea (*Ledum groenlandicum*), cloudberry (*Rubus chamaemorus*), crowberry (*Empetrum nigrum*), mosses (*Sphagnum* spp.), Tamarack (*Larix laricina*) and cotton grass (*Eriophorum*). The dense and medium tree canopy on the northern and southern end of the site, respectively, ranges in height from 3 m – 5 m, while the mostly open canopy in the middle of the site ranges from 0.5 m – 1.5 m in height.

The microtopographical structure of the peatland is similar in places to the hummocky terrain at the Airport site. The northern end of the site near the road is relatively flat, with small (0.25 m^2) broadly spaced hummocks ~ 0.20 m in height. A slight downward slope leads to the bowl-shaped mid-section of the peatland, which sits ~1 m below the north and south ends of the site. Large (> 0.75 m^2) hummocks rising up to 1.25 m in height alternate with large depressions with surface areas up

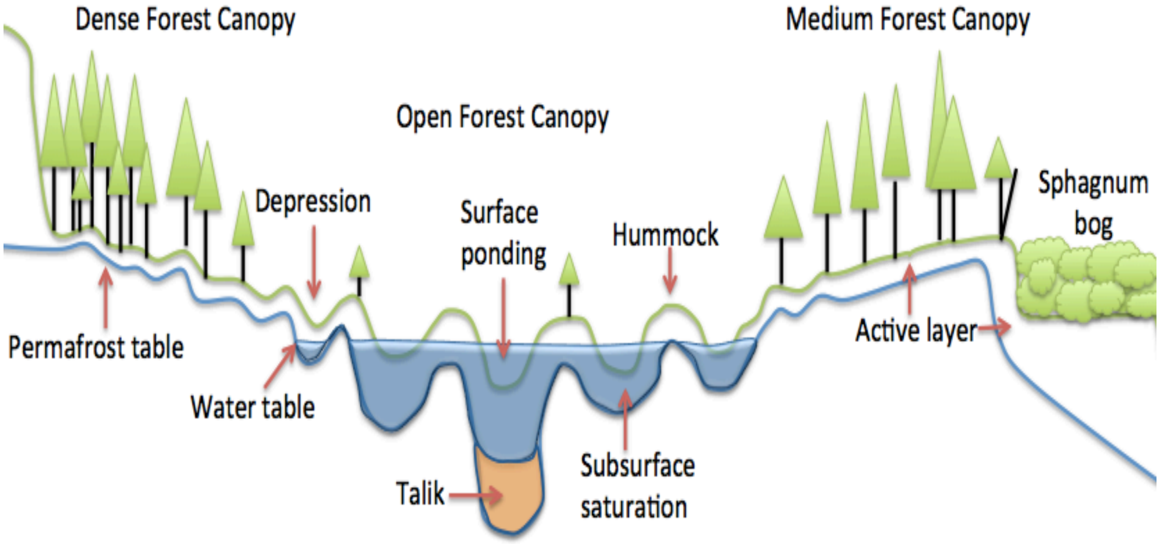


Figure 1.5: Schematic detailing the bowl shaped structure of the Pontoon Lake site. Variable surface topography is also depicted, from the steep slope adjacent to the dense forest canopy, to the hummocky terrain of the peatland, to the sphagnum bog bordering the Pond and the 'unnamed' Lake. Surface and subsurface saturation are also represented, in addition to talik formation beneath saturated depressions. Canopy cover varies across the site, with an open canopy in the middle and a more dense canopy on either side. Frost table remains relatively stable, except for the middle of the site where water accumulates.

to 2 m^2. The largest depression may be considered as a very small pond with an area of ~ 8 m^2. It was inundated with water for the entire summer, although the ponded area decreased as the summer progressed. The southern end of the site is elevated ~ 1 m above the mid-section of the peatland. It is mostly flat with a medium forest cover. The very southern edge of the peat plateau sits ~ 1 m above a sphagnum moss bog, which was saturated for much of the summer months. There is no evidence of bog water seeping into the peatland and thus degrading the plateau edge, as the plateau frost table remained stable throughout the summer (Figure 1.5).

Degradation at the site is prominent in the mid-section, where the open forest canopy allows intense solar radiation penetration and its bowl-shaped structure encourages water to accumulate, creating optimal conditions for microbial activity. Minor disturbances were also observed in the mid-section of the site from a frequently used all terrain vehicle pathway, which compressed the peat in some areas, potentially contributing to accelerated active layer thaw. Where water accumulated in large depressions, the active layer thawed quickly and taliks were observed using the active layer probe (Figure 1.5). Where a canopy cover exists, the permafrost table remains stable and degradation was not observed.

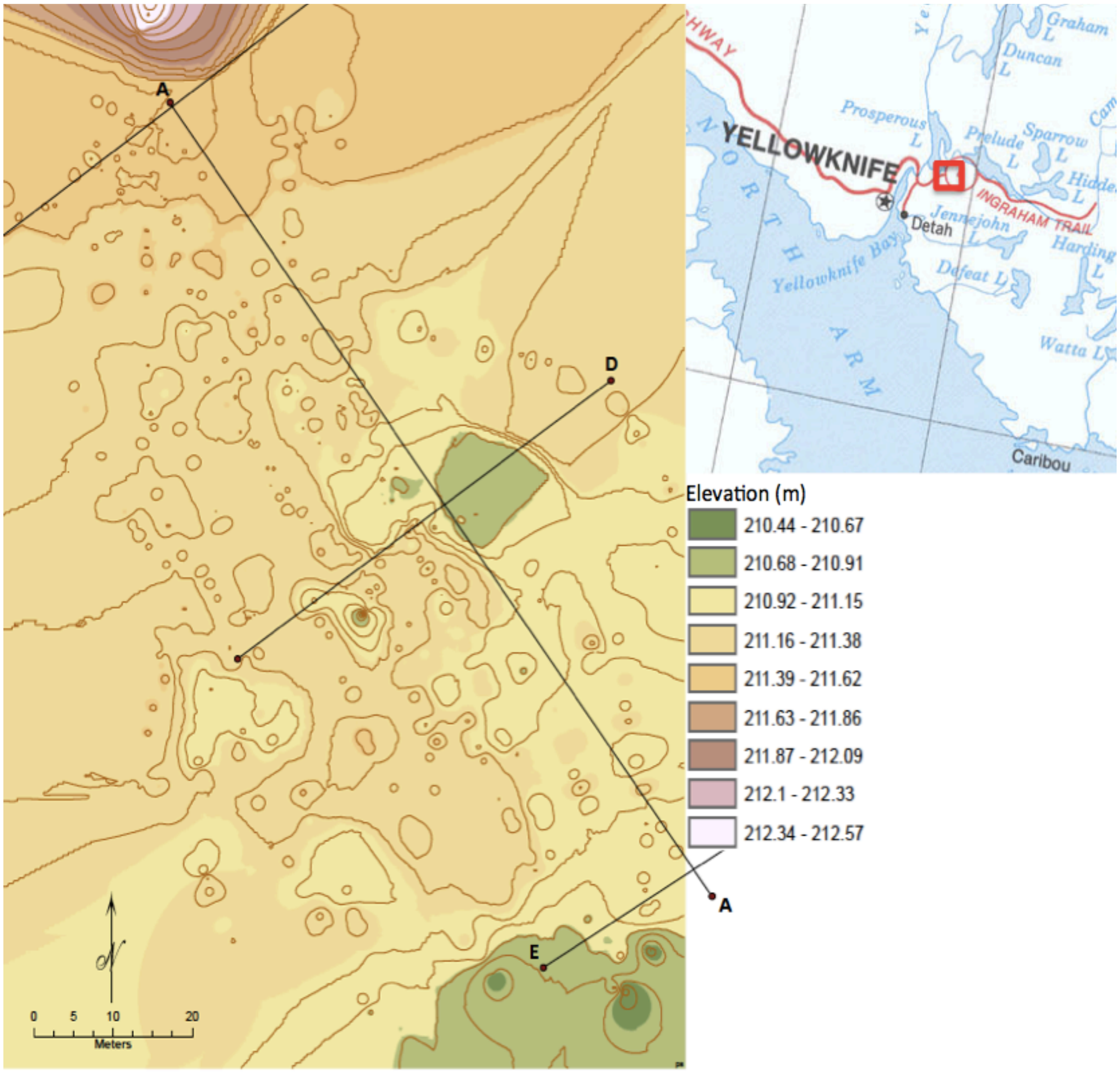


Figure 1.6: Topographic map of the Pontoon Lake site with superimposed transect locations created using data collected from a Leica differential GPS survey.

1.3 Thesis Outline

The overall objective of this thesis is to assess the transitioning of two peatland sites using a space-for-time approach to determine the potential physical changes that may occur given predicted climate change. Additionally, the study aims to quantify the current DOC stocks within each peatland, and characterize the C composition over time and space in order to determine its quality and lability. A laboratory core experiment was conducted to quantify the relative contributions of DOC from hummocks to depressions and determine how the export and quality of DOC may be influenced by air temperature and precipitation input. These broad objectives will be explored through four chapters.

The first chapter provides an introduction to the key drivers behind the physical landscape degradation observed in many peatlands across the Canadian subarctic. By focusing on the climate and microtopographical structure of the peatland, the complex positive feedbacks associated with permafrost thaw are explored. Additionally, an introduction to dissolved organic matter (DOM) and dissolved organic carbon (DOC) is presented, focusing on definitions and environmental significance. The following chapters will build upon this background information and delve further into the data collected from both research sites, as well as the laboratory core experiment. A description of each study site is also presented, outlining the defining characteristics of each research site.

The second chapter focuses on the physical changes of the two peatland sites that were observed over the course of 2012-2013. Here, field measurements of snow, frost table position, ground temperature, soil moisture, ground penetrating radar (GPR) surveying, and litter decomposition will be presented and analyzed to determine how these peatlands may transition under a changing climate. A gradation of change within each peatland will be identified, with healthy, stable areas representing a natural equilibrium state and heavily degraded areas representing the future vision of these peatlands under changing climate conditions.

The third chapter uses the Liquid Chromatography – Organic Carbon Detection method to analyze the composition of DOM from piezometers at both field sites. From this, inferences can be made about which components of DOM are preferentially consumed by microbes and determine changes to the DOM composition as microbial degradation and C production persists over time. Coupled with DOC concentration data, it is possible to identify where large accumulations of C have occurred within the research sites, and determine its potential for export based on the site hydrology, as well as the C quality and lability characteristics.

Finally, the fourth chapter presents absorbance scans and LC-OCD data collected from a laboratory core experiment conducted on two peat monoliths representing a hummock and a depression. These prominent microtopographical features of peatlands in the Canadian subarctic are often in the same immediate proximity, however because they physically behave quite differently, their chemical response to changing climatic conditions must be quantified. Here, differences in DOM composition between the hummock core and the depression core will be evaluated while simultaneously altering the hydrological and thermal conditions of the cores. Using the Yellowknife climate record (1945 – 2013) of air temperature and precipitation, the changing climate conditions over the course of the experiment will simulate the average climatic conditions experienced each month of the year at the field sites. DOM composition and DOC concentration data will be compared to the climate conditions of the cores at the time of sampling in an effort to determine the effects of changing thermal and hydrological conditions on the quality (lability) and export of DOM from peat.

References

Aukes, P. 2012. *Use of liquid chromatography – organic carbon detection to characterize dissolved organic matter from a variety of environments*. Unpublished master's thesis, Waterloo University, Waterloo, Canada.

Baltzer, J., Veness, T., Chasmer, L. E., Sniderhan, A. E., Quinton, W. L. 2014. Forests on thawing permafrost: fragmentation, edge effects, and net forest loss. *Global Change Biology.* 20, 824-834.

Beilman, D. W., Robinson, S. D. 2003. *Peatland permafrost thaw and landform type along a climatic gradient.* Proceedings of the 8th International Conference on Permafrost. Zurich, Switzerland, July, 2003. Vol 1. A.A, pp. 61-65. Balkema Publishers, Lisse, the Netherlands.

Blodau, C., Basiliko, N., Moore, T. R. 2004. Carbon turnover in peatland mesocosms exposed to different water table levels. *Biogeochemistry.* 67, 331-351.

DeConto, R. M., Galeotti, S., Pagani, M., Tracy, D., Schaefer, K., Zhang, T., Pollard, D., Beerling, D. J. 2012. Past extreme warming events linked to massive carbon release from thawing permafrost. *Nature.* 484, 87-92.

Evans, C.D., Monteith, D.T., Cooper, D.M. 2005. Long-term increases in surface water dissolved organic carbon: Observations, possible causes and environmental impacts. *Environmental Pollution.* 137, 55-71.

Fenner, N., 2002. *The effects of climate change on dissolved organic carbon release from peatlands.* PhD Thesis. University of Wales, Bangor.

Gorham, E. 1991. Northern peatlands: Role in the carbon cycle and probable responses to climatic warming. *Ecological Applications.* 1, 182-195.

Guan, X.J., Spence, C., Westbrook, C.J. (2010). Shallow soil moisture – ground thaw interactions and controls – Part 2: Influences of water and energy fluxes. *Hydrology and Earth System Sciences.* 14, 1387-1400.

IPCC, 2014: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 688 pp.

Johannessen, O. M., Bengtsson, L., Miles, M. W., Muzmina, S. I., Semenov, V. A., Alekseev, G. V., Nagurnyi, A. P., Zakharov, V. F., Bobylev, L. P., Pettersson, L. H., Hasselmann, K., Cattle, H. P. 2004. Arctic climate change: observed and modelled temperature and sea-ice variability. *Tellus Series A: Dynamic Meteorology and Oceanography.* 56, 328-341.

Laiho, R. 2006. Decomposition in peatlands: Reconciling seemingly contrasting results on the impacts of lowered water levels. *Soil Biology & Biochemistry.* 38, 2011-2024.

Laudon, H., Tetzlaff, D., Soulsby, C., Carey, S., Siebert, J., Buttle, J., Shanley, J., McDonnell, J. J., McGuire, K. 2013. Change in winter climate will affect dissolved organic carbon and water fluxes in mid-to-high latitude catchments. *Hydrological Processes.* 27, 700-709.

Lyon, S. W., Morth, M., Humborg, C., Giesler, R., Destouni, G. 2010. The relationship between subsurface hydrology and dissolved carbon fluxes for a sub-arctic catchment. *Hydrology and Earth System Sciences.* 14, 941-950.

Marhaba, T.F., Van, D. 2000. The variation of mass and disinfection by-product formation potential of dissolved organic matter fractions along a conventional surface water treatment plant. *Journal of Hazardous Materials.* 74, 133-147.

Meteorological Service of Canada (MSC). 2014. National climate data archive of Canada, Environment Canada: Dorval, Quebec.

Moore, T.R., Basiliko, N. 2006. Decomposition in Boreal Peatlands, in *Boreal Peatland Ecosystems.* 125-143. Berlin, Germany. Springer.

Moore, T. R., Dalva, M. 2001. Some controls on the release of dissolved organic carbon by plant tissues and soils. *Soil Science.* 166, 38-47.

Oke, T. R. 1978. Boundary Layer Climates. Routledge, Cambridge, p. 435.

Quinton, W. L., Baltzer, J. L. 2012. The active layer hydrology of a peat plateau with thawing permafrost (Scotty Creek, Canada). *Hydrogeology Journal*. 21, 201-220.

Quinton, W. L., Marsh, P. 1999. A conceptual framework for runoff generation in a permafrost environment. *Hydrological Processes.* 13, 2563-2581.

Reynolds, B., Fenner, N. 2001. Export of organic carbon from peat soils. *Nature.* 412, 785.

Schiff, S., Aravena, R., Mewhinney, E., Elgood, R., Warner, B., Dillon, P., Trumbore, S. 1998. Precambrian Shield wetlands: Hydrologic control of the sources and export of dissolved organic matter. *Climatic Change.* 40, 167-188.

Schindler, D.W., Curtis, P.J., Parker, B.R., Stainton, M.P. 1996. Consequences of climate warming and lake acidification for UV-B penetration in North American boreal lakes. *Nature*. 379, 705-708.

Schuur, E. A. G., McGuire, A. D., Schadel, C., Grosse, G., Harden, J. W., Hayes, D. J., Hugelius, G., Koven, C. D., Kuhry, P., Lawrence, D. M., Natali, S. M., Olefeldt, D., Romanovsky, V. E., Schaefer, K., Turetsky, M. R., Treat, C. C., Vonk, J. E. 2015. Climate change and the permafrost carbon feedback. *Nature*. 520, 171-179.

Spence, C. 2006. Hydrological processes and streamflow in a lake dominated watercourse. *Hydrological Processes.* 20, 3665-3681.

Spence, C., Kokelj, S. V., Ehsanzadeh, E. 2011. *Precipitation trends contribute to streamflow regime shifts in northern Canada.* Proceedings of symposium H02 during the International Union of Geodesy and Geophysics 2011 conference, Melbourne, Australia, July, 2011. 346, 3-8.

Williams, T. J. 2012. *Recovery of linear disturbances in a discontinuous permafrost peatland environment.* Unpublished master's thesis, Wilfrid Laurier University, Waterloo, Canada.

Wright, N., Hayashi, M., Quinton, W.L. (2009). Spatial and temporal variations in active layer thawing and their implication on runoff generation in peat-covered permafrost terrain. *Water Resources Research.* 45, WO5451.

Chapter 2

Using Field Observations to Determine the Physical Drivers Behind Peat Plateaux Degradation and Permafrost Loss

2.1 Introduction

Peat systems are an integral and prominent biological component of northern boreal ecosystems. These systems have developed over lengthy time periods in a wide range of subarctic landscapes where topographical structure and surficial geology offer usually non-limiting water supply for peat growth. The combination of low mean annual air and ground temperatures result in slow decomposition rates which, over centuries, allow the build-up of an insulating organic layer, allowing the preservation of permafrost in this southern zone of discontinuous permafrost. The upper structure of the subsurface peat, referred to as the active layer, thaws and freezes in accordance with seasonal heating and cooling, and usually consists of moderately decomposed remains of mosses, shrubs, roots, and wood (Zoltai, 1972). Aggradation of permafrost is encouraged by a feedback whereby a shallow active layer reduces moisture storage capacity in the peat, thereby reducing downward heat transfer and promoting a continuously cold subsurface (Woo & Young, 2006). The majority of biological and hydrologic activity takes place in the active layer; the porous, less decomposed surface layer that represents the transition zone from living organic material to the deeper, saturated and greatly humified peat deposits of the lower subsurface (Nungesser, 2003).

The physical characteristics of peat, notably its water retention capacity, thermal and hydrologic conductivity and its porosity (> 75%) (Guan et al., 2010) combine with the physiographic nature of the landscape to produce a variety of forms broadly classified at wetlands (bogs, fens) or periglacial (palsas, peat plateaux) landforms. Peat plateaux are typically elevated approximately 1 m above the surrounding wetlands and are subject to elevation changes as peat accumulates over long periods of time (Zoltai, 1972). Prominent surficial features of many peat plateaux, hummocks are low mounds rising from the surface alternating with lower, flatter depressions and inter-hummock flowpathways (Quinton & Marsh, 1999). This kind of patterned ground develops in part from differences in decomposition rates, with hummock plant species decomposing more slowly than depression species, causing faster peat accumulation on hummocks than in depressions (Johnson et al., 1990; Johnson & Damman, 1991; Nungesser, 2003; Moore et al., 2007). As a result of differential decomposition rates between the acrotelm and the catotelm, hydraulic conductivity in depressions changes abruptly with depth, retaining and reinforcing water content differences within these microtopographical features through wetter surface conditions and prolonged saturation of the subsurface (Nungesser, 2003; Quinton & Marsh, 1999).

Acting as catchments for the surrounding hummocks, ice-rich depressions become saturated following the spring freshet. As surface pools form, heat is conducted vertically and laterally through the peat, aided by the elevated thermal conductivity in the presence of water (Oke, 1978). Depressions have become “hot spots” within peat plateaux for accelerated permafrost loss and degradation, with increasing evidence mounting supporting a strong link between soil moisture and ground thaw (Wright et al., 2009; Guan et al., 2010; Williams, 2012). Because of the heat retention properties of water, persistent saturation or near-saturation throughout the thaw season creates warm conditions within depressions, prolonging the freeze-back period and potentially elevating peat decomposition rates (Schuur et al., 2015). An early snowfall in the fall may then insulate the ground, controlling the amount of winter freezing by preventing heat loss and potentially aiding in the formation of supra-permafrost taliks. These taliks, a layer of perennially unfrozen peat existing between the permafrost table and the seasonally frozen active layer, allow liquid water to exist year-round within the peat, acting as a heat source for further active layer thickening and permafrost loss (Williams, 2012).

Ground surface elevation changes can be a large contributor in determining soil wetness, which invariably influences the ground thermal regime. Guan *et* al. (2010) found that at a peatland site in the Baker Creek Watershed outside of Yellowknife, NT, the locations of surface ponding following the spring freshet were the same locations with the deepest active layers at the end of the thaw season. Similarly, Wright *et* al. (2009) studied active layer development on the peat plateaus of Scotty Creek and found that the spatial variability of active layer thaw was strongly correlated to soil moisture distribution. A positive feedback relationship was identified whereby preferential thaw occurred beneath wet depressions, inducing a hydraulic gradient toward the depression, increasing moisture content and promoting further thaw. This process has the potential to promote areal growth of depressions and the degradation of peat plateau edges bordering with wetlands, further degrading the permafrost below (Baltzer et al., 2014). The implications of the positive feedback induced by elevated soil moisture in the peat extend beyond the physical impacts of permafrost thaw and landscape degradation, Water moving through the subsurface flowpathways of the peat may undergo changes before potentially discharging into surface water systems. Of particular interest is the potential for large stocks of carbon (C), accumulated within the catotelm over centuries, to become environmentally available following permafrost thaw. As these landscapes continue to transition under warming temperatures and increased precipitation inputs (IPCC, 2014; Environment Canada, 2014), particularly in the fall period (Spence et al., 2011), the geochemical functioning of these ecosystems will also be altered.

Initiated by microtopographical differences in surface elevation, increased near surface soil moisture may result in dramatic morphological changes occurring within depressions, which ultimately affect the adjacent surrounding hummocks as they too begin to degrade. These changes are conducive to a prolonged freeze-back period, potentially encouraging active layer thickening, supra-permafrost talik formation, and vegetation loss thereby increasing insolation at the ground surface. In addition, as a result of prolonged active layer warming, the probability of increased microbial activity and thus decomposition rates in peat is elevated during the winter period, when microbial degradation is usually considered relatively insignificant. Degradation such as this is easily recognized at both the Airport and

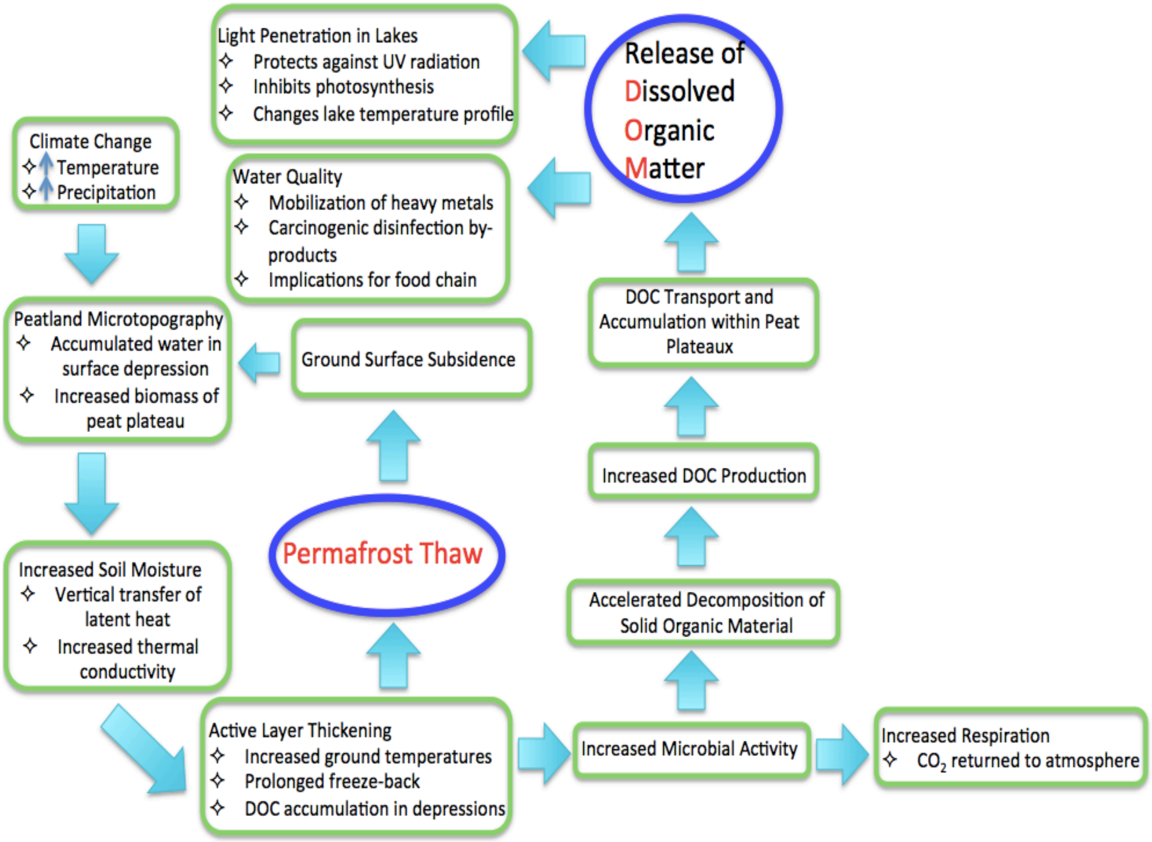


Figure 2.1: Conceptual model outlining the primary processes governing changes to the physical and geochemical characteristics of the Airport and Pontoon Lake research sites. Rising temperatures and increased precipitation begin a positive feedback for water accumulation, altering the ground thermal regime and thickening the active layer. Permafrost regeneration is impeded by the elevated volumetric water content of the peat, resulting in ground surface subsidence and the export of dissolved organic matter (DOM) into surface water bodies.

Pontoon Lake sites, as areas where water has seasonally pooled experience prolonged warm conditions and subsurface saturation, preventing vegetation growth, and ultimately resulting in the transitioning of the affected peat into an inundated bog-like environment. The complex nature of the interactions involving climate, the physical structure, as well as the biological and hydrological nature of the peatland are ultimately what will determine whether a system degrades or not, and are summarized in Figure 2.1.

2.2 Objectives

The overall goal of this chapter will be to evaluate peatland degradation on various spatial scales, from large, site-wide observations, down to a small, microtopographical scale focused on individual hummocks and depressions within the primary Airport site and the secondary Pontoon Lake site. Using extensive field measurements, this goal will be achieved by meeting the following specific objectives:

1) to observe the spatial and temporal progression of climate driven landscape change with respect to the hydrological and active layer characteristics of two peatland sites by measuring seasonal active layer thaw and soil moisture conditions along a series of pre-defined transects;
2) to develop an understanding of how peatland degradation occurs over time by evaluating hummocks and depressions across the sites with different microtopographical structure and size to determine whether they are degrading or in a steady-state, and to use a space-for-time approach to determine if degraded features are the future vision for presently non-degraded areas.

2.3 Methods

2.3.1 TDR Probes and Air Temperature Sensors

Decagon 5TM soil moisture and soil temperature probes were installed at the Airport site and Pontoon Lake on October 4, 2012 and October 6, 2012, respectively. Although not calibrated, literature suggests that the probes record VWC within 25% of actual VWC (Spence et al., 2010). The sampling site locations were determined to represent the larger research site based on characteristics of microtopography, canopy cover, vegetation, and where ponded water has degraded the peat plateau. An air temperature and relative humidity sensor was also installed at each research site. Both the probes and sensors immediately began logging soil temperature (°C), volumetric soil moisture (m^3/m^3), air temperature (°C), and relative humidity (%) on an hourly time step recorded using Decagon EM50 Digital/Analog data loggers. Data logging site locations can be observed on the site map, and a complete list of probe depths at each site is summarized in table 2.1.

In order to quantify the differences in ground thermal and moisture regimes across the research site, probes were installed in both the degraded and non degraded areas of the site (Figure 2.2). At each data-logging site, a pit was dug (dimensions roughly 40 cm x 30 cm x 60 cm) where probes were inserted into the face of the pit. The probe closest to the surface was kept at a constant depth of 10 cm for all sites. Probes were inserted into the peat by first cutting a 2mm horizontal slit in the peat wall using a knife with a 6 cm blade at the 10 cm depth. Subsequent probe installation at each pit was determined upon visual inspection of changing peat characteristics with depth, paying close attention to where changes in color or peat texture occurred, indicating visible stages of peat decomposition. Once inserted, probe wires were taped together using duct tape, the hole was backfilled with the excavated peat, and the wires were buried just beneath the surface. Data loggers were secured to wooden dowels above the peat surface using zip-ties, and probes were connected to appropriate ports on the data loggers. The wires visible above the surface were encased in PVC tubing to avoid animal disturbance, and secured to the wooden dowel using duct tape. Air temperature and relative humidity sensors were secured onto the tops of the same wooden dowel as the data loggers at a height of ~ 60 cm from the ground surface using zip-ties.

Table 2.1: TDR probe depth (cm), air temperature and relative humidity (RH) sensors associated with each logging station.

Site	Probe #	Probe Depth (cm)
Logsite1 – Airport Site	1	N/A – Air temp/RH
	2	10
	3	20
	4	30
	5	41
Logsite2 – Airport Site	1	N/A
	2	10
	3	25
	4	40
	5	54
Logsite3 – Pontoon Lake	1	N/A – Air temp/RH
	2	10
	3	25
	4	45
	5	55
Logsite4 – Pontoon Lake	1	10
	2	25
	3	40
	4	50
	5	25 (placed in adjacent hummock)
Logsite5 – Airport Site	1	7.5
	2	22
Logsite6 – Pontoon Lake	1	9
	2	23

2.3.2 Ground Heat Flux (Q_g)

The ground heat flux (Q_g) was calculated for the Airport and Pontoon Lake sites to quantify heat loss/gain differences between degraded and non-degraded portions of each site. Q_g was calculated using the calorific method described in Petrone et al. (2000). Specifically, soil moisture and ground temperature data from

Log1, Log2, Log3, and Log4 were used to calculate Q_g on a half hourly basis, which is expressed by equation 2.1 below

$$Q_g = C_S \frac{\partial T}{\partial t} \partial z \quad [\mathrm{W\ m^{-2}}]$$ **Equation 2.1**

where C_S (MJ K^{-1} m^{-3}) is the depth integrated volumetric heat capacity of the peat, T (K) is the temperature of the substrate at depth z (m) and time t (s).

2.3.3 Transects and Active Layer Probing

During initial site instrumentation in October 2012, a series of transects were created at each research site to provide temporally and spatially comparable data representative of environmental conditions within the plateaux. The creation of transects also assists in classifying the landscape into areas of disturbed and likely degrading peat, and areas of stable, non-degrading peat. For instance, transect B (Figure 2.2) at the Airport site loosely represents the transition zone between the non-degrading north end of the site, and the degrading south end. As such, transects enable us to observe the temporal change occurring among different areas of the peat plateaux. The consistency and repetitive nature of transect probing also allowed comparison of physical parameters such as surface terrain microtopography with frost table depth, and observe how these parameters interact and transform as the thaw season progresses.

Upon visual inspection of each site, transects were designed to cover the range of microtopographical variability, canopy cover, and potential permafrost degradation possible at each of the sites. Two transects were created at the Airport site and labeled A and B (Figure 2.2). Transect A is ~ 94 m in length and runs north-south from non-degraded to degraded peat. Transect B is ~ 56 m and runs west-east.

At Pontoon Lake, two transects were created, labeled A and B, and are ~ 128 m and 98 m, respectively (Figure 2.3). These transects are oriented north-south from a non-degraded forested area, to an open (*i.e.* treeless) and degraded area, to a sparsely forested non-degraded area of the site. These transects were the studies primary transects and were probed on a weekly basis from June – September 2013.

In June 2013, four more transects were created at the Airport site. These transects were designed to act as secondary grid transects and were probed on a bi-weekly basis to assist in accounting for variability within the site. Due to similarities between transect A and B at Pontoon Lake, transect B was eliminated and three more transects were added perpendicular to the primary transect A.

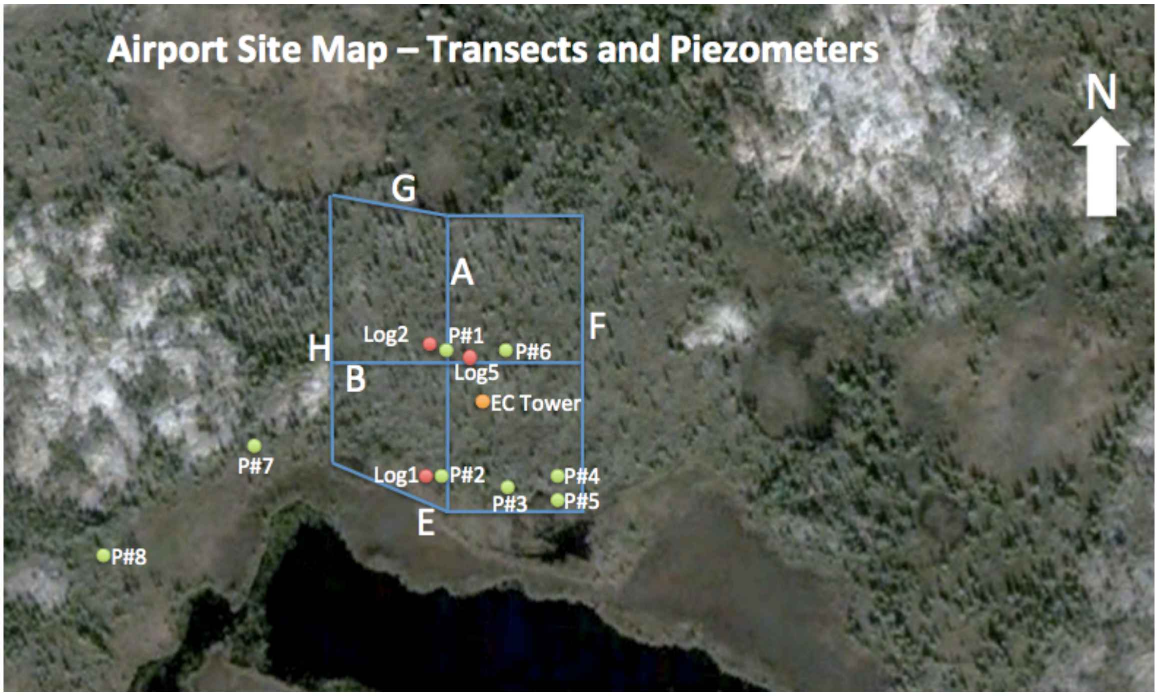


Figure 2.2: Relative locations of the Airport site primary and secondary transects, piezometers, data logging sites, and the eddy covariance and meteorological station (EC tower). The main road is directly north of transect G, while the bog encircling the pond is south of transect E.

The depth of the active layer is a baseline parameter used to spatially characterize the thermal responses of heat input to the peat. Probing the peat plateau along the same transects on a consistent basis makes it possible to see how microtopographical differences in surface terrain play a role in controlling active layer growth response. Additionally, probing provided an indication of where preferential thawing is taking place. Active layer probing commenced in early October 2012 following primary transect formation, while the active layer depth was near its maximum. During the 2013 field season, probing began on June 3 approximately three weeks after the spring freshet, and ended on October 19.

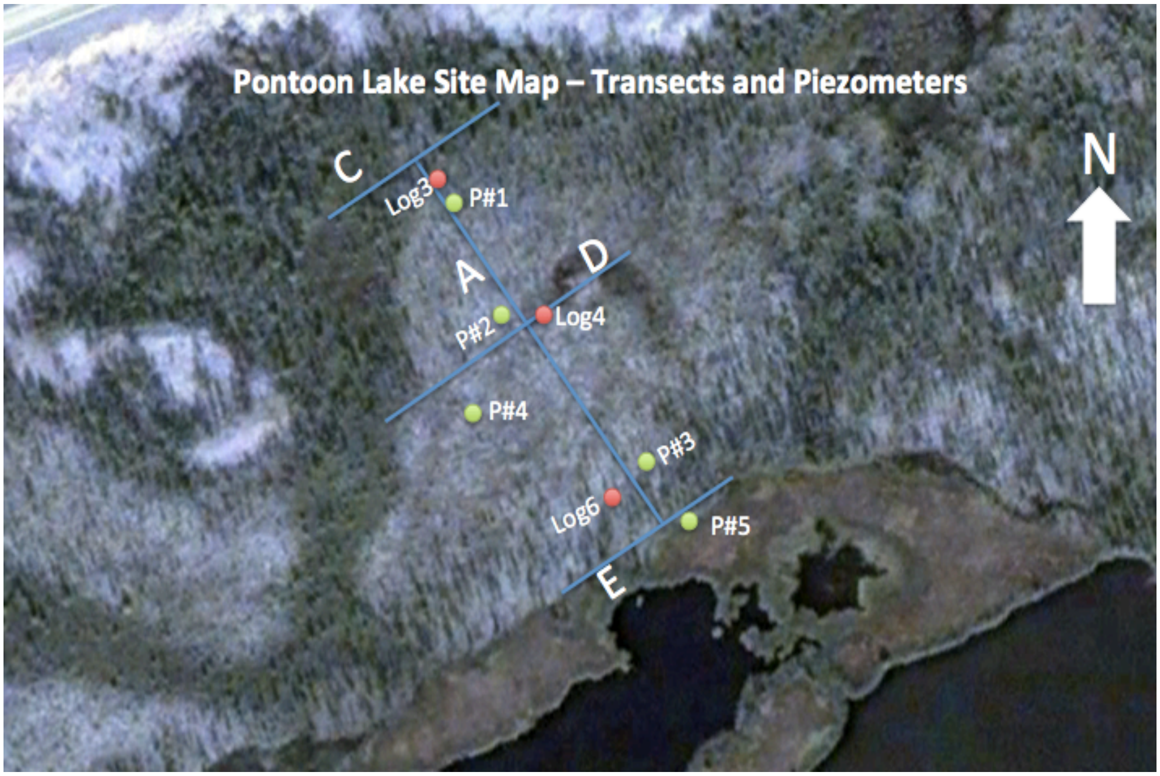


Figure 2.3: Relative locations of the Pontoon Lake primary and secondary transects, piezometers, and data logging sites. The main road is located north of transect C, while the lake is located south of transect E.

A 1.5-meter, stainless steel graduated rod with a tapered end and 1-cm diameter was used to determine thaw depth. Primary transects were probed on a weekly basis however individual points along each transect were not specifically probed on every occasion, though individual hummocks and depressions were probed on a continuous basis throughout the thaw season (with exact location varying slightly (+/- 20 cm – 1 m) each time). Although probing the same feature (*i.e.* hummock or depression) consistently, this approach was taken to avoid compaction of the peat that would have occurred had there been individual repetitive probing locations. Additionally, this approach allowed us to monitor the evolution of the active layer of the entire site, and not only certain specified points along each transect, providing a broad overview of change. Data recorded while probing each point included documenting immediate surrounding vegetation, ground temperature (°C) at the frost table measured using a stainless steel Thermo Scientific ground temperature probe, and UTM reference coordinates (+/- 4 m).

2.3.4 Snow Surveys

At the Airport site and Pontoon Lake, snow depth (cm, using a metal ruler at 30 points within 5 m^2 of the density sample), and density (cm^3/ cm^3, filling a 250 cm^3 cylindrical tube) were measured and snow water equivalent (SWE) was calculated (cm, depth x density) during the 2012/2013 and 2013/2014 winter seasons, beginning on January 19th and December 13th and ending on April 6th and March 27th, respectively. At each site, due to vertical differences in snowpack density attributed to differences in snowfall characteristics at the time of deposition and formation of depth hoar, two samples (upper half/lower half) were taken and the average density utilized for determining SWE. Snow survey sites were not transect specific, rather they were chosen on each occasion to represent site characteristics such as canopy cover and microtopographical variations.

2.3.5 GPR Surveys

A ground penetrating radar (GPR) survey was used at each site to image the subsurface and corroborate the results of active layer probing. A MALA GS GPR system with a 250 MHz shielded antenna designed to penetrate 4-5 m was used to conduct surveys on April 6 – 7, 2013 during maximum freeze, and on October 18, 2013 during maximum thaw, at both Airport and Pontoon lake sites. The surveys were carried out along the primary and secondary grid transects of both sites, producing a total of 6 transects at the Airport site and 4 transects at the Pontoon lake site.

In April, The GPR unit was pulled over the snowpack, which had a mean depth of 44 cm at the Airport site and 40 cm at Pontoon Lake. Pathways along the transects were first created in a grid formation by walking through and compressing the snowpack ensuring a smooth path for the GPR unit. In October, when active layer progression was most pronounced, large woody debris was removed from each transect, and the GPR unit was pulled over the peat surface. UTM coordinates were recorded at 10 m intervals along each transect.

2.3.6 Litter-bags

Peatlands are characterized by substantial accumulation of organic matter, resulting in significant carbon accumulation. Carbon dioxide, methane gas, dissolved organic carbon and solid C are the products of plant tissue and organic matter decomposition. Thus, quantifying the rate of decomposition and the controls on these rates will enable some predictive capability as to how peatland systems may respond to a warmer and wetter climate in the future, and how this may affect C stores and losses to surface waters. To achieve this, a litter-bag study was conducted at each site similar to that of Moore et al. (2007) and Karberg et al. (2008).

Litter-bags were installed at both the Airport and Pontoon Lake sites in depressions on October 6, 2013. At the Airport site, the litterbags were installed in a depression within the degraded portion of the site adjacent to Log1. At Pontoon Lake, litter-bags were installed in a depression in an open canopy area adjacent to Log4 (Figure 2.3). Both sites represent warmer and wetter conditions than surrounding hummocks and closed canopy areas. The depths of the litter-bags at each site can be seen in Table 2.2, as well as the type and mass of material encased in each bag.

Table 2.2: Litter-bag depth of installation (cm), organic contents, and weight (g) of organic matter encased within each litter-bag installed at both the Airport and Pontoon Lake sites.

Site	Depth (cm)	Material	Dry Weight (g)
Airport	10	Leaves	4.33
		Stems	1.04
		Lichen	4.93
		Labrador Tea leaves	0.76
		Fine roots	0.47
	25	Slightly decomposed sphagnum	7.0
	40	Slightly decomposed sphagnum	11.0
Pontoon Lake	10	Lichen	6.0
		Labrador Tea leaves	2.0
		Fine roots	0.5
	25	Slightly decomposed sphagnum	7.0
	40	Slightly decomposed sphagnum	11.0

Litter-bags were constructed using fiberglass mosquito netting, mesh size 1.5 x 2 mm. Bags were sewn using nylon fishing line to create bags of 20 x 15 cm. One side of the bag was left unsewn until material was encased. Recently senesced material was collected from the peat surface to a depth of 5 cm for surface litter-bags. Slightly decomposed sphagnum moss was collected from a depth of 10-15 cm for litter bags installed at 25 and 40 cm below the peat surface. All material was oven dried at 70 °C for at least 24 hours. Once dried, material was placed into bags, ensuring each bag encased > 3g of material, while not being tightly packed. Labeled plastic tags were attached to each bag using nylon fishing line of ~ 50 cm. The line was attached to the bag at one end; the tags were encased in a zip-lock bag and buried near the peat surface. Triplicate bags were created for each depth of installation, for a total of 18 bags between the Airport site and Pontoon Lake site.

Bags were installed at each site by first digging a pit ~ 60 cm in depth. Using a knife, a narrow slit was cut in the face of the pit at the appropriate depth. The slit was then made larger by cutting and removing small pieces of peat to create room for the bag. The objective was to make a small hole in the face of the peat similar to the dimensions of the bag, so that the bag may then be inserted into the pit face without contracting. Triplicate bags were installed at each depth. Bags installed at the same depth were placed side-by-side with ~ 15 cm of undisturbed peat between them. Once all bags were installed, the pit was then backfilled with its original peat, and bag tags were buried near the surface.

Litter-bags were removed from both sites on October 19, 2014 after greater than one year of incubation. All bags were stored at 4 °C for 3 weeks until analysis. The material was then removed from each bag and oven dried at 70° C for at least

24 hours. Material was then weighed separately, and mass loss per bag was determined.

2.4 Results

2.4.1 Snow Surveys

Snow surveys conducted at the Airport site during season 1 (Jan. 20 – April 7, 2013) and season 2 (Dec. 13, 2013- March 27, 2014) show an increase in average snow depth from the beginning of the season to the end. Season 1 initial measurements on Jan. 20, 2013 show a mean snow depth of 37 (σ = 5) cm, while season 2 initial measurements on Dec. 13, 2013 show a mean snow depth of 27 (σ = 4) cm. Measurements showed little difference in snow depth across the site at all measurement dates. Season 1 and season 2 snow depth peaked at the end of the annual snow year averaging 47 (σ = 4) cm and 50 (σ = 6) cm respectively. Snow densities reached 0.25 gm/cm^3 during season 1, while season 2 was similar with snow densities of 0.22 gm/cm^3 at the end of the snow season. Snowpack water equivalent (SWE) also reached its maximum during these time periods at 11.7 cm and 10.8 cm, representing 40% and 43%, respectively, of the long-term (1942-2010) mean annual precipitation received in the Yellowknife, NT region.

Like the Airport site, mean snow depth at Pontoon Lake also increased from the beginning of each season to the end. Season 1 initial measurements on Jan. 19, 2013 show a mean snow depth of 32 (σ = 4) cm, while season 2 initial measurements on December 13, 2013 show a mean snow depth of 25 (σ = 5) cm. Snow depth measurements showed little variation within the site, except on the March 7, 2013 survey where σ = 24 with a mean snow depth of 40 cm. Pontoon Lake is characterized by highly variable canopy cover within the site, and it is likely that strong winds in conjunction with this resulted in large snow depth variability. Snow depth and density reached their maximum at the end of the snow season, averaging 40 ($\sigma = 24$) cm and 49 ($\sigma = 7$) cm and 0.23 and 0.22 in season 1 and season 2, respectively. SWE also peaked during this time period at 9.37 cm in season 1 and 11 cm in season 2.

2.4.2 Active Layer Development

Differences in surface topography, topology (location in space, connectivity), and typology (vegetation, degradation of peat) resulted in considerable variation in active layer development as the thaw season progressed (Buttle, 2006). Active layer probing commenced at the Airport site on June 3, 2013 following the spring freshet. It is uncommon for peat to be saturated at the ground surface; however, surface depressions in the warmer and more degraded area of the site were commonly found with water tables at or above the ground surface. The non-degraded and colder area of the peatland, elevated ~ 1 m above the degraded portion of the site, with moderate canopy cover was generally quite dry with little to no surface ponding. Towards the middle of the site where canopy cover becomes sparse and ground temperatures warm, surface ponding was present within subsided depressions vegetated only with Sphagnum mosses. At Pontoon Lake, surface ponding was limited to the largest and most degraded depressions, located in the treeless middle area of the site.

At the beginning of the thaw season the frost depth measurements were somewhat consistent across the Airport site peatland, with mean depth differences ranging from 2-5 cm between hummocks and depressions (Table 2.3). As the thaw season progressed, the magnitude of the difference in frost table depth between hummocks and depressions became increasingly larger. When the frost table reached its maximum depth on August 21, 2013, the difference between mean hummock and mean depression frost table depth on Transect A was 44 cm, while at Transect B the difference was even larger at 76 cm. At Pontoon Lake on the same date, the difference between mean depression and mean hummock frost table depth is 39 cm on Transect A and 75 cm at Transect B (Table 2.4). These results indicate that the position of the frost table fluctuates in accordance with surface topography, although surface topography may not be the sole driver of this pattern.

The relationship between frost table depth and surface microtopography was consistent for the majority of the thaw season. The wettest areas of the site are associated with larger soil volumetric water content (VWC), leading to larger soil ice content when freeze occurs. Following the spring freshet, the wet depressions experienced a similar rate of thaw as the dry hummocks. The initial progression of the frost table at these wet sites during the early stages of thaw was unexpectedly slow, and is likely due to the relatively large amount of energy required to thaw solid ice in the peat profile. However, water drainage from hummocks to depressions is hypothesized to have increased the rate of thaw to match that of the dry hummocks as thaw continued. As the thaw season progressed, mean thaw depth of the wetter depressions quickly surpassed that of the drier hummocks (Table 2.3, Figure 2.4) due to the increase of comparatively warm liquid water content in the peat.

Table 2.3: Airport site primary transects mean frost table (FT) depth (cm), standard errors of the mean (SEM) (cm) for transects, depressions and hummocks, mean FT depth of depressions and hummocks for each probing date of the 2013 thaw season. Values indicated by * include frost table depths that exceeded the maximum frost probe measurement depth and were therefore recorded as 150 cm.

Date	Mean FT Depth (cm)	SEM (cm)	Mean Depression FT Depth (cm)	SEM (cm)	Mean Hummock FT Depth (cm)	SEM (cm)
Transect A						
June 3	25.3	1.2	23.8	1.5	26.6	1.8
June 14	27.9	1.0	30.0	1.9	26.1	1.1
June 19	32.6	1.8	35.8	3.2	29.2	1.2
July 3	36.9	1.8	37.8	2.0	36.6	2.7
July 9	44.1	1.7	47.9	1.7	39.1	2.4
July 23	58.8*	6.6*	73.9*	7.4*	43.6	2.6
July 31	74.3*	9.4*	106.7*	16.1*	46.4	2.6
August 7	76.2*	9.9*	100.7*	17.9*	48.9	3.7
August 14	87.4*	10.0*	123.4*	12.1*	51.7	3.5
August 21	91.5*	9.8*	111.0*	12.0*	67.1	10.1
October 18	87.0*	8.0*	103.9*	11.5*	64.9	8.7
Transect B						
June 3	27.8	1.3	31.3	2.2	25.9	1.1
June 14	33.6	1.8	34.6	2.0	33.3	2.4
June 19	37.9	6.0	51.2	14.6	30.3	2.1
July 3	45.7	2.3	51.0	0.8	37.8	2.1
July 9	53.1*	8.3*	61.9*	17.2*	42.4	2.5
July 23	61.7*	8.6*	83.8*	21.4*	47.3	3.0
July 31	81.9*	12.0*	112.2*	17.1*	61.0	13.1
August 7	87.8*	14.2*	117.0*	15.4*	46.8	2.8
August 14	91.8*	11.3*	119.9*	14.4*	59.0	7.6
August 21	101.9*	11.8*	127.3*	8.5*	51.3	1.3
October 18	102.8*	11.8*	129.0*	12.2*	67.8	14.2

Table 2.4: Pontoon Lake transect A and D mean frost table (FT) depth (cm), standard errors of the mean (SEM) (cm) for transects, depressions and hummocks, mean FT depth of depressions and hummocks for each probing date of the 2013 thaw season. Values indicated by * include frost table depths that exceeded the frost probe measurement depth and were therefore recorded as 150 cm.

Date	Mean FT Depth (cm)	SEM (cm)	Mean Depression FT Depth (cm)	SEM (cm)	Mean Hummock FT Depth (cm)	SEM (cm)
Transect A						
June 4	25.3	0.8	25.2	0.8	26.4	1.0
June 14	28.3	1.1	28.6	1.1	28.0	1.3
June 19	25.0	1.1	33.0	1.1	32.8	1.7
July 4	36.8	1.1	35.5	1.1	38.1	1.4
July 11	42.2	1.3	43.9	1.3	42.4	1.7
July 24	49.5	5.0	55.1	5.0	45.3	1.5
August 1	58.1*	6.8*	66.5*	6.8*	50.1	2.0
August 8	56.4*	6.3*	61.0*	6.3*	50.4	1.4
August 15	66.7*	7.3*	73.5*	7.3*	53.2	1.6
August 21	85.4*	10.2*	95.3*	10.2*	56.0	2.6
October 19	68	4.0	77.7	4.0	59.0	2.8
Transect D						
June 4	27.8	1.5	27.8	2.0	28.0	1.5
June 19	35.2	2.0	41.0	2.4	36.0	4.2
July 4	39.6	3.7	40.4	5.3	37.7	1.5
August 1	73.7*	12.4*	86.9*	21.3*	47.3	4.3
August 21	92.8*	14.4*	130.0*	18.5*	55.5	3.6
October 19	74.3*	6.4*	82.9*	11.5*	75.4	7.4

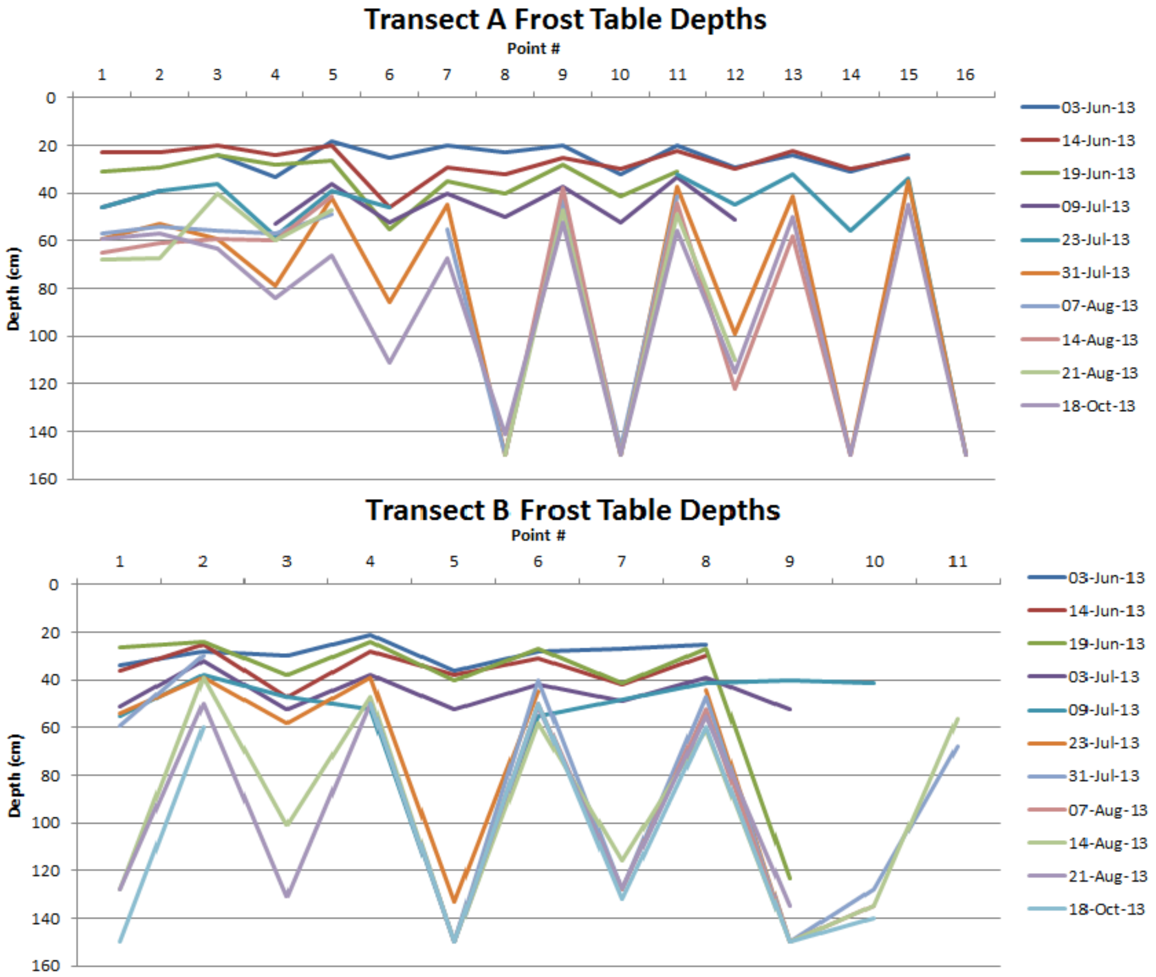


Figure 2.4: Airport site primary transects frost table depth (cm) per probing location (point #) from June 3rd – October 13th, 2013.

The increasing SEM observed over the course of the thaw season with respect to the overall mean frost table depth and the mean frost table depth of hummocks and depressions can be attributed to a large spatial variability in thaw rate at both research sites. Increases in the overall mean frost table depth SEM are due to the large disparity in frost table depth between hummocks and depressions, which became more pronounced as the thaw season progressed.

The largest increase in the SEM occurs with depressions, as these features are unstable (*i.e.* the active layer thaws deeper than the pervious year and may not freeze-back fully) and particularly influenced by the physical conditions surrounding them. Small depressions in the non-degrading portions of each site are often under a canopy cover where less moisture is present. Large depressions at each site often act as water catchments for the surrounding hummocks and are also locations of minimal canopy cover. The combination of depression size, moisture content, and canopy cover act to determine the rate and extent to which a particular depression will thaw. Furthermore, as the thaw season progressed, supra-permafrost taliks were observed beneath the seasonally frozen active layer (Figure 2.5) in locations mainly located south of transect B at the Airport site and in the mid-section of the Pontoon Lake site. These features, found exclusively beneath the largest and wettest depressions where canopy cover is minimal, failed to freeze-back fully during the previous winter, allowing liquid water to exist year-round above the permafrost table. As thaw commenced during the 2013 season, the frozen layer between the liquid water and the thawed active layer became increasingly thinner until the frost probe eventually broke through and the active layer was suddenly deeper than the 150 cm frost probe. The combination of taliks and individual depression characteristics resulted in pronounced differences in thaw depth as the summer season progressed, causing the SEM to increase over time.

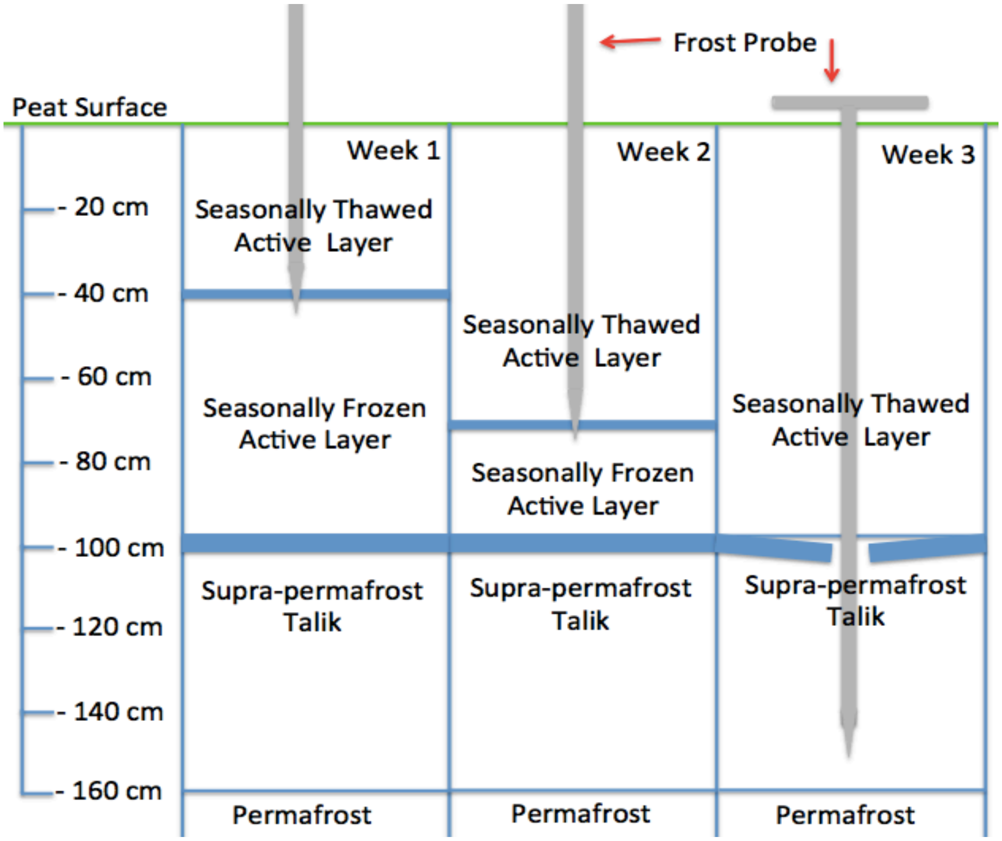


Figure 2.5: Depiction of active layer thaw observed at the Airport and Pontoon Lake sites. Week 1 and Week 2 illustrate active layer deepening above a supra-permafrost talik. Week 3 illustrates the "break through" of the frost probe when the active layer thaws to a thin frozen boundary separating the seasonally thawed ground from the perennially unfrozen supra-permafrost talik. These taliks were observed to form beneath the largest and wettest depressions where canopy cover is minimal.

Table 2.5: Description of location, vegetation cover, ground moisture and active layer conditions for each data-logging site at both the Airport and Pontoon Lake sites. Data collected at each logging site includes soil temperature and volumetric water content, while air temperature and relative humidity sensors record at Log1 and Log3 only.

Site	Description
Log1 – Airport Site	Located near subsiding degraded edge where peat plateau meets bog; was likely a hummock but has since subsided and flattened; sparse canopy cover; near/at saturation for much of the year; deep active layer
Log2 – Airport Site	Located in non-degrading area of the site on hummock; moderate canopy cover; reduced soil moisture; stable active layer, *i.e.* frost table thaws and refreezes completely to the approximate same depth year after year.
Log3 – Pontoon Lake	Located close to road in non-degraded area; full canopy

	cover; moderate soil moisture; stable active layer
Log4 – Pontoon Lake	Located in degraded middle area of site; very sparse canopy cover; depression near saturation for much of the year; deep active layer; intense solar radiation receipt; probes located in depression at 10, 25, 40, and 50 cm depth as well as in adjacent hummock at 25 cm depth

A wide range of ground moisture conditions existed at the Airport and Pontoon Lake sites, both on a larger site scale between degraded and non-degraded areas of the peatland and on a smaller scale between hummocks and depressions. The changing ground moisture conditions within the sites are a large contributor to temperature gradient changes with depth and the pattern of active layer development observed during the thaw season.

The physical characteristics that define peat include a large porosity (70-80%). Therefore, when peat is dry it is comprised of 70-80% air space, and when it is saturated this air space is replaced by water. The heat capacity of water is approximately four times greater than air and consequently peat with a large VWC will warm slowly and retain heat for longer than if it were dry. Dry peat reacts faster to changes in air temperature, resulting in warmer ground temperatures during the thaw season and a faster freeze-back during autumn. Furthermore, due to the heat retention properties of liquid water, a saturated depression may not freeze-back fully in the winter, especially if a large snowpack is effectively insulating the ground from heat loss, leading to the development of supra-permafrost taliks in the largest and wettest depressions generally located south of transect B at the Airport site and in the bowl-shaped mid-section of the Pontoon Lake site. Log1, located in the wet and degraded portion of the Airport site on what was once likely a hummock but has now degraded and subsided, and Log2, located in the non-degraded and dry portion of the site upon a non-degraded hummock, are representative of the relationship observed between VWC and thaw while probing the active layer along each of the transects. Additionally, the differences in thaw and freeze-back timing of Log3, representing a closed forest canopy, and Log4, representing a wet depression under an open canopy support the observed relationships between VWC, radiation receipt, and active layer thaw.

The relationship between temperature and peat VWC is reflected in the data collected from the Log1 (degraded) and Log2 (non-degraded) TDR probes (Table 2.5), with the exception of initially similar thaw rates. During the thaw season, Log1 and Log2 reached maximum temperatures of 10.87° C and 15.06° C at 10 cm on August 16 and June 25, respectively (Figure 2.7). However, at lower and wetter depths of 40 cm, Log1 falls below 0 °C on January 2, 2014 while log two falls below 0 °C on December 13, 2013. So, while Log2 initially warms faster and to greater temperatures at the ground surface, increased VWC at depth is causing Log1 to retain its heat for a longer period of time than Log2. The observed relationship between VWC and temperature at depth is also reflected in data collected from Log4 at the Pontoon Lake site (Table 2.5) at 25 cm between a depression and the directly adjacent hummock, approximately 30 cm away.

As Figure 2.6 shows, the depression at Log4 maintained a higher VWC than the hummock before freeze-back occurred, and during the freshet, the depression reaches a peak VWC of 87% while the hummock reaches a peak VWC of 72%.

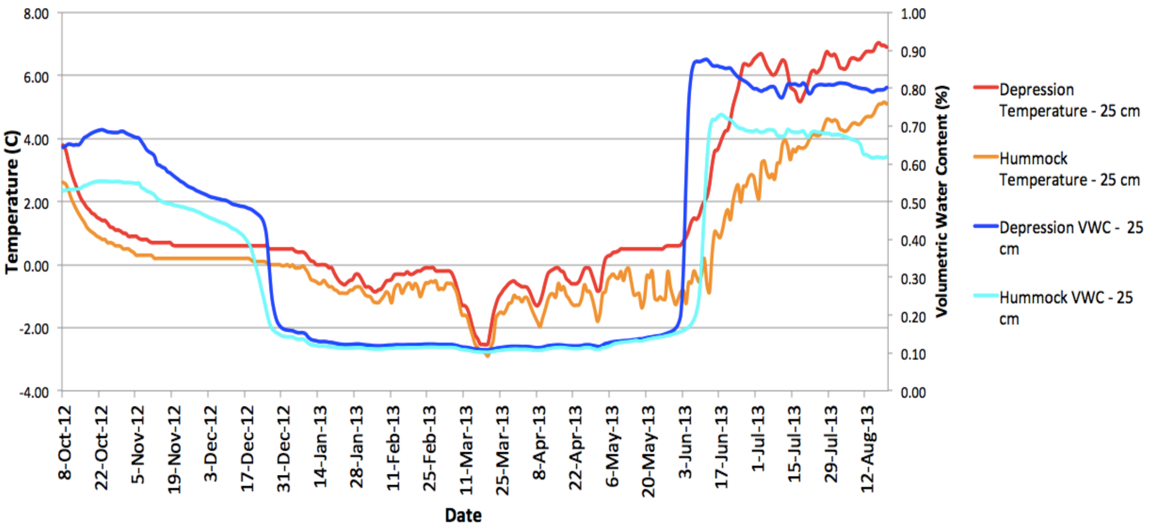


Figure 2.6: Ground temperature and VWC of the Log4 depression at 25 cm versus the Log4 adjacent hummock at 25 cm depth.

During freeze-back, the hummock falls below 0 °C on January 7, 2013, while the depression remains above 0 °C until January 18, 2013. During thaw, the depression exceeds 0 °C on May 4, 2013, 39 days before the hummock reaches positive temperatures on June 12, 2013. The differences in thaw and freeze-back timing can be attributed to the larger VWC within the depression, retaining heat for a longer period of time than the adjacent hummock, similar to what is observed at Log1 and Log2. Meltwater likely pooled on the depression surface, contributing to the larger peak VWC following the freshet and creating a positive feedback for accelerated ground thaw. Although the temperature and VWC differences between the hummock and depression at Log4 are not as significant as the differences between Log1 and Log2 (Figure 2.7, Figure 2.8, respectively), they are representative of the hydrological and thermal differences between hummocks and depressions, even over distances as small as 30 cm. While Log1 and Log2 are represent different areas of the Airport site and have different canopy covers, it is the VWC differences between them causing the same patterns of thaw and freeze-back timing observed on a smaller scale at Log4.

Canopy cover and thus radiation receipt at the ground surface are also important drivers behind active layer thaw, coupling with peat water content to deepen thaw, raise winter ground temperatures, and ultimately aid in the formation of supra-permafrost taliks. During the 2013 freeze-back season, Log4 at 10 cm depth reached a minimum temperature of -4.5 °C on March 17, while the on the same date at the same depth the drier and closed spruce canopy Log3 was -8.8 °C. At 25 cm depth on March 17, the minimum temperatures of Log4 and Log3 were -2.5 °C and -7.8 °C, respectively. At 50 cm, Log4 remained at 0°C for the entire winter season, while Log3 saw a minimum temperature of -4.4 °C at 55 cm on March 20. Furthermore, at 25 cm, Log4 thawed on June 5, 2013, 15 days sooner than Log3 (June 20). Additionally, while VWC at Log4 remained >90% from June 27 through August 12 at 40 cm, the peak VWC of Log3 at 45 cm was 64% on July 6, after which VWC declined and remained between 30-40% for the rest of the thaw season. The differences in winter minimum temperatures and thaw timing observed between Log3 and Log4 can be attributed to differences in VWC between the two sites, however the open canopy cover at Log4 is likely encouraging these differences further, causing deeper heat penetration into the peat during the summer, preventing freeze-back at depths below 50 cm in the winter.

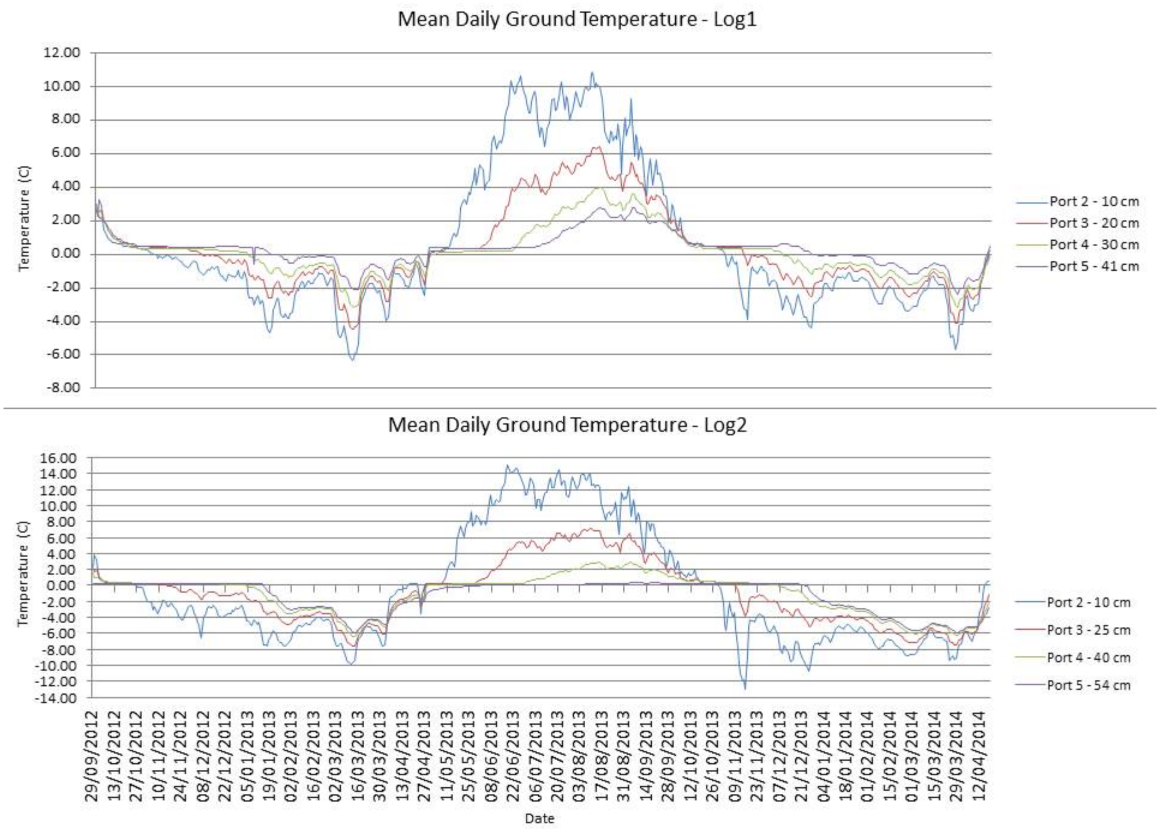


Figure 2.7: Mean daily ground temperature (°C) record for all TDR probes at both Log1 (degraded) and Log2 (non-degraded) at the Airport site from October 2012 – April 2014. Probe depths range from 10 – 54 cm depth.

When compared to Log1, Log4 experiences similar active layer thaw depths and elevated VWC for much of the thaw season. With canopy cover as the largest difference between the sites, Log4 reached a minimum winter temperature of -1.1 °C at 40 cm on March 18, 2013, while Log1 reached a minimum of -2.1 °C at the same depth on the same date (Table 2.6, Figure 2.7). Additionally, Log1 froze on January 28, 2013, while Log4 froze on March 8, 2013, despite the VWC of Log1 exceeding that of Log4 by >30% prior to freeze. Following the freshet, Log4 warmed sooner and faster than Log1. Towards the end of summer on August 18, Log4 at 40 cm reached 4.6 °C while Log1 was 2.6°C at the same depth. These results indicate that although Log1 maintains a higher VWC than Log4, the open canopy forest of Log4 combined with its often elevated VWC delayed its freezing and quickened its thaw following the freshet.

Table 2.6: Log4 and Log1 freeze-back dates at 40 cm, and minimum and maximum temperatures experienced at 40 cm with dates for the 2013 season.

Site	Date	Depth	Temperature (°C)
Log4	March 8, 2013	40 cm	0
Log4	March 18, 2013	40 cm	-1.1
Log4	August 18, 2013	40 cm	4.6
Log1	January 28, 2013	40 cm	0
Log1	March 18, 2013	40 cm	-2.1
Log1	August 18, 2013	40 cm	2.6

Following the 2013 Spring freshet, the top 10 cm in the peat profile at both Log1 and Log2 exceeded 0° C on April 4 (Figure 2.7). Throughout May 2013, the freezing front at each logging site descended in relative unison with the other, down to 40 cm. Log1 at 40 cm reached > 0° C on May 5, while Log2 at the same depth reached > 0° C on May 11. These results are somewhat unexpected as Log1 had a much larger VWC at the time of freeze-up, resulting in a larger ground ice content prior to thaw. One would expect a larger ground ice content to extend the zero curtain effect due to an increased need for latent heat absorption to melt the ice, thus delaying thaw at the degraded site. However, the formation of supra-permafrost taliks containing liquid water observed during active layer probing in degraded depressions can provide an additional source of heat beneath the seasonally frozen active layer, causing the thaw rate between the degraded and non-degraded sites to occur simultaneously until mid-June. Thus, although the wet Log1 and dry Log2 initially experienced similar rates of temperature increase and active layer thaw, Log2 warmed faster and to greater temperatures than Log1. However

Log1 experienced deeper active layer thaw for a longer period of time than Log2. These results are reflected in the ground heat flux (Q_g) calculations, as the wetter logging sites experienced a greater Q_g which is associated with deeper active layer thaw.

At the Airport site, Log1 generally had a larger total Q_g than Log2 throughout the 2013 thaw season, which is expected to cause deeper ground thaw (Figure A.1) (Carey and Woo, 1998). At Pontoon Lake, the upper most TDR probe (10 cm) at Log4 (Figure 2.3, Table 2.5) began malfunctioning on July 17. Up until this date, Q_g at Log4 exceeded that of Log3 (Figure A.2). Following July 17, the ground heat fluxes at both logging sites were generally even despite the exclusion of Q_g values from the malfunctioning surface probe. Had these values been included, the calculated ground heat flux at Log4 would have remained larger than Log3 for the entirety of the thaw season. These results, presented in Appendix A, indicate that although the largest temperature gradients occur at drier locations, soil heat flux at the wetter locations is larger. These findings are consistent with those of Halliwell et al. (1987) who found that the reduction in thermal conductivity from drying peat is important in reducing the ground heat flux, and that wet depressions have higher Q_g fluxes than dry hummock tops.

For the purposes of this chapter, the freeze-back dates given are defined as the date at which ground temperature falls below 0° C and does not reach ≥ 0° C until the following thaw season. The thaw date is defined as the date at which ground temperatures exceed 0° C and does not reach ≤ 0° C until freeze-back occurs the following autumn. During the 2012-2013 and 2013-2014 freeze-back periods, Log1 and Log2 saw marked differences in the rate of ground freezing. The difference in the timing of the downward moving freezing front between the two logging sites was more pronounced during the first freeze-back season. In 2012-2013 at 10 cm, Log2 began freezing 17 days before Log1. At 40 cm, Log2 began freezing 18 days before Log 1. Additionally, Log2 at 25 cm froze 49 days before Log1 at 30 cm. During the 2013-2014 freeze-back season at 10 cm, log2 froze 3 days before log1, while at 40 cm, log2 froze 46 days sooner than Log1. Additionally, Log2 at 54 cm froze 29 days before Log1 at 40 cm. These results indicate that the drier, less degraded area of the site is responding to cooler air temperatures sooner than the wet and degraded portion of the site, which is freezing at a slower rate than that of the non-degraded portion of the site. These differences in freeze-back timing can be attributed to differences in VWC during freeze-up. Interestingly, the Spring of 2013 saw no major differences in thaw timing between the two logging sites.

Considerable variation of VWC exists both within the entire research site, and within the peat profile of each logging site. The wide range of moisture conditions throughout the thaw season can be attributed to small-scale variations in surface topography (*i.e* hummocks and depressions) and location within the research site (*i.e* degraded or non-degraded). Depressions are a small example of larger-scale degradation occurring at the Airport site. They are relatively wet, and act as catchments mainly for snowmelt water from contributing areas, in this case surrounding hummocks. Where flowpathways do not lead to an outlet, water is trapped within a bowl-shaped frost table acting as a barrier to drainage. As the trapped water eventually warms, it thaws the active layer deeper. Field observations (noted above) from both the Airport and Pontoon Lake sites suggest that wetter locations within the sites experience significantly deeper thaw in the summer, and prolonged freeze-back during the autumn. What is presumed to be a perennially unfrozen layer beneath the seasonally frozen layer was also observed within the degraded portion of the sites and within the largest and wettest depressions, and was absent from the wet, smaller depressions. TDR probes installed at the Airport and Pontoon Lake sites demonstrate the positive relationship between VWC and active layer thaw (Figure 2.8).

The wettest surface conditions at both research sites were observed following the spring freshet in early June. Following the freshet peak flow, water pooled in many surface depressions leaving most of the hummocks dry. Across the sites, the flooded areas shrunk as summer progressed, except for the largest and most degraded depressions, which, in some cases, maintained surface ponding until mid-July. Because of the large variability in VWC from the peat surface to lower depths in the peat profile, VWC for the total peat profile is expressed as a median value. While variation in VWC throughout the thaw season does exist, daily median soil moisture at Log1 increased over the summer from 15% on June 1 to 75% on September 30, or at an average rate of 0.66% per day over 92 days (Figure 2.8). Log2 saw no significant change in median VWC over the course of the summer, with a VWC of 19% on June 1 and 18% on September 30. Large precipitation events on July 12 and September 9 of 10.2 and 11.4 mm, respectively, had little-to-no effect on daily average VWC of the peat profile at both of these logging sites. Soil moisture was raised 1-3% for approximately 3 days immediately following the events before returning to pre-event moisture levels.

At both logging sites, initial VWC at the time of freeze was less than the VWC at the time of thaw, likely due to inputs of snowmelt water during thaw. Immediately following snowmelt, VWC at Log1 spiked at 37% at 10 cm. At the same depth, VWC at Log2 spiked at 17%. Log1 and Log2 had similar soil moisture contents of 13% and 16%, respectively, prior to freezing in 2012 (Figure 2.8). These results indicate the possibility of water contribution from elevated hummocks into low-lying depressions during the spring freshet.

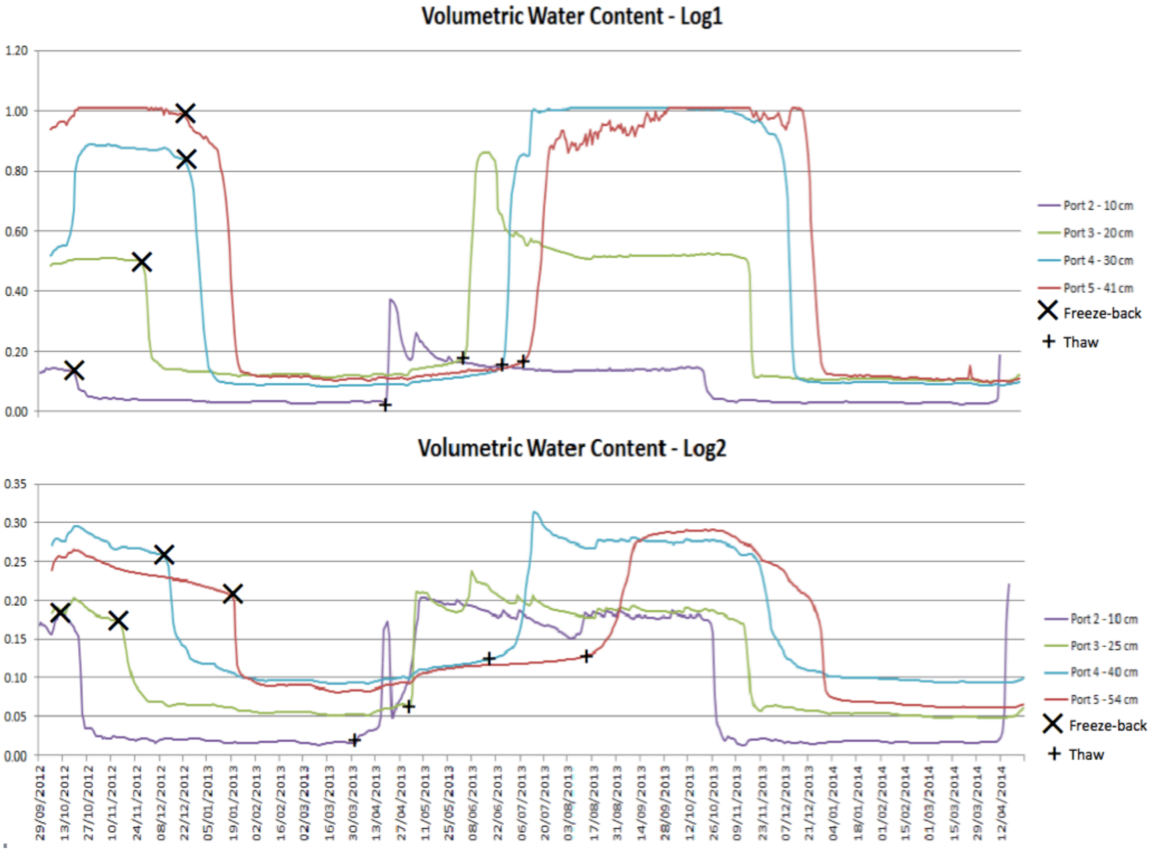


Figure 2.8: Volumetric water content (%) record for all TDR probes at both Log1 (degraded) and Log2 (non-degraded) at the Airport site from October 2012 – April 2014. Probe depths range from 10 – 54 cm depth. '×' symbols indicate freeze-back timing, while '+' symbols indicate active layer thaw timing.

The top 10 cm of the peat profile remained consistent between Log1 and Log2, with VWC remaining between 15-20% for the majority of the summer. Below 10 cm, the sites varied considerably. At Log2, peak VWC of 32% occurred at 40 cm on July 14 before declining and remaining at ~ 28% for the entirety of the thaw season. In contrast, Log1 reached saturation at 30 cm on July 19, while at 40 cm VWC was maintained between 85-100% from July 19 until December 12. The combination of frost table probing, temperature, and VWC data collected reveal that the degraded portion of the site experiences a prolonged thaw season, that the rate of thaw within a depression significantly exceeds that of a hummock, and that almost all of the flooded and/or wet areas following the spring freshet were the same areas that experienced the deepest thaw at the end of the summer. To further confirm these findings, ground penetrating radar (GPR) was used to image the subsurface (Figure 2.9) permafrost boundary along each transect at the Airport site.

GPR surveying at the Airport site was an important step in identifying the pattern of active layer thaw within the peatland. We recorded a strong, mostly continuous reflection from the permafrost table on both primary and secondary transects (Figure 2.9). As expected, the reflections appear to mimic the surface topography in October, while in April reflections are minimal in the absence of thawed ground. The October survey results indicate that the largest areas of thaw are depressions, with the largest depressions experiencing deeper thaw. To confirm the findings of the GPR survey, active layer probing was conducted along the same transects on the same day, and yielded similar results whereby the deepest thaw was associated with the largest and wettest depressions.

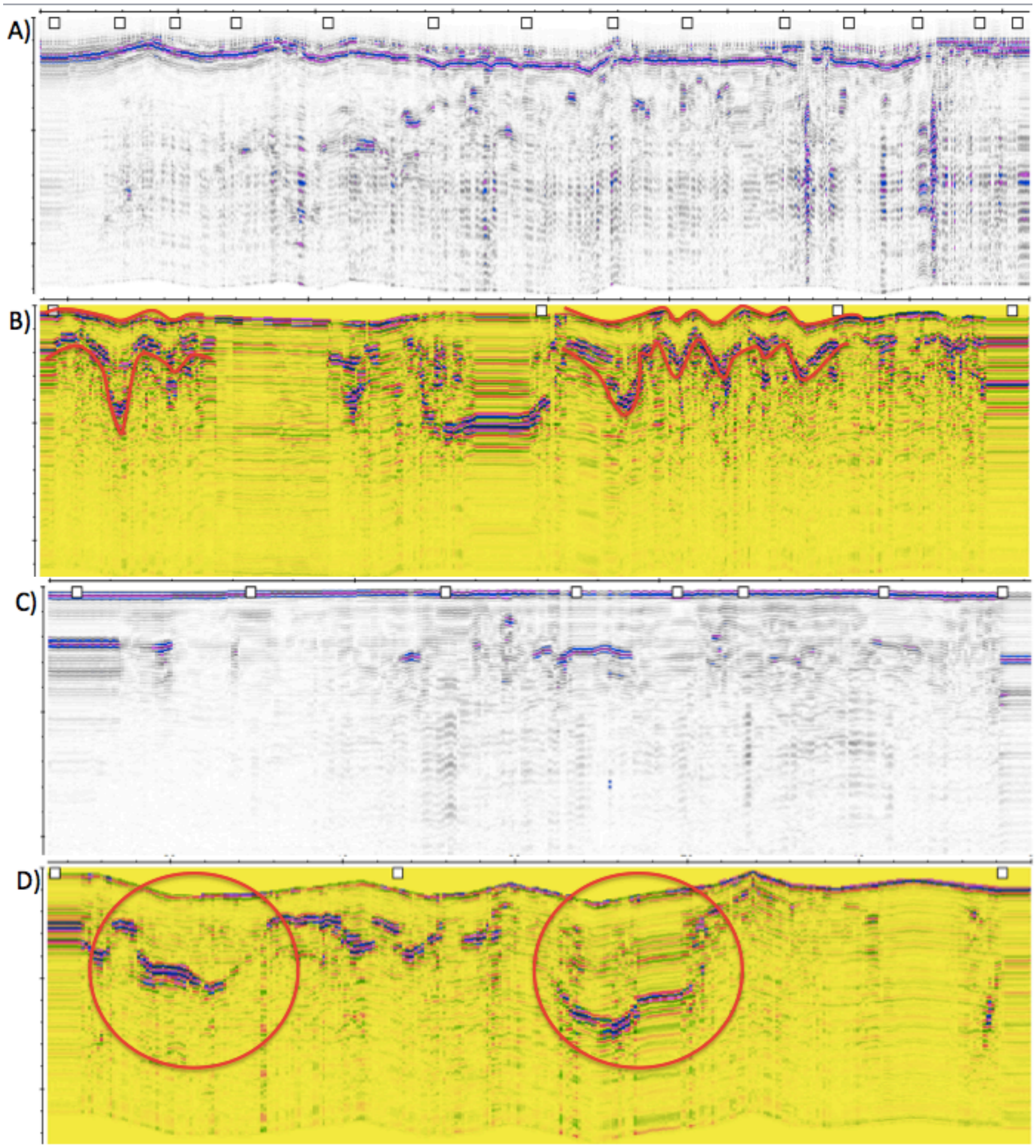


Figure 2.9: GPR images of primary transects at the Airport site. A) and C) images represent maximum freeze during April 2013, while images B) and D) represent maximum thaw in October 2013. Red lines indicate areas of significant thaw. A) Transect A during maximum freeze. Transect follows a southerly route from the road to the pond. Permafrost table is at the surface; B) Transect A during maximum thaw. As indicated by the superimposed red lines, the permafrost table mimics the surface topography where a clear signal is recorded; C) Transect B during maximum freeze. Transect follows a west to east route. Permafrost table is at the ground surface; D) Transect B during maximum thaw. The red circles indicate large depressions where surface pooling existed for much of the thaw season.

2.4.3 Litter-bags

Boreal peatlands are often characterized by substantial amounts of organic matter accumulation in the absence of conditions that are conducive to rapid decomposition of plant litter. The imbalance between accumulation and decomposition rates allows the build up of a partially decomposed layer that gradually becomes thicker as plant litter remains over centuries. This accumulation of organic matter is often attributed to inhibited decomposition rates associated with cool temperatures, anoxic conditions, functionally limited decomposer communities, and litter with high quantities of naturally slow to decompose substrates (Moore and Basiliko, 2006). Litterbags, a common method of quantifying decomposition rates in peatlands, are an inexpensive means of comparing decomposition rates at different depths in the peat profile, and also among different peatlands that may experience different hydrological, chemical, or litter quality characteristics.

The main controls on litter decomposition in peatlands can be identified as climate (temperature and precipitation), position within the peat profile, and litter and peat chemistry (Moore and Basiliko, 2006). It is well known that increasing temperatures and precipitation lead to increases in decomposition, while anoxic conditions and cooler temperatures may decrease litter breakdown. Litterbags are often buried at different depths of the peat profile, and left for timespans ranging from 2 – 25 years. Due to time constraints of the study, litterbags were left at both the Airport and Pontoon Lake sites for just over one year. With such a comparatively short timespan, it was expected that little-to-no litter mass would be lost between the time of installation and the time of extraction, however this was not the case (Table 2.7).

Table 2.7: Airport and Pontoon Lake sites litter-bag depths (cm), original weight of organic matter encased in each bag (g), final weight or organic matter upon litter-bag retrieval (g), total mass loss of organic material (g), and % total loss of original material mass. Total loss decreases with increasing depth in the peat profile.

Site	Depth (cm)	Weight (g) October 2012	Weight (g) October 2013	Total Loss (g)	Total Loss (% original mass)
Airport Site	10	11.5	8.5	3	26 %
	25	7	5.5	1.5	21 %
	40	11	9.2	1.8	16 %
Pontoon Lake	10	8.5	6.8	1.7	20 %
	25	7	6.2	0.8	11 %
	40	11	9.9	1.1	10 %

Between October 2012 and October 2013, litterbags at the Airport and Pontoon Lake sites placed at 10 cm depth lost 26% and 20%, respectively, of the original mass encased in each bag (Table 2.7). At both sites, decomposition decreased with increasing depth in the peat profile, with decomposition rates decreasing by 5% per 15 cm increase in depth at the Airport site. Losses were more dramatic at Pontoon Lake, with decomposition rates decreasing rapidly between 10-25 cm depth in the peat profile. These results are consistent with those of other litterbag studies whereby decomposition decreases with depth in the peat profile due to cooler temperatures and increased flooding frequency leading to anoxic conditions at depth.

Litter quality is also an important consideration in decomposition studies. Microbial communities need certain nutrients like nitrogen (N) so that they may synthesize nitrogen-containing cellular components, such as amino acids. Carbon is also necessary for microbes so that they may build essential organic compounds and obtain energy. On average, microbes demand approximately 1 g of nitrogen for every 24 g of carbon in their food. Thus, if the C/N ratio of the soil solution exceeds about 25:1, there will be a microbial demand for N, reducing microbial populations and decay rates of organic material (Brady and Weil, 2009). It is probable that the recently senesced surface material collected and incorporated into the peat at 10 cm depth contained higher amounts of readily available nutrients and more labile C than the partially decomposed and humified peat encased in the deeper litterbags, thus contributing to the higher mass loss seen in the litterbags closest to the surface. Additionally, the observed decreasing ground temperatures with increasing peat depth likely influenced the similar pattern of decreasing decomposition rate with increasing depth, as higher temperatures accelerate decomposition at the peat surface and cooler temperatures inhibit decomposition at lower depths in the peat profile. It is likely that had the litterbag study continued for years to come, the decomposition rate would decrease as valuable nutrients and labile carbon are depleted.

2.5 Discussion

2.5.1 Active Layer Thaw

The timing of snowfall in the autumn and early winter, as well as the snow depth over the freeze-back season are both important factors in the timing and penetration depth of winter freezing. The effect of snow cover on the ground thermal regime has the potential to dictate the depth of winter freeze-back due to its insulating properties. Snow arriving early in the season will insulate the ground sooner, preventing deep frost penetration and potentially encouraging the development of taliks, ultimately reducing winter freeze-back. Because snow cover was mostly consistent across both research sites, the timing of the first snowfall does not appear to be an important aspect in the variability of winter freeze-back seen between degraded and non-degraded areas of the sites. Though taliks were observed during the thaw season, the large spatial variability in their existence is not likely to have been caused by the generally uniform snowcover seen during the 2012 and 2013 winter seasons. However, the depth of accumulated snow at the end of the winter season just prior to thaw has the potential to promote large variability in near surface soil moisture come spring, especially if surface microtopography is conducive to redirecting meltwater into depressions.

In order for permafrost aggradation to occur, a general long-term trend must occur whereby the depth of freeze-back during the winter exceeds the depth of thaw the following thaw period. If the seasonally frozen active layer has completely thawed before winter freeze-back commences, any further energy inputs to the ground will go towards warming the subsurface further and potentially thawing permafrost (Williams, 2012). Given the large differences in the thaw rates between hummocks and depressions, it appears as though depressions are not regenerating permafrost, while hummocks appear to be in a steady state. The main difference between steady-state hummocks and degrading depressions has been identified as variability in soil moisture and depression storage, with depressions accumulating water following the spring freshet. If snowmelt water were only transferred vertically through the soil profile, one would expect the pre-freeze soil moisture to equal the post-thaw soil moisture, plus inputs from snowmelt. Given this scenario and an evenly distributed snowcover, the change in volumetric soil moisture between pre-freeze and post-thaw should be equal between hummocks and depressions. However, depressions had a significantly greater increase in volumetric soil moisture as compared to hummocks following the spring freshet. Given these results, it appears as though significant lateral flow is occurring from hummocks to depressions during and following the spring freshet.

The observed differences in frost table depth between the degraded and non-degraded portions of the sites, as well as within individual hummocks and depressions, appears to be driven by two main factors; soil moisture and solar radiation penetration into the ground, which becomes intense under an open forest canopy in the summer months. The relationship between soil moisture conditions of the peat and thermal conductivity has been well documented to strongly influence the timing and rate of ground freeze and thaw. A high thermal conductivity at or near the ground surface during the summer months leads to increased thaw, and similarly an elevated thermal conductivity during the winter leads to increased freezing. The thermal conductivity of a dry peat is about 0.06 W m^{-1} K^{-1}, while a saturated peat has a thermal conductivity approximately 8.3 times greater at 0.50 W m^{-1} K^{-1}. During the winter, the thermal conductivity of a frozen saturated peat is approximately 3.9 times greater than an unfrozen saturated peat due to the fact that the thermal conductivity of ice is 2.24 W m^{-1} K^{-1} versus the 0.57 W m^{-1} K^{-1} thermal conductivity of water (Oke, 1978; Williams, 2012). As a result, a frozen saturated peat will experience maximum thermal conductivity during the spring, leading to accelerated thaw following the freshet. A dry site will experience much less variation in thermal conductivity since the conductivities of an unsaturated thawed soil are not significantly different from that of an unsaturated frozen soil (Williams, 2012). This will result in similar thaw and freeze-back depths, establishing a stable permafrost table year after year.

The relationship between ground soil moisture and thermal conductivity has the potential to cause significant ground thaw where saturation exists, such as where the peat plateau meets the bog at the Airport site, and in depressions where water has pooled at both the Airport and Pontoon Lake sites. However, significant ground thaw has also been observed in unsaturated areas, particularly at Pontoon Lake where the forest canopy is open, allowing for uninhibited receipt of solar radiation. In the mid-section of the site, the forest canopy remains open, partially due to pockets of peat saturation and surface ponding that repeatedly occur during thaw seasons after rain events, inhibiting vegetation growth and in some cases causing vegetation death. Significantly greater ground thaw was observed in the middle of the site as compared to the adjacent forested areas. In the absence of a tree canopy, the incoming radiation is uninhibited and acts to warm the ground surface. This heat is then efficiently transferred downward due to a high thermal conductivity attributed to elevated soil moisture. Because the specific heat of water is approximately four times that of air, as the ground surface warms and heat is conducted downward, the water within the pore space of the peat is able to retain and thus conduct vertically for much longer than if the pore space were filled with air. Thus, conditions conducive to deeper active layer thaw are created when soil moisture is elevated and incoming radiation is uninhibited by a forest canopy.

The relationships between surface microtopography, soil moisture, canopy cover, and thaw depth outlined above are reflected in the data collected from each of the logging sites. Based upon temperature and VWC data obtained between 2012-2014, it appears as though the surface microtopography, and thus the physical structure of the peatland coupled with a changing climate, are the initial drivers behind the evident and perhaps accelerating (given future predicted climate) degradation of underlying permafrost. The redirection of meltwater, during and following the spring freshet, is the most significant source of water to low-lying depressions throughout the entire year, and has the potential to create a positive feedback mechanism for further thaw. During the 2013 field season, precipitation inputs during the summer were insufficient in affecting the soil moisture content below approximately 15 cm depth. Following the freshet, the accumulated water in depressions warms as a result of increasing air temperatures and in some cases, intense solar radiation receipt at the ground surface. Although the air space in a dry site such as Log2 (Figure 2.2) may react faster to increasing temperatures, the lowered thermal conductivity and heat capacity results in shallower total active layer thaw. When freeze-back occurs, heat dissipation from the saturated peat will occur more slowly than a dry site. If snowfall arrives early in the season, it will insulate the peat and the saturated active layer may not freeze back fully, creating an area of unfrozen peat between the permafrost and the seasonally frozen upper active layer, enabling microbial breakdown of DOM throughout the entire winter season.

2.5.2 Decomposition of Solid Organic Matter

The large accumulation of organic matter in peatlands is primarily caused by deposition via vegetation and slow litter decomposition rates under environmental conditions that are not conducive to prolonged periods of significant microbial activity. At each site, there was a pronounced decrease in decomposition rates between the surface litterbags at 10 cm and the deeper litterbags at 25 and 40 cm. Generally, decomposition rate will depend on multiple factors, of which the most important have been identified as substrate quality, environmental conditions (moisture, temperature), microbial communities present, and nutrient availability (Laiho, 2006). These factors are all related and connected: environmental conditions and nutrient availability will interact to determine vegetation composition, which in turn largely controls substrate quality, which then regulates decomposer communities along with environmental conditions and nutrient availability. Because of these factors, surface litter is more susceptible to accelerated decomposition than the partially decomposed organic material found at depth. The pattern of decreasing decomposition rate with increasing depth in the peat profile was observed at both research sites, with pronounced decomposition differences seen between the litterbags at 10 cm and those at 25 and 40 cm depths.

Surface litter including leaves, needles, fine roots and mosses are the most susceptible to rapid decomposition as compared to organic material found beneath the acrotelm. The combination of good aeration, warmer surface conditions, high nutrient availability in the fresh litter and microbial ease of access all regulate the higher decomposition rates observed in the top 10 cm of the peat as compared to depths below 10 cm which may experience lower quality organics and anoxic conditions. Although these relationships have been well established and likely have a large impact on the decomposition rates observed at both research sites, the combined effects of the environment, nutrient availability, substrate quality and decomposer communities are complex and are subject to change from site to site. Nevertheless, the observed 26% and 20% losses of material from the surface litterbags at the Airport and Pontoon Lake sites over a 1-year period are significant as most boreal litters decompose at a rate of 9-32% over two years (Lahio, 2006).

2.6 Conclusions

The observations from this study further the understanding of the key physical and environmental drivers behind permafrost loss beneath peat plateaux, and help to explain how microbial degradation of organic matter is related to the environmental, nutrient, and substrate quality characteristics of the peatland in question. The key findings of the study, as well as a conceptual model (Figure 2.10) depicting the feedback processes preceding permafrost loss, are outlined below:

1. The physical microtopographical structure of the peatland, *i.e.* the ratio of hummocks to depressions, is the largest physical control on the ultimate fate of peat plateaux. During and following the spring freshet, meltwater is redirected from hummocks into depressions, creating saturated conditions while hummock tops remain dry. Continuous and prolonged saturation reduces and eventually prevents vegetation growth, reducing the canopy cover and exposing

the ground surface to uninhibited solar radiation. The saturation of depressions creates a positive feedback for heat retention within the peat, degrading the permafrost below. The saturated conditions and heat retention within depressions act to further degrade adjacent peat around the depression edges, growing the surface area of the depression and creating pockets of permafrost-free, wetland-like conditions. Eventually, the entire peatland may lose its permafrost and degrade into a bog environment.

2. An increase in the soil moisture of the peat has a greater potential to promote ground thaw compared to increases in solar radiation receipt at the ground surface alone. Due to the strong relationship between soil moisture and thermal conductivity, heat is transferred downward and retained for longer periods of time when elevated soil moisture conditions are present. While winter snowfall may also play a large role in the ground thermal regime, intense radiation receipt at the ground surface has been identified as the second largest factor in active layer and permafrost degradation. The combined effects of elevated soil moisture and intense solar radiation receipt at the ground surface will have the largest impact on ground thaw, and will degrade the underlying permafrost faster than either factor acting alone.
3. Given current increasing temperature and precipitation trends in the Yellowknife region, as well as IPCC (2014) predictions of warmer, wetter soils and increased winter snowfall in subarctic Canada, it is likely that both studied peatland sites will succumb to further degradation and permafrost loss as the degradation processes reviewed and inferred form differences in measured soil

temperature and soil moisture between hummocks and depressions will likely accelerate in the future. Increased water content in the peat will initiate a positive feedback mechanism for increased ground temperatures and further thaw, making previously sequestered organic material environmentally available for elevated microbial activity. Should snowfall begin arriving earlier in the autumn season, there is increased potential for ground insulation before the active layer is fully frozen, promoting the creation of supra-permafrost taliks. The snowpack acts to insulate the ground from winter air temperatures, while also reducing heat loss from the subsurface. The combined effects of snowpack insulation raise soil temperatures, enabling elevated winter microbial activity and decomposition. During this stage of peatland degradation and accelerated decomposition rates, the potential for elevated DOC export to surface water bodies will rise. However, as snowfall continues to increase over the next decades while permafrost is thawing, there is potential for extended periods of flooding, which could act to slow decomposition due to prolonged periods of saturated, anaerobic conditions. In this advanced stage of peatland degradation, while permafrost will be lost, the potential for large quantities of DOC release into surrounding water bodies is reduced as decomposition rates are slowed and the peatland remains in a saturated, bog-like condition with little water movement.

The chosen research sites represent a gradation of systems in change, and portray the range of conditions that typify peatlands in the Yellowknife, NT area. The conditions observed at each logging site enable a space-for-time approach whereby degraded portions of the site represent the future vision of the non-degraded areas given current climate change predictions. The susceptibility of each logging site to future degradation will depend on its location within the peatland, as well as its microtopography, soil moisture, vegetation cover, and changing climatic conditions.

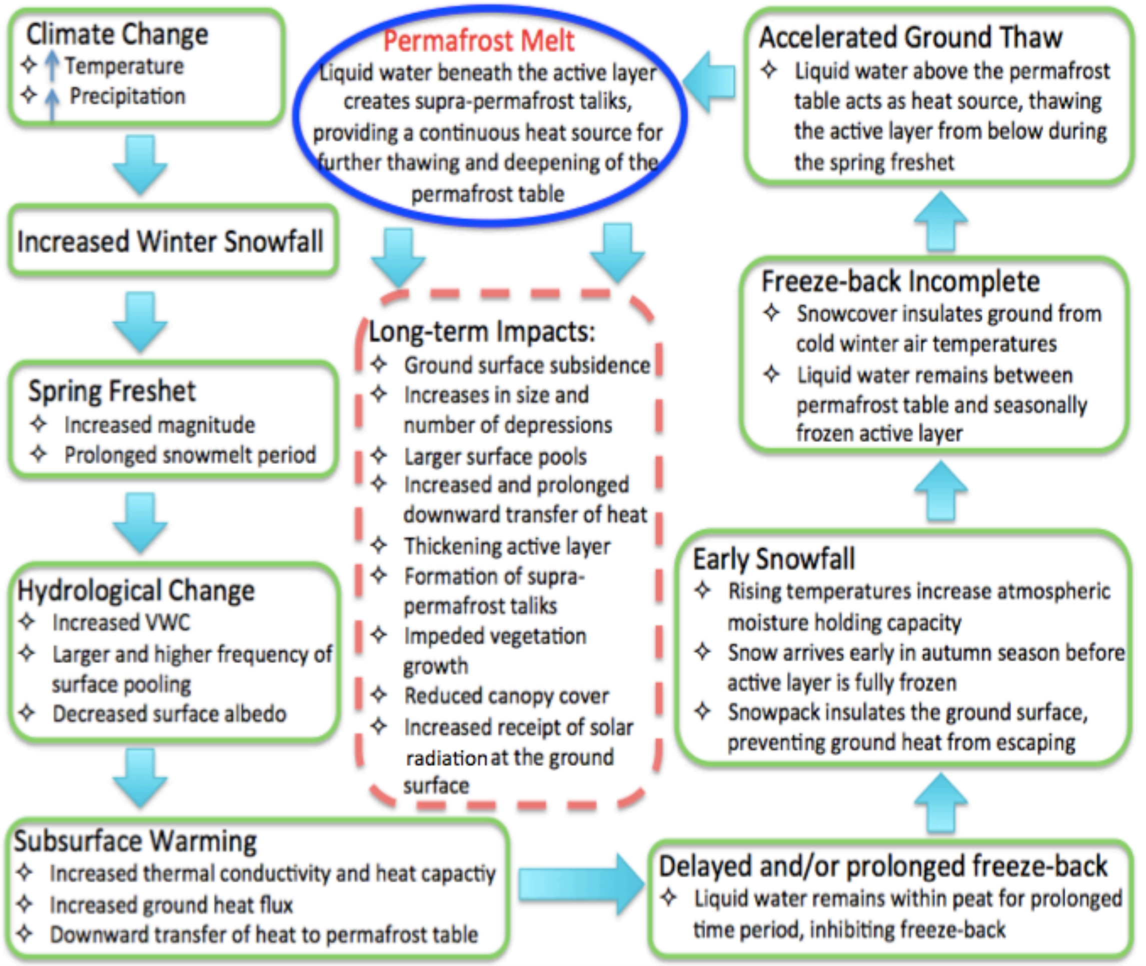


Figure 2.10: Conceptual model of the positive feedbacks associated with peatland degradation, which eventually lead to permafrost loss. Beginning with climate change, permafrost melt is the end result of a variety of physical processes that act to encourage deeper active layer thaw and incomplete freeze-back. Long-term impacts are summarized.

Log1 and Log4 are currently in degrading states whereby saturated conditions exist throughout the peat profile for much of the thaw season, creating positive feedbacks for continued warming, reduced winter freeze-back and a prolonged thaw period, enabling elevated microbial activity year round. While Log1 has subsided from a hummock into a flattened depression-like feature, likely accelerated by its close proximity to the Airport bog and pond, a sparse vegetation cover still exists, sheltering the site and reducing radiation receipt at the ground surface. In contrast, the vegetation cover at Log4 is essentially non-existent, which can be attributed in part to the saturated conditions experienced in the bowl shape mid-section of the site for much of the thaw season. The lack of canopy cover allows uninhibited solar radiation receipt at the peat surface, which when combined with elevated VWC, makes Log4 the most susceptible of all the logging sites to further degradation given future climate change.

Although Log2 and Log3 currently appear to be in a stable condition, *i.e.* the active layer thaws and re-freezes more or less to the same depth each year, seemingly small increases in temperature and precipitation into the system may initiate a positive feedback for increased active layer thaw, which once begun, may not end until complete permafrost loss. While Log2 maintains healthy vegetation atop a relatively dry hummock, the surrounding depressions create potential for eventual subsidence as they degrade and expand. In contrast, Log3 is located under a dense forest canopy, protecting it from incoming solar radiation. Additionally, the slightly elevated position of Log3 above the degrading mid-section of the Pontoon Lake site reduces the potential for saturation. The combined effects of canopy cover and its elevated position make Log3 the least susceptible of all the logging sites to climate driven degradation.

In the future, as climate warms and precipitation inputs increase, it is likely that each logging site will succumb to warmer ground temperatures resulting in active layer thickening and permafrost loss. It is likely that in years to come, Log3 will degrade into a state similar as Log2, while Log2 will degrade into a similar state as Log1. Both Log1 and Log4 are likely to degrade more rapidly than Log2 and Log3, becoming increasingly saturated and eventually degrading into a permafrost free, bog-like state.

References

Aukes, P. 2012. *Use of liquid chromatography – organic carbon detection to characterize dissolved organic matter from a variety of environments*. Unpublished master's thesis, Waterloo University, Waterloo, Canada.

Baltzer, J.L., Veness, T., Chasmer, L.E., Sniderhan, A.E., Quinton, W.L. 2014. Forests on thawing permafrost: fragmentation, edge effects, and net forest loss. *Global Change Biology.* 20, 824-834.

Brady, N. C., Weil, R. R. 2010. *Elements of the nature and properties of soils*, 3rd edn. Boston, MA. Prentice Hall.

Britta, A., Sannel, K., Kuhry, P. 2009. Holocene peat growth and decay dynamics in sub-arctic peat plateaus, west-central Canada. *Boreas.* 38, 13-24.

Buttle, J. 2006. Mapping first-order controls on streamflow from drainage basins: the T^3 template. *Hydrological Processes.* 20, 3415-3422.

Carey, S.K., Woo, M.K. 1998. The role of ground ice in active layer thaw, in *Proceedings of the 7th International Conference on Permafrost.* 127-131. Canadian National Committee for the International Permafrost Association, Yellowknife, Northwest Territories, Canada.

Evans, C.D., Monteith, D.T., Cooper, D.M. 2005. Long-term increases in surface water dissolved organic carbon: Observations, possible causes and environmental impacts. *Environmental Pollution.* 137, 55-71.

Gorham, E. 1991. Northern peatlands: Role in the carbon cycle and probable responses to climatic warming. *Ecological Applications.* 1, 182-195.

Guan, X.J., Westbrook, C.J., Spence, C. 2010. Shallow soil moisture – ground thaw interactions and controls – Part 1: Spatiotemporal patterns and correlations over a subarctic landscape. *Hydrology and Earth System Sciences.* 14, 1375-1386.

Halliwell, D.H., Rouse, W.R., Weick, E.J. 1987. Surface energy balance and ground heat flux in organic permafrost terrain under variable moisture conditions, in *Permafrost: Fifth Canadian Proceedings.* 223-229. Quebec City, QC. Nordicana No. 54, Université Laval.

Huber, S.A., Balz, A., Abert, M., Pronk, W. 2011. Characterisation of aquatic humic and non-humic matter with size-exclusion chromatography – organic carbon detection – organic nitrogen detection (LC-OCD-OND). *Water Research.* 45, 879-885.

Hur, J., Park, M-H., Schlautman M.A. 2009. Microbial transformation of dissolved leaf litter organic mayyer and its effects on selected organic matter operational descriptors. *Environmental Science & Technology.* 43, 2315-2321.

IPCC, 2014: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 688 pp.

Johnson, L.C., Damman, A.W.H. 1991. Species controlled sphagnum decay on a south Swedish raised bog. *Oikos*. 61, 234-242.

Johnson, L.C., Damman, A.W.H., Malmer, N. 1990. Sphagnum macrostructure as an indicator of decay and compaction in peat cores from an ombrotrophic south Swedish peat-bog. *The Journal of Ecology.* 78, 633-647.

Karberg, N.J., Scott, N.A., Giardina, C.P. 2008. Methods for estimating litter decomposition, in *Field measurements for forest carbon monitoring.* 103-111. New York, NY. Springer.

Laiho, R. 2006. Decomposition in peatlands: Reconciling seemingly contrasting results on the impacts of lowered water levels. *Soil Biology & Biochemistry.* 38, 2011-2024.

Lilienfein, J., Qualls, R.G., Uselman, S.M., Bridgham, S.D. 2004. Adsorption of dissolved organic carbon and nitrogen in soils of a weathering chronosequence. *Soil Science Society of America*. 68, 292-305.

Marhaba, T.F., Van, D. 2000. The variation of mass and disinfection by-product formation potential of dissolved organic matter fractions along a conventional surface water treatment plant. *Journal of Hazardous Materials.* 74, 133-147.

Moore, T.R., Basiliko, N. 2006. Decomposition in Boreal Peatlands, in *Boreal Peatland Ecosystems.* 125-143. Berlin, Germany. Springer.

Moore, T.R., Bubier, J.L., Bledzki, L. 2007. Litter decomposition in temperate peatland ecosystems: The effect of substrate and site. *Ecosystems.* 10, 949-963

Nungesser, M.K. 2003. Modelling microtopography in boreal peatlands: hummocks and hollows. *Ecological Modelling.* 165, 175-207.

Oke, T.R. 1978. Boundary layer climates. Routledge, Cambridge.

Petrone, R.M., Rouse, W.R., Marsh, P. 2000. Comparative surface energy budgets in western and central subarctic regions of Canada. *International Journal of Climatology.* 20, 1131-1148.

Quinton, W.L., Marsh, P. 1999. A conceptual framework for runoff generation in a permafrost environment. *Hydrological Processes*. 13, 2563-2581.

Schiff, S., Aravena, R., Mewhinney, E., Elgood, R., Warner, B., Dillon, P., Trumbore, S. 1998. Precambrian Shield wetlands: Hydrologic control of the sources and export of dissolved organic matter. *Climatic Change.* 40, 167-188.

Scott, E.E., Rothstein, D.E. 2014. The dynamic exchange of dissolved organic matter percolating through six diverse soils. *Soil Biology & Biogeochemistry.* 69, 83-92.

Schindler, D.W., Curtis, P.J., Parker, B.R., Stainton, M.P. 1996. Consequences of climate warming and lake acidification for UV-B penetration in North American boreal lakes. *Nature*. 379, 705-708.

Spence, C., Guan, X.J., Phillips, R., Hedstrom, N., Granger, R., Reid, B. 2010. Storage dynamics and streamflow in a catchment with variable contributing area. *Hydrological Processes.* 24, 2209-2221.

Spence, C., Kokelj, S.A., Kokelj, S.V., Hedstrom, N. 2014. The process of winter streamflow generation in a subarctic Precambrian Shield catchment. *Hydrological Processes.* 28, 4179-4190.

Tranvik, L.J. 1993. Microbial transformation of labile dissolved organic matter into humic-like matter in seawater. *FEMS Microbiology Ecology*. 12, 177-183.

Williams, T.J. 2012. *Recovery of linear disturbances in a discontinuous permafrost peatland environment.* Unpublished master's thesis, Wilfrid Laurier University, Waterloo, Canada

Woo, M.K. 1986. Permafrost hydrology in North America. *Atmosphere-Ocean.* 24, 201-234.

Woo, M.K., Young, K.L. 2006. High Arctic wetlands: Their occurrence, hydrological characteristics and sustainability. *Journal of Hydrology.* 320, 432-450.

Wright, N., Hayashi, M., Quinton, W.L. 2009. Spatial and temporal variations in active layer thawing and their implication on runoff generation in peat-covered permafrost terrain. *Water Resources Research.* 45, WO5451.

Zoltai S.C. 1972. Palsas and peat plateaus in central Manitoba and Saskatchewan. *Canadian Journal of Forest Resources*, 2, 291-302.

Chapter 3

Using the Liquid Chromatography – Organic Carbon Detection Method to Assess Spatial and Temporal Patterns in Compositional Changes to DOM Derived from Degrading and Non-degrading Peat

3.1 Introduction

Peatlands, currently estimated at a mere 6.4% of the world's land area, or 12% of Canadian land area (Britta et al., 2008), represent a wide variety of wetlands that are characterized by an organic soil and a large accumulation of partially decomposed plant litter. Peat-accumulating wetlands are ecosystems whose rate of photosynthetic production of organic matter is greater than that of its decomposition, resulting in a build up of soil organic matter that may take centuries to fully decompose (Freeman et al., 2004). In a mature and natural ecosystem, there is generally a balance between the release of carbon as CO_2 by microbial activity, and the input of carbon as plant residue. However, due to the cold climate of subarctic Canada, as well as the oxygen deficiency frequently experienced in these saturated environments, decomposition rates are often inhibited (Brady & Weil, 2009). This allows for the build up of organic matter over time, that may take years to centuries to break down, depending on the environmental conditions present in the soil (temperature, soil moisture), and the quality of the added residues as a food source for microbes (lignin and polyphenol content, C:N ratio). The conditions conducive to rapid decomposition include sufficient soil moisture, good aeration with about 40% air-filled pore space, and warm temperatures. Given these broad requirements, it is unclear how predicted climate variability may influence each of these factors, and how carbon stocks will respond in terms of C composition and release into ground and surface water bodies.

Peatlands act as an atmospheric C sink, sequestering about 12% of current human emissions. The bulk of this C accumulation is sequestered in highly decomposition-resistant sphagnum litter. Thus, changes in the chemical nature and therefore decomposability of this litter may potentially affect the C balance of the peatland, and on a larger scale, the global carbon budget. The quality, and thus degradability of litter may be a function of the concentration of resistant compounds or the concentration of specific nutrients, such as nitrogen (Limpens & Berendse, 2003). Soil moisture and radiative warming of air and surface soils may also influence the degradability of litter. For example, the addition of moisture to the ground can change the surface albedo, thus changing net shortwave radiation absorption and the net energy budget (Oke, 1987).

Litter quality is among the most important factors in quantifying decomposition rates within a peat system. The ratio of carbon to nitrogen (C:N), as well as the content of large and complex molecules of lignins and polyphenols, all influence the rate at which soil microorganisms can break down and decompose organic matter. Vascular plants that can tolerate the predominantly cold, saturated, low-nutrient conditions of subarctic peatlands have tough, lignin rich parts which support low levels of microbial activity, resulting in slow decomposition rates (Yavitt et al., 1997; Moore & Basiliko, 2006). These poor quality resources are partially responsible for the extremely high levels of humified carbon and nitrogen found in the soils of mature peatlands and boreal forests (Brady & Weil, 2009). The C:N ratio is also an important determinant of litter quality and plays a role in decomposition rates, as soil microbes demand 1 g of N for every 24 g of C they consume. Therefore, if the C:N ratio exceeds about 25:1, decomposition will slow as microbes must scavenge enough N so they may continue their decay of organic materials. Microbial activity and thus degradation rates are often quantified by measuring respired CO_2, however C is also released from the peat in large quantities as dissolved organic matter (DOM), of which approximately 50% is comprised of dissolved organic carbon (DOC), and can accumulate in pore waters and become exported into surface water bodies, having serious consequences for human and ecosystem health.

DOM is derived from the degradation of organic material. In the subarctic, the highest concentrations of DOM are often found in water originating from wetlands and bogs, where large stocks of partially decomposed organic material exist. DOM is an important environmental constituent as it can absorb light in surface waters, hindering photosynthesis but protecting aquatic organisms from harmful ultraviolet (UV) radiation while regulating the thermal structure of the water body (Schindler et al., 1996). DOM is also important in relation to drinking water quality, as it affects the general taste and color, but also because during the chlorination of water carcinogenic disinfection-by-products (DBP) are created (Marhaba & Van, 2000). Furthermore, DOM has the ability to complex with and mobilize heavy metals (i.e. mercury) and other organic contaminants, which can be a major concern for overall water quality (Aukes, 2012).

Dissolved organic carbon (DOC) (which comprises approximately 50% of DOM) is often used as a proxy measurement for DOM, as it is easier to measure. Establishing DOC concentration is an important aspect of DOM analysis, however it does not determine whether the carbon is available for microbial consumption (*i.e.* labile) or if it is difficult to break down (*i.e.* recalcitrant). To achieve this, the Liquid Chromatography – Organic Carbon Detection (LC-OCD) method is used. The individual components of DOM listed in order of decreasing molecular weight are biopolymers (BP), humic substances (HS), building blocks (BB), low-molecular-weight neutrals (LMW-N) and low-molecular-weight acids (LMW-A). While BP are the largest molecules, HS commonly comprises up to 80% of DOM and is made up of a heterogeneous mixture of large, complex molecules. BB are essentially degraded humic substances of a lower molecular weight, while the final two fractions of DOM are of low molecular weight and are often rapidly utilized by soil microbes (Aukes, 2012), making them the most labile. The decomposition of organic material leaves behind a lower quality, less labile form of DOM. Labile components of DOM can be considered as those that soil microbes consume relatively quickly, often leaving behind the HMW, complex components which may be broken down slowly over time (Evans et al., 2004; Aukes, 2012). As such, it is highly important to characterize the quality, and thus lability, of DOM to determine the relative speed at which decomposition occurs, and thus the relative rate at which DOC is produced. Of equal importance is determining how physical changes to the system brought on by climate change, *i.e.* thermal and hydrological changes, will affect the production and export of DOC from northern peatlands. An improved understanding of DOM fractionation and the underlying mechanisms of DOC regulation are fundamentally important components in the quest to predict future shifts in the biogeochemistry of aquatic ecosystems (Laudon et al., 2013).

As climate predictions for the Canadian subarctic suggest warmer temperatures and increased precipitation (IPCC, 2014), it is important to determine potential changes to DOC chemistry with respect to the different stages of peat plateaux degradation observed at both the Airport and Pontoon Lake sites. As air temperatures rise, the growing season will lengthen, prolonging the period of time where microbial degradation of organic material can occur at elevated rates. Additionally, an increase in precipitation, particularly in the autumn period (Spence et al., 2011) when the active layer is at its deepest, may have potential to pulse large concentrations of C downward in the peat profile. As evaporative losses act to further concentrate DOC at depth, there is potential for large storm events to export significant quantities of DOM into surface/subsurface flowpathways of the peatland into adjacent surface water bodies. The risk of C export from peatlands is enhanced if predicted warmer and wetter soils prevent the complete freeze-back of the active layer during the winter, allowing liquid water to remain in the peat year-round and potentially migrate toward surface water bodies. As such, understanding the quality and quantity of the potentially labile C will further our understanding of potential environmental outcomes.

3.2 Objectives

The overall goal of this chapter will be to spatially evaluate the DOM characteristics of both the Airport and Pontoon Lake sites, including DOC concentration and composition, to determine C quality and potential for export into surface water bodies. Using the LC-OCD methodology, this goal will be achieved by meeting the following specific objectives:

1) to use the DOC concentration data of samples obtained from both research sites to determine possible hydrological patterns, such as where possible subsurface flowpathways may exist in the peat;
2) to evaluate the overall composition of the DOM derived from each research site and determine whether or not a pattern exists between DOM composition and the range of degradation at both sites;
3) to determine how the quality of DOM changes spatially within and among the two research sites, and temporally over the course of the 2013 summer season.

3.3 Methods

3.3.1 Piezometers and Groundwater Sampling

In order to repeatedly extract water samples from within the peat throughout the time span of the study, three piezometers were installed at each research site in October 2012 while the active layer was at its deepest (Figure 2.2, Figure 2.3). Using PVC tubing, piezometers were constructed and inserted in pre-drilled holes in degraded and non-degraded areas of each site. At 2 cm intervals on the bottom 30 cm of each piezometer, small slits were made to allow water to enter the tube. These slits were covered with nylon material to prevent particulate material from entering the tube. Once piezometers were installed, caps were placed on top, again preventing outside material from entering the tube. On June 13, 2013 five more piezometers were installed at the Airport site (Figure 2.2), while three more were added to Pontoon Lake (Figure 2.3) for the purposes of gaining more representative samples of water chemistry from a wider range of locations within the site. The reader is referred to the site maps (Figure 2.2, Figure 2.3) for visual reference of piezometer locations.

3.3.2 Dissolved Organic Carbon and LC-OCD Analysis

All chemical analysis was completed at the Environmental Geochemistry Laboratory at the University of Waterloo. Dissolved organic carbon (DOC) concentrations, along with a set of standards (created using potassium hydrogen phthalate) with concentrations of 1, 2, 5, 10, and 20 mg/L were analyzed using a Shimadzu TOC-LCPH+TNM-L Total Organic Carbon analyzer (precision: ± 0.02 mg/L). Samples with DOC concentrations greater than 50 mg/L were then diluted using deionized (DI) water to be within the range of standards. Samples and standards were acidified using 20% phosphoric acid, after which they were injected into the analyzer and combusted at 680 °C, converting the DOC in CO_2. Carbon concentrations were then measured by a non-dispersive infrared (NDIR) spectrum.

DOC characterization was completed using a Liquid Chromatography-Organic Carbon Detection (LC-OCD) (precision: 0.09 mg/L) method similar to that of Huber et al. (2011) and Aukes (2012). First, samples were diluted to obtain a DOC range of 1-5 mg/L in order to gain optimal results. The LC-OCD uses a Toyopearl

HW-50S (Toso, Japan) size-exclusion column. The mobile phase is created using a pH 6.85 phosphate buffer comprised of potassium dihydrogen phosphate and sodium hydrogen phosphate dehydrate, and passes through UV-irradiation to purify it of any organics. The sample is then injected into the mobile phase and passed through an in-line 0.45 μm filter, after which, it is directed into a by-pass or the size-exclusion column. The bypass will measure the overall DOC concentration and UV-absorbance at 254 nm. Once passing through the column, the sample enters the UV Detector, after which it is acidified using phosphoric acid. The mobile phase then enters the organic carbon detector (OCD), where the sample is thinly spread over a UV-lamp, causing the organic carbon to oxidize into CO_2. A highly-sensitive infrared detector then measures the CO_2, and the data are collected over time as the sample elutes from the size exclusion chromatography (SEC) column. The results were analyzed using customized software (ChromCALC, DOC-LABOR, Karlsruhe, Germany).

The LC-OCD separates the DOC into hydrophilic and hydrophobic components, defined as the total sample that elutes from the SEC column and the fraction that remains on the column, respectively. The hydrophilic portion is further subdivided into five categories listed in order of their retention time and molecule size from largest to smallest: biopolymers (BP), humic substances (HS; includes both humic and fluvic acids), building blocks (BB), and low-molecular-weight neutrals (LMW-N) and acids (LMW-A). The elution time depends on molecule size, with the largest molecules eluting first, and the smallest molecules eluting last. The reader is referred to Aukes (2012) for a more detailed explanation of the LC-OCD analysis method and further description of its end products.

3.4 Results

3.4.1 Carbon

Dissolved organic carbon (DOC) is an important constituent of the carbon cycle, particularly where it is derived from large masses of decomposing organic material. A suite of complex biogeochemical processes that retain, transform, and release DOC into surface water bodies regulates the movement of DOC through peat. Sorptive processes are well known to potentially decrease losses of DOC to passing water, however the ability of a soil to sorb DOC is highly contingent upon the summative influences of soil texture, structure, organic matter content, and mineral composition (Scott & Rothstein, 2014; Liliefein et al., 2004). At the Airport site, there is evidence of decreasing DOC concentration along two possible flowpathways, which can potentially be attributed in part to sorptive processes. Additionally, differences in solid organic matter decomposition rates may attribute to the differences in DOC concentration observed in different areas of the sites.

Piezometer #1 (P1) is located in the cold, non-degraded area of the site that is elevated ~ 1 m above the degrading edge of the plateau (Figure 2.2) and ~ 2 m above the pond. It is possible that this gradual slope (0.03) may allow a flow pathway to exist between P1, the low-lying P2 and P3, and the pond (Figure 2.2, Figure 3.1). Due to low VWC at P1 for the majority of the summer, obtaining a large enough sample size for DOC analysis and comparison was difficult, however dramatic changes in DOC concentration were not observed at most piezometer locations between June 13 and July 16. On July 16, 2013, DOC concentration at P1 was 138.0 mg/L, while on June 13-19, 2013 DOC concentrations at P2, P3 and the pond were 101.3 mg/L, 70.9 mg/L, and 41.2 mg/L, respectively (Figure 3.1). The same pattern of DOC decrease from P1 to the pond is also present on Oct. 18, 2013 (Figure 3.3). Additionally, visual inspection of the peat topography and the presence of bog vegetation where water has pooled indicates the existence of a flow pathway originating from the raised peat plateau, to the lower lying P4 and P5. P4 is located in a seasonally wet depression where common bog vegetation, such as cotton grass, is present. P5 is located ~ 2 m toward the bog from P4, on the border where the bog meets the peat plateau (Figure 2.2). On June 13, 2013, the DOC concentration at P4 was 304.5 mg/L, while it was 116.1 mg/L at P5, and 41.2 mg/L in the pond surface water (Figure 3.1). While it is possible that a flow pathway connects each of these piezometers and could explain the large variability in DOC concentration over a relatively small distance, other possible explanations exist.

Long-term build up of DOC within stagnant or very slowly moving subsurface water could also explain the high DOC concentrations seen at the Airport site. Following all summer 2013 precipitation events, TDR probes located at Log1 and

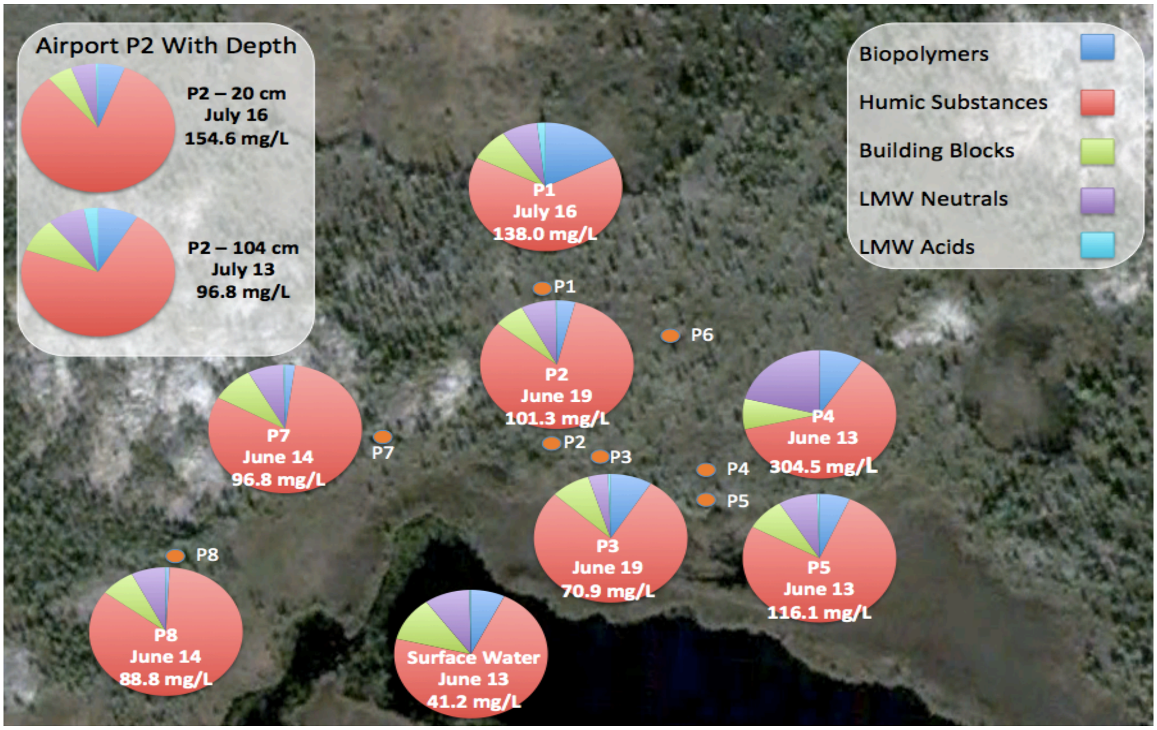


Figure 3.1: Airport site DOC concentrations (mg/L) during the 2013 thaw season for piezometers 1-5, 7-8. Decreasing DOC from P1 to P2, P3, and the pond indicates a possible subsurface flow pathway. An additional flow pathway potentially exists between P4 to P5 and the pond. Decreasing DOC concentration with depth is also indicated for P2.

Log2 indicate no change in VWC below ~ 15 cm depth, indicating that the most significant input of water to the peat below 15 cm depth is during the spring freshet (Figure 2.8). Water from the freshet infiltrates downward through the peat profile, where it remains over long time periods, contributing to prolonged freeze-back during the autumn, and also accumulating DOC as it infiltrates and remains over time. Sampling piezometers prior and subsequent to precipitation events over the course of the 2013 summer season saw no major differences in DOC concentration (Figure 3.2). Had these storm events been a significant source of water to the peat at depth, DOC concentration would be expected to increase as new DOC is carried from the surface and deposited downward in the peat profile.

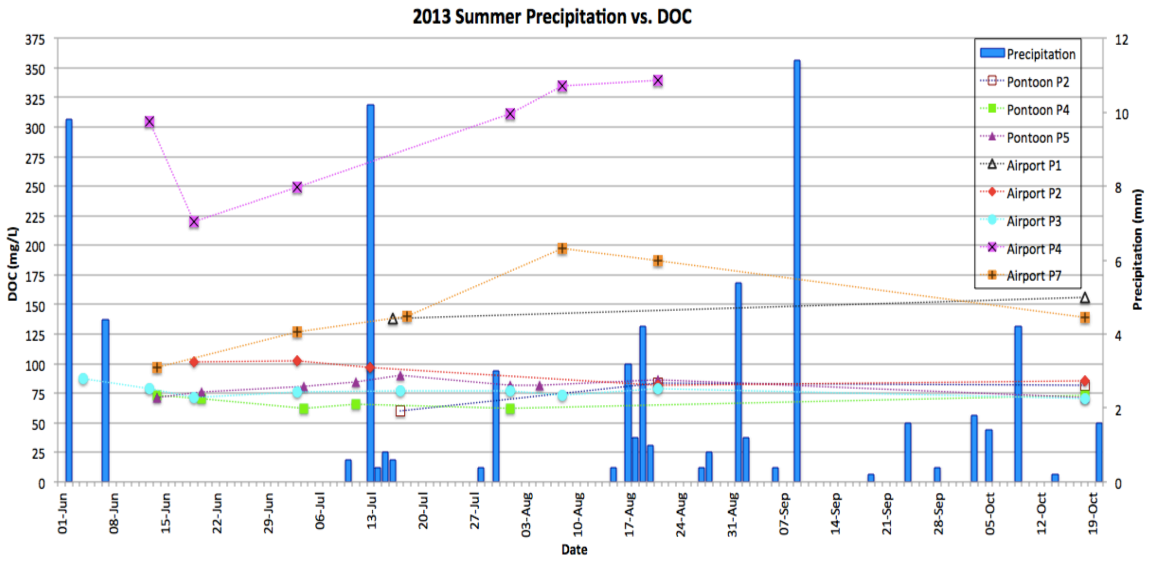


Figure 3.2: DOC concentrations (mg/L) from the Airport and Pontoon Lake sites compared to precipitation input (mm) over the course of the 2013 thaw period.

P1 at the Airport site shows a consistently elevated DOC concentration compared to many samples taken from other piezometers. Studies have shown that high flow rates do not necessarily correspond to elevated DOC concentrations. In fact, continuous flushing can act to decrease contributions of DOC to streams and surface water bodies (Schiff et al. 1998). VWC data collected at the Airport site shows little reaction to inputs from precipitation (Figure 2.8), and P1 remained relatively dry (VWC < 30%) throughout the thaw season. It's likely that the vascular plants surrounding P1 in conjunction with the extended daylight hours of the thaw season contributed to high evaporation/evapotranspiration rates, thus preventing precipitation from reaching depths greater than ~ 15 cm in the peat profile. The high DOC concentrations observed at P1 during the dry summer and early fall period could be a result of little-to-no flushing from precipitation, elevated decomposition rates under a lower water table, and warmer ground conditions compared to spring and winter. Additionally, it's well known that a burst of microbial activity often occurs following a re-wetting event of the peat after a prolonged drought period (Evans et al., 2005; Moore & Basiliko, 2006). It is possible that because P1 remained dry for the majority of the thaw season, the rare occurrence of a re-wetting event at depth accelerated DOC production rates over short time periods.

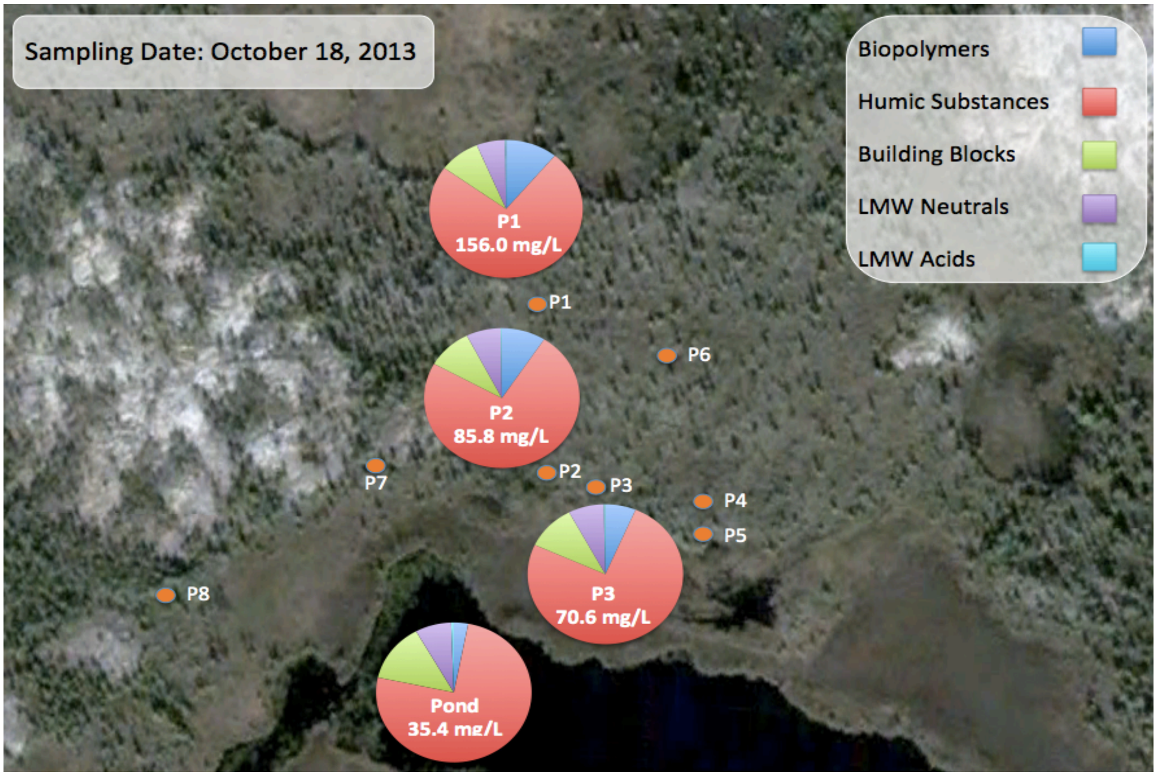


Figure 3.3: Airport site DOC concentrations (mg/L) during maximum thaw in October 2013. Decreasing DOC between P1 and the pond identifies a possible subsurface flow pathway.

Other piezometers at the Airport site also exhibited consistently elevated DOC concentrations during the 2013 thaw period, particularly P4 and P7 (Figure 2.2, Figure 3.2) where visual inspection of the surface topography, vegetation species and persistent saturation indicate these low-lying areas receive water from surrounding elevated hummocks and/or bedrock outcrops. At these locations, the water table was consistently at or very near the ground surface for the majority of the thaw season, likely resulting in anoxic conditions and indicating an upslope linkage to a water source. The elevated water table likely impedes decomposition and the production of DOC. Additionally, if we have confidence in previous studies showing a reduction of DOC from continual flushing, then it could follow that significant flushing events do not appear to be occurring at P4 and P7 due to the high DOC concentrations. Therefore, the elevated DOC concentration at P4 and P7 may not result from high production rates, but from high accumulation rates in the absence of water flushing.

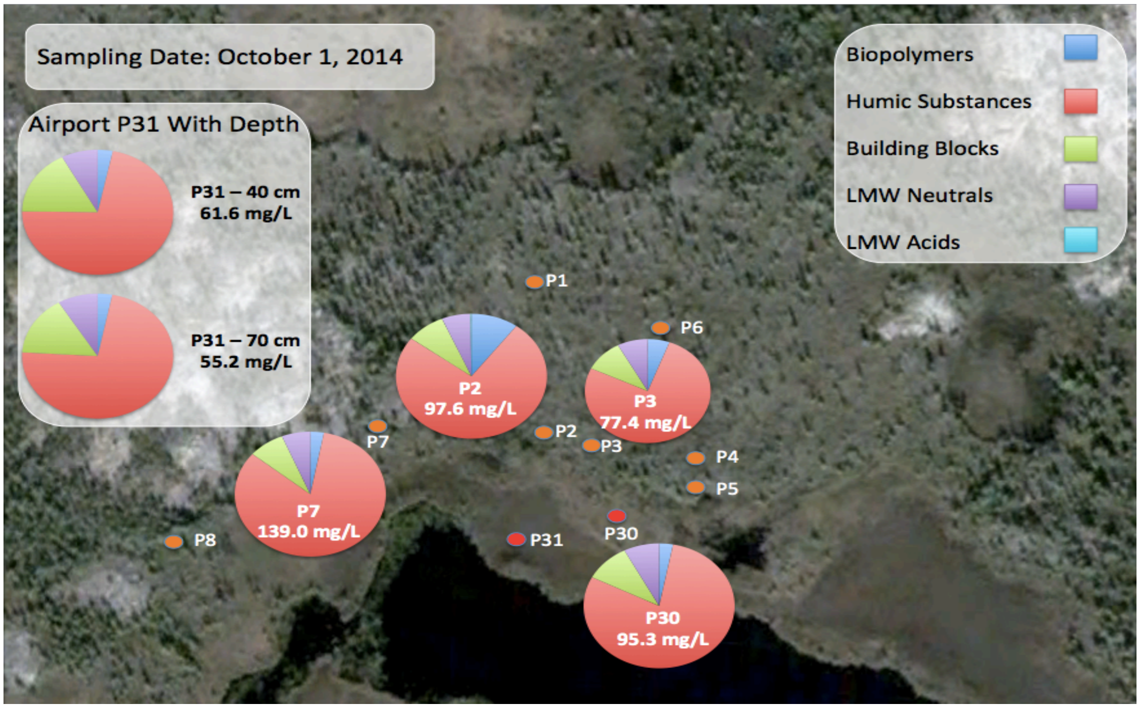


Figure 3.4: Airport site DOC concentrations (mg/L) during maximum thaw in October 2014. A new sampling location at P31 in the bog encircling the pond indicates decreasing concentration with depth similar to P2 in July 2013.

DOC concentration is also subject to change with depth in the soil profile, which was observed at the Airport and Pontoon Lake sites in July 2013 at P2 and October 2014 at P31 in the bog encircling the Airport site pond (Figure 3.1, Figure 3.4). As the litter-bag experiment demonstrated, the highest rates of decomposition are found closest to the ground surface where oxygen is plentiful, ground temperatures are high, and the input of fresh litter and recently synthesized labile organic matter is available (Moore et al., 2007). These shallow, organic rich horizons with high dissolved organic matter (DOM) production rates are often the locations of new, labile carbon, while old recalcitrant carbon remains at depth. At the Airport site on July 16, 2013, P2 at 20 cm has a DOC concentration of 154.6 mg/L, while the DOC concentration at 104 cm is significantly lower at 96.8 mg/L (Figure 3.1). However, it does not appear that the sample obtained from 20 cm depth is more labile than the sample from 104 cm depth. In fact, the deeper sample contains higher fractions of the more labile building blocks, low molecular weight (LMW) neutrals and LMW acids, while the shallower sample contains a higher proportion of humic substances, which are more resistant to breakdown. While the DOC concentration at P31 on October 14, 2014 also decreased from 61.1 mg/L at 40 cm to 55.2 mg/L at 70 cm, almost no differences were observed in composition (Figure 3.4). The lack of changes in C composition between 40 cm – 70 cm and the comparatively low C concentration at P31 could indicate that the higher quality, labile, more readily available C is above 40 cm depth. The low DOC concentration could also indicate slow organic matter decomposition rates, likely as a result of anaerobic conditions for prolonged periods of time at depth in the bog.

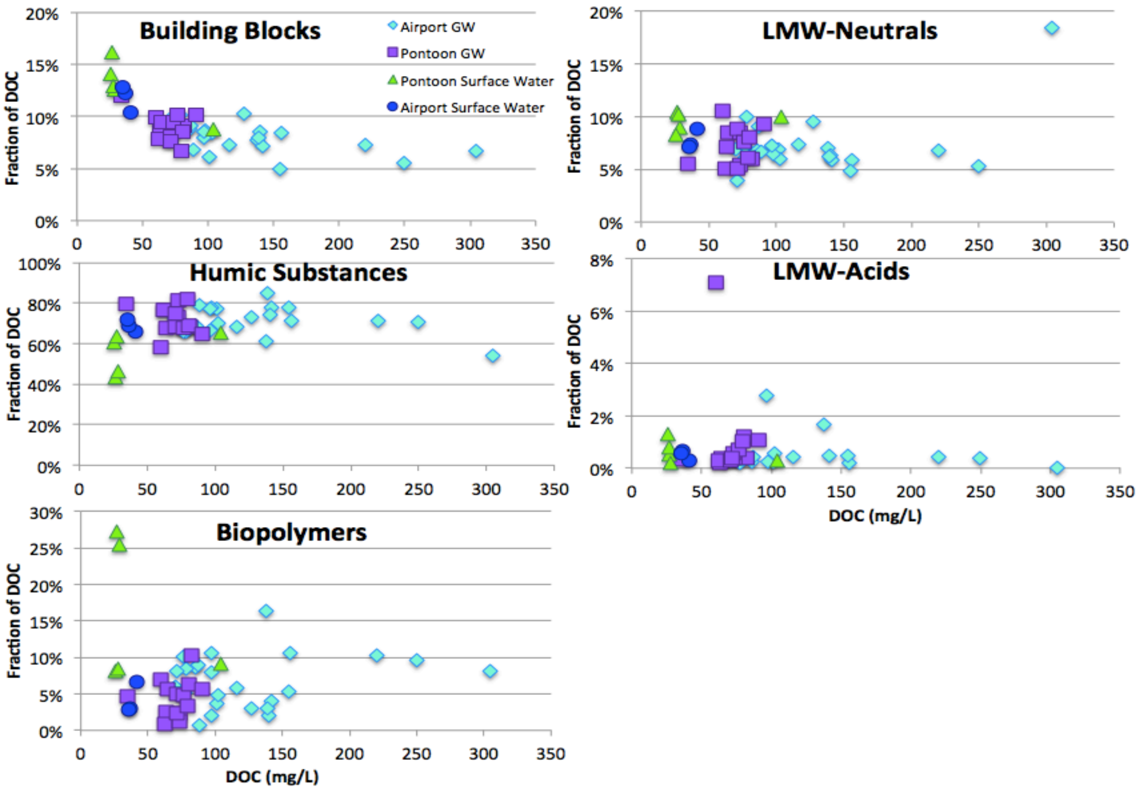


Figure 3.5: Compositional breakdown of DOM components vs. DOC concentration (mg/L). The five main compositional categories are included: building blocks, humic substances, biopolymers, and low molecular weight neutrals and acids. All samples collected and analyzed using the LC-OCD method are represented, including surface water samples from both research sites.

The overall composition of the DOM across the Airport site remained relatively consistent during the sampling periods. In most cases, HS and BB comprised the majority of the sample, with LMW-N and BP comprising the rest (Figure 3.5). LMW-A comprised a very small fraction in all cases, ranging from 0.2% - 2% of the sample, while HS generally comprised 60% - 80% of total DOM. These results indicate that fresh DOM leached from surface litter is likely rapidly degraded, leaving behind a recalcitrant form of DOM comprised mainly of HS with a small proportion of LMW molecules. Given that the proportion of HS remains high within all the samples taken, it is likely that microbes preferentially consume the LMW molecules and leave behind a more aromatic, lower quality and less labile form of DOM following decomposition.

At Pontoon Lake, DOC concentrations are consistently lower than those at the Airport site, while some similar patterns in DOM composition are observed (Figure 3.5). As with the Airport site, samples obtained from the surface water bodies of Pontoon Lake and the Pontoon pond contain lower concentrations of DOC than samples obtained from the peatland (Figure 3.6). The lowest proportions of the recalcitrant HS were found in samples from Pontoon Lake, comprising 43 – 46% of the total DOM, or just over half the proportion of HS found in groundwater samples from both research sites. This could be explained by a number of processes that alter the composition of DOM, particularly microbial transformation and UV irradiation (Aukes, 2012). Multiple studies have determined that photochemical transformations of HS can degrade DOM into more labile components (de Haan, 1993; Sulzberger & Durisch-Kaiser, 2009; Aukes, 2012). Additionally, the irradiation of natural organic matter (NOM) has been found to increase LMW fractions, which resulted in an increase in biodegradability of NOM (Dahlén et al., 1996; Frimmel, 1998; Aukes, 2012). It is likely that the lower proportion of HS and the higher proportion of LMW molecules found in the samples obtained from the water surface at the Pontoon pond and particularly from Pontoon Lake can be attributed to compositional changes caused by UV irradiation, in addition to low DOC production rates (Figure 3.6). While surface water samples obtained from each site were collected at the water surface, it is likely that DOM composition changes dramatically with increasing depth in the water column as DOC at shallower depths absorbs incoming UV radiation.

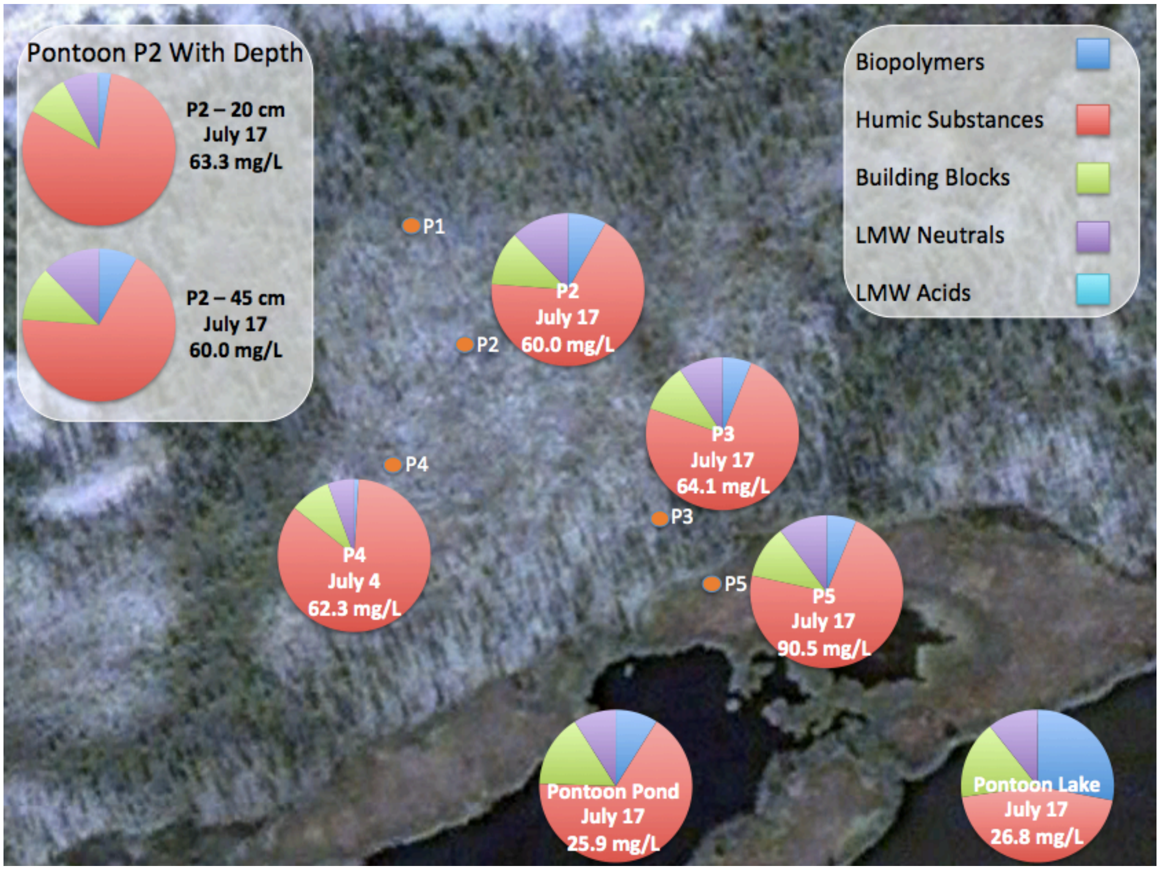


Figure 3.6: Pontoon Lake DOC concentrations (mg/L) during July 2013 showing reduced concentrations in surface waters and a decreasing DOC concentration with increasing depth in the peat profile at P2.

The LC-OCD can further characterize HS to determine whether it is comprised more of humic or fluvic acids. In doing so, the source of the HS can be determined. Humics that are of higher molecular weight and aromaticity are comparable to humics formed in pedogenic environments. Humics of lower molecular weight and aromaticity are more like microbial-derived humics (Pieter Aukes, *pers. comm., 2014*). The differentiation between pedogenic and microbial-derived humics provides information on the rate of DOM degradation. A shift from a pedogenic to a microbial origin indicates active microbial degradation and a shift from more aromatic and lower quality HS to lower molecular weight and aromaticity HS is occurring. The HS-diagram illustrates the shifts seen in HS between June 2013 and October 2014 (Figure 3.7).

It is evident that patterns of active microbial breakdown of DOM and degradation of solid organic material and thus production of DOC are occurring at both of the research sites. The Airport site HS diagram indicates two general sample clusters: the samples originating from areas where surface ponding existed for the majority of the thaw season and thus the entire peat profile remained saturated, and samples originating from areas where saturation may have existed, but not in the upper ~ 30 cm of peat. The P4, P7, and P8 piezometers were all located in areas where the growth of healthy bog vegetation (sphagnum mosses, cotton grass) exists in addition to persistent surface ponding and peat saturation (Figure 2.2). Each of these locations experienced very little change in molecular weight and aromaticity as the thaw season progressed (Figure 3.7), indicating low microbial activity, reduced DOC production, and slow rates of biodegradation. Each of these piezometers are also located in low-lying areas, acting as catchments for upslope water sources. P7 lies at the base of a bedrock outcrop, while P4 is in a depression at the interface between the bog and peat plateau. The elevated DOC concentrations found at each of these locations (Figure 3.2) suggest high solid organic matter decomposition rates, however the HS diagram indicates only small shifts in molecular weight and aromaticity. This could mean that the production of DOC may not be occurring within the saturated conditions of P4 and P7, but that outside sources of DOC are accumulating in these low-lying catchments.

Alternatively, P2, P3 and P5 in the visibly degraded areas of the site (Figure 2.2) where no vascular plants exist and surface ponding is minimal show significant shifts from a pedogenic origin to a microbial origin, indicating active microbial processes are occurring. P2 in particular shows the largest shift from pedogenic processes to a microbial processes, both with increasing depth in the peat profile and over the timespan of the 2013 thaw season (Figure 3.7). Canadian subarctic peatlands accumulate peat at an average rate of 0.31 mm/yr (Gorham, 1991; Britta et al., 2009), meaning at P2, the organic material at 104 cm is centuries, if not millennia, older than the material at 20 cm. The solid material at 104 cm has been exposed to microbial degradation for a longer time period and is of lower molecular weight and aromaticity than the material at 20 cm, meaning it is likely more easily consumed by microbes than the complex, HMW compounds comprising the material at 20 cm. Additionally, the significant shift observed in the P2 samples between June 19 and October 18 indicates that microbial degradation, and thus the production of DOC, did occur over the course of the thaw season.

P1 in the dry, non-degraded portion of the site (Figure 2.2) also experienced a comparatively large decrease in molecular weight and aromaticity (Figure 3.7), indicating active decomposition of DOM. In the absence of saturation, oxic conditions in combination with repeated wetting and drying are conducive to accelerated decomposition rates. Unlike a saturated site, a dry site has greater decomposition potential due to the lowered water table and exposure to oxygen. While the organic material deposited on the surface of a dry site experiences oxic conditions for decades as it is incorporated deeper into the peat profile, material at

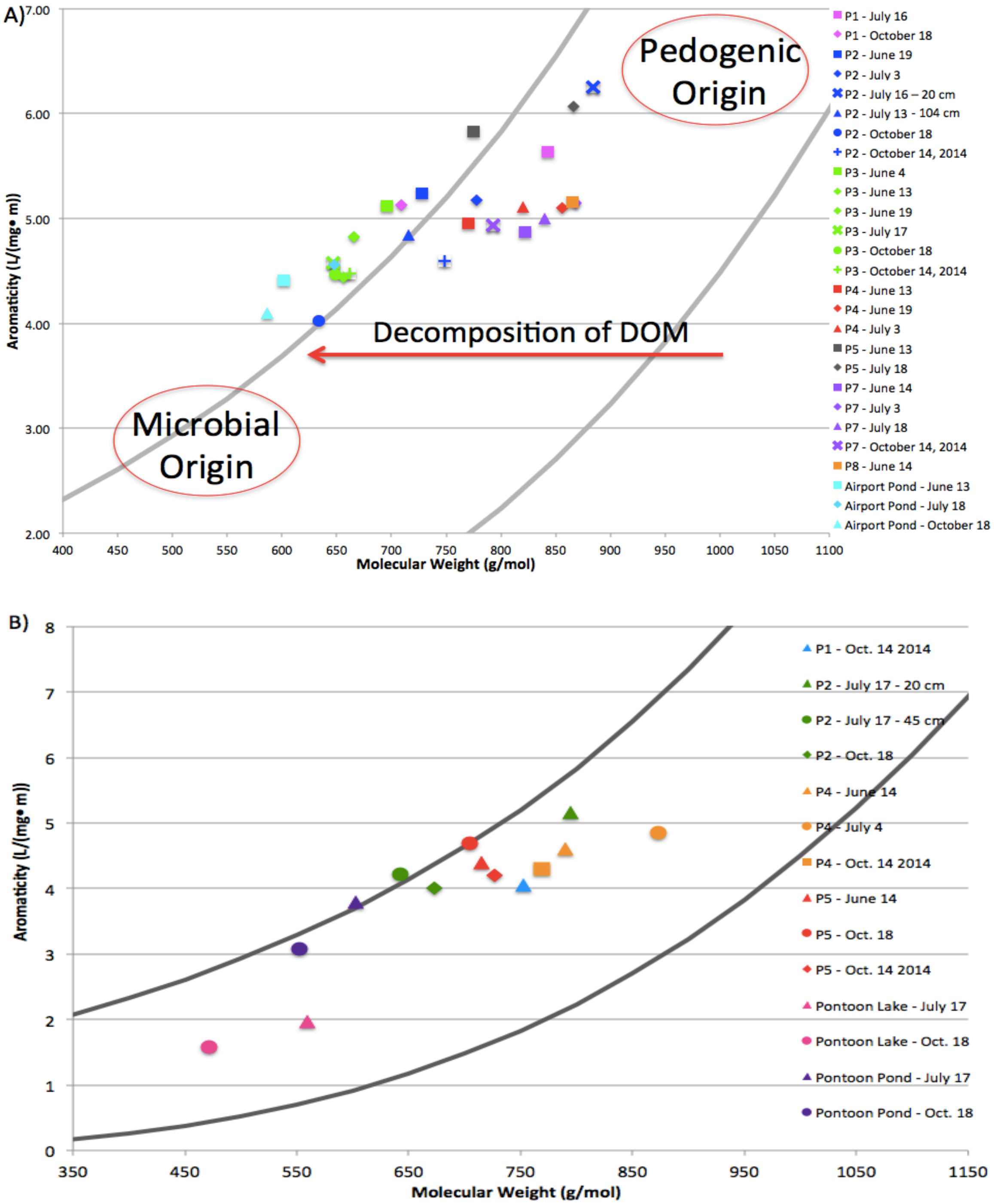


Figure 3.7: Humic substances diagram illustrating the humic aromaticity (L/mg·m)) versus humic molecular weight (g/mol) of humics from samples collected from ground and surface water environments. A) Ground water environments include samples from piezometers located in the degraded and non-degraded areas of the Airport site, while the pond is identified as the main surface water environment sampled. B) Samples obtained from piezometers at the Pontoon Lake site representing variable canopy cover and stage of peat degradation. Surface water environments include Pontoon Lake and the adjacent Pontoon pond. All dates

correspond to the 2013 season unless otherwise stated. Black lines indicate the boundaries of natural waters, as suggested by Huber et al. (2011)

a wet site will decompose much more slowly as anoxic conditions dominate the entire peat profile. Therefore, the decomposition potential is greater at a site where saturation does not exist in the upper peat profile, allowing organic material to reach its maximum mass losses before transitioning into the anoxic zone below the water table (Laiho, 2006).

At Pontoon Lake, similar shifts are present, particularly in the P2 and surface water samples (Figure 3.7). Like P2 at the Airport site, P2 at Pontoon Lake exhibits a shift in both aromaticity and molecular weight as depth increases from 20 cm to 45 cm below the ground surface. P2 is located in an actively degrading depression (Figure 2.3) with a water table at ~ 35 cm depth on July 17, after previously being ponded following snowmelt in early June. The July 17 samples indicate a decrease in molecular weight and aromaticity with an increasing depth in the peat profile as decomposition advanced with depth from 20 cm to 45 cm. However, between July 17 and October 18, no shift on the HS diagram occurs, indicating a very slow rate of biodegradation and low levels of microbial activity at 45 cm during the thaw season. It's possible that because VWC remained elevated (> 80%) below 25 cm in the peat profile (Figure 2.6), degradation may have been slowed under a depleted oxygen supply. A similar scenario may also be occurring at P5, which saw very little change from June 2013 to October 2014 (Figure 3.7).

P5 at Pontoon Lake sits in a saturated sphagnum bog (Figure 2.3) where healthy vegetation exists bordering the peat plateau. During the 2013 thaw season, the bog remained saturated below ~ 10 cm depth, likely resulting in anoxic conditions throughout the thawed portion of the profile. Because anaerobic decomposition is significantly slower than aerobic decomposition (Laiho, 2006), it is possible that the rate of humic decay in the anoxic conditions is very minimal, causing every sample originating from saturated conditions (Airport P4 and P7, Pontoon P5) to show minimal shifts on the HS diagrams over the course of the 2013 thaw season (Figure 3.7)

The surface water samples from both the Airport and Pontoon Lake sites also indicate a shift towards lower molecular weight and aromaticity of HS (Figure 3.7). This can likely be attributed to a combination of low lever of DOC production and microbial activity and UV irradiance breaking down HMW molecules at the water surface. It is likely that because DOC in the upper water column absorbs incoming UV radiation, in the absence of water column mixing the aromaticity and molecular weight likely increase with water depth as conditions likley become anoxic and microbial activity slows.

The LC-OCD can further characterize DOM through the use of ultraviolet (UV) absorption to gain information about relative aromaticity of the DOM. The specific UV absorbance (SUVA; absorbance at 254 nm standardized to DOC concentration) has been documented to positively correlate with DOM aromaticity, and in turn, the bioavailability of the DOM. An increase in SUVA is correlated to an overall increase in the aromaticity of the DOC, which in turn suggests an increase in the proportion of HMW molecules and a decrease in biodegradation (Kalbitz et al., 2003). While SUVA is not a direct measurement of aromaticity but rather a measurement of absorbance that has been correlated to aromaticity, it can still provide valuable information about the quality of DOC found at the Airport and Pontoon Lake research sites. While surface water samples collected from each site contain the largest variability in SUVA values, likely due to UV breakdown of DOM, there are distinct differences in SUVA values from groundwater samples obtained at the Airport site versus those obtained from Pontoon Lake. In most cases, groundwater samples from the Pontoon Lake site represent a lower SUVA than samples from the Airport site (Figure 3.8), indicating a potentially higher amount of biodegradation and likely an elevated source of DOC.

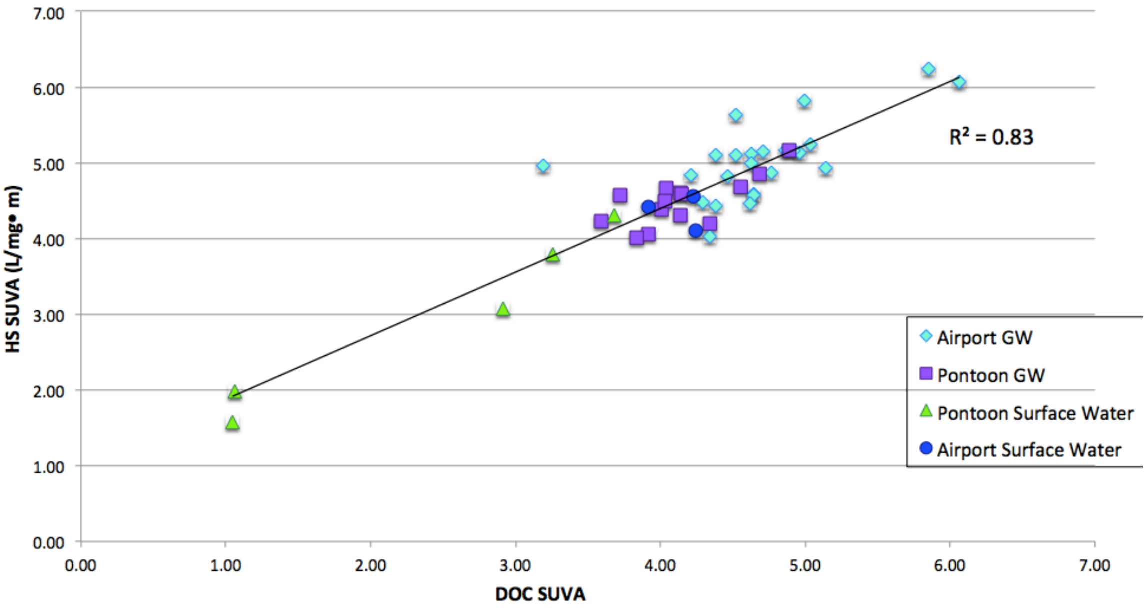


Figure 3.8: Illustrating the strong linear relationship between DOC SUVA and HS SUVA for all ground and surface water samples collected from the Airport and Pontoon Lake sites over the 2013 summer season. Surface water samples generally represent the lowest DOC SUVA and HS SUVA, with the Airport groundwater samples representing the highest SUVA and aromaticity.

Although not particularly high in quality or lability, the concentrations of DOC in the samples from both the Airport and Pontoon lake sites are exceptionally high (Figure 3.2). Typical DOC concentrations range between 2 – 25 mg/L in surface waters and 0.1 – 17 mg/L in ground waters (Aukes, 2012). It is not uncommon for litter leachate to reach DOC concentrations of 100 mg/L or more, however the concentration usually decreases rapidly with depth in the soil profile due to sorptive processes. At the Airport site, DOC concentrations reached 155 mg/L at 70 cm depth, indicating a large, potentially mobile carbon stock throughout the entire peat profile.

3.5 Discussion

3.5.1 Carbon Accumulation at Depth

The high decomposition rates observed at both research sites create potential for increased DOC production and downward leaching of the important nutrients carbon and nitrogen. While decomposition below approximately 40 cm may be inhibited by the presence of a water table and resulting anoxic conditions in addition to cold temperatures, DOC concentrations are still elevated down to approximately 70 cm. The results of the carbon portion of this study provide some insight into the composition, quality and most-likely sources of the elevated DOC concentrations found throughout both research sites. The leaching of DOC from the surface to depths exceeding 70 cm is likely due to the downward pulsing of water during the spring freshet. As the most significant source of water to the peat at depth over the entire year, the freshet, generally lasting 2-3 weeks, has the potential to carry large concentrations of DOC from the rapidly decomposing surface layer, to the less biodegradable and colder catotelm. Additionally, as the freezing front migrates downward through the peat profile during freeze-back, impurities are absolved from the water during ice formation, concentrating DOC at depth. In addition to the downward leaching of DOC from the peat surface, the absolving of DOC from the downward moving freezing front may also contribute to the accumulation of DOC at lower depths in the peat profile (Adams & Allan, 1987). As the slow breakdown of this DOM progresses, it leaves behind a more aromatic and lower quality (less labile) form (Aukes, 2012). The decreases in DOC concentration with increasing depth observed at the Airport site at P2 (Figure 3.1) and P31 (3.4), as well as at Pontoon Lake at P2 (Figure 3.6), support the litterbag results from Chapter 2 indicating slower decomposition, and thus reduced DOC production, as depth increases (Table 2.6). Additionally, the high proportion of HS (Figure 3.6) in the samples indicates that although decomposition is occurring, the DOM is of poor quality to soil microbes and will likely remain and accumulate further under restricted decomposition conditions at depth.

As VWC data from Chapter 2 suggests, the spring freshet is the most significant source of water to the peat throughout the entire year (Figure 2.8). At both the Airport and Pontoon Lake sites, peat VWC below 15 cm failed to increase significantly following a precipitation event. Therefore, it is assumed the largest pulse of DOC through the peat profile occurs during snowmelt. Following infiltration, the snowmelt water likely remains mostly stagnant within the peat at depth where it either reenters the hydrological cycle by means of evapotranspiration, or very slowly moves downslope towards open water, carrying with it large concentrations of DOC. A version of this process was potentially observed at the Airport site at P4 and P7, whereby DOC concentrations were high (Figure 3.2) but the HS diagram indicated very low microbial decomposition of humics (Figure 3.7). The surface topography surrounding P4 and P7 indicates the possibility that these piezometers may be receiving drainage from the peat plateau and an upslope bedrock outcrop, respectively, leading to the accumulation of DOC in the absence of decomposition under saturated conditions.

3.5.2 DOM Composition

The data provided by the LC-OCD analysis revealed patterns and differences in DOM composition on both spatial and temporal scales. Over time, the composition of the DOM did not appear to change dramatically, with the highest proportion of DOM comprised of HS in all samples. The labile components of DOM can be considered as those that were consistently low in each sample, or those that fluctuated throughout the thaw season. While HS and BB remained relatively consistent within all DOM samples, proportions of BP, LMW-N, and LMW-A were consistently low or fluctuated throughout the sampling period.

The HS-diagrams (Figure 3.7) are a useful tool in distinguishing differences in HS character and molecular weight distribution, and offers valuable information about the decomposition rate of HS. Although not all samples indicated significant change, P2 in the warm, wet and degrading portions of the Airport site saw a decrease in molecular weight, over both the timespan of the thaw season and with increasing depth in the peat profile, indicating the most significant case of a change in the character of HS. The same shifting pattern in HS character with increasing depth in the peat profile was observed at P2 at Pontoon Lake, however at 45 cm depth, a shift in HS was not observed over the thaw season. Likely due to saturated conditions below ~ 30 cm depth, the HS diagram reveals that decomposition of humics was very slow where VWC was elevated, potentially due to slow microbial breakdown in what are assumed to be anaerobic conditions.

The composition of the majority of samples from both research sites represents a recalcitrant form of DOM, characterized by elevated proportions of HS. Some studies (Tranvik, 1993; Hur et al., 2009; Aukes, 2012) have found non-humic components of DOM to be more bioavailable than HS. Thus, the high proportions and stability of HS within the samples, in conjunction with the low or non-existent proportions of LMW molecules, suggests that humics may not be rapidly degraded by microbes and are therefore considered low quality, less labile components of DOM. The inability of microbes to efficiently break down the complex HS leads to a drawn out degradation of these recalcitrant compounds, allowing the accumulation of DOM at depth over centuries. While a large portion of the accumulated DOM remains encased within permafrost, climate warming has the potential to accelerate and prolong thaw periods, warming and melting the deeper and permanently frozen peat, thus enabling the previously sequestered DOM to become environmentally available once again.

3.6 Conclusions

The carbon portion of this study evaluated the quality and lability characteristics of the DOM originating from the Airport and Pontoon Lake research sites, with the key findings of the study outlined below:

1) While decomposition rates of solid organic material and DOC concentrations of both research sites remained elevated, the quality of the DOM was not high. Although active microbial degradation of DOM was observed, the

composition of the DOM as identified by the LC-OCD analysis was mainly comprised of HS, with very few LMW molecules found throughout the sampling period.

2) While groundwater DOC concentrations at Pontoon Lake were lower than those at the Airport site, the composition, and thus quality of the DOM, did not change significantly between the two sites. Furthermore, DOC concentration changes over the course of the 2013 thaw season did not appear to be influenced by precipitation events, or by increasing ground temperatures as thawing of the active layer progressed.
3) The study determined that water movement through the peatland for the majority of the thaw season is likely minimal, allowing the build up of DOC within depressions over long time periods. Although DOC production at the peat surface is likely elevated due to high solid organic matter decomposition rates, saturation at lower depths of the peat profile likely inhibits DOC production while DOM is slowly degraded over time. While there is potential for mass DOC release into surface water bodies, it is unlikely to take place unless multiple large flushing events occur in conjunction with elevated decomposition rates and continuous degradation of the permafrost underlying the peatland.
4) The HS diagrams reveal patterns in the breakdown of HS whereby consistently saturated areas experiencing prolonged surface ponding are subject to very slow decomposition rates. Alternatively, where saturation does not exist in the upper ~ 30 cm of the peat profile, decomposition, and

thus the production of DOC, is occurring. Additionally, areas where high DOC concentrations were found in conjunction with very slow rates of biodegradation suggest that DOC is originating from upslope sources and accumulating over time in low-lying catchment depressions.

References

Adams, W. P., Allan, C. 1987. Aspects of the chemistry of ice, notably snow, on lakes. *Seasonal Snowcovers: Physics, Chemistry, Hydrology.* NATO ASI Series. 211, 393-466.

Aukes, P. 2012*. Use of liquid chromatography – organic carbon detection to characterize dissolved organic matter from a variety of environments*. Unpublished master's thesis, Waterloo University, Waterloo, Canada.

Brady, N. C., Weil, R. R. 2010. *Elements of the nature and properties of soils*, 3rd edn. Boston, MA. Prentice Hall.

Britta, A., Sannel, K., Kuhry, P. 2008. Holocene peat growth and decay dynamics in sub-arctic peat plateaus, west-central Canada. *Boreas.* 38, 13-24.

Dahlén, J., Bertilsson, S., Pettersson, C. 1996. Effects of UV-A irradiation on dissolved organic matter in humic surface waters. *Environment International.* 22, 501-506.

Evans, C. D., Monteith, D. T., Cooper, D.M. 2005. Long-term increases in surface water dissolved organic carbon: Observations, possible causes and environmental impacts. *Environmental Pollution.* 137, 55-71.

Freeman, C., Fenner, N., Ostle, N. J., Kang, H., Dowrick, D. J., Reynolds, B., Lock, M. A., Sleep, D., Hughes, S., Hudson, J. 2004. Export of dissolved organic carbon from peatlands under elevated carbon dioxide levels. *Nature*. 430, 195-198.

Frimmel, F. H. 1998. Impact of light on the properties of aquatic natural organic matter. *Environment International.* 24, 559-571.

Gorham, E. 1991. Northern peatlands: Role in the carbon cycle and probable responses to climatic warming. *Ecological Applications.* 1, 182-195.

De Haan, H. 1993. Solar UV-light penetration and photodegradation of humic substances in peaty lake water. *Limnology and Oceanography.* 38, 1072-1076.

Huber, S. A., Balz, A., Abert, M., Pronk, W. 2011. Characterisation of aquatic humic and non-humic matter with size-exclusion chromatography – organic carbon detection – organic nitrogen detection (LC-OCD-OND). *Water Research.* 45, 879-885.

Hur, J., Park, M. H., Schlautman, M. A. 2009. Microbial transformation of dissolved leaf litter organic matter and its effects on selected organic matter operational descriptors. *Environmental Science & Technology.* 43, 2315-2321.

IPCC, 2014: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 688 pp.

Kalbitz, K. J., Schmerwitz, D., Schwesig, D., Matzner, E. 2003. Biodegradation of soil-derived dissolved organic matter as related to its properties. *Geoderma*. 113, 273-291.

Laiho, R. 2006. Decomposition in peatlands: Reconciling seemingly contrasting results on the impacts of lowered water levels. *Soil Biology & Biochemistry.* 38, 2011-2024.

Lilienfein, J., Qualls, R. G., Uselman, S. M., Bridgham, S. D. 2004. Adsorption of dissolved organic carbon and nitrogen in soils of a weather chronosequence. *Soil Science Society of America*. 68, 292-305.

Limpens, J., Berendse, F. 2003. How litter quality affects mass loss and N loss from decomposing *Sphagnum*. *Oikos.* 103, 537-547.

Marhaba, T. F., Van, D. 2000. The variation of mass and disinfection by-product formation potential of dissolved organic matter fractions along a conventional surface water treatment plant. *Journal of Hazardous Materials.* 74, 133-147.

Moore, T. R., Bubier, J. L., Bledzki, L. 2007. Litter decomposition in temperate peatland ecosystems: The effect of substrate and site. *Ecosystems.* 10, 949-963

Moore, T.R., Basiliko, N. 2006. Decomposition in Boreal Peatlands, in *Boreal Peatland Ecosystems.* 125-143. Berlin, Germany. Springer.

Oke, T. R. 1978. Boundary Layer Climates. Routledge, Cambridge, p. 435.

Schiff, S., Aravena, R., Mewhinney, E., Elgood, R., Warner, B., Dillon, P., Trumbore, S. 1998. Precambrian Shield wetlands: Hydrologic control of the sources and export of dissolved organic matter. *Climatic Change.* 40, 167-188.

Schindler, D. W., Curtis, P. J., Parker, B. R., Stainton, M.P. 1996. Consequences of climate warming and lake acidification for UV-B penetration in North American boreal lakes. *Nature*. 379, 705-708.

Scott, E. E., Rothstein, D. E. 2014. The dynamic exchange of dissolved organic matter percolating through six diverse soils. *Soil Biology & Biochemistry.* 69, 83-92.

Spence, C., Kokelj, S. V., Ehsanzadeh, E. 2011. *Precipitation trends contribute to streamflow regime shifts in northern Canada.* Proceedings of symposium H02 during the International Union of Geodesy and Geophysics 2011 conference, Melbourne, Australia, July, 2011. 346, 3-8.

Sulzberger, B., Durisch-Kaiser, E. 2009. Review Article: Chemical characterization of dissolved organic matter (DOM): A prerequisite for understanding UV-induced changes of DOM absorption properties and bioavailability. *Aquatic Sciences.* 71, 104-126.

Tranvik, L. J. 1993. Microbial transformation of labile dissolved organic matter into humic-like matter in seawater. *FEMS Microbiology Ecology.* 12, 177-183.

Yavitt, J. B., Williams, C. J., Weider, R. K. 1997. Production of methane and carbon dioxide in peatland ecosystems across North America: effects of temperature, aeration, and organic chemistry of peat. *Geomicrobiology Journal.* 14, 299-316.

Chapter 4

Assessing the Effects of Climate (Temperature and Precipitation) on DOC Release from Peat

4.1 Introduction

Arctic permafrost regions are estimated to contain 1700 Pg of organic carbon (OC), which is approximately twice the currently estimated C stock of the entire atmosphere or approximately 50% of the estimated below-ground global organic C pool (Elberling et al., 2013; Spencer et al., 2015). Most of this C has been locked within permafrost for centuries, excluded from the contemporary C cycle and resistant to microbial degradation. However, increasing evidence of permafrost thaw in the circumpolar north creates uncertainties for the fate of these massive C stocks. Numerous studies have highlighted long-term permafrost loss and active layer thickening in peatlands throughout the circumpolar zone of discontinuous permafrost (Wright et al., 2009; Guan et al., 2010; Baltzer et al., 2014; Spencer et al., 2015), leading to ground surface subsidence and having dramatic implications for the hydrological and thermal properties of the system (Williams, 2012). Despite exporting more organic carbon (OC) per unit area than any other biogeographical land type in the world (Reynolds & Fenner, 2001), thawing permafrost continues to alter the functioning of these systems, potentially having global consequences for the C cycle and accelerating global warming. While DOC is a ubiquitous component of the freshwater C cycle, the consequences of its increased export include altering the thermal regime of surface water bodies through the attenuation shortwave radiation, reducing primary productivity below the water surface, mobilizing heavy metals and influencing metal solubility, and implications for human health due to its role as a precursor of carcinogenic disinfection by-products. (Aukes, 2012; Peacock et al., 2014). As such, examining DOM composition characteristics to determine its quality as a food source for soil microorganisms is necessary. To address this, DOM can be characterized using ultraviolet (UV) absorption.

As aromatic structures and unsaturated carbon entities absorb the UV, specific ratios can be used to determine the relative aromaticity or molecular size distribution of the DOM (Aukes, 2012). Specifically, the E_2:E_3 ratio uses the absorbance at 250 and 365 nm, respectively, as an indicator of DOM aromaticity and molecular weight (Dahlen et al., 1996; Agren et al., 2008), while the specific UV absorbance (SUVA; absorbance at 254 nm standardized to DOC concentration) has been found to be well correlated to the degree of aromaticity (Weishaar et al., 2003; Aukes, 2012). Additionally, an increasing E_2:E_3 ratio may be interpreted as an increasing proportion of the higher quality low molecular weight (LMW) compounds, corresponding to a decrease in UV absorbing humic compounds. While UV techniques are commonly used in DOM characterization, they are usually used in conjunction with other DOM characterization techniques, such as the LC-OCD method, to determine a more detailed account of the specific fractions comprising the DOM.

The predicted changes in subarctic climate are conducive to elevating the probability of increased microbial activity and thus decomposition rates and DOC production, as elevated soil moisture combined with increasing air temperatures warm the peat and prolong the freeze-back period in the fall, thus extending the period of time when microbial activity is significant. In the subarctic landscape, terrestrial-to-surface water flowpathways link peat formations with surface water bodies. Where these flowpathways exist it would be expected that water bodies receiving this drainage will experience elevated concentrations of dissolved organic matter (DOM), of which dissolved organic carbon (DOC) comprises approximately 50% by mass. The role these unique environments play in elemental transformations and transport means that their importance to global biogeochemical cycling and sequestration is much greater than their proportional surface area coverage would suggest (Schlesinger & Bernhardt, 2013).

The data presented in Chapter 2 and Chapter 3 of this thesis suggests that the physical microtopographical structure of the peatland, *i.e.* the proportion of hummocks to depressions, is perhaps the strongest determinant of future degradation. Due to their ability to redirect snowmelt water into low-lying depressions, hummocks are hydrologically important to the peat plateau, while they are also potential contributors of large DOC mass to surrounding depressions and surface water bodies. Litter-bag results presented in Chapter 2 highlight the rapid decomposition of fresh organic debris contained within the top 10 cm of the peat profile. As a by-product of decomposition, large masses of DOC are potentially created in this surface layer, which wets and dries frequently in accordance with precipitation input. Additionally, results from piezometer #1 (P1) at the Airport site show (Figure 2.2, Figure 2.8, Figure 2.9), the dry and non-degrading areas of the site, similar to hummocks, maintain an elevated DOC concentration as compared to water samples taken from the degraded portion of the site near the pond. It is thought that the repetitive dry periods experienced by hummocks throughout the thaw season cause a burst of microbial activity following re-wetting by snowmelt or precipitation (Evans et al., 2005; Moore & Basiliko, 2006). Increased air temperature during the summer months elevates evaporation rates, increasing the depth of oxidation of the peat as well as depth to the water table. The combination of these events, in addition to non-limited nitrogen (N) availability, leads to increased microbial activity and thus decomposition when the dry peat re-wets. If infiltrating water is redirected from hummocks into adjacent depressions, significant contributions of DOC from hummocks to depressions may occur.

During the spring freshet, the large influx of snowmelt water creates the potential for water movement within the peat, exporting large masses of DOC into downslope surface water bodies. Thus, quantifying the input of DOC from water infiltrating and moving from a hummock into a depression is important in order to estimate future potential export. For the same purposes, quantifying the DOC concentration of water that infiltrates and remains stagnant in the peat, similar to that of a depression, is also of key importance. Coupling this information with DOM composition information provided by the LC-OCD, DOC molecular weight distribution information, nitrogen availability, as well as variable temperature and water input may be insightful in determining the key drivers behind elevated DOC concentrations in peat.

4.2 Objectives

The profound influence of peatland microtopography on the hydrological functioning of these climatically sensitive landscapes has been explored in Chapter 2 of this thesis. During the largest hydrological event of the year, the spring freshet, hummocks direct meltwater downslope into low-lying depressions. As depressions remain ice-saturated during this early stage of active layer thaw, water begins to pool, changing the surface albedo and ultimately influencing the thermal properties of the peat for the remainder of the summer season. As the subarctic climate warms, there is potential for an increased frequency of extreme weather events, which could alter the existing pattern of peat wetting and drying. Changes in the patterns and frequency of peat wetting and drying may potentially alter DOC export from peat, as well as the C composition and quality. As such, the overall goal of this chapter will be to quantify the potential export of DOC and N from hummocks and depressions, and measure how seasonal changes in climate (temperature, precipitation) may affect the export and quality of DOC. Using a BioChambers growth chamber, this goal will be achieved by meeting the following specific objectives:

1) to conduct a laboratory core experiment on a peat monolith extracted from the Airport Site, outside of Yellowknife, NT, in order to determine if DOC export from a hummock is potentially a significant contributor to DOC accumulation in depressions;
2) to simultaneously replicate the climatic and hydrological conditions of a hummock and a depression using peat monoliths to determine if DOC quality and export is affected by changes in temperature and fluctuating volumetric moisture content of the peat.

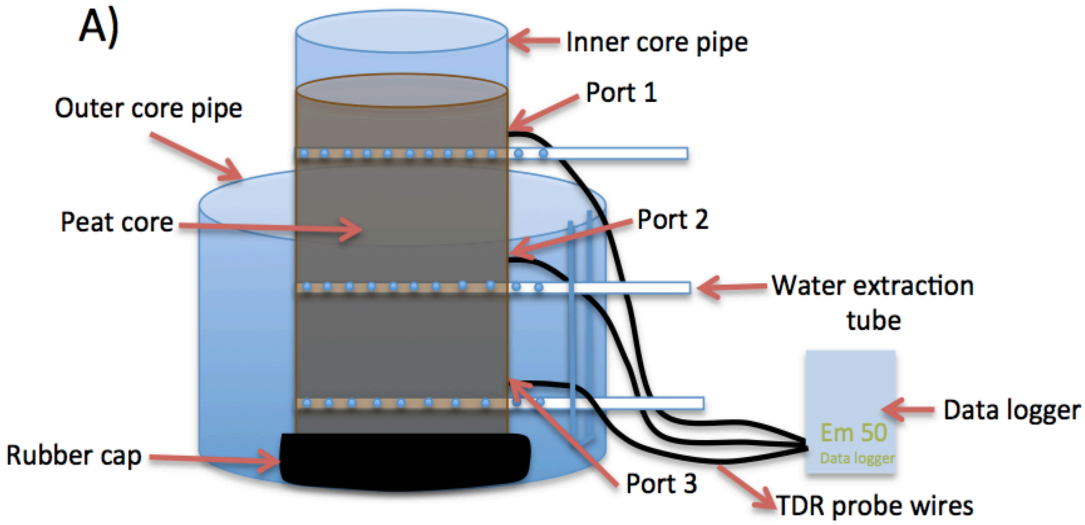
4.3 Methods

4.3.1 Core Set-Up

In October 2012, two peat monoliths were extracted from the non-degraded portion of the Airport site adjacent to Log1, by first cutting the peat into sections measuring approximately 23 cm x 28 cm at the surface, and to depths of 50 cm. Roots were carefully cut as to not disturb the structure of the peat. Monoliths were removed and wrapped multiple times in clear plastic wrap before being placed in individual coolers. The monoliths were kept at approximately 4 °C in the coolers and transported back to the Centre for Cold Regions and Water Science lab in Waterloo. In the lab they were kept in a cold room at 4 °C for just over one year until the experiment began in February 2014.

On February 6 and 7 the monoliths were removed from their coolers and labeled as Core 1 and Core 2. Core 1 was used to simulate a depression while Core 2 was used as a flow-through experiment to represent a hummock. Upon the removal of cores from the coolers, they were slowly and carefully shaved down on the sides using a knife, from a rectangular to circular shape so that they fit snugly into the 20 cm diameter plastic pipe that would house them for the entirety of the experiment. Prior to the experimental set-up, plastic pipes were cut to lengths of 50 cm and 30 cm for Core 1 and Core 2, respectively. However, it was decided that in order to gain samples from the experiment that could be applied to natural peatland systems where peat is often in excess of 30 cm, a longer and thus deeper peat core should be used for Core 2. Core 2 was then replaced from its original 30 cm monolith to a 40 cm core extracted from the Airport site on the same date, therefore the top 9.5 cm of

Core 2 was raised above the top of the 30 cm pipe. Six holes were drilled in the side of the pipe for Core 1 to allow for insertion of instruments to measure soil moisture and temperature and water extraction, while two holes were drilled in the pipe for Core 2 (Figure 4.1). Both cores then had a 20 cm diameter circular plastic piece glued to the bottom of the core pipe to impede the flow through of water from Core 1, while Core 2 had ~ 30 randomly placed holes drilled in the bottom to allow for water to escape mimicking the natural drainage characteristics of a hummock. For the purposes of insulating the inner peat cores, a second larger pipe 30 cm in length and 40 cm in diameter was used as a shell so that insulation could be used in the 10 cm gap between inner and outer core pipes (Figure 4.3). The outer core pipes were similarly sealed at the bottom (similar to the inner core pipes), with ~ 40 holes drilled in the bottom for Core 2 to allow throughflow. A rectangular section ~ 4 cm x 15 cm was then cut out of the side of the outer core pipe to allow space for TDR probe wires and water extraction tubes (Figure 4.1).



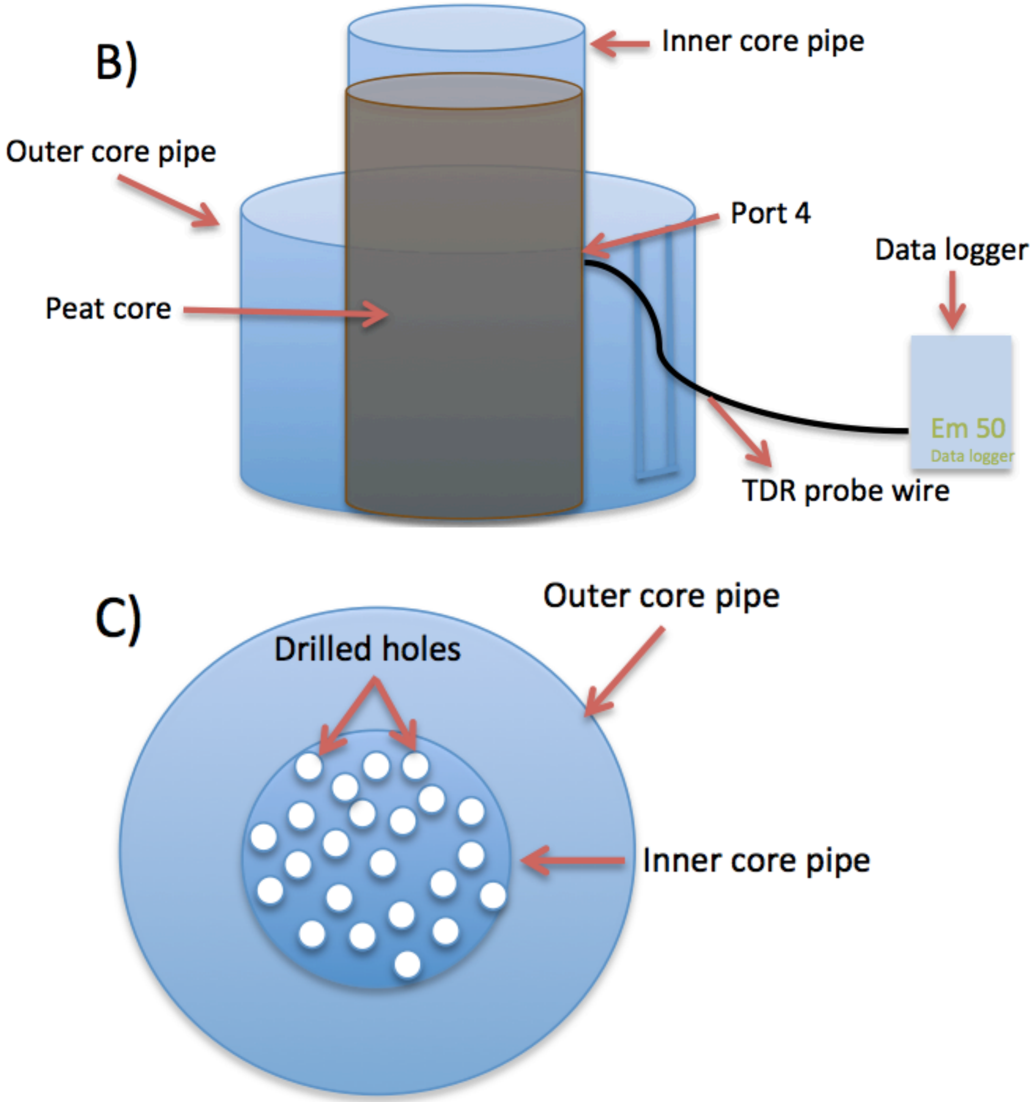


Figure 4.1: A) Experimental set-up of Core 1 illustrating sample extraction tubes, inner and outer core pipes, the rubber cap sealing the bottom of the inner core pipe, and TDR probes measuring soil moisture and temperature; B) Experimental set-up of Core 2 illustrating inner and outer core pipes and TDR probe measuring soil moisture and temperature; C) The base of Core 2 depicting the inner and outer core pipes and the holes drilled through the bottom of the inner core pipe to allow for water throughflow into the catchment bucket beneath Core 2.

Both cores were instrumented with Decagon 5TM soil moisture and soil temperature probes measuring internal core temperature (°C) and volumetric water content (m^3/m^3). Core 1 was instrumented with three probes at 10, 25.5 and 40 cm from the top of the core pipe. The single TDR probe installed in Core 2 was inserted into the core midsection at 15.5 cm. The cores were then placed top down and the core pipes were carefully placed over the cores. Probe wires were fed through the pre-drilled holes in the core pipe. During this process, the Core 1 peat compressed ~ 5 cm while Core 2 compressed ~ 0.5 cm. Once the peat cores were within the tubes, the water extraction tubes were inserted.

Water extraction tubes 1 cm in diameter were installed in Core 1 using rigid plastic tubing. Small holes were drilled along the top of the length of tube in contact with the peat to allow for water infiltration and extraction (Figure 4.2). Tubes were then wrapped in Nytex to impede the entrance of large organic debris and secured using zip-ties. To ease the installation, a long stainless steel rod was inserted through each core pipe hole to create a small opening in the peat. The water extraction tubes were then inserted into the core across its entire 20 cm diameter. A 1 mm diameter, 55 mm long tygon tube with numerous perforations was inserted into each of the water extraction tubes. A syringe was used to extract aliquots of soil water for chemical analyses from each extraction port. All holes in the core pipe were then sealed using Plumbers Putty to avoid water leakage. Tubes were installed at depths of 14 cm, 29.5 cm, and 42.5 cm from the surface of the core pipe.

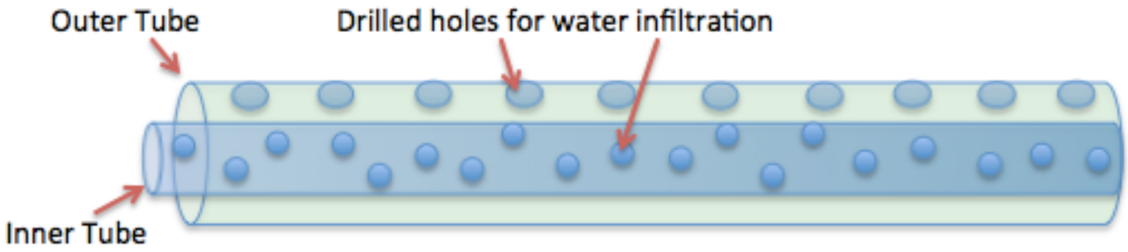


Figure 4.2: Inner and outer water extraction tubes with drilled holes to allow for water infiltration. Tubes were inserted laterally into Core 1 with water extracted using a 60 ml syringe attached to the inner tube.

Following tube installation, inner core pipes were placed within outer core pipes. The gap between the pipes was filled with fiberglass insulation (Figure 4.3). The bottoms of the cores were heavily insulated, as deeper peat experiences a delayed response to temperature change as compared to surface peat in the natural landscape. The top of Core 2 was left un-insulated, while one layer of insulation was wrapped and taped around the top of Core 1. Probe wires were then attached to a Decagon EM50 Digital/Analog data logger and cores were placed into a Biochambers growth chamber for the remainder of the experiment. With a temperature range from -10 °C to 20 °C, the Biochambers growth chamber was suitable for lowering and raising winter and summer peat temperatures to those observed at both research sites. While illuminating the chambers was an available option, the close proximity of the lights to the cores, as well as the uninhibited receipt of light at the peat surface was determined to be unrealistic to what peat at the Airport site naturally experiences.

Following the commencement of the experiment, it was discovered that subsequent to the simulated spring freshet, water had been leaking from the bottom of Core 1. To remedy this, a rubber cap was placed on the bottom of the core pipe and secured tightly using a hose clamp (Figure 4.1).

4.3.2 Water Additions, Experiment Schedule, and Sampling

The experiment was designed to simulate an entire year of air temperature and precipitation conditions experienced in the Yellowknife region. This was achieved by examining climate data provided by Environment Canada (C. Spence) spanning from 1942-2010. To shorten the timeline of the experiment, each month was compressed into 3 - 5 day intervals. For each simulated month, the growth chamber was adjusted to the appropriate monthly mean air temperature, however, the minimum possible temperature of the chamber was limited to -10 °C, therefore during the simulated winter months air temperatures were slightly warmer than in reality (Table 4.1). Although initially thought to be a limitation of the experiment, core temperatures were sufficiently lowered to match those of ground temperatures experienced in the field during the winter, which typically range between 0 °C to -10 °C.

Snow was collected at the Airport site in February 2014, placed in coolers, and transferred back to the lab. Coolers were kept at room temperature until snow had partially melted, at which point they were placed in a fridge at 4 °C. Water additions took place each month following the simulated melt period (Table 4.1). The volume of snowmelt water added to each core was determined by first calculating the core surface area. The surface area was then multiplied by the mean annual incoming precipitation (272 mm/yr) to give the total volume of water to be added over the simulated year. The percentage of total annual precipitation received each month was then calculated and multiplied by total precipitation, resulting in the monthly contribution of precipitation to each core. Water was added evenly to the core surfaces in 100 ml increments using a graduated cylinder. Each 100 ml addition was allowed to infiltrate before the next addition took place.

The cores were placed in the -10 °C chamber for 48 hours to ensure freezing, following which the experiment began simulating the month of January. The cores remained frozen until the simulated spring freshet in April and May, at which time water additions began. Because incoming precipitation during the winter months falls as snow, the water additions for the months of January, February, March, and April (simulating spring snowmelt) were added together, half of which was added in April, while the second half was added to the May water additions (Table 4.1). Following the June water additions, it was discovered that water had been leaking from Core 1, resulting in a VWC of only 18%. Possible leakage points from drilled holes in the core pipes and water extraction tubes were thoroughly plugged, at which point the spring melt volume plus June rainfall was re-added to the core, for a total added water volume of 5800 ml. After discovering that water was still leaking from the core, a rubber cap was placed on the bottom of the inner core pipe, sealing and preventing further leakage. The experiment was suspended for six days while the core VWC lowered, at which point it resumed from the simulated month of March.

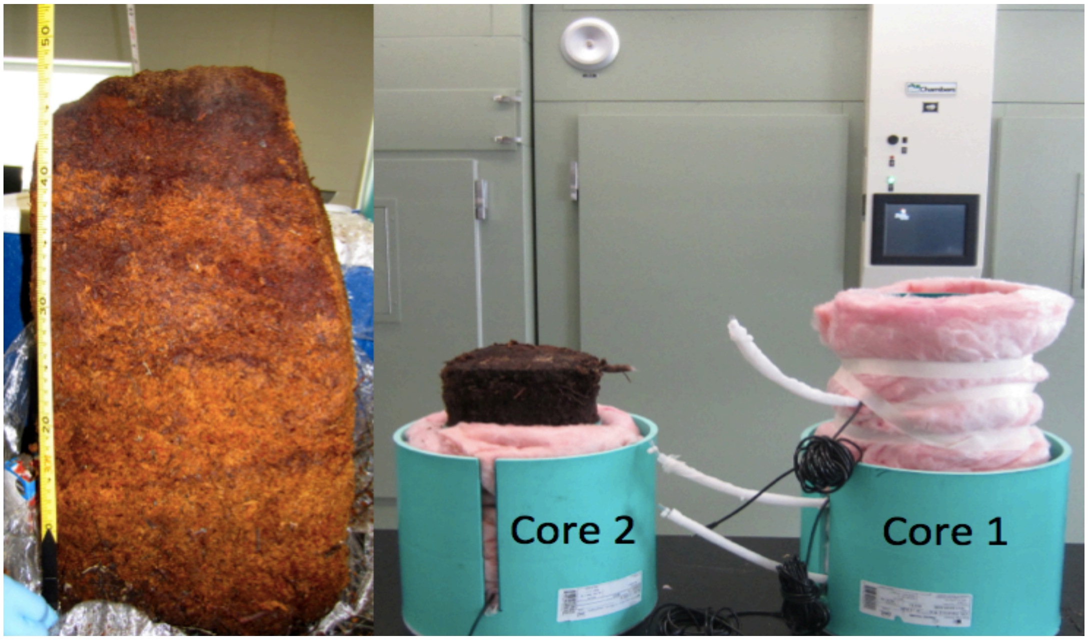


Figure 4.3: Photograph of peat monolith before trimming to the appropriate diameter (left) and final experimental set-up of Core 1 and Core 2 with BioChambers growth chamber in the background (right).

Table 4.1: Core experiment schedule including the specified timespan, programmed chamber air temperature, and water additions (ml and mm) for each simulated month.

Date	Simulated Month	Temperature (°C)	Water Addition (ml)	Water Addition Depth (mm)
February 7 – 12, 2014	January	-10	0	0
February 12 – 17, 2014	February	-10	0	0
February 17-22, 2014	March	-10	0	0
February 22 – 27, 2014	April	-6.5	810	25.8
February 27 – March 4, 2014	May	4.5	1345	42.8
March 4, 2014	June	13	746	23.7
March 4, 2014	N/A	13	2900	92.3
March 10 - 13, 2014	March	-10	0	0
March 13 - 17, 2014	April	-6.5	810	25.8
March 17 - 21, 2014	May	4.5	1345	42.8
March 21 - 25, 2014	June	13	746	23.7
March 25 - 30, 2014	July	13	1167	37.1
March 30 – April 2, 2014	August	16.5	1297	41.3
April 2 - 6, 2014	September	7	1086	34.6
April 6 - 11, 2014	October	-1.5	1021	32.5
April 11 - 16, 2014	November	-10	795	25.3
April 16 - 18, 2014	December	-10	0	0
April 18 - 21	December	0	550	17.5

Water sampling methods between the cores varied, as Core 1 used a syringe and water extraction tubes and Core 2 was a flow through experiment whereby a bucket was placed beneath the core to catch dripping water. Following water additions, the accumulated water in the Core 2 catchment bucket was sampled immediately using a 60 ml syringe, filtered through a 0.45 μm filter and kept at 4 °C until DOC and DOM size fractionation analysis.

The Core 1 sampling method included the use of the water extraction tubes. As noted above, three water extraction tubes were installed in the core, however only the bottom tube was used in the experiment. Due to water leakage at the beginning of the experiment, combined with the inability to draw an adequate sample volume from the two shallower tubes, the bottom tube was the sole means of water extraction. Core 1 was sampled immediately prior to the next month of water additions. This allowed water to sit within the peat as it naturally would in a saturated depression. A 60 ml syringe was attached to the 1 mm diameter inner tygon tube, and samples were filtered and stored in the same manner as Core 2.

Following the simulated freeze-back period, temperatures were lowered to -10 °C for the simulated November and December months. However, while the chamber air temperature was representative of air temperatures in Yellowknife during the winter months of November and December, the internal core temperatures were significantly lower than those observed at the field sites during these months. To account for this, the chamber air temperature was raised during the December simulation on April 18 from -10 °C to 0 °C in order to achieve internal core temperatures more representative of the December ground temperatures observed at both research sites (Table 4.1).

4.3.3 Chemical Analysis

All chemical analysis was completed at the Environmental Geochemistry Laboratory at the University of Waterloo. The reader is referred to Chapter 3 of this thesis and Aukes (2012) for a full description of the dissolved organic carbon (DOC) and Liquid Chromatography-Organic Carbon Detection (LC-OCD) methodology used to analyze all samples obtained from the core experiment.

Total nitrogen (TN) was analyzed using Shimadzu TOC-LCPH+TNM-L Total Organic Carbon analyzer with a total nitrogen unit (precision: ± 0.008 mg/L) and standards of 0.1, 0.2, 0.5, 1, 5, 10, and 20 mg N/L. Like the DOC method, samples were first diluted using DI water to be within range of the set of standards.

Absorbance scans for all wavelengths (200 nm – 800 nm) for each sample were also completed, however as these scans are affected by DOC concentration, samples with higher concentrations will result in higher absorbance. To correct for the influence of DOC concentration, ultraviolet absorbance was also measured, from which Specific Ultra-violet Absorbance (SUVA; L/mg•m) was calculated using the corresponding absorbance at 255 nm divided by the overall DOC concentration of the sample, and is represented by equation 4.1 below:

$$SUVA = \frac{(A/l)}{C} \qquad \textbf{Equation 4.1}$$

where *A* is the absorbance at 255 nm, *l* is the path length of the quartz cuvette (m), and *C* is the DOC concentration of the sample (mg/L). Additionally, Nanopure water was used as a blank in order to subtract background absorbance. Furthermore, E_2:E_3 ratios were calculated by dividing the measured absorbance at 255 nm by the absorbance at 365 nm, similar to Aukes (2012), which provides valuable information about the molecular weight distribution of the samples.

4.4 Results

4.4.1 Temperature and VWC

The internal core temperatures of both Core 1 and Core 2 followed the pattern of air temperature change closely (Figure 4.4). Throughout the entirety of the experiment, core temperatures remained within 2.3 °C of the programmed air temperature within the chamber. For the experimental set-up, insulation was used to create a thermal gradient between the core surface and lower sections where water was to be drawn from. The insulation was inadequate to create such a gradient, however a temperature gradient within the peat was created as the approximately 4 °C snowmelt water was added to the core. Immediately following water application, the top 10 cm rapidly changed temperature. When air temperatures in the chamber were cool (< 4 °C), water additions warmed the peat by as much as 8.6 °C. When air temperatures were warmer (> 4 °C), water additions cooled the peat by as much as 2.6 °C. In all instances, the bottom of the core experienced the smallest temperature change following water additions (<1 °C).

As precipitation water was added to the thawed cores *i.e.* peat temperatures were > 0 °C, some patterns were observed. In Core 1, ports 1 (top) and 2 (middle) experienced very brief spikes in VWC, with rapid decline to original VWC levels (Figure 4.5). While saturation was not achieved in the depression core base (port 3), the VWC was notably higher than shallower depths, as water accumulated each simulated month following the simulated spring freshet. Port 4 in Core 2 reacted to water additions similarly to ports 1 and 2 in Core 1, where a sharp increase in VWC was observed following water additions, however the simulated hummock (Core 2: port 4) experienced a more gradual decline in VWC.

It was observed that while adding water to Core 2 while it was frozen (< 0 °C), much of the water (~ 80-90%) flowed continuously through the core and into the catchment bucket within a matter of minutes. However, throughout the majority of the thaw period, it was difficult to obtain a sample from Core 2, as temperatures were warmer and the peat retained most, if not all, of the water added. During thaw periods, the maximum through-flow was estimated at 20% of the total water addition for that simulated month. The same process may potentially be occurring at the research sites, whereby a portion of snowmelt originating from frozen hummocks is running into lower-lying depressions during the spring freshet when the peat remains mostly frozen. Hummocks maintain a low VWC prior to freeze-back (Figure 2.8), unlike depressions which form ice lenses, inhibiting vertical infiltration and causing surface pooling. Water movement through hummocks is not influenced by the formation of ice lenses, which allows water to move vertically and laterally into adjacent depressions. If no water contributions from hummocks to depressions were occurring, one would expect the VWC at the time of freeze to equal the VWC at the time of thaw, plus inputs from snowmelt. Given more or less an equal snowcover between hummocks and depressions, the inputs from snowmelt should be equal between them, raising their VWC by the same proportion. However, following thaw at the Airport site, the VWC of depressions was raised up to 20% more than the VWC of hummocks, at 10 cm depth. This process could potentially explain why the VWC of depressions following thaw is observed to be substantially greater than at the time of freeze, while the VWC of hummocks remains largely unchanged.

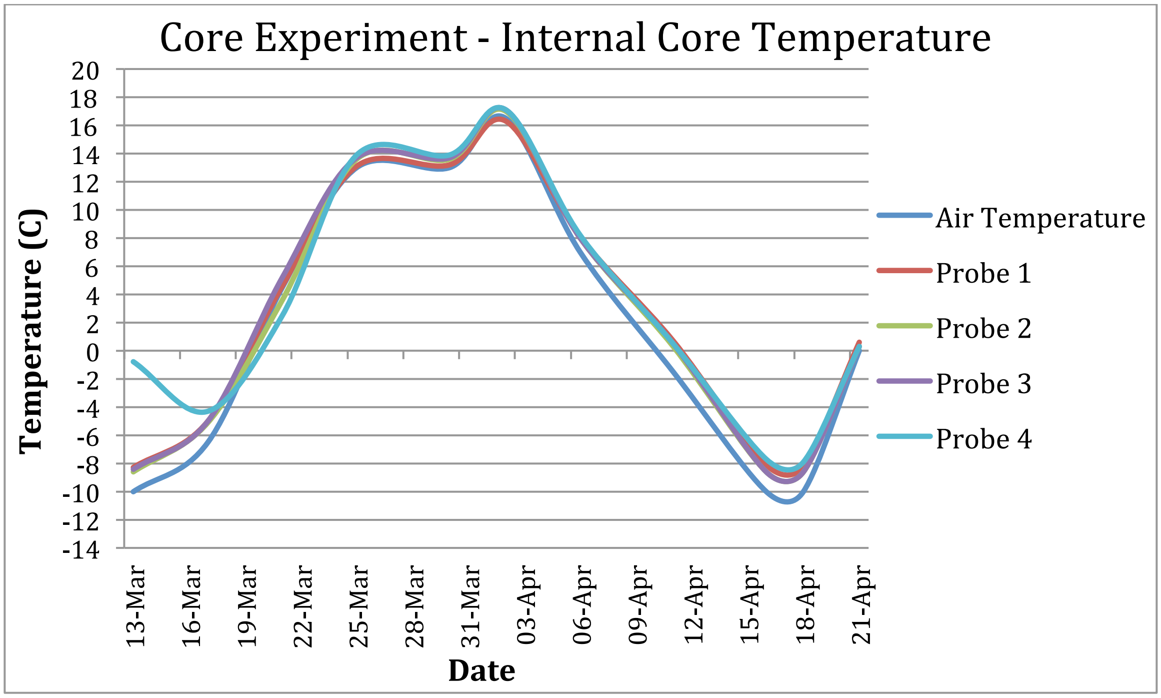


Figure 4.4: Internal core temperatures of Core 1 (recorded at 10, 25.5, and 40 cm) and Core 2 (recorded at 15.5 cm) versus the programmed air temperature of the chamber.

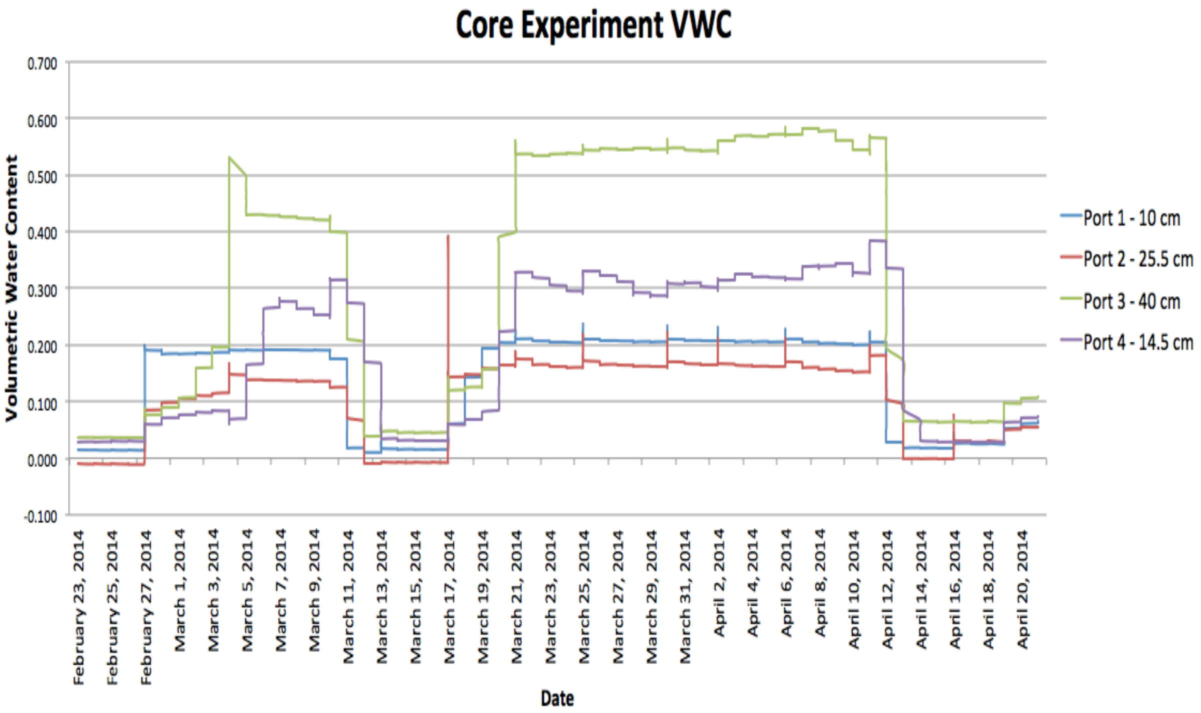


Figure 4.5: VWC of Core 1 (ports 1, 2, and 3) and Core 2 (port 4) throughout the entire core experiment.

The VWC conditions of both cores are similar to the ground moisture conditions seen at both the Airport and Pontoon Lake sites (Figure 2.6). While port 3 in Core 1 didn't reach saturation which is common at depths of 30 cm or more in a depression in the natural system, it had a significantly higher VWC than shallower depths of the core (Figure 4.5), which is the same pattern observed at the research sites (Figure 2.8). Core 2, representing a flow-through hummock, mimicked the ground moisture conditions expected in a real-world hummock, maintaining a mean VWC of 31% throughout the replicated summer season (Figure 4.6). Aside from the large peak in VWC following the freshet at Log3, the Core 2 VWC remained within close proximity of hummock soil moisture values recorded at both field sites. Although the probe in Core 2 was located at 15.5 cm depth, the recorded VWC most closely replicated the moisture conditions of the Log2 and Log3 hummocks at 40 cm depth. While the bulk density of peat has a tendency to increase with depth in the natural system, reducing the peat hydraulic conductivity, the drainage holes at the bottom of Core 2 allowed for water to flow freely through the core without disruption. Given the ~ 4% difference in VWC between port 1 and 2, where water flowed through freely before accumulating at the base of Core 1, it is likely that Core 2 also experienced a relatively uniform VWC throughout it's 40 cm of peat. As such, water flowing through the 40 cm length of Core 2 experienced similar moisture conditions to that of water infiltrating a hummock in the natural system at a similar depth.

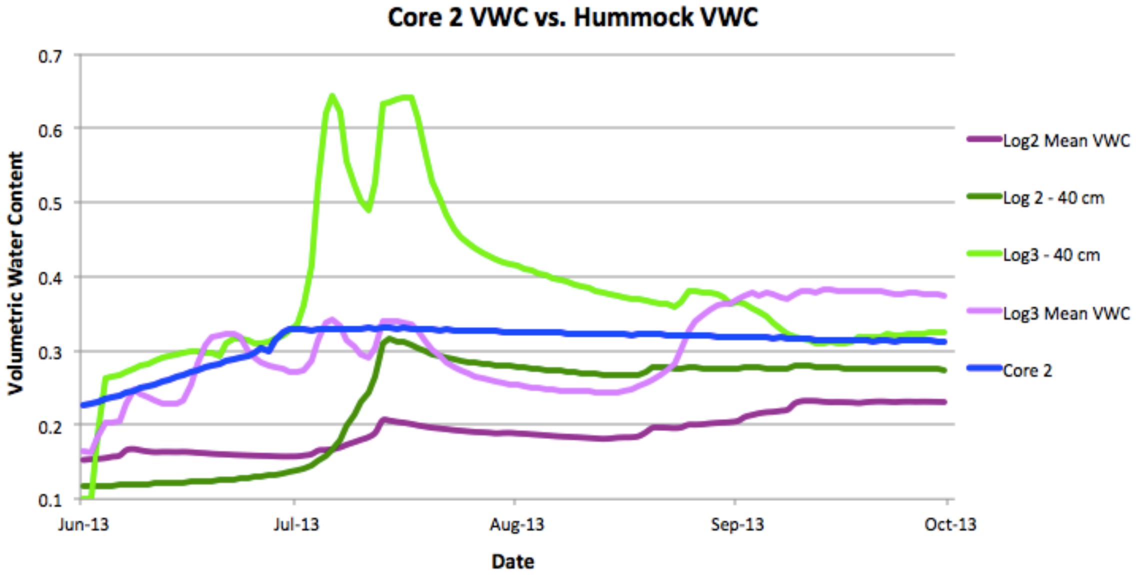


Figure 4.6: VWC of Core 2 recorded during the simulated June – October months compared to Log2 and Log3 mean VWC and Log2 and Log3 VWC recorded at 40 cm during the timespan of June – October 2013.

4.4.2 Chemical Analysis

Both Core 1 and Core 2 had a similar VWC at the beginning of the experiment (11% and 8%, respectively), and show no discernible relationship between the mean VWC of the core and the resulting DOC concentration. Additionally, the DOC concentration in the accumulated water at the base of Core 1 may be expected to increase over time as water is flushed through the core during each water addition, potentially transporting large DOC mass to the core base as it infiltrates. However, as water continued to accumulate at the bottom of the depression core throughout the experiment, no relationship was observed between the elevated VWC of the Core 1 base and the DOC concentration extracted from port 3. A possible relationship may exist between the volume of water added to the cores and DOC export, whereby higher volumes of added water to Core 1 led to an increased concentration of DOC in the extracted water (Figure 4.7). However, this relationship only holds true for the last three samples collected, while the first two exhibit outlier results. Additionally, this trend was not observed in data obtained from Core 2, which had a similar VWC as Core 1 when the experiment began (Figure 4.8). A possible explanation for this pattern is that the Core 1 May sample and Core 2 May and December samples were collected while the cores were frozen. The comparatively low DOC concentrations in these samples could indicate preferential flow through the frozen peat, creating restrictions on infiltrating water to liberate existing DOC mass from the remainder of the peat. It’s possible that because the water additions may have been restricted to these preferential flowpathways while the core was frozen, the remainder of the core was not in contact with infiltrating water and thus could not have contributed to raise the DOC concentration of the sample.

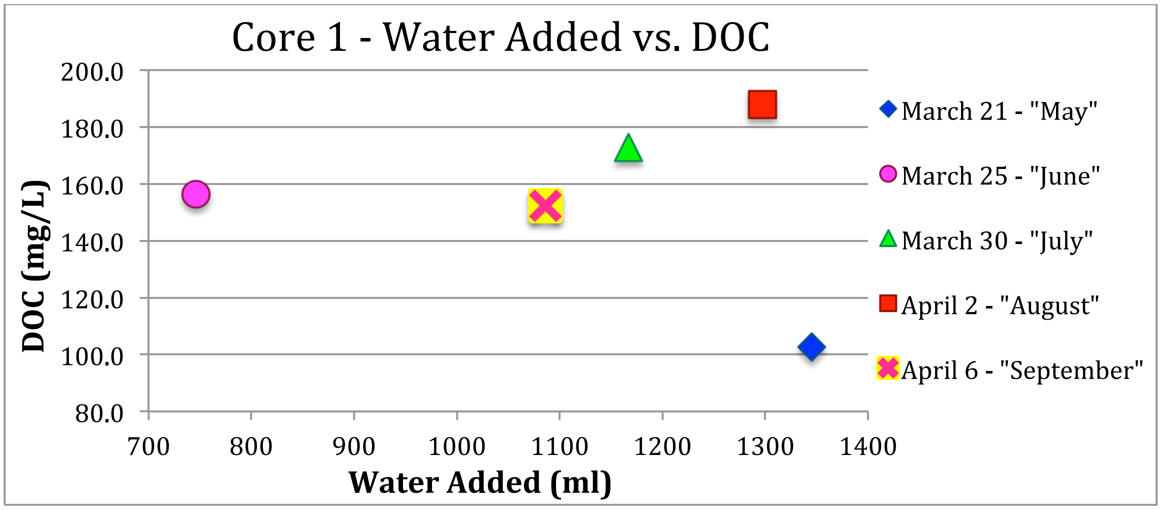


Figure 4.7: Core 1 simulated precipitation additions (ml) versus sample DOC concentration (mg/L) for the simulated months of May – September.

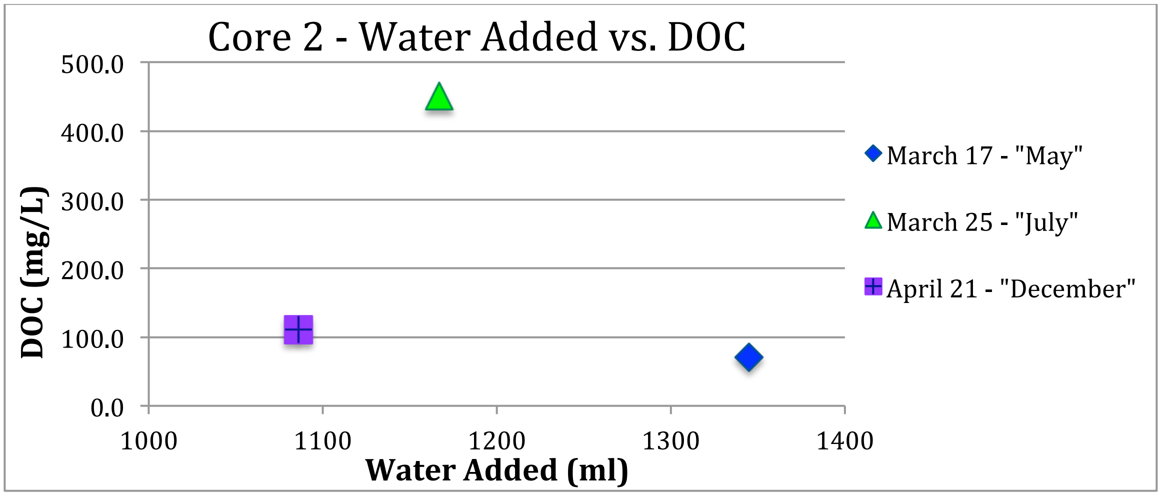


Figure 4.8: Core 2 simulated precipitation additions (ml) versus sample DOC concentration (mg/L) for the simulated months of May, July, and December.

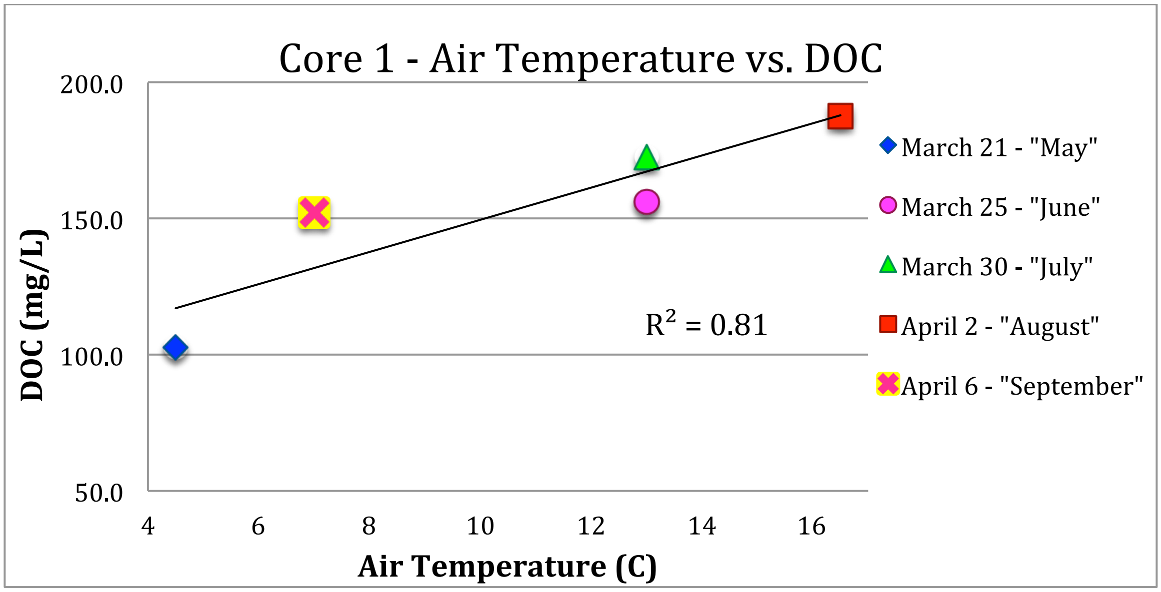


Figure 4.9: Core 1 programmed air temperature (°C) versus sample DOC concentration (mg/L) for the simulated months of May – September.

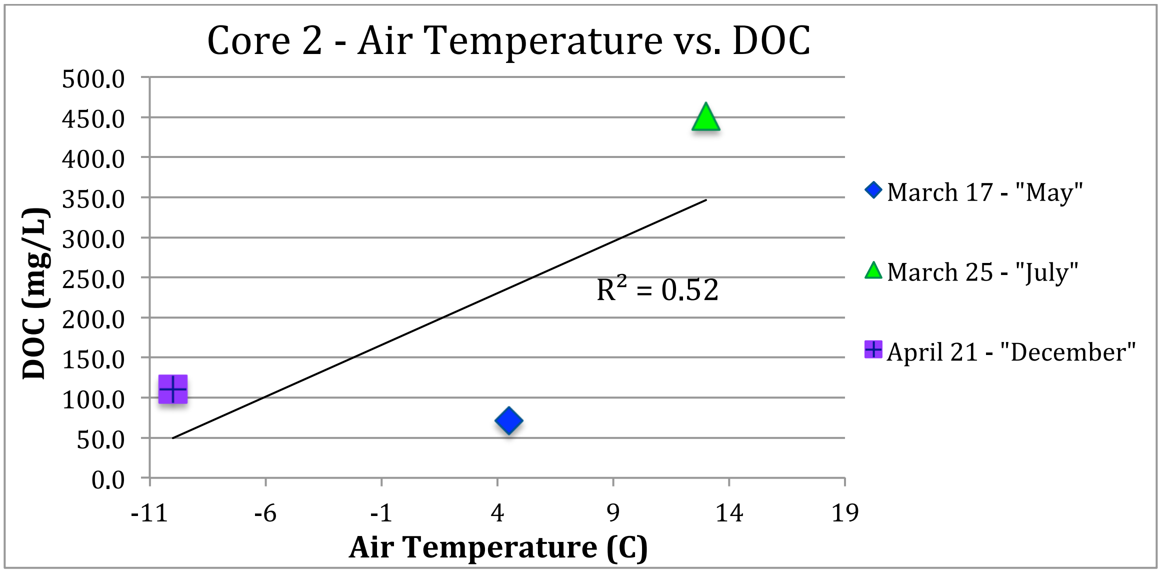


Figure 4.10: Core 2 programmed air temperature (°C) versus sample DOC concentration (mg/L) for the simulated months of May, July, and December.

The Core 1 DOC results indicate a strong relationship between air temperature and DOC concentration within extracted pore water ($R^2 = 0.81$, significant at the 95% CI) (Figure4.9). While the Core 2 samples collected on March 25 ("July") and April 21 ("December") indicate a similar relationship between air temperature and DOC concentration, the sample collected on March 17 representing the simulated month of May is inconsistent with the observed pattern (Figure 4.10). As the first water samples collected from both cores during the experiment, the May water additions were added to the peat while it was frozen (< 0 °C), as the previous simulated month (April) had a mean air temperature of -6.5 °C. So, while the May water remained stagnant within Core 1 while it warmed and thawed over a period of four days prior to being sampled, the Core 2 water addition flowed through frozen peat and was sampled immediately. While the air temperature of the simulated month of May was 4.5 °C (Table 4.1), the Core 2 sample representing the month of May flowed through the core, which at the time, had an internal temperature of -4.3 °C. To account for the differences between the programmed air temperature of the simulated month and the internal core temperature at the time of sampling, the mean core temperature for the entire simulated month was compared to the sample DOC for Core 1. Because the Core 2 water additions flowed through the core and were sampled immediately, the mean core temperature was calculated using the temperatures of the previous simulated month prior to sampling the core. In doing so, the significance of the relationship between temperature and DOC increased dramatically in Core 1 and Core 2 (relative to the previous comparisons of air temperature vs. DOC concentration), with R^2 values of 0.95 and 0.99, respectively (Figure 4.11, Figure 4.12).

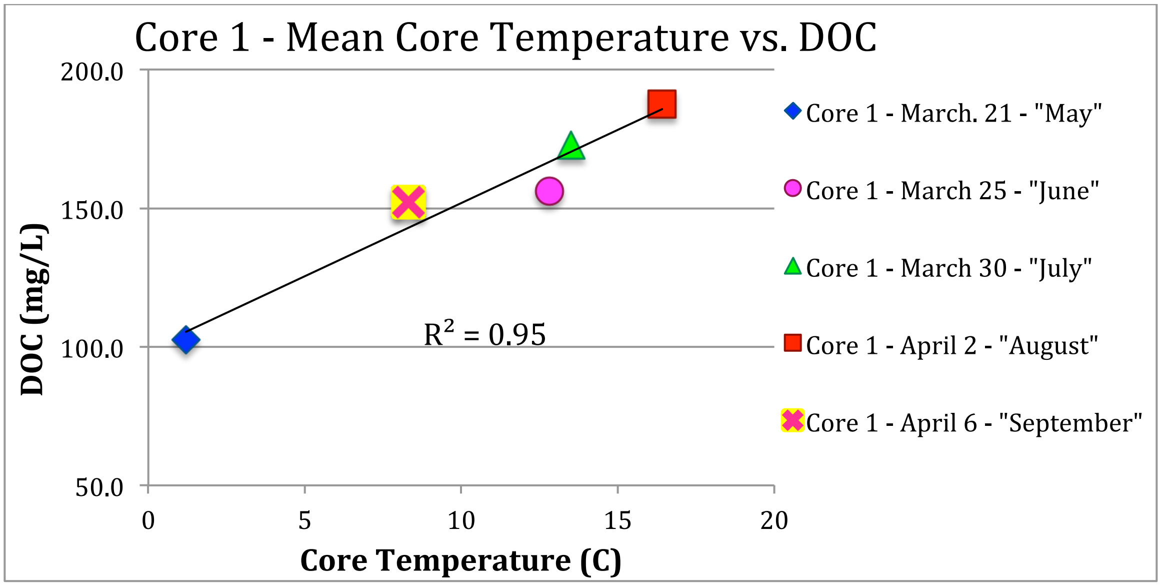


Figure 4.11: Core 1 mean core temperature (°C) versus sample DOC concentration (mg/L) for the simulated months of May – September.

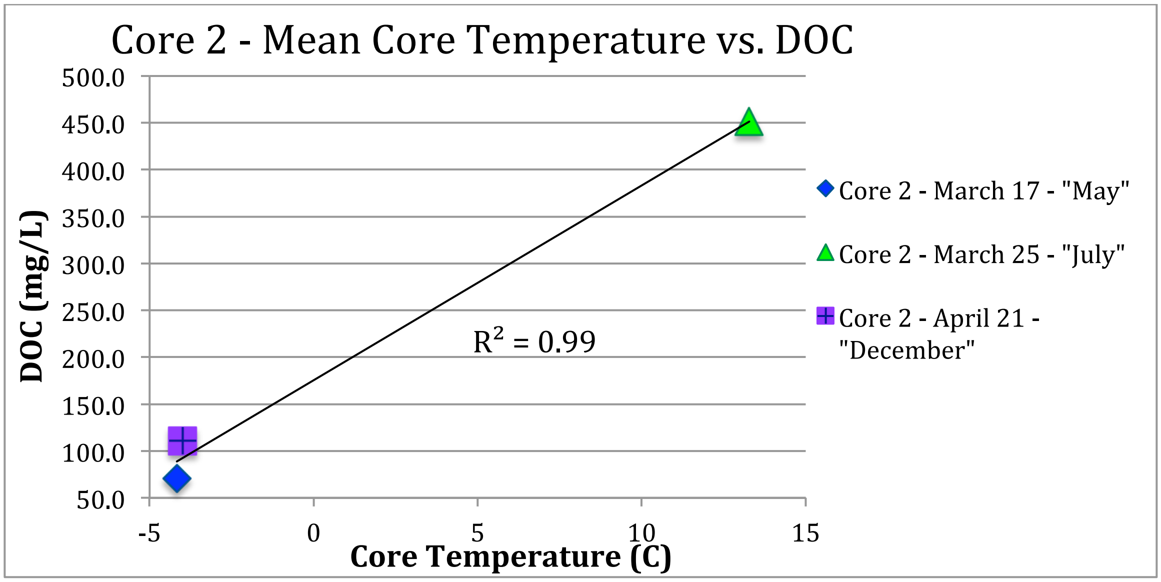


Figure 4.12: Core 2 mean core temperature (°C) versus sample DOC concentration (mg/L) for the simulated months of May, July, and December.

As the programmed air temperature within the chamber increased, so did the internal core temperature, as well as the DOC concentration within the extracted water. Over the course of the experiment, the mean core temperatures for Core 1 were raised from 1.2 °C to 16.4 °C, or a total temperature increase of 15.2 °C. During the same time period, DOC export increased by 85 mg/L (Figure 4.11). Core 2 saw a more dramatic change, whereby mean core temperatures increased from -4.2 °C to 13.3 °C, or a 17.5 °C temperature increase, and total DOC export increased by 380 mg/L (Figure 4.12). Comparing the mean core temperatures, as well as the temperature range throughout the sampling period of the experiment, to real-world peat temperatures may give insight into the likelihood of similar DOC concentrations occurring at the research sites.

Mean ground temperatures at Log1 and Log2 were calculated on a daily basis and produce values representing a mean profile (0-40 cm) temperature (Figure 4.14). The temperature range of the cores is similar to the real-world mean ground temperature range recorded in the Log1 (Figure 2.2, Table 2.5) and Log2 (Figure 2.3, Table 2.5) peat profile. The maximum and minimum mean temperatures experienced at Log1 were 5.9 °C and -4 °C, respectively, significantly lower than the maximum mean temperature of Core 1 at 16.4 °C (Figure 4.13). Additionally, the total mean temperature increase of Core 1 over the course of the experiment was 15.2 °C, while at Log1 the total mean temperature increase over the course of 2013 was 9.9 °C. Furthermore, the maximum mean temperature of Core 2 was 13.3 °C while the maximum mean temperature of Log2 was 8 °C. While the temperature increase (maximum temperature – minimum temperature) in Core 2 over the course of the experiment was 17.5 °C, the mean temperature increase at Log2 over the course of 2013 was similar at 16 °C, only a 1.5 °C difference in temperature range between Core 2 and Log2 (Figure 4.13, Figure 4.14). The large discrepancy in mean maximum temperatures between the cores and the Log1 and Log2 sites is largely due to the natural insulation provided by surrounding peat at the field sites.

While an attempt at insulating the cores was made, it was largely ineffective, and therefore the peat cores reacted to changes in the chamber temperature very quickly. However, the range of mean profile temperatures experienced within the cores is similar to the range of mean ground temperatures experienced in a hummock and depression in the natural system.

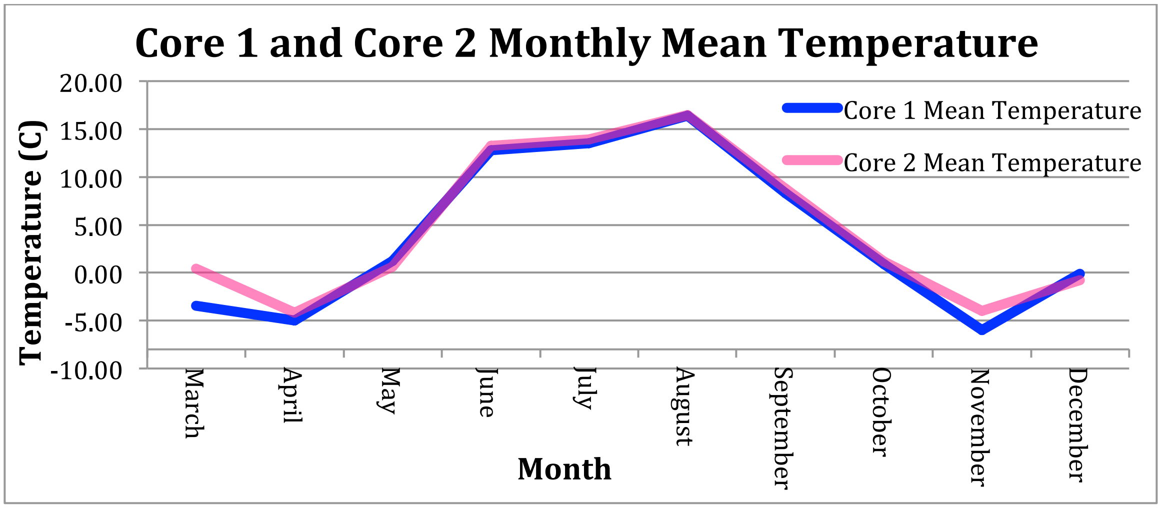


Figure 4.13: Comparison of the Core 1 and Core 2 mean internal core temperature (°C) for each simulated month of the experiment.

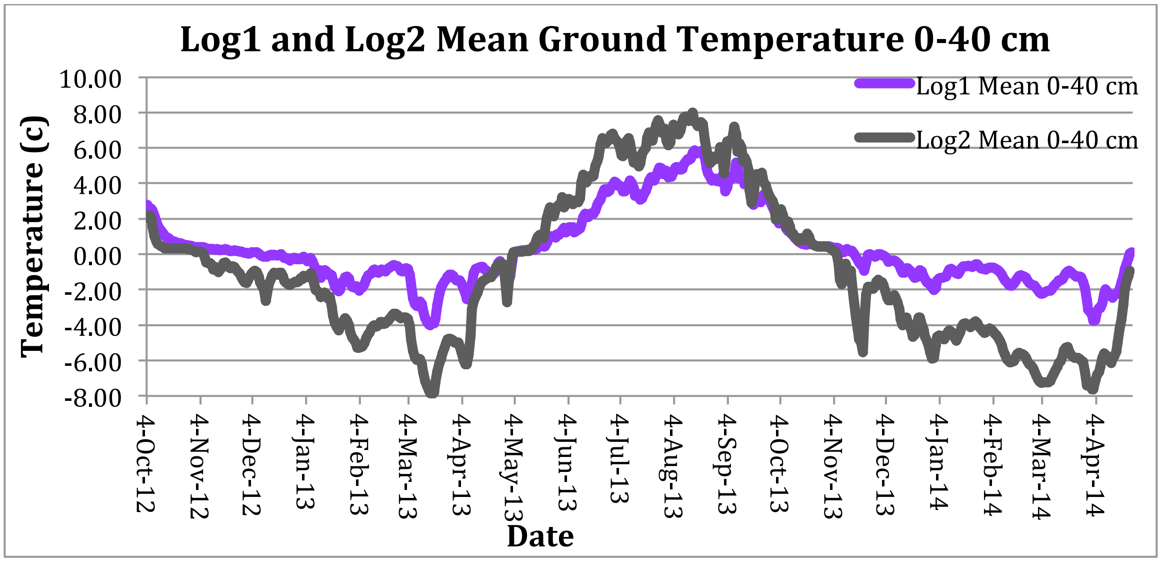


Figure 4.14: Comparison of the mean ground temperatures recorded at 0-40 cm depth at the Log1 and Log2 logging sites from October 2012 – April 2014.

A potential explanation for the observed changes in DOC concentration is that as the experiment progressed, the residence time of water within the peat in Core 1 was increasing, resulting in elevated DOC within the water. However, toward the end of the experiment on April 6th following an air temperature decrease from 16.5 °C to 7 °C and a mean core temperature decrease from 16.8 °C to 8 °C, DOC concentration also decreased from 188 mg/L to 152 mg/L, which could mean that temperature and not residence time is the main controlling factor in DOC concentration as the microbial community is evidently sensitive to temperature. The same relationship between Biochamber temperature and DOC concentration was observed in Core 2, with DOC rising from 71 mg/L to 451.0 mg/L with an air temperature increase from 4.5 °C to 13 °C and an internal core temperature change from -4.3 °C to 13.9 °C. When the temperature was lowered to -10.0 °C, or an internal core temperature of 0.3 °C, DOC concentration also decreased to 111 mg/L.

While determining DOC concentrations is a vital component of establishing potential real-world implications of climate warming, characterizing the DOM is also a necessary step in determining the environmental consequences of climate induced C export. As such, absorbance scans for all wavelengths were conducted, which measure the aromatic UV responding components of the DOM, and indicate the expected results whereby higher DOC concentration within the sample leads to increased absorbance. To correct for the influence of higher DOC concentrations resulting in higher absorbance, SUVA was calculated and reveals an increasing trend over the course of the experiment, ranging from 3.63 to 4.08 L/(mg•m) in Core 1, and 3.36 to 4.41 L/(mg•m) in Core 2, indicating an increasing aromaticity (Figure

4.16). The increases in SUVA values over the course of the experiment do not appear to be influenced by the temperature fluctuations of the chamber. The SUVA values are slightly lower than the SUVA values of samples obtained from the piezometers at the Airport and Pontoon Lake research sites during the summer of 2013, which generally ranged from 4.00 to 5.00 L/(mg•m). Additionally, while SUVA has been correlated to the degree of aromaticity of the DOM, it is not necessarily a measure of aromaticity itself. The increasing SUVA over the course of the experiment does indicate an increase in the aromatic components present in the bulk DOM, which has been correlated to an increase in the aromaticity of DOC (Weishaar et al., 2003), and is inversely related to the amount of biodegradation.

The E_2:E_3 ratios were also calculated for each sample, representing the absorbance at 255 and 365 nm, respectively. Results from the combined Core 1 and Core 2 samples can be fit by an exponential relationship ($R^2 = 0.88$, $n = 8$) between the absorbance at 255 and 365 nm and the mean core temperature, whereby increases in temperature resulted in an increased E_2:E_3 ratio, indicating increasing proportions of high quality, LMW compounds (Figure 4.15). Over the course of the experiment, the mean temperature of Core 1 during the sampling period was raised from 4 °C to 16.8 °C, while the E_2:E_3 ratio also increased from 2.6 to 14.4. When the core temperature was subsequently lowered to 8 °C, the E^2:E^3 ratio also decreased to 4.4. Core 2 saw a similar relationship between core temperature and the E_2:E_3 ratio, whereby core temperatures during the sampling period were raised from -4.3 °C to 13.9 °C and the ratio increased from 1.5 to 10.6. When the core temperature was subsequently lowered to 0.3 °C, the E_2:E_3 ratio also decreased to 1.0. While the degradation of DOC has been found to result mainly in DOM composition of lower quality, more aromatic and less labile compounds consisting mainly of humics, the increasing E_2:E_3 ratio suggests an increase in the often labile, LMW compounds as the core temperatures increase.

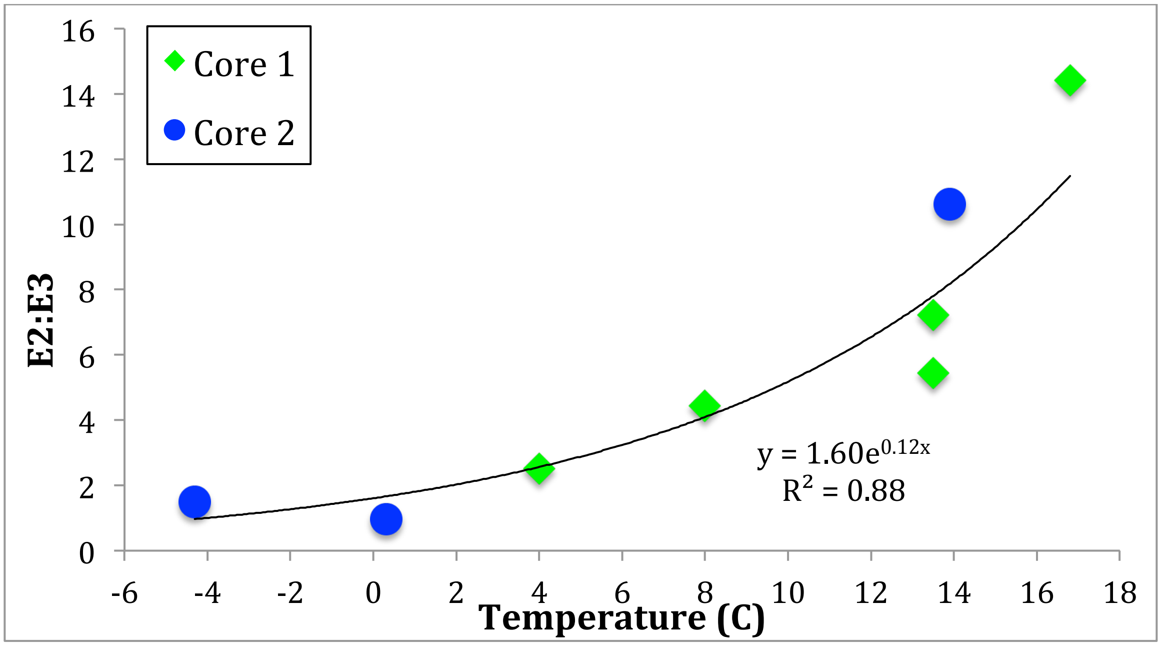


Figure 4.15: Core 1 and Core 2 E_2:E_3 ratios versus internal core temperature (°C).

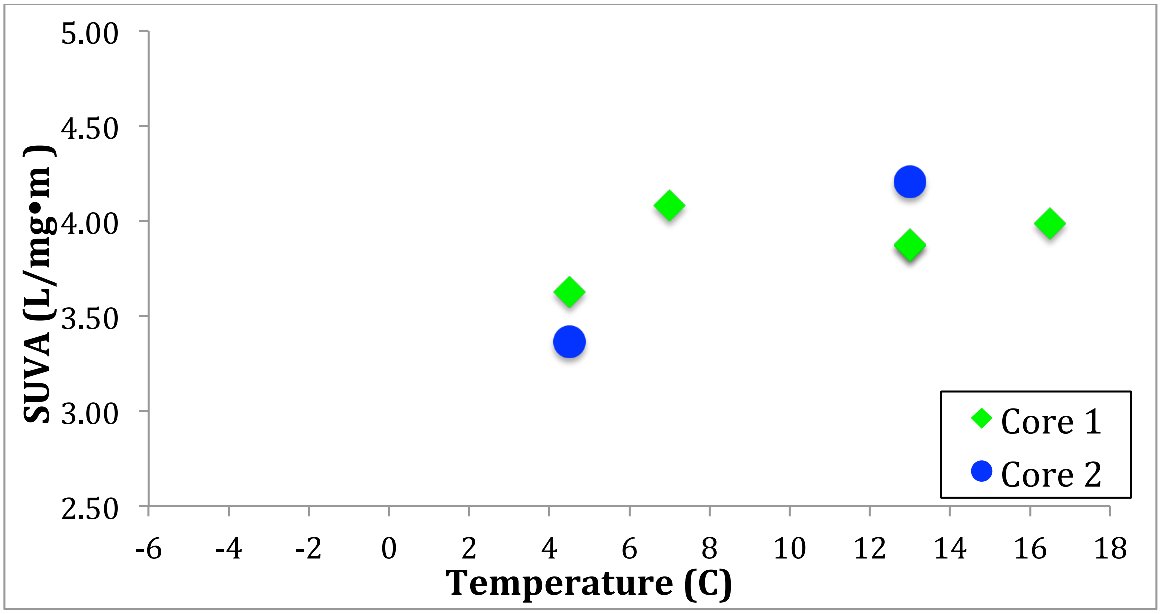


Figure 4.16: Core 1 and Core 2 SUVA (L/mg•m) values versus internal core temperature.

Throughout the entire experiment, total nitrogen (TN) decreased from 3.56 mg/L to 2.60 mg/L in Core 1. In Core 2, TN was more variable, rising from 4.56 mg/L to 23.0 mg/L on March 25, before dropping to 7.75 mg/L on April 21 (Figure 4.17). There does not appear to be a relationship between TN variability and changes in temperature, or with changes in the volume of water added to Core 1. Core 2 exhibits a relationship between temperature change and TN concentration. Over the course of the experiment, as temperature increased and decreased, so did the concentration of TN in the collected water. Additionally, the elevated N concentration of 23.0 mg/L in Core 2 on March 25 coincides with the maximum DOC concentration recorded over the course of the experiment of 451.0 mg/L, also on March 25.

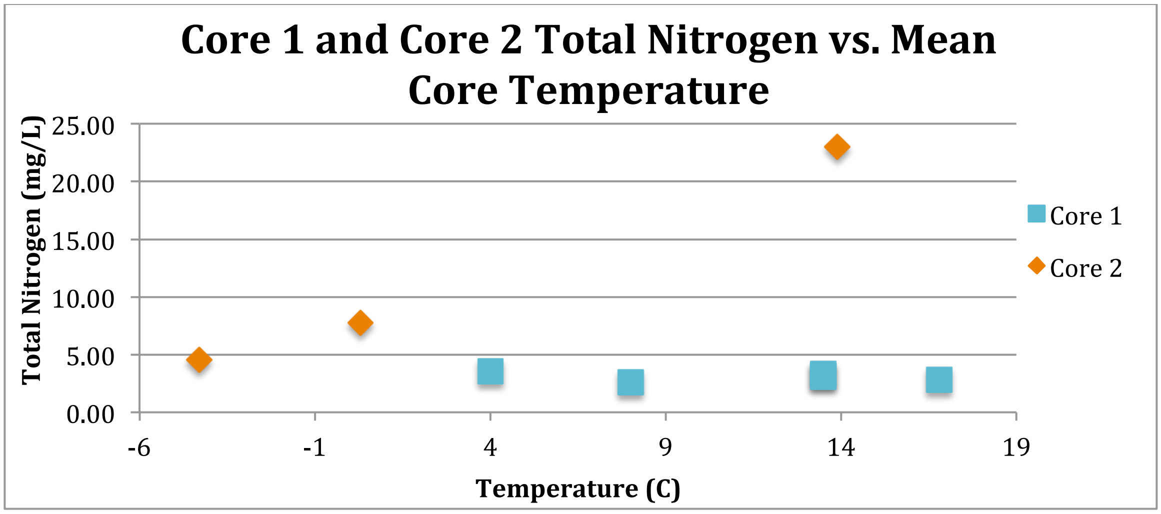


Figure 4.17: Core 1 and Core 2 mean core temperature (°C) versus total nitrogen concentration.

The decomposition of C has been linked with the availability of nitrogen, meaning the C:N ratio can provide valuable information about the biodegradability of DOM (Aukes, 2012). The molar DOC:TN ratios calculated for Core 1 indicate a mostly nitrogen-poor environment, with the exception of March 21 (May) with a ratio of 24.7. While a high C/N ratio usually indicates low levels of biodegradation in nitrogen limited environments, a low ratio could indicate active microbial breakdown of C in a non-limiting nitrogen supply. Additionally, a high C:N ratio leads to microbes taking up N from surroundings, while a low ratio could indicate the microbial mineralization of N. The ratios calculated for Core 2 on March 17, March 25, and April 21 all indicate a nitrogen rich environment with ratios of 13.2, 18.8, and 12.3, respectively. While Core 1 had an initially ideal ratio of 24.7 on March 21, the ratio peaked at 56.6 on April 2, indicating a nitrogen poor environment not conducive to rapid decomposition. It is possible that as the experiment progressed, the increasing VWC at the base of Core 1 where samples were extracted from depleted oxygen within the peat, creating an anoxic environment and allowing denitrification to occur. It's possible that shallower depths of the core maintained an ideal DOC:TN ratio in the absence of elevated VWC, thus enabling elevated biodegradation to occur at shallower depths of the core.

To gain further information about the quality, lability and the potential for microbial breakdown of DOM, the LC-OCD method was utilized to analyze DOM composition. The Core 1 results indicate substantial variability in DOM composition from the beginning of the sampling period to the end, specifically in the proportion of LMW components, which decreased rapidly following the May sampling period (Figure 4.18). While groundwater samples from the Airport and Pontoon Lake sites typically maintained DOM comprised of 70-80% humics, the May sample collected from Core 1 indicates HS comprising only 60%. Additionally, while proportions of LMW components typically comprised 5-10% of DOM at the research sites, the

LMW-N of the Core 1 May sample comprise 31% of total DOM. As discussed in Chapter 3, the LMW fractions of DOM can be the most labile, as they are rapidly consumed by microbes, unlike the complex, high molecular weight (HMW) humic substances (HS) which remained relatively unchanged in proportion as the experiment progressed.

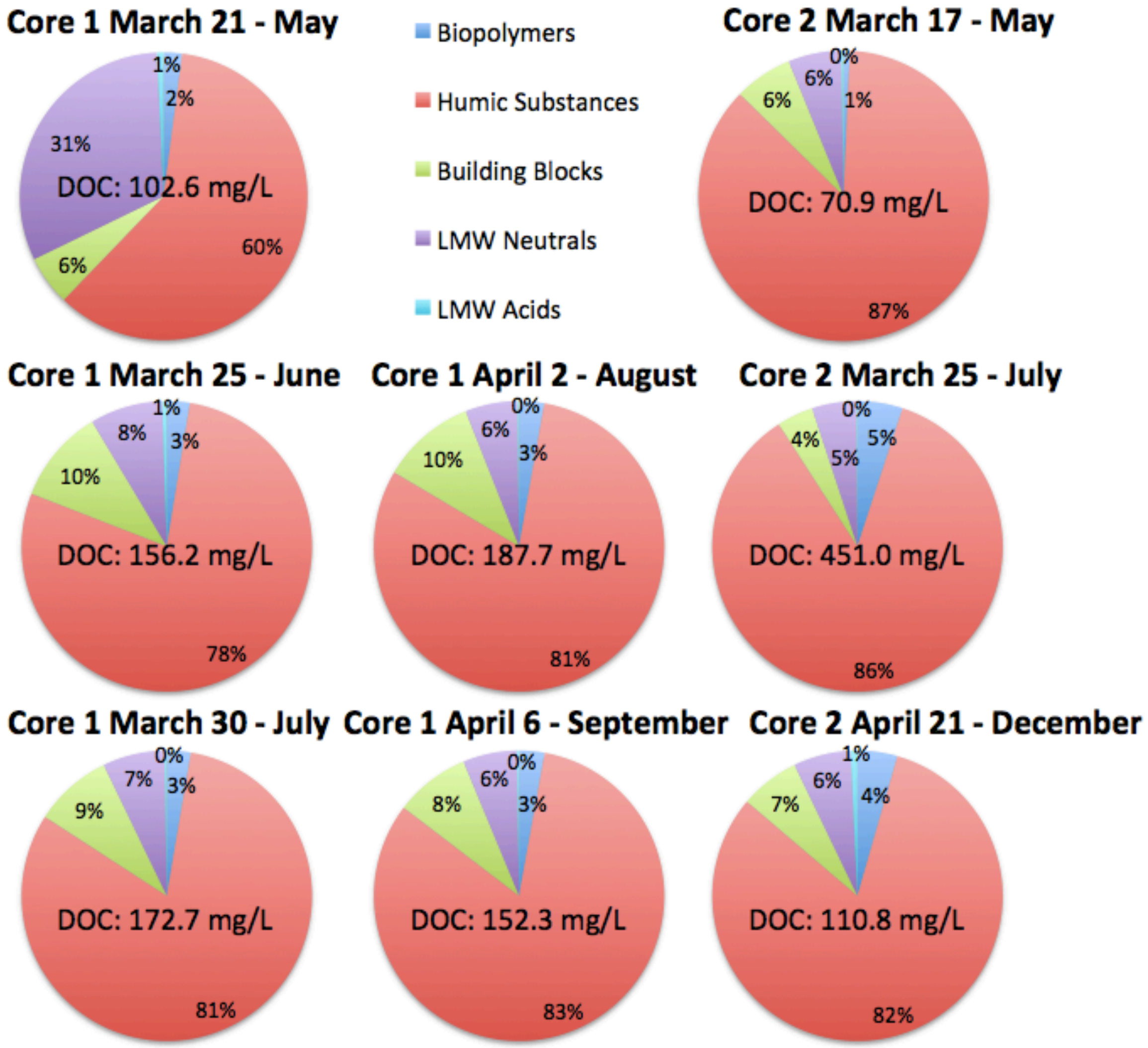


Figure 4.18: DOM composition charts for Core 1 (May-September) and Core 2 (May, July, December) detailing the DOC concentration of each sample in addition to the proportional fractions of biopolymers, humic substances, building blocks, LMW neutrals and LMW acids comprising the DOM found in each sample.

The majority of DOM composition changes occurred in Core 1 immediately following thaw. Changes in DOM composition observed between the Core 1 May and June samples are indicative of rapid microbial breakdown of LMW, likely non-aromatic compounds. The observed increase in molecular weight from 815 g/mol in May to 898 g/mol in June is concurrent with the increasing proportion of HMW HS from 60% in May to 78% of DOM composition in June. These results suggest that the LMW components of DOM may be rapidly utilized by microbes, making them high quality and labile components. The relatively stable proportion of HS in Core 1 from June onwards is indicative of slow microbial breakdown of DOM, making HS a likely low quality, less labile component of DOM.

While the increasing DOC concentration from May-August in Core 1 indicates elevated decomposition rates under warming temperatures, DOM composition remained relatively consistent from June-September in Core 1. As indicated by the increasing molecular weight and SUVA (Figure 4.16), decomposition leaves behind a more aromatic, lower quality (less labile) form of DOM. Alternatively, the E_2:E_3 ratio suggests an increase in the non-aromatic, LMW compounds, which is not supported by the LC-OCD compositional results (Figure 4.15). However, comparison of aromaticity to DOC SUVA indicates a linear relationship ($r^2 = 0.94$, $n = 8$), but with a slope smaller than a 1:1 line (slope = 0.9), the relationship indicates that HS are not the majority of aromatic UV absorbing components, and an elevated proportion of low molecular weight aromatic (aLMW) components may exist (Aukes, *personal communication,* 2015). Additionally, Chin et al. (1998) found that a significant portion of pore water DOM may be comprised of aromatic, LMW substances that resist attack and accumulate over time, potentially increasing the E_2:E_3 ratio as the experiment progressed. So, while microbes rapidly utilize LMW compounds during decomposition of DOM, UV absorbing aLMW substances may be left behind to accumulate over time due to their refractory nature, thus increasing the E_2:E_3 ratio as the experiment progressed (Figure 4.15).

Although the Core 2 DOC concentrations varied significantly over the course of the experiment, the DOM composition remained relatively constant (Figure 4.18). The LMW-A remained non-existent within the samples, while the LMW-N comprised a consistent 5-6% of DOM. The largest change in DOM composition observed in Core 2 was between May and July when BP were raised from 1% to 5% of total DOM. While only small compositional changes were observed in samples obtained from Core 2, the DOM composition of most samples obtained from Core 1 and Core 2 compare well to samples obtained from both research sites. Similar patterns in DOM composition were observed between the research sites and the core experiment samples, whereby the majority of DOM is comprised of HS, LMW components comprise very small proportions, and BB and BP comprise the remainder of DOM with relatively equal proportions (Figure 3.1, Figure 3.3, Figure 3.4, Figure 3.6). So, while the experimental core temperatures were raised above typical ground temperatures recorded at the research sites during the summer months, the same pattern in the proportions of HS, BB, BP, and LMW compounds was observed and remained relatively constant between the study sites and the core samples.

4.5 Discussion

4.5.1 Relationship between temperature, VWC, and DOC concentration

It is well known that the rate of both DOC production and consumption are highly dependent on temperature (Schiff et al., 1998; Reynolds & Fenner, 2001; Evans et al., 2004). The relationship observed between air and internal core temperature and DOC concentration is likely a result of the environmental conditions of the cores throughout the experiment. Conditions conducive to rapid decomposition and mineralization include sufficient soil moisture (approximately 60%), and warm temperatures. A sudden increase in temperature or periodic stresses such as drying can act to accelerate overall mineralization due to the burst of microbial activity following the event (Brady & Weil, 2009). During the simulated spring and summer months, the precipitation additions to the cores were often in excess of one litre in volume and were followed by periods of dryness, which can promote spikes in DOC export when the peat re-wets. Additionally, while the cores were stored at 4 °C from the time of extraction to the time of the experiment, they remained relatively dry without any water additions until the simulated spring freshet. These conditions could have potentially contributed to the large release of DOC observed from each core throughout the experiment.

The programmed air temperature and volumes of simulated precipitation are somewhat different to the natural environments at both Pontoon Lake and the Airport site. Using a constant average monthly air temperature ignores the diurnal temperature changes between day and night, as well as the sometimes-large variability among air temperatures over a monthly period. Furthermore, because the cores react to temperature change much faster than peat at either research site, the internal core temperatures, particularly during the summer period, were sometimes not representative of the ground temperatures experienced in the natural system (Figure 2.7). Additionally, subjecting the peat cores to an entire month of simulated precipitation in one application creates unrealistic moisture conditions within the peat, as large volumes of water are pulsed through the peat cores similarly to a spring freshet. Nonetheless, the overall volumetric water content of Core 2 remained similar to that of a typical hummock at the field site (Figure 2.8, Figure 4.6).

Water additions to Core 1 exceeded annual precipitation in the natural system by approximately 65% due to water leakage and subsequent re-addition of simulated precipitation at the beginning of the experiment, however the majority of this water was drained from the bottom of the core and contributed minimally to raising the overall core VWC. Core 1 experienced drier conditions than reality throughout the experiment, except for port 3 at 40 cm, which leveled out at ~ 60% soil moisture, similar to what is expected of a depression at either the Airport or Pontoon Lake research sites (Figure 2.8, Figure 4.5). Even with these limitations, important relationships between environmental variables have been discovered. For instance, it appears as though larger volumes of water added to the cores do not have as great an effect on DOC concentration as the peat temperature does (Figure 4.7, Figure 4.8, Figure 4.11, Figure 4.12). Additionally, residence time of the accumulated water in Core 1 did not appear to increase DOC concentration within the extracted water (Figure 4.11). Instead, programmed air temperature played the biggest role in the DOC concentration of samples obtained from the cores due to its role in dictating the internal core temperature, which in turn is assumed to affect microbial activity. The water leakage from Core 1 at the beginning of the experiment and subsequent re-addition of water likely resulted in reduced DOC concentrations, as consistent flushing has been found to reduce DOC concentrations in passing water (Schiff et al., 1998). As such, DOC concentrations from Core 1 likely represent a reduced estimate of DOC concentrations that may be expected in the natural system.

Over the course of the experiment the peat cores were subjected to seasonal freeze-thaw fluctuations in soil and air temperature, creating similar thermal conditions within the peat to what many high latitude peatland ecosystems experience throughout the year. It is thought that fluctuations in air temperature may play a critical role in the patterns of nutrient mobilization seen in northern ecosystems. Multiple studies (Evans et al., 2004; Freeman et al., 2001b; Moore & Dalva, 2001) have indicated a positive influence of temperature on soil DOC production and export. Peat warming laboratory experiments show that increases in temperature correspond with increased phenol oxidase activity, an enzyme responsible for degrading high levels of recalcitrant compounds found in peat. Enzymatic hydrolysis is the process of breaking down high molecular weight organic matter into small molecules easily utilized by microorganisms, and is widely regarded as the rate-limiting step in decomposition (Evans et al., 2005; Reynolds & Fenner, 2001). High amounts of recalcitrant phenolic compounds in peat inhibit enzymatic hydrolysis. However, rising temperatures increases phenol oxidase activity, degrading recalcitrant phenolic compounds, increasing the rate of enzymatic hydrolysis, and ultimately increasing decomposition rates (Evans et al., 2004). While the current chemical analysis of the samples cannot confirm these processes, it is possible that the high internal temperature of the peat cores during the simulated thaw period contributed to triggering this mechanism for increased organic matter decomposition and DOC production.

Both cores were subjected to ideal conditions for rapid decomposition and mineralization. Sufficient aeration with approximately 60% soil moisture along with warm temperatures are all well known to increase microbial activity and the breakdown of soil organic matter (SOM). Periodic stresses, such as severe drying, are also well known to accelerate overall mineralization due to the burst of microbial activity observed following each time the soil re-wets (Brady & Weil, 2009). Although drying did occur in the cores in the time periods between simulated precipitation events, the drying was not enough to be considered severe. Changes in peat VWC never exceeded a 5% reduction in water content between water additions (Figure 4.5), making it unlikely that drying of the peat during the experiment contributed significantly to the large concentrations of DOC in the extracted water. However, due to the > 1 year period of time the cores spent in storage at 4 °C without any water additions, it is possible that the re-wetting of the peat during the simulated spring freshet accelerated decomposition after a burst of microbial activity following thaw.

4.5.2 Hydrological Observations

Although the timing of water additions and temperature fluctuations of the chamber may be more extreme than what peat in the natural system experiences, important relationships between DOC and the hydrological and thermal conditions of the peat were observed. In particular, the rapid infiltration and subsequent through-flow of water in Core 2 while the core was frozen (< 0 °C) may help to explain the fate of snowmelt water at the field sites while the ground is still frozen during the spring freshet, usually the largest hydrological event of the year in subarctic peatlands. While many studies have documented higher infiltration into thawed peat (> 0 °C) as opposed to frozen peat (< 0 °C), especially once the active layer has reached > 15 cm depth (Gray et al., 2001; Janowicz et al., 2002; Zhang et al., 2010), the opposite relationship was observed during the core experiment. When adding water to the frozen Core 2, which had a VWC of 17% prior to freeze, infiltration and through-flow occurred almost immediately. While the total volume of through-flow water in the catchment bucket was not measured, it's estimated that approximately 80 – 90% of water added to the frozen core was captured in the catchment bucket below the core. Once the core had thawed, precipitation-source through-flow was minimal if it occurred at all, indicating the peat retained most, if not all of the water added to the 40 cm length core.

The hydrological observations from the core experiment are supported by results from both research sites, and may provide insight about water contributions from hummocks into depressions during snowmelt. During the spring freshet while the majority of the peat profile was frozen, the VWC of Log1 was raised by 20%

more than Log2 at 10 cm depth, despite an even snowcover. Furthermore, peat VWC following precipitation events in the summer failed to increase below ~ 15 cm in hummocks and depressions, indicating most if not all of the precipitation was retained in the upper 15 cm of the peat profile. These results indicate that when peat is frozen infiltration may be unlimited, and when peat is thawed its water holding capacity is large enough to retain precipitation inputs in the upper 15 cm of the profile.

Infiltration into frozen soils is complicated by the complex relationships between the surface entry conditions of the soil and the transmission conditions within the soil (Janowicz et al., 2002). Assuming uniform infiltration in the absence of macropore flow, soil moisture in the upper horizon is often considered the most significant parameter governing the infiltration of water into frozen peat (Gray et al., 1970). A large VWC at the time of freeze-back has the potential to form ice lenses within the peat, inhibiting infiltration. While the upper most 10 cm of the peat profile at Log1 (degraded) and Log2 (non-degraded) maintained a similar VWC between 14-18% prior to freeze-back in 2012, below 10 cm the VWC varied significantly between the logging sites. At 30+ cm, the VWC of Log1 was > 80% prior to freeze-back. At the same depth, the VWC of Log2 was < 25% prior to freeze-back (Figure 2.8). It is likely that the elevated VWC of Log1 prior to freeze-back in 2012 created ice lenses in the peat at depths as shallow as 30 cm, causing snowmelt water to pool on the peat surface during the 2013 freshet. At Log2, the low VWC throughout the peat profile wasn't conducive to the formation of ice lenses, allowing uninhibited infiltration during the 2013 snowmelt. It's likely that during the freshet, snowmelt water infiltrated hummocks and was subsequently drained into low-lying depressions, elevating depression VWC and initiating a positive feedback for accelerated warming (Figure 2.10).

The core experiment was integral in demonstrating that during the spring freshet, water is moving rapidly through frozen peat into depressions, which potentially means large masses of DOC are also susceptible to export from hummocks into depressions at this time. The low VWC of hummocks prior to freeze allows infiltration during snowmelt to occur rapidly in the absence of ice lenses. However, the core experiment also demonstrated that the water holding capacity of peat while it's thawed (> 0 °C) is such that even when large volumes of water (>1300 ml or >42 mm) were added to the core, throughflow into the Core 2 catchment bucket did not occur. Additionally, peat VWC at the Airport and Pontoon Lake sites was not affected by precipitation below ~ 15 cm depth. As such, contributions of DOC from hummocks into depressions may be minimal, except during the spring freshet while the peat remains mostly frozen and infiltration is uninhibited. As Core 2 demonstrated with the May and December samples, there is potential for the mass export of DOC while the peat is frozen.

4.5.3 DOM composition

The core experiment absorbance scans and compositional data provide valuable information about the quality of DOC from each core. However, the large variability in hummock conditions experienced in the natural system may produce highly variable DOM composition. While the pattern of DOM composition in the core samples was similar to patterns observed in samples from the research sites, most samples obtained at the field sites originated from wet depressions and represent the DOM composition of those depressions, plus the DOM contributions from surrounding hummocks. Although attempts were made to extract water from hummocks, these dry sites experience low VWC for the majority of the thaw season, reducing the probability of obtaining a water sample. While the core experiment suggests that DOM from Core 2 is comprised mainly of low quality HS, the presence of vascular plants atop hummocks in the natural system, in conjunction with hummock topography, creates large seasonal and inter-seasonal variability in the hummock thermal and hydrological conditions. Alternatively, depressions in the natural system maintain relatively little variability in their conditions, as the catotelm, and in some instances the acrotelm, remain saturated for most of the thaw season, creating anoxic conditions and preventing vegetation growth. In the presence of saturation, depressions also experience a smaller temperature range than hummocks and react to changing air temperatures much more slowly. Conversely, hummocks experience more extreme temperatures, warming faster and to higher temperatures than depressions during the summer, and cooling to lower sub-zero temperatures more quickly during the winter providing an environment more conducive to production and consumption of DOC.

4.5.4 Climate Change and DOC

While the core temperature was observed as the strongest influence controlling DOC concentration, the volume of water added to the cores was also observed as a potentially large influence. With air temperatures already beginning to rise in the circumpolar north, seasonal hydrological change in the form of increased autumn runoff events and cold season streamflow has also been reported (Spence et al., 2011). With the freshet as the largest hydrological event of the year, mass movement of DOC from hummocks to depressions will likely only occur during snowmelt. However, should autumn runoff events increase in magnitude, especially when the peat is re-freezing, there is potential for a second large DOC mass export event as hummocks contribute water to depressions. Should this occur, many of the positive feedbacks discussed in Chapter 2 (Figure 2.10) may be initiated, ultimately increasing peat degradation and potentially increasing DOC mass export. The results from Core 1 and Core 2 indicate that there is potential for the large mass export of DOC from hummocks into depressions. Additionally, depressions themselves also produce large concentrations of DOC, but in the absence of a large hydrologic event, DOC will likely accumulate and remain over time. Should the magnitude of the freshet increase, the potential for mass DOC export from the peatland into adjoining water bodies will be heightened.

Current IPCC (2014) climate predictions for the Canadian subarctic indicate rising air temperatures and increased precipitation, resulting in warmer and wetter soils. These predictions are conducive to long-term physical landscape degradation and biogeochemical change. Evidence of measurable winter gas emissions to the atmosphere demonstrate that microbial activity at sub-zero temperatures, and thus likely DOC production and consumption, is occurring in frozen peat (Schimel & Clein, 1996; Panikov, 2009). With the possibility of future increasing winter snowfall, the magnitude of the spring freshet may increase in coming years. Should the degradation of these peatlands continue for decades to come, it is likely that the production and mass export of DOC will increase over time as microbial activity occurs year-round beneath the seasonally frozen active layer. The combination of increasing year-round DOC production in conjunction with climate change predictions and an increased magnitude of the spring freshet may result in the formation of new subsurface flowpathways, promoting the transport of DOC from the subsurface peat to surface water systems (Lyon et al., 2010). The presence of liquid water within supra-permafrost taliks beneath the seasonally frozen active layer may further elevate winter microbial activity and form subsurface connectivity between depressions as trapped heat further degrades underlying permafrost. As Chapter 2 revealed, the presence of elevated VWC within depressions causes these low-lying areas to act as "hot spots" within the peat plateaux, degrading surrounding hummocks and likely initiating hummock subsidence. It is probable that these morphological shifts in peatland microtopography, in conjunction with predicted climate change, will produce a wetland-like system in the future and change the carbon chemistry reaching surface water systems. Given the landscape degradation scenarios presented in Chapter 2, in conjunction with the elevated DOC concentrations recorded at the research sites and during the core experiment, it is likely that large mass export of C from degrading peatlands will occur under predicted warmer and wetter conditions.

4.6 Conclusions

The core experiment portion of this study aimed to explore the influences of peatland microtopography on potential DOC transport from hummocks to depressions, while simultaneously evaluating the effects of climate on DOC export and quality. Unexpectedly, the experiment also highlighted a crucial hydrological phenomenon that may provide insight into the fate of snowmelt water originating from hummock tops in the natural system. The observed relationships between hydrology, climate, and DOC are outlined below:

1. The experiment suggests that the internal peat temperature is the largest direct influence on DOC concentration from the cores. While the programmed air temperature indirectly dictated DOC concentration, its influence on the core temperature at the time of sampling was ultimately determined as the strongest contributor to elevating DOC concentration. Although subsurface peat in the natural system is well insulated by the surrounding peatland, the top 10 cm of the peat profile remains dry and is susceptible to warming beyond 14 °C (Figure 2.7) on hummock-tops. With similar peat temperatures experienced during the core experiment, it is not unlikely that the warm ground temperatures of the upper peat profile in the natural system may experience similar DOC production and subsequent downward transport, as was demonstrated during the core experiment.
2. While the volume of precipitation added to the cores during each simulated month did not appear to have a strong affect on DOC concentration it is possible that the conditions within the cores at the time of sampling may have prevented the water from interacting with the entirety of the peat comprising the cores. Samples collected while the cores remained frozen represent the smallest DOC concentration. It is possible that preferential flowpathways exist within the cores, promoting rapid throughflow and

preventing the infiltrating water from liberating DOC from the remainder of the peat. Although these flowpathways may result in lower DOC concentrations due to frequent flushing, they may also represent a rapid means of water movement, and thus DOC export, through the peat while it is frozen. Should the magnitude of the spring freshet increase in coming years, new flowpathways may be created, liberating previously sequestered DOC and rapidly exporting it downslope.

3. Although both peat monoliths were extracted from the natural peat plateau at the Airport site, they were stored at 4 °C for approximately 1 year prior to the experiment. DOM characteristics are heavily impacted by the surrounding physical, chemical, and biological conditions of its origin. While this could have been a limitation of the experiment, LC-OCD analysis reveals that DOM composition from the core experiment is proportionally similar to the DOM composition collected at both research sites. It appears as though the proportions of each component of DOM are constrained within certain intervals, with HS comprising the majority of the sample, LMW components comprising very little, and BB and BP comprising the rest. This pattern was also observed at the field sites, revealing comparable DOM characteristics between the experiment samples and samples collected at the research sites. Although the Core 1 May sample indicated an unusually high proportion of LMW-N, it was quickly depleted as microbes likely preferentially consume these LMW compounds, making them labile and high quality components of DOM. Throughout the core experiment, the DOM composition of both cores

(with the exception of the Core 1 May sample) remained relatively constant with no detectable response to the changing climate conditions of the chamber.

4. The hydrological observations of the core experiment may explain why the VWC of depressions in the natural system rises significantly higher than that of hummocks following snowmelt. While Core 2 was frozen, water additions flowed through the peat rapidly and collected in the catchment bucket below. Conversely, while the core was thawed, the water holding capacity of the peat prevented throughflow, in some cases retaining 100% of the added water within the peat. In the natural system, the ground remains frozen throughout the spring freshet. It is likely that the hydrological findings of the peat experiment represent similar processes occurring during snowmelt in the natural system whereby water flows continuously through the frozen hummocks, into the surrounding downslope depressions. As the experiment demonstrated, the throughflow water acts as a transport mechanism for DOC. Although it is unlikely that contributions of DOC from hummocks into depressions will occur during the summer while the peat is thawed, the core experiment suggests that while the peat is frozen during the spring freshet there is large potential for mass DOC export from hummocks into depressions. As depressions continue to accumulate DOC and expand their boundaries as they further degrade, the potential for subsurface interconnectivity of depressions is increasing and is promoted by the formation of supra-permafrost taliks. Should the spring freshet increase in

magnitude as predicted while degradation simultaneously continues, larger volumes of water carrying DOC will be pulsed through the frozen peat and may accumulate within thawed taliks beneath the seasonally frozen active layer. As this accumulation occurs, it creates potential for lateral water movement, and may potentially result in the future release of massive stores of DOC into surface water systems.

References

Agren, A., Buffam, I., Berggren, M., Bishop, K., Jansson, M., Laudon, H. 2008. Dissolved organic carbon characteristics in boreal streams in a forest-wetland gradient during the transition between winter and summer. *Journal of Geophysical Research.* 113, 1-11.

Aukes, P. 2012*. Use of liquid chromatography – organic carbon detection to characterize dissolved organic matter from a variety of environments*. Unpublished master's thesis, Waterloo University, Waterloo, Canada.

Baltzer, J.L., Veness, T., Chasmer, L.E., Sniderhan, A.E., Quinton, W.L. 2014. Forests on thawing permafrost: fragmentation, edge effects, and net forest loss. *Global Change Biology.* 20, 824-834.

Brady, N. C., Weil, R. R. 2010. *Elements of the nature and properties of soils*, 3rd edn. Boston, MA. Prentice Hall.

Dahlén, J., Bertilsson, S., Pettersson, C. 1996. Effects of UV-A irradiation on dissolved organic matter in humic surface waters. *Environment International.* 22, 501-506.

Eberling, B., Michelsen, A., Schadel, C., Schuur, E. A. G., Christiansen, H. H., Berg, L., Tamstorf, M. P., Sigsgaard, C. 2013. Long-term CO_2 production following permafrost thaw. *Nature.* 3, 890-894.

Evans, C. D., Monteith, D.T., Cooper, D.M. 2005. Long-term increases in surface water dissolved organic carbon: Observations, possible causes and environmental impacts. *Environmental Pollution.* 137, 55-71

Freeman, C., Fenner, N., Ostle, N. J., Kang, H., Dowrick, D. J., Reynolds, B., Lock, M. A., Sleep, D., Hughes, S., Hudson, J. 2004. Export of dissolved organic carbon from peatlands under elevated carbon dioxide levels. *Nature*. 430, 195-198.

Gray, D. M., Norum, D. I., Wigham, J. M. 1970. Infiltration and physics of flow of water through porous media. *Handbook on the Principles of Hydrology.* Edited by D. M. Gray. Canadian National Committee of the International Hydrological Decade, Ottawa.

Gray, D. M., Toth, B., Zhao, L., Pomeroy, J. W., Granger, R. J. 2001. A deterministic approach of modeling and scaling frozen soil infiltration during snow ablation. *Hydrological Processes*. 15, 3095-3111.

Guan, X. J., Westbrook, C. J., Spence, C. 2010. Shallow soil moisture – ground thaw interactions and controls – Part 1: Spatiotemporal patterns and correlations over a subarctic landscape. *Hydrology and Earth System Sciences.* 14, 1375-1386.

Janowicz, J. R., Gray, D. M., Pomeroy, J. W. 2002. *Characterisation of snowmelt infiltration scaling parameters within a mountainous subarctic watershed.* Proceedings of the 59th Eastern Snow Conference, Stowe, Vermont, USA, 2002. 67-81.

IPCC, 2014: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 688 pp.

Lyon, S. W., Morth, M., Humborg, C., Giesler, R., Destouni, G. 2010. The relationship between subsurface hydrology and dissolved carbon fluxes for a sub-arctic catchment. *Hydrology and Earth System Sciences.* 14, 941-950.

Marhaba, T. F., Van, D. 2000. The variation of mass and disinfection by-product formation potential of dissolved organic matter fractions along a conventional surface water treatment plant. *Journal of Hazardous Materials.* 74, 133-147.

Meteorological Service of Canada (MSC). 2014. National climate data archive of Canada, Environment Canada: Dorval, Quebec.

Moore, T. R., Basiliko, N. 2006. Decomposition in Boreal Peatlands, in *Boreal Peatland Ecosystems.* 125-143. Berlin, Germany. Springer.

Peacock, M., Evans, C. D., Fenner, N., Freeman, C., Gough, R., Jones, T. G., Lebron, I. 2014. UV-visible absorbance spectroscopy as a proxy for peatland dissolved organic carbon (DOC) quantity and quality: considerations on wavelength and absorbance degradation. *Environmental Science: Processes & Impacts.* 16, 1445-1461.

Reynolds, B., Fenner, N. Export of organic carbon from peat soils. *Nature.* 412, 785.

Schiff, S., Aravena, R., Mewhinney, E., Elgood, R., Warner, B., Dillon, P., Trumbore, S. 1998. Precambrian Shield wetlands: Hydrologic control of the sources and export of dissolved organic matter. *Climatic Change.* 40, 167-188

Schlesinger, W. H., Bernhardt, E. S. (2013). Biogeochemistry: An analysis of global change (3rd Ed). Waltham, MA: Academic Press.

Schimel, J. P., Clein, J. S. 1996. Microbial response to freeze-thaw cycles in tundra and taiga soils. *Soil Biology & Biogeochemistry.* 28, 1061-1066.

Spence, C., Kokelj, S. V., Ehsanzadeh, E. 2011. *Precipitation trends contribute to streamflow regime shifts in northern Canada.* Proceedings of symposium H02 during the International Union of Geodesy and Geophysics 2011 conference, Melbourne, Australia, July, 2011. 346, 3-8.

Spencer, R. G. M., Mann, P. J., Dittmar, T., Eglinton, T. I., McIntyre, C., Holmes, R. M., Zimov, N., Stubbins, A. 2015. Detecting the signature of permafrost thaw in Arctic rivers. *American Geohysical Union.* 10, 1-6.

Weishaar, J. L., Aiken, G. R., Bergamaschi, B. A., Fram, M. S., Fujii, R., Mopper, K. 2003. Evaluation of specific ultraviolet absorbance as an indicator of the chemical composition and reactivity of dissolved organic carbon. *Environmental Science & Technology.* 37, 4702-4708.

Williams, T.J. 2012. *Recovery of linear disturbances in a discontinuous permafrost peatland environment.* Unpublished master's thesis, Wilfrid Laurier University, Waterloo, Canada

Wright, N., Hayashi, M., Quinton, W.L. 2009. Spatial and temporal variations in active layer thawing and their implication on runoff generation in peat-covered permafrost terrain. *Water Resources Research.* 45, WO5451.

Zhang, Y., Carey, S. K., Quinton, W. L., Janowicz, J. R., Pomeroy, J. W., Flerchinger, G. N. 2010. Comparison of algorithms and parameterisations for infiltration into organic-covered permafrost soils. *Hydrology and Earth System Sciences.* 14, 729-750.

Chapter 5

Conclusions

5.1 Summary of Processes

To summarize the numerous processes and complex feedbacks discussed throughout this thesis, a conceptual model (Figure 5.1) was created and details the relatively small-scale processes that interact over time both seasonally and inter-seasonally to produce large-scale landscape degradation and ecosystem collapse. Beginning in the summer season, future warming air temperatures and increased precipitation (IPCC, 2014) will elevate microbial activity and decomposition, while simultaneously increasing peat thermal conductivity and active layer thickness. The autumn season brings an increasing frequency of large runoff events (Spence et al., 2011), promoting DOC export and ice lens formation during freeze-back, and the potential for an early snowfall insulates the ground, reducing the depth of freeze-back and potentially aiding the formation of supra-permafrost taliks. The presence of liquid water in the peat profile during the winter period acts as a source of heat, degrading permafrost below and elevating winter microbial activity. With a potentially higher snowfall, the magnitude of the spring freshet will increase, resulting in surface pooling, vegetation death, DOC export, and elevated solar radiation absorption at the ground surface. The continuous cycling of these processes leads to site-wide degradation as depressions expand, eventually causing the peat plateaux to subside and resemble an inundated bog.

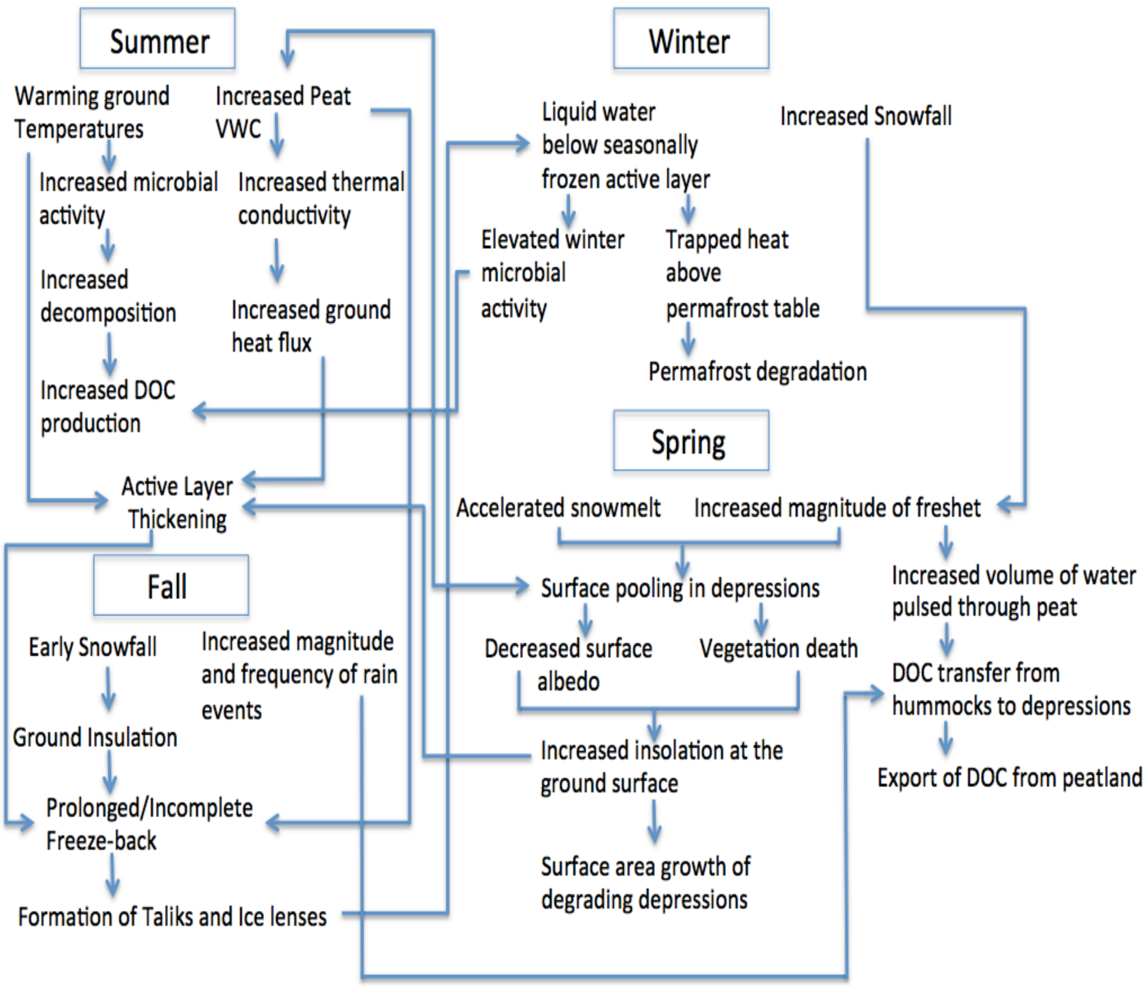


Figure 5.1: Conceptual model of the various feedbacks, discussed in chapters 1-4 of this thesis, which interact on a continuous basis to produce a degrading peatland system. The interaction of these processes results in permafrost loss and DOC export from the peat plateau, while the physical landscape subsides into a wetland-like state.

5.2 Evolution of Peat Plateaux

The study of two peat plateaux in the Yellowknife region has shown how the interactions of numerous complex feedbacks initiated by the changing subarctic climate drive the degradation and eventual evolution of peat plateaux into a wetland-like state. The evolution of conditions observed at both research sites indicate that site-wide degradation does not occur simultaneously. Instead, the areas most vulnerable to water interaction and accumulation (depressions and plateau edges) act as “hot spots” for permafrost loss, and gradually expand their boundaries outward over time as thermal and hydrological positive feedbacks interact to further degrade underlying permafrost. As the progression of degradation expands the surface area of the permafrost-free “hot spots”, complete freeze-back of the active layer within depressions during the winter months is no longer possible due to the combined effects of snowcover insulation and saturated conditions. As depression boundaries expand vertically and laterally, supra-permafrost taliks form and create the potential for elevated winter microbial activity, subsurface interconnectivity between depressions, and water movement beneath the seasonally frozen active layer.

At both the Airport and Pontoon Lake sites, which are typical of much of the taiga shield, an evolution of conditions associated with landscape degradation were observed. As each logging site indicated, there are numerous stages of degradation before complete permafrost loss and wetland conditions occur. This study demonstrated that the most probable indication of the future functioning of a peatland is its current microtopographical structure. The ability of microtopography to dictate the hydrological functioning of the system makes it the most important precursor to permafrost loss of the future. In the absence of flowpathways exiting the peatland, snowmelt water is directed into depressions where it accumulates, beginning a lengthy transition from a stable state into a significantly degraded condition (Figure 5.1).

5.3 Characterization of DOM

As a byproduct of landscape evolution, geochemical change is an expected outcome of shifting physical conditions. This study used LC-OCD analysis of DOM to effectively characterize an extensive data set originating from a number of different physical landscape conditions within two peatland sites. Although not particularly high in quality, microbial decomposition of DOM was observed at both sites over the course of the 2013 thaw season. Interestingly, regardless of the DOC concentration, the proportions of each DOM component remained relatively constant despite the sample origin. The majority of DOM was comprised of HS in all instances, with degraded humics (BB), biopolymers and LMW-N comprising the rest of the DOM. In all cases, LMW-A were non-existent.

As expected, the LC-OCD analysis identified differences in DOM composition consistent with the origin of the sample. Surface water samples were found to have a consistently lower DOC concentration (< 50 mg/L) and aromaticity, while groundwater samples originating from the peatland maintained higher DOC concentrations (> 70 mg/L) and showed signs of slow microbial breakdown of HS under saturated conditions. As the HS diagrams (Figure 3.7) in Chapter 3 show, HS originating from surface waters changed over time and was different from HS collected from the peat plateaux, indicating that microbial production, decomposition and UV irradiation play an important role in the transformation of HS and DOM in this type of environment. Conversely, groundwater must first infiltrate through the upper subsurface layers of the peat, where DOM composition may be reworked. Because the surrounding environment heavily influences DOM, the physical, chemical and biological influences of the subsurface may play an important role in determining DOM composition. Additionally, as Chapter 4 demonstrated, during the spring freshet hummocks likely contribute large masses of DOC to surrounding depressions, which act as drainage catchments for snowmelt water. As such, the large accumulation of DOC within depressions receiving snowmelt water is probable. The presence of saturated conditions and low ground temperatures allows for little decomposition to occur, and where these conditions exist in addition to elevated DOC concentrations, it is likely DOM is accumulating from an upslope source.

5.4 Core Experiment

The core experiment was integral in demonstrating the connection between climate and carbon export from peat. Important relationships between the thermal and hydrological functioning of the cores and DOC export were revealed over the course of the experiment. It was observed that while Core 2 (functioning as a hummock) was frozen, uninhibited infiltration and throughflow of water occurred. Conversely, while the core was thawed, the entirety of the water additions were retained within the peat. Although the capped bottom of Core 1 (functioning as a depression) did not allow for throughflow, it is likely that similar rapid infiltration and percolation through the peat occurred while the core was frozen. These structural differences in experimental design provided insight into the hydrological functioning and geochemical response of the natural system during the spring freshet. Furthermore, the increasing frequency of autumn runoff events in the Canadian north since the 1990s (Spence et al., 2011) creates potential for a second large mass DOC export event, in addition to during the spring freshet. Should these runoff events occur during freeze-back while the peat is frozen or partially frozen, it is probable that similarly to the freshet, DOC will be transported within the peatland from hummocks into depressions, as well as being exported from the peatland into surface water systems.

Although DOC concentrations were lowest while the cores were frozen, the uninhibited infiltration of water through the peat resulted in vertical DOC transfer within the system. Furthermore, as a byproduct of a degrading peat plateau, subsurface interconnectivity amongst depressions is a potential likelihood of supra-permafrost talik formation, in turn leading to the development of defined subsurface flowpathways. When combined with the effects of a degrading peat plateau potentially creating future subsurface flowpathways exiting the peatland, mass export of DOC into surface water systems is likely to occur during each successive spring freshet, and possibly during freeze-back. Currently, it appears as though both the Airport and Pontoon Lake peatlands are in a transitioning period whereby supra-permafrost taliks exist with little-to-no interconnectivity between them. Both sites likely experience the subsurface movement of water downslope, particularly at the Airport site from the interior of the plateau to its edges where thermal degradation is already in progress, however in the absence of defined flowpathways the rate of movement is very gradual while the peat is thawed. Although water movement during the summer months may be negligible over a short time period, the cumulative movement over a decade or more may contribute substantially to the accumulation of DOC in the subsided and degraded low-lying areas and into downslope water bodies. Should the peat plateaux continue to degrade as predicted, subsurface flowpathways may form, aiding in the transfer of DOC, especially during the spring freshet when water moves rapidly through the frozen peat. As peat temperatures warm, decomposition of solid organic matter will increase, resulting in higher DOC concentrations within peat pore waters and likely elevated DOC mass export when large hydrological events occur.

In addition to inter-system transfer and export, there is also the potential for substantial accumulation of DOC in areas susceptible to receiving high volumes of snowmelt water, such as P4 at the Airport site. While data suggests decomposition and summer water movement at P4 to be minor, saturation existed for the majority of the summer while elevated DOC concentrations (220 – 340 mg/L) were consistently found. These findings suggest an upslope source of DOC, and given the insignificant effects of summer precipitation on peat below approximately 15 cm depth, it is likely that DOC transport is occurring during the spring freshet as water is rapidly pulsed through the frozen peat and transferred downslope. While these processes are likely occurring throughout the peatland and result in DOC accumulation in depressions across both research sites, areas like P4 at the Airport site are particularly susceptible to mass DOC export due to the close proximity to the degrading plateau edge bordering the bog and pond. So, while DOC export from the interior of the peat plateau may be very unlikely in the absence of defined flowpathways, it may still be gradually transferred over time within the system causing DOC to accumulate near the plateau edge, making it susceptible to export with each successive spring freshet.

The core experiment also revealed important relationships between climate and DOC concentration. Despite a relatively small number of samples extracted from the cores (n = 8), a strong relationship between core temperature and DOC concentration was observed in both cores. A relationship between the volume of water added to the cores and the resulting DOC concentration was less obvious, however important discoveries were still made. It was observed that while the cores were at their lowest temperatures, DOC concentration in the cores was also at its lowest, regardless of the volume of water added. These observations aid in determining the potential for future DOC export from the research sites. As the core experiment demonstrated, water moves rapidly through frozen peat, and although DOC concentrations in samples from the cores were lowest during the simulated spring period, the potential for DOC export is highest during this time. As climate warms (IPCC, 2014) and annual precipitation increases, the magnitude of the spring freshet will also likely increase. The combination of the spring freshet with the rapid movement of water through the peat will inevitably result in DOC transport, as was the case during the core experiment. While DOC mass export from the peatland may not occur from the plateau interior directly to surface water bodies in the absence of flowpathways, the movement of DOC from the plateau interior to its edges where it accumulates is an integral process preceding export.

Although the experiment demonstrates that warming temperatures result in higher DOC concentrations, the lack of water movement during the summer at both research sites suggest that DOC export currently is minimal. However, the relationship between temperature and DOC suggests that as peat temperatures increase, decomposition of solid organic material is increasing, and thus the production and decomposition of DOC is also rising. The litterbag results presented in Chapter 2 of this thesis reveal substantial mass losses over just a one-year period, indicating high decomposition rates. Although mass losses were higher than reported in other studies (Laiho, 2006), the litter-bag method was replicated closely (Moore et al., 2007; Karberg et al., 2008) giving confidence in the high mass loss results. As the peat plateaux continue to degrade, complete freeze-back during the winter may become impossible, leading to elevated microbial activity in the thawed ground below the seasonally frozen active layer during the winter months. As the production of DOC continues throughout the winter within the most heavily degraded areas there exists a higher potential for increased DOC transport and export during the spring freshet.

The cumulative effects of the processes described above are likely to have a number of negative consequences to surrounding ecosystems, particularly surface water systems. It is likely that these processes are not occurring solely at the studied research sites, and that many peatlands in the Yellowknife region are undergoing similar landscape transitions. It is also likely that as climate changes in the coming decades temperatures will warm and precipitation will increase across subarctic Canada. These changes are likely to affect all peatlands in the Yellowknife region, as conditions become favorable to permafrost degradation and the numerous positive feedbacks discussed in this thesis and in Figure 5.1 begin to transform the landscape, both physically and chemically. This thesis demonstrates the interconnectivity of the most influential processes driving the transition of these environments and the various positive feedbacks contributing to further degradation. Acting like a domino effect, each changing aspect of the environment leads to further change, until eventually the entire system has transformed into a degraded manifestation of its original, natural state.

References

IPCC, 2014: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 688 pp.

Laiho, R. 2006. Decomposition in peatlands: Reconciling seemingly contrasting results on the impacts of lowered water levels. *Soil Biology & Biochemistry.* 38, 2011-2024.

Karberg, N. J., Scott, N. A., Giardina, C. P. 2008. Methods for estimating litter decomposition. In: Hoover, C. M. ed. *Field Measurements for Forest Carbon Monitoring.* Spring, New York, NY

Appendix A

Calculated Ground Heat Flux

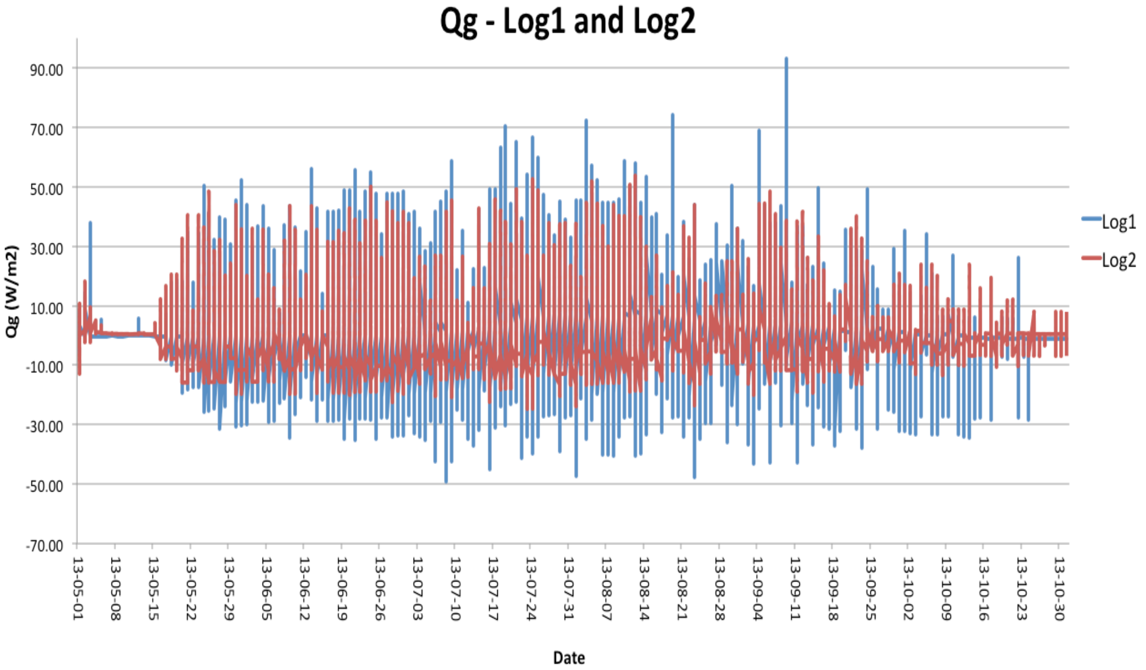


Figure A.1: Comparison of Log1 and Log2 ground heat flux from May – October 2013

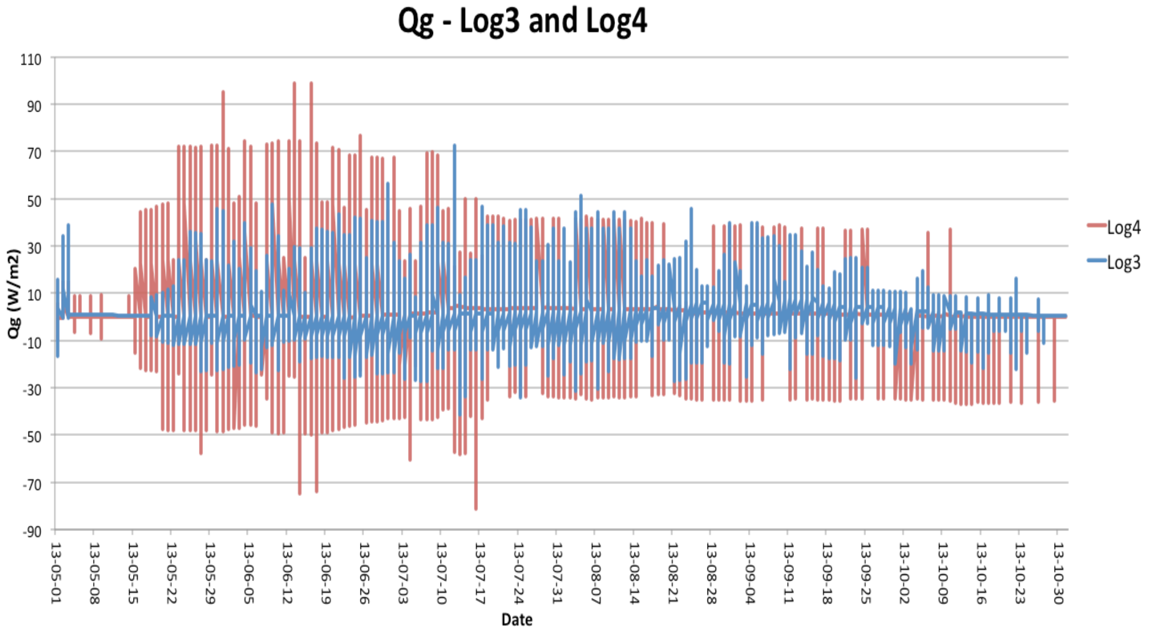


Figure A.2: Comparison of Log3 and Log4 ground heat flux from May – October 2013. The Log4 surface probe (10 cm) began malfunctioning and is therefore not included in the Q_g calculations beyond July 17.