Examining changes to forest and permafrost distribution in the southern Northwest Territories and northeastern British Columbia

by

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ABSTRACT

Examining changes to forest and permafrost distribution in the southern Northwest Territories and northeastern British Columbia

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The Canadian subarctic is currently among the most impacted regions in the world as it is experiencing rapid climatic and environmental change. This has led to unparalleled permafrost degradation, which has important implications for wide-ranging boreal peatland landscapes and the associated local hydrology and ecology. Determining and monitoring the state of underlying permafrost as well as the patches of forest above them has risen to the forefront of subarctic research given the dramatic and broad-scale land cover changes that are presently being observed. The first manuscript and second chapter of this thesis examines the amount and rate of change to landcover between the 1970s and present-day. This study also addresses changes to these landcover variations across a latitudinal gradient by considering climatic and environmental factors that correspondingly vary with latitude. The second manuscript and third chapter of this thesis evaluates landcover as a predictor of underlying permafrost presence or absence. The findings of these chapters will aid in furthering the understanding of the relationship climate change has on accelerating permafrost and forest loss in Canada’s subarctic.
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CHAPTER 1.0: Introduction

Permafrost is a fundamental and defining characteristic of northern environments. However, it is also highly sensitive to external forcing and is undergoing accelerated degradation throughout much of Canada’s north. An area of particular note is the southern Northwest Territories and northeastern British Columbia, which largely fall within Canada’s discontinuous or fringe permafrost zone and are highly susceptible to widespread permafrost thaw (Bonnanventre et al., 2012; Quinton et al., 2011). Not only has this area been experiencing dramatic climate warming, but it is also undergoing regionally-unparalleled industrial expansion (Hinzman et al., 2005; Quinton et al., 2011). Determining and mapping the past and future changes to permafrost in the subarctic is a pressing research topic, particularly given these recorded and predicted changes.

It is well understood that temperature (i.e. average annual temperature ≤0°C) is the dominant control on permafrost distribution. However, on a more local scale, there is still considerable variability across the landscape (Bonnanventre & Lewkowicz, 2011; Bonnavventure et al., 2012; Brown, 1960). In the boreal peatlands of the southern discontinuous permafrost zone, this pattern has been at least partially explained by the relationship that exists between landcover and permafrost; where forest cover is often indicative of thick permafrost rising above the surrounding environment (i.e. permafrost plateaus) while wetlands are underlain by permafrost-free ground (Baltzer et al., 2014; Quinton et al., 2011; Wright et al., 2009). Using landcover as a proxy for permafrost condition has emerged as an appropriate and innovative method of monitoring these vulnerable and remote environments due to the infeasibility of permafrost ground sampling throughout the region’s entirety (Baltzer et al., 2014; Quinton et al., 2011). This also falls within the larger literature trend of accepting the inherent
research limitations in the arctic and subarctic and instead moving towards developing accurate remote techniques of determining permafrost condition (Baltzer et al., 2014; Bonnaventure & Lewkowicz, 2011; Bonnaventure et al., 2012). Not only is landcover much more visible and easily monitored in comparison to underlying permafrost, but the increased availability of remote sensing products has opened these regions to improved research efforts. This is also an important trend as the focus shifts towards understanding the broader surface changes of these transitioning ecosystems to more successfully predict the rate and amount of permafrost degradation (Etzelmuller et al., 2001; Pastick et al., 2013; Rees, 1990). Most previous studies that attempted to address either or both topics have largely been limited to small areas and have typically been isolated to well-studied sites with extensive and comprehensive instrumentation and data records (Baltzer et al., 2014; Quinton et al., 2011). However, given the uniqueness and heterogeneity of these environments, there is a need to address these opportunities across a wider spatial range.

These research topics can be addressed through remote sensing methods, which have become a preferred research technique for isolated and rapidly changing areas, such as in the context of measuring and delineating forest to wetland conversion as well as the associated permafrost change (Nguyen et al., 2009; Sabins, 1987; Stevens & Wolfe, 2012). The foremost advantage of remote sensing is the ability to quickly and relatively inexpensively acquire data over large areas of Earth’s surface, particularly those that are not easily accessible, thereby addressing the principle limitation of many previous studies (Jensen, 2004; Panda et al., 2010; Pastick et al., 2013; Smith & Burgess, 2004). This approach is particularly beneficial in the boreal peatlands given that easily distinguishable landcovers are increasingly being used to represent permafrost condition and quality (Baltzer et al., 2014; Chasmer et al., 2011).

Additionally, the repetitive or cyclical coverage that is often associated with remote methods
provides a unique benefit for monitoring changes to the features present in transitioning permafrost landscapes across both time and space (Jensen, 2004; Panda et al., 2010; Schuur & Abbott, 2011; Schuur et al., 2015). The identified benefits to utilizing remote sensing in this region, specifically when in combination with field methodologies, form the basis of this research as addressed in the subsequent research question.

This research seeks to evaluate the relationship between landcover change and permafrost thaw through the following overarching research question: To what extent can landcover be used as a proxy for permafrost condition across the subarctic boreal peatland landscapes found throughout the southern Northwest Territories and northeastern British Columbia? This research question is analyzed and addressed through two key research objectives:

1. The first objective of this research is to determine the amount and rate of change to landcover between the 1970s and present-day while exploring the climatic controls on differential rates of change across a latitudinal, and thus climatic gradient between the southern Northwest Territories and northeastern British Columbia.

2. The second objective of this research is to determine if landcover is a successful predictor of underlying permafrost in two boreal peatland study regions at different latitudes.

Due to the nature of these research objectives, this thesis is organized as two distinct manuscripts; the first addresses the linkages between forest loss and climatic factors across a latitudinal gradient (Chapter 2) and the second evaluates landcover as a predictor of underlying permafrost distribution (Chapter 3). A summary of findings as well as an assessment of the research is outlined in Chapter 4.
CHAPTER 2.0: Climate change and permafrost thaw-induced forest loss in northwestern Canada’s fringe permafrost zone

Abstract

Permafrost distribution throughout the Canadian subarctic is not particularly well understood due to a combination of the remoteness and size of the region, spatial and temporal heterogeneity, limited data availability, and incomplete monitoring networks. These factors not only highlight the challenges associated with establishing a comprehensive understanding of the changing distribution of permafrost under the impacts of climate change, but also further emphasize the need to improve techniques of remotely capturing and analyzing permafrost distribution. Landcover, which is highly visible and easily identified through remote sensing data, has been proposed as an emerging method; where forest cover is often indicative of permafrost plateaus, while wetlands are underlain by permafrost-free ground. Recent warming throughout the subarctic boreal peatlands has led to rapid and widespread permafrost degradation and has also corresponded with a significant decrease in forest cover and wetland expansion. This study quantifies landcover change and net forest loss at 10 subarctic boreal peatland sites in the southern Northwest Territories and northeastern British Columbia between 1970 and 2010. Historical air photos and optical remote sensing images were assessed using a change detection approach over 10 km² areas of interest. Variable patterns of net forest loss at each site ranged from 6.9% to 11.6% over the 40-year study period. These differential rates of landcover change can be explained in part through climatic and environmental factors that vary latitudinally across the selected sites. Change statistics – net change, forest gain and forest loss were significantly correlated with an assortment of factors that varied across the 10-site transect.
2.1 Introduction

It is well established that an average annual temperature of \( \leq 0^\circ C \) is the dominant control on permafrost presence (Bonnaventure & Lewkowicz, 2011; Bonnaventure et al., 2012; Brown, 1960; Hayashi et al., 2007). However, the discontinuous permafrost zone is also inherently defined by variability in permafrost presence or absence across the landscape due to local factors (Bonnaventure & Lewkowicz, 2011; Bonnaventure et al., 2012; Brown, 1960). In the fringe permafrost zone, and specifically the boreal peatlands within it, this pattern has been at least partially explained by the relationship that exists between landcover and permafrost; where forest cover often indicates the presence of permafrost rising above the surrounding environment (i.e. permafrost plateaus) while bogs, fens and other wetlands are permafrost-free (Baltzer et al., 2014; Quinton et al., 2011; Wright et al., 2009).

Boreal peatlands encompass a broad portion of Canada’s boreal ecosystem and 37% are underlain by permafrost found in the southern discontinuous permafrost zone (Tarnocai, 2006). At the southern permafrost margin or in the fringe permafrost zone, permafrost exists near 0°C, approaching an unsuitable thermal state (Kwong & Gan, 1994). Much of this region is peatland dominated and the relationship between landcover and permafrost has made it ideal to study in regards to changing permafrost distribution (Baltzer et al., 2014; Quinton et al., 2011; Wright et al., 2009). In these environments, forest and wetland landcovers are increasingly being used to represent and monitor the state of the underlying permafrost as well as the overall condition of the landscape due to the difficulty of permafrost ground sampling across large areas of remote subarctic terrain (Baltzer et al., 2014; Chasmer et al., 2011; Quinton et al., 2011). Over recent decades, these distinguishable landcovers have also been used to establish a transition from forest to wetland-dominated landscapes driven by permafrost thaw (Baltzer et al., 2014; Quinton...
et al., 2011; Wright et al., 2009). Landcover change is easily measured and because the connection between permafrost thaw and landcover change has been well demonstrated, remote sensing platforms have been increasingly used to improve research efforts in these regions. This is an important trend as the focus shifts towards understanding the broader surface changes of these transitioning ecosystems and more successfully predicting the rate and amount of permafrost degradation (Etzelmuller et al., 2001; Pastick et al., 2013; Rees, 1990).

While these fringe permafrost zone environments have always experienced natural and expected cycles of permafrost aggradation and degradation over time, warming over recent decades has disrupted this natural cycle and distinct and consistent patterns of permafrost thaw now dominate the region (Beilman et al., 2001; Chasmer & Hopkinson, 2017; Schuur & Abbott, 2011; Turetsky et al., 2007; Wright et al., 2009). This emerging trend has been shown to have the most dramatic impacts in areas with rising temperatures, particularly those with annual average temperatures nearing 0°C, indicating a climatic effect (Beilman & Robinson, 2003; Halsey et al., 1995; Prowse & Furgal, 2009; Quinton et al., 2011). This increased permafrost thaw has many distinct environmental implications including hydrologic and ecologic changes. Given the broad range of peatland structures and functions that may be affected, determining the amount and rate of permafrost thaw, especially in relation to climate change, is an increasingly important area of study.

Previous permafrost modelling and mapping initiatives, have indicated substantial permafrost thaw and degradation, which has in turn led to forest loss through plateau collapse and wetland inundation (Baltzer et al., 2014; Quinton et al., 2011; Wright et al., 2009). Plateau-loss is occurring at an unprecedented rate and much faster than new peat plateaus can form (Hayashi et al., 2004; Quinton et al., 2009; Quinton et al., 2011). This transition is also due to the
associated tree species, and of particular note - the keystone species black spruce, which begins to decompose and die once their environment becomes saturated due to their relative intolerance to waterlogging (Islam & McDonald, 2004; Iwata et al., 2012). These degradation processes are also typically positive feedback associations. Where, as more forest disappears from the landscape through the above mechanisms, the wetland terrain replacing the forest further exposes the surface to solar radiation and increases the moisture content and thus thermal conductivity (Jorgenson et al., 2010; Robinson & Moore, 2000; Turetsky et al., 2007). Both positive feedback mechanisms accelerate plateau collapse and the loss of remaining tree cover, further escalating the land cover transition towards permafrost-free wetlands (Jorgenson et al., 2010; Robinson & Moore, 2000; Turetsky et al., 2007).

This study aims to determine the extent and rate of change to landcover between the 1970s and present-day across 10 boreal peatland sites spanning the latitudinal extent of the fringe permafrost zone in the southern Northwest Territories and northeastern British Columbia. The observed areal changes will be described using the latitudinal span of sites and these changes will also be attributed to climatic factors that vary correspondingly. Annual and seasonal climatic factors such as temperature and precipitation as well as changes to environmental elements such as fragmentation or growing season may have important consequences. These climatic and environmental factors can be used to assess a site’s vulnerability to not only transition from forest to wetland but also has implications for the permafrost loss that is occurring over the same time period.
2.2 Study Area

2.2.1 Boreal Peatlands

Up to 80% of the world’s boreal ecoregions are located in northern environments underlain by permafrost (Helbig et al., 2016). In Canada, much of the subarctic boreal forests are classified as wetland-dominated thermokarst landscapes, where the fringe permafrost zone of the southern NWT and northeastern BC is almost exclusively covered by boreal peatlands (Helbig et al., 2016; Olefeldt et al., 2016). These boreal peatlands are characterized by a patchwork landscape of boreal forest, underlain by permafrost plateaus and adjacent wetlands that are permafrost-free (Baltzer et al., 2014; Quinton et al., 2011; Wright et al., 2009). Permafrost is a dominant characteristic of these subarctic boreal peatlands, and uniquely, even if climatic conditions such as air or soil temperature are individually unsuitable for permafrost, peat’s insulating properties allow for the ground to remain frozen year-round (Beilman et al., 2001; Turetsky et al., 2007; Wright et al., 2009). The presence of peat-rich organic soils in combination with vegetation structure and snow accumulation are key controls in determining the distribution of permafrost and is almost exclusively responsible for any permafrost found on the climatic fringes between the discontinuous and sporadic zones (Halsey et al., 1995; Helbig et al., 2016; Vitt et al., 1994; Wright et al., 2009). Subarctic peatlands are comprised of three distinct landscape features: permafrost plateaus, channel fens, and flat bogs, each with unique hydrologic, edaphic and vegetative characteristics (Quinton et al., 2009; Zoltai, 1971; Zoltai & Tarnocai, 1975).

Permafrost plateaus, also referred to as peat plateaus, are essentially mounds that remain perennially frozen for two or more consecutive years. These plateaus represent the transitional nature of these landscapes, as they are the product of long-term peat accumulation (Beilman et
al., 2001; Turetsky et al., 2007; Zoltai & Johnson, 1985). Effectively, peat accumulates within the wetland landscape features and over time, will rise above the surface to form a peat plateau or may attach itself to an existing permafrost structure (Robinson & Moore, 2000). In both cases, the insulating properties and low thermal conductivity of peat minimizes surface warming allowing frost bulbs to develop and permafrost to propagate (Beilman et al., 2001; Robinson & Moore, 2000; Turetsky et al., 2007).

Permafrost or peat plateaus are the site of numerous vegetation types. Specifically, mosses and lichens are the first to establish, followed by shrubs and the characteristic keystone species – black spruce (Picea mariana) (Chasmer et al., 2011; Iwata et al., 2012; Robinson & Moore, 2000). This black spruce canopy dominates the plateaus where tree cover can range from fully forested (>70% tree cover) to wooded (30-70% tree cover) (Halsey et al., 1995; Quinton et al., 2009). The increased vegetation cover on these mature permafrost plateaus further insulates the ground through decreased incoming solar radiation and also contributes organic matter (e.g. roots, needles, woody debris, etc.) to the thickening peat layer (Chasmer et al., 2011; Quinton et al., 2008; Robinson & Moore, 2000; Williams & Quinton, 2013).

While plateau features are largely defined by the aggradation of peat and proliferation of permafrost, peat plateaus will eventually degrade as well (Robinson & Moore, 2000). Plateau degradation is occurring at an increasing rate due to warming trends throughout the arctic and subarctic. The instability associated with this increased thaw will result in the peat plateaus collapsing into the surrounding wetland features (Chasmer et al., 2011; Quinton et al., 2011; Robinson & Moore, 2000; Wright et al., 2009). Beyond climatic warming, this permafrost thaw also naturally occurs due to heat transfer from the wetland features as well as water infiltration.
either via precipitation or from the fens/bogs themselves (Hayashi et al., 2007; Quinton et al., 2009; Quinton et al., 2011).

2.2.2 Areas of Interest

This research was conducted along a north-south transect comprised of 10 sites running from the southern Northwest Territories, specifically south of Fort Simpson, to northeastern British Columbia, north of Fort Nelson. This transect is approximately 150 kilometres in length and has been divided into three categories based on latitudinal and climatic similarities – the Mackenzie region, the Trout Lake region and the NWT/BC border region, all of which are characterized by boreal peatland landscapes within Canada’s fringe permafrost zone (Figure 2.1). Specific sites were selected as areas of interest by considering two factors. Firstly, the selected site must be a peatland complex that contains all three major land classes (plateaus, bogs and fens). Secondly, there must be sufficient remote sensing coverage both temporally (i.e. approximately a 40-year historical record) and spatially (i.e. must have adequate overlap between historical photographs and contemporary satellite imagery).

![Figure 2.1: Details and mapped locations of 10 selected areas of interest (A-J) as divided and grouped into three latitudinal regions.](image-url)
The targeted areas of interest are characterized by a dry continental climate with short summers and long, cold winters with the mean annual air temperature ranging from -3.4°C to -2.5°C across the 10 sites (Natural Resources Canada, 2017). Over the 1970-2010 study period, average annual temperatures increased approximately 0.9°C, which is part of a longer-term trend across these subarctic sites that has observed up to 1.4°C in warming over the past century (Natural Resources Canada, 2017).

As is characteristic of the boreal peatlands that dominate the fringe permafrost zone, peat is the dominant soil type and covers the entirety of the targeted study sites and may be as deep as eight metres before mineral soil is reached (Aylesworth & Kettles, 2000; Quinton et al., 2009). Despite the insulating properties associated with a peat soil of this depth, recent decades have shown a significant decrease in permafrost cover in this area, which has also corresponded with increased water on the landscape. This has been observed through a transition from permafrost plateaus and boreal forest dominating the landscape to an increase in wetland cover (Baltzer et al., 2014; Bonnaventure & Lewkowicz, 2011; Quinton et al., 2011). This transitioning and climatically sensitive environment provides an ideal opportunity to study how these visible changes to the surface may act as a meaningful indicator for the condition of the underlying permafrost.

2.3 Methods

2.3.1 Remote Sensing Methods

Panchromatic Worldview 1 and 2 imagery captured in 2010 and 2011 were combined with 1970 and 1971 historical aerial photographs over each of the 10 study sites. The historical imagery was georeferenced using multi-temporal stationary marks as tie points. Given the remoteness of the region and limited permanent anthropogenic features, seismic line
intersections and distinct lake shore boundary forms were selected in each image (Chasmer et al., 2010). The georeferencing process used no fewer than 30 tie points at each site and the historical image was adjusted using a first order polynomial. The adjusted historical aerial photographs (~1-1.5m resolution) and satellite imagery (0.3m resolution) were then subset to a 2.5-kilometer by 4-kilometer area, which was delineated using NAD 1983 Zone 10N over each study area.

Landcover classifications were then completed by manually digitizing the 10-square kilometer subsets in ArcGIS (ESRI, Redlands, California) into two classes: ‘forest’ and ‘wetland’, representing the landcovers that are thought to be indicative of permafrost and permafrost-free ground, respectively. Lakes, streams, seismic lines and drill pads were also digitized at both sites when applicable and all landcover types were classified and distinguished based on unique spectral signatures. To determine the amount of landcover change that occurred over the approximately 40-year study period, the total area of forested landcover as a proportion of the total 10km² area was calculated for both the historical and present-day imagery at each site and areas of forest gain or loss were then identified and enumerated. To account for differences in proportional forest area between sites, spatial changes to the distribution of treed landcovers were reported as percentages of only the forested land. These change detection analyses included three measurements: net-forest change between the historical and satellite imagery (reported as a percentage), and its two components – forest loss and forest gain. In order to focus on changes to landcover that could be attributed to permafrost thaw, areas that experienced forest loss or gain that could be confidently explained by forest-fires (as per the Canadian National Fire Database, 2015) or industrial development were removed from these change detection calculations (Burton et al., 2008). These seemingly thaw-induced changes to the areal distribution of treed landcovers were then reported as net-forest loss between the historical and satellite imagery and were
quantified as percentages for each site. All landscape change statistics (net change, loss and gain) were significant at the 10 sites across the 40-year study period ($p<0.05$).

**2.3.2 Climate Data Methods**

Modelled mean annual air temperature (MAAT) as well as monthly air temperature and precipitation data were sourced from Natural Resources Canada (NRCAN) (2017). The temperature and precipitation grids were produced using the ANUSPLIN suite of programs (Hutchinson, 2004; Hutchinson, 2011; McKenney et al., 2006; McKenney et al., 2011). The procedure used by NRCAN involved fitting a smoothing algorithm across existing Meteorological Service of Canada climate data and variables such as latitude, longitude and a hypsometric correction for elevation (McKenney et al., 2006; McKenney et al., 2011). The obtained historical climate grids cover the time period of 1901-2010 and have latitudinal and longitudinal limits of 24.0-85.0°N and 178.0-50.08°W (McKenney et al., 2006; McKenney et al., 2011). The resolution of the NRCAN grid, as determined by the resolution of the trivariate spline model inputs (latitude, longitude and elevation), was approximately 30km. Additionally, temperature data had average mean absolute error (i.e. accuracy) values ranging from 0.4 to 1.6°C and average mean error (i.e. bias) values ranging from 0.02 to 0.23°C while precipitation data had mean absolute errors ranging from 6.7 to 8.9% and mean error values ranging from -1.6 to -2.3% (McKenney et al., 2006; McKenney et al., 2011). While mean errors were generally minimal, it is important to acknowledge that winter errors in the temperature dataset were highest in northwestern Canada (although this pattern was not observed year-round) (McKenney et al., 2006; McKenney et al., 2011). Despite this, the model appeared to avoid bias as both positive and negative residuals were observed, meaning these errors are more likely due to temperature variability induced by the northern latitude and proximity to complex topography.
(McKenney et al., 2006). Additionally, despite the challenges associated with measuring winter precipitation, higher errors relative to summer precipitation were not observed given the relatively larger amounts of precipitation collected during summer months (McKenney et al., 2006).

The obtained climate grid was then re-projected to centre on the 10 areas of interest included in this study. The data were then reanalyzed as a mean annual air temperature dataset covering a variety of time periods within the entire 1901-2010 span of the data, while more seasonal factors - both temperature and precipitation - were confined to the period of time covered by this study (1970-2010). The centre point of each boreal peatland study area was then used to extract the climate variables for each year from 1901 to 2010. From this re-analysis product, changes in temperature and precipitation across the same time periods were also calculated. Despite the errors recognized in northwestern Canada, these climate data products have been previously applied to climate change and forest-related research throughout Canada (McKenney and Pedlar, 2003; McKenney et al., 2007a; McKenney et al., 2007b; Price and Scott, 2006).

2.3.3 Statistical Methods

The landcover change measures of net forest loss, forest loss and forest gain are the values remaining after the areas directly impacted by forest fire or industrial clearing were removed. To explore the potential mechanisms associated with these landscape change statistics, a variety of variables were explored. These factors included: latitude, longitude, a measure of fragmentation in the form of perimeter area ratio, two average annual temperature measurements over different time periods, the average annual temperature range during the study period, six change in temperature measurements with varying time periods and lags as well, average annual
temperature range over the study period, seasonal temperature and precipitation components – recorded as both averages and changes over the study period, length of the growing season. Three landscape-change metrics (net loss, loss and gain) from all 10 sites were measured for strength and direction of association with 22 identified monotonic factors using a Spearman rank-order correlation coefficient (2-tailed, significant at 0.05 level).

Given the possibility of the multiple comparisons or multiplicity problem emerging (i.e. a greater likelihood of false positives or Type I errors occurring when a greater number of inferences or comparisons are made), the Benjamini-Hochberg (1995) procedure was applied. The false discovery rate method described by Benjamini and Hochberg (1995) controls the proportion of rejected null hypotheses by employing more stringent significance thresholds for individual correlations. This procedure is widely used as it is less conservative than the original Bonferroni correction, which has the opposite affliction where the number of false negatives or Type II errors can be falsely inflated (Benjamini and Hochberg, 1995).

2.4 Results

2.4.1 Landcover Change

The 10 mapped areas of interest cover a latitudinal gradient of 59.96°N to 61.30°N and a MAAT gradient of -3.44°C to -2.55°C. All 10 sites experienced net forest loss attributed to permafrost thaw regardless of the variability in proportion of forest at each 10 km² area of interest. The amount of treed landcover ranged from 64% to 33% in 1970 and in 2010 those proportions ranged from 61% down to 31% as the transition from a forest- to wetland-dominated landscape progressed (Figure 2.2). The same sites with the highest and lowest proportional forest cover in the historical images remained as the sites that had the greatest and least forest in 2010. Linear disturbances (e.g. winter roads or seismic cut lines) varied from 0 km to 27.4 km within
the 10 km$^2$ subsets and further areas of industrial development, specifically drill pads, were absent in all sites but site I (Hossitl Creek) where the cleared area totaled approximately 4.5 ha.

<table>
<thead>
<tr>
<th>Site A: Scotty Creek, NWT</th>
<th>Site B: Deep Lake, NWT</th>
<th>Site C: Trout Lake, NWT</th>
<th>Site D: Trout River Tributary, NWT</th>
<th>Site E: Paradise River, NWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δ Forest:</td>
<td>0.49 – 0.44</td>
<td>0.54 – 0.49</td>
<td>0.37 – 0.33</td>
<td>0.33 – 0.31</td>
</tr>
</tbody>
</table>

Figure 2.2: The proportion of each 10km$^2$ subset classified as forested, and predictably underlain by permafrost, between 1970-2010. Areas of forest loss and gain are presented alongside areas burned by forest fire during the study period and areas of linear disturbance.

Changes to forested landcovers were assessed for all areas except those directly impacted by forest fire or linear disturbance layers and were reported as percentages of total forested area to help account for differing proportions of forests and wetlands between sites. Maximum net forest loss was recorded at the northernmost site, Scotty Creek, at 11.6% over the 40-year period and the minimum net loss was observed at Hossitl Creek in northeastern British Columbia at 6.9% (Figure 2.3). When grouped into the three latitudinal classes: Mackenzie Region, Trout Lake Region and Border Region, average net forest loss rates decreased at lower latitudes. The average net loss value in the northernmost Mackenzie Region was 11.15%; the more central
Trout Lake Region averaged 9.74%; and for the sites in the southernmost Border Region, two of which are in BC, the average was 8.5% over the study period. While the net forest loss values are largely consistent within the latitudinal groupings, the sites in the southern portion of the transect do not follow the same pattern as the two southernmost sites specifically experienced much lower net forest loss values over the study period.

![Figure 2.3: Relationship between net forest loss (i.e. loss-gain) and latitude over the 40-year study period at the 10 selected study sites (p<0.05).](image)

Thaw-induced net forest loss was then separated into the two consequent components: loss and gain (Figure 2.4). Forest loss follows a similar trend to net forest loss until the border region where forest loss increases with decreasing latitude. The average loss values for the three regions are 11.7% in the Mackenzie Region, 10.4% in the Trout Lake Region and 14.1% in the Border Region. Only the southernmost region, which has a maximum loss of 16.3%, has values that differ greatly from the previously described net forest loss values. The differences in these values can be explained by the forest gain statistics. At seven of the 10 sites, forest gain over the 40-year study period is occurring at negligible rates ranging from 0.2% to 1%. However, approaching the NWT-BC border, forest gains are accounting for as much as 9.4% of the landscape change. Therefore, the lower net forest loss observed at the more southerly sites,
especially the two in BC, is not due to the fact that less loss is occurring but more so that the loss is being offset by forest expansion over the same time period.

2.4.2 Controls on Landscape Change

The three landscape change components were assessed for strength of correlation with 22 factors that were identified as potential controls. These factors were: latitude, longitude, a fragmentation measure in the form of initial plateau perimeter-area ratio, two averaged temperature measurements over different time periods (1901-2010 and 1970-2010), six change in temperature measurements covering different time periods and lags (1901-2010, 1920-1970, 1930-1970, 1940-1970, 1950-1970 and 1970-2010), average annual temperature range, average annual precipitation, average summer and winter temperature and precipitation, days in the growing season, changes to both summer and winter temperature and precipitation, and finally, the number of snow-free weeks. Of these 66 (3x22) potential relationships, 29 emerged as significant controls on one or more of the three landscape change statistics after the false discovery rate correction as determined by a Spearman rank-order correlation coefficient (ρ) (Table 2.1).
Table 2.1: Non-parametric correlation associations between net forest loss, forest loss and forest gain with (a) latitude, longitude, original (1970/71) perimeter-area ratio, and all annual climatic variables: average temperatures (1901-2010 & 1970-2010), change in temperature (1901-2010, 1920-1970, 1930-1970, 1940-1970, 1950-1970, 1970-2010), average annual temperature range, and average annual precipitation; and (b) all seasonal factors over the study period (1970-2010): average summer and winter temperature, average summer and winter precipitation (1970-2010), change in summer and winter temperature (1970-2010). Significant (p<0.05) correlations (r) have been highlighted by bold text.

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<tr>
<td>Net</td>
<td>0.758</td>
<td>-0.285</td>
<td>0.006</td>
<td>-0.491</td>
<td>-0.491</td>
<td>0.383</td>
<td>-0.648</td>
<td>-0.729</td>
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<td>-0.720</td>
<td>0.661</td>
<td>0.673</td>
<td>-0.636</td>
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<tr>
<td>Loss</td>
<td>-0.387</td>
<td>0.166</td>
<td>-0.055</td>
<td>0.647</td>
<td>0.647</td>
<td>-0.646</td>
<td>0.472</td>
<td>0.418</td>
<td>0.345</td>
<td>0.444</td>
<td>-0.411</td>
<td>-0.313</td>
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<tr>
<td>Gain</td>
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<td>0.442</td>
<td>-0.442</td>
<td>0.794</td>
<td>0.794</td>
<td>-0.383</td>
<td>0.758</td>
<td>0.754</td>
<td>0.752</td>
<td>0.671</td>
<td>-0.721</td>
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<tr>
<td>Net</td>
<td>0.273</td>
<td>-0.782</td>
<td>-0.636</td>
<td>-0.612</td>
<td>0.690</td>
<td>0.691</td>
<td>0.333</td>
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<tr>
<td>Loss</td>
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<td>0.387</td>
<td>0.436</td>
<td>0.362</td>
<td>-0.171</td>
<td>-0.313</td>
<td>-0.483</td>
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<td>0.420</td>
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<tr>
<td>Gain</td>
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<td>0.612</td>
<td>-0.527</td>
<td>-0.587</td>
<td>-0.602</td>
<td>0.726</td>
<td>0.430</td>
</tr>
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Latitude has both a positive correlation with net forest loss and a negative correlation with forest gain; where increasing latitude corresponds with an increase in net forest loss while lower latitudes correspond with higher rates of afforestation. Average temperatures, both over the length of the record (1901-2010) and the study period, are positively correlated with both forest loss and gain between 1970 and 2010. Change in temperature over the length of the modelled record was also significantly correlated with forest loss, while change in temperature over the study period, as well as the four selected time periods before the first image, were found to be significantly correlated with both net loss and gain. The four time periods encompassing 50, 40, 30 and 20 years before the start of the study period attempt to account for any lags in landscape change associated with changes to temperature (Camill & Clark, 2000; Chasmer & Hopkinson, 2017). The magnitude of change in temperature over each of these time periods was significantly negatively correlated with net loss and positively correlated with any forest gain.
Changes in temperature confined to the study period showed an opposite relationship where increases in temperature corresponded with increases in net forest loss while any decreases in MAAT over the study period corresponded with decreases in forest gain. A broader annual temperature range corresponded with further conversion to wetland (i.e. a higher net forest loss rate) and less forest gain on similar magnitudes. Average winter temperature over the study period was negatively correlated with net forest loss and positively correlated with forest gain between 1970 and 2010, while average summer temperature did not emerge as a significant contributor. The change in both summer and winter temperatures over the 40-year study period were both positively correlated with net forest loss indicating a greater positive change in temperature over the two seasons would lead to greater net forest loss over the same time period. Average annual precipitation was significantly negatively correlated with net forest loss and positively correlated with forest gain. Seasonally, average summer precipitation emerged as a negative correlation with net landcover change and positive with forest gain, while average winter precipitation did not emerge as a significant factor. Changes to summer precipitation did not appear as significant with any landcover change measurement. However, changes to winter precipitation emerged as significant in both directions, where a negative relationship emerged with net forest change and a positive correlation with forest gain.

2.5 Discussion

Previous thaw-induced landscape monitoring initiatives have demonstrated significant permafrost thaw and degradation, which has been observed through forest loss and plateau collapse corresponding with wetland expansion (Baltzer et al., 2014; Quinton et al., 2011; Wright et al., 2009). These patterns are also observed across all 10 sites along the latitudinal gradient in this study. This is evidenced by the net forest loss (i.e. loss > gain) observed at each
site indicating that forest loss and forest to wetland conversion are the dominant components at all sites along the latitudinal and thus, climatic gradient included in this study. Generally, net forest loss decreased with decreasing latitude, ranging from 11.6% at the northernmost site to 6.9% at the southernmost site. Both forest loss and gain were essentially consistent across the seven sites in the Mackenzie and Trout Lake regions with average loss rates of 10.8% and gains of 0.6%. Once the border region is reached, both forest losses and gains increase dramatically ranging from 12.3%-16.3% and 2.2%-9.4%, respectively.

While it can be confidently stated that there is a significant relationship between landcover change and latitude, most of this signal is likely due to climatic factors that vary latitudinally, which can have distinct impacts on landcover change. Climate change in the boreal peatlands of the fringe permafrost zone is most clearly present through subsurface thawing, which is evident by a transition from forest to wetland, as represented by the net forest loss statistic. Two principal thaw-induced mechanisms are understood to be responsible for this landscape succession; plateau inundation from the surrounding wetlands and/or peat overmaturation, as observed through fissures or cracks forming in plateaus, which then further predispose the area to collapse and inundation (Beilman & Robinson, 2003; Hayashi et al., 2004; Quinton et al., 2003; Quinton et al., 2009; Zoltai, 1993; Zoltai & Tarnocai, 1975). This thaw-induced forest loss has been well established as the dominant mechanism responsible for landcover change in these environments (Baltzer et al., 2014; Beilman & Robinson, 2003; Quinton et al., 2011). This relationship was further founded as observed by the positive correlation between change in temperature over the study period and net forest loss (Baltzer et al., 2014; Beilman & Robinson, 2003; Quinton et al., 2011). Additionally, a wider range of annual temperatures, particularly when a site’s range expands to a warmer MAAT, was also
found to lead to more rapid landscape turnover between forest and wetland (Beilman & Robinson, 2003). MAAT shifts were additionally indicated through positive correlations between changes in both summer and winter temperature over the study period where greater amounts of warming in both seasons increased net forest loss.

This study further replicates the dominant findings of forest to wetland conversion, as higher average temperatures over both analyzed time periods corresponded with greater forest loss rates but also introduced an additional positive correlation with forest gain. The relationship between higher temperatures and greater afforestation is less well established but forest expansion and increased productivity have been proposed as potential responses to climate warming (Baltzer et al., 2014; Soja et al., 2007). This relationship has not typically been observed in smaller scale studies (such as those at Scotty Creek) but this study indicates that over a large swath of sites, a positive relationship between temperature and forest growth may be present. However, it is important to note that no permafrost is expected to have returned to these areas despite the afforestation that is occurring, given the generally warmer climatic conditions (Jorgenson et al., 2010; Robinson & Moore, 2000; Turetsky et al., 2007).

This study presents supplementary evidence to the point that warming temperatures may be related to increases in forest productivity and expansion in addition to the expected relationships with losses (Baltzer et al., 2014; Soja et al., 2007). Significant positive correlations were established between changes in temperature in the 50, 40, 30 and 20 years leading up to start of the study period and forest gain between 1970-2010, whereas the opposite was found between these change in temperature statistics and net forest loss over 1970-2010. As such, forest gain increased with more positive temperature change while net forest loss was amplified by more stable temperatures and relatively lower temperature increases. In addition to the
somewhat contentious theories that forest expansion is directly a product of climate, a secondary explanation indirectly correlates afforestation with climate. This hypothesis involves a gradual drainage and ultimately a drying of boreal peatland sites as thaw processes progress beyond the introduction of thaw runoff to the transportation and removal of that newly introduced water (Camill 1999; Chasmer & Hopkinson, 2017; Ketteridge et al., 2013; Murphy et al., 2009). This process is completed over time through increasing thaw-related wetland expansion, which correspondingly increases drainage density and accelerates clearing water from the landscape (Chasmer & Hopkinson, 2017; Connon et al., 2014; Quinton et al., 2003).

The Canadian subarctic has not only been experiencing increased climatic warming, but climate change has also led to increased rain-on-snow events, a shift towards earlier spring melt, and overall decreased snowpack – all of which appear to increase permafrost degradation (Hinzman et al., 2005; Pachauri & Reisinger, 2007; Putkonen et al., 2009). Research over recent decades has shown distinct and consistent patterns of permafrost thaw across subarctic environments associated with wetter annual conditions and/or temperatures nearer to annual average temperatures of 0°C – the climatic maximum to establish or maintain ice (Halsey et al., 1995; Prowse & Furgal, 2009; Quinton et al., 2011). However, the relationships with precipitation, especially when seasonally resolved, are much more complex and less consistent in the literature.

Peatland hydrology in the Canadian subarctic is the result of many complex interacting factors that vary seasonally. Permafrost plateau features, where forested areas are dominantly located have a large hydraulic gradient associated with elevation above the water (Quinton et al., 2009; Price et al., 2005). As a result, any precipitation-based runoff associated with permafrost landscape features can be related to two suprapermafrost layer conditions based on the mobility
and hydraulic conductivity of the suprapermafrost layer and the depth of the frost table (Quinton & Baltzer, 2013). Shallower frost tables leave the active layer in the highly porous portion of the profile, so any rainfall events occurring over these areas result in increased infiltration and subsurface drainage into the adjacent fens and bogs (Quinton & Gray, 2003). However, climate change has led to thickening of the suprapermafrost layer, as observed by a deeper frost table, beyond the expected summer thaw season (Price et al., 2005). This new and more dominant condition may be responsible for the relationships between landcover change and summer precipitation found in this study. Where, due to a deeper frost table, the active layer will be less porous and have lower hydraulic conductivity resulting in decreased subsurface runoff and an increase in overflow to the surrounding wetlands (Quinton & Gray, 2003). The subsequent conditions would result in warm-season precipitation having a more moderated effect on landscape change, where peat plateaus will become saturated from surrounding wetlands more so than from direct rainfall infiltration. However, this will still lead to forested plateaus eventually collapsing into the surrounding wetland features as the associated tree species, and especially the keystone black spruce, begin to decompose in their newly inundated environment due to their intolerance to waterlogging (Islam & McDonald, 2005; Iwata, Harazono, & Ueyama, 2012).

The study area is characterized as a dry continental climate with short summers and long, cold winters. As such, landscape hydrology in this region is largely impacted by winter snowfall events given that approximately 46% of annual precipitation falls as snow (Quinton et al., 2009). The impacts of snow on these landscapes are incredibly complex and environmentally-variable, but increased snow accumulation ultimately provides additional insulation to the ground and underlying permafrost (Chasmer & Hopkinson, 2017; Osterkamp, 2007). However, the additional intricacy associated with this seemingly simple relationship is that this insulating snow
layer can both increase and decrease permafrost thaw. During mid-winter, when air temperatures reach their annual minimum, greater snow depth actually shields the ground from the extreme cold keeping the subsurface relatively warmer and further degrading the contained permafrost (Chasmer & Hopkinson, 2017; Hinkel & Hurd, 2006; Osterkamp, 2007). However, when snow depth is maintained or further amassed for a longer time period the opposite net effect is seen. Greater snow cover insulates the ground and the underlying permafrost from warming temperatures, particularly through high albedo decreasing shortwave radiation absorption and delaying meltwater movement and the associated thermal conduction via latent heat transfer (Chasmer & Hopkinson, 2017; Wright et al., 2008; Wright et al., 2009). This relationship appears to be the dominant mechanism observed in this study given that decreases in winter precipitation appear to lead to greater permafrost thaw (and the associated forest-to-wetland conversion), while greater snow accumulation increases forest gain, potentially though reduced plateau saturation following snowmelt.

The results presented in this study advance the existing body of research by quantifying the landcover change that is occurring across a broad latitudinal span of the fringe permafrost zone while targeting boreal peatland environments. This study also examines potential climatic mechanisms behind the variable landcover change rates observed across this latitudinal and climatic gradient. However, other factors also vary across this latitudinal gradient, which may further impact changes to landcover and introduce critical landscape interactions with the thaw-induced changes explored in this study. Prior studies in the fringe permafrost zone have identified fragmentation as a significant factor influencing landcover change, and specifically forest loss, however this relationship was not revealed in this study (Baltzer et al., 2014; Chasmer et al., 2011; Payette et al., 2004). Furthermore, anthropogenic developments such as
seismic lines, winter roads or drill pads for the oil and gas industry were not included in this analysis, but may have impacts on these landscapes even beyond the initial forest clearing and fragmentation. Most immediately, seismic lines have been shown to result in surface subsidence that promotes the accumulation of water and the expansion of hydrologic features such as wetlands where permafrost (and their resulting black spruce canopies) cannot regenerate (Williams et al., 2013). However, some literature also proposes that when linear disturbances are introduced or expanded on a landscape, they may also increase drainage density much in the same way as fens or, on a different scale, streams (Chasmer & Hopkinson, 2017; Connon et al., 2014; Quinton et al., 2003). Ultimately the resultant higher connectivity via new drainage pathways has the ability to dry a landscape over time leading back to the concept that black spruce forest may be able to re-establish once enough time has passed and enough water has drained from the soils (Camill, 1999; Murphy et al., 2009; Ketteridge et al., 2013; Waddington et al., 2015). Connecting these processes with the existing literature addressing fragmentation impacts presents an opportunity for further study and may be particularly prevalent in areas that have already experienced significant permafrost thaw. These environments may be further along in the anticipated landscape succession and may be moving beyond the initial phase where wetland expansion is the dominant process (Figure 2.5) (Chasmer & Hopkinson, 2017; Camill, 1999; Murphy et al., 2009; Ketteridge et al., 2013; Waddington et al., 2015).
2.6 Conclusion

The results presented in this study across a latitudinal gradient in northwestern Canada’s subarctic fringe permafrost zone have established that substantial changes to forest cover and permafrost cover have occurred over a 40-year period. The extent of net forest loss presented as a percentage of initial forested area ranged from 6.9-11.6% while the two components of this statistic, loss and gain, occurred at rates ranging from 10.1-16.3% and 0.2-9.4%, respectively. The latitudinal patterns and distribution of these changes to landcover also established that forest cover change at the more southerly sites, and particularly those in northeastern British Columbia, was occurring considerably less linearly and uniformly than at the more northerly sites in the transect. A variety of mechanisms were explored to help explain how these relationships change across space. Latitude, the factor this study was largely designed around, emerged as significant,
as did other related factors that varied across the 10 sites. Net forest change was negatively correlated with a site’s degree of industrialization and change in MAAT over the study period as well as 50, 40, 30 and 20 years leading up to start of the study. Forest gain was also correlated, although positively, with the same change in temperature records as well as average temperatures over the study period and over each site’s entire modelled record. These results emphasize the need to define changes to landcover, and thus changes to permafrost distribution, across a wider range of sites and climate scenarios in the discontinuous permafrost zone.
CHAPTER 3.0: Evaluating landcover as a predictor of underlying permafrost distribution patterns at two subarctic boreal peatland sites

Abstract

The discontinuous permafrost zone of the Canadian subarctic is currently among the most rapidly changing environments in the world as it is undergoing previously unparalleled climatic warming and industrial expansion. Despite much of the discontinuous permafrost zone experiencing similar climate conditions, it is also defined by significant permafrost spatial variability across the landscape. This pattern is in part explained by the relationship that exists between landcover and permafrost; where forest cover is often indicative of permafrost plateaus while wetlands are underlain by permafrost-free ground. Research was conducted at two subarctic sites: Scotty Creek Basin, NWT and Hossitl Creek Basin, BC, both of which have experienced a significant decrease in permafrost cover, while also experiencing widespread forest loss and wetland expansion. A change detection analysis was run at each site between historical aerial photographs and present-day optical satellite imagery. This analysis provided the amount of forest loss observed at each site, which was then combined with ground-verification data in the form of permafrost presence or absence sampling to evaluate the efficacy of using landcover as a predictive tool. Scotty Creek Basin served as an example of greater and more unidirectional net forest loss and additionally served as a location where landcover performed well as a proxy for underlying permafrost. Contrarily, Hossitl Creek Basin experienced lower net forest loss due to landcover change occurring less uniformly and was also found to be a site where remotely sensed landcover data was largely ineffective as a predictor of underlying permafrost presence or absence. Augmenting the understanding of the unique conditions contributing to differential changes in forest and permafrost distributions is critical for predicting future interactions as well as developing new and more suitable monitoring techniques.
3.1 Introduction

Permafrost is a fundamental and defining characteristic of many northern, cold region environments. However, it is also highly sensitive to external forcing and is undergoing an accelerated degradation throughout much of Canada’s north. Much of this rapidly degrading permafrost occurs below Canada’s boreal forest and particularly in the boreal peatlands that occur throughout the discontinuous and fringe permafrost zones (Bonniventure et al., 2012; Johannessen et al., 2004; Quinton et al., 2011). Not only has this area experienced dramatic climate warming, but it has also undergone regionally unparalleled industrial expansion which has further exacerbated permafrost thaw (Bonniventure et al., 2012; Hinzman et al., 2005; Quinton et al., 2011).

Permafrost in Canada’s discontinuous and sporadic permafrost zones is largely found within the boreal peatlands of the area. Boreal peatlands are inherently cold and wet environments that have distinct and landform-dependent vegetation profiles that are particularly suited to maintaining permafrost. In these environments forest cover typically occurs on permafrost plateaus elevated above the water table, whereas the surrounding tree-free wetlands are underlain by permafrost-free ground (Baltzer et al., 2014; Quinton et al., 2011; Wright et al., 2009). The relationship between forest cover and the state of underlying permafrost has been anticipated for decades (Zoltai, 1971; Zoltai & Tarnocai, 1975). However, the increasingly urgent issue of climate change has reestablished the importance of recording and mapping ice extent across northern cold regions. Despite some success with these techniques, northern research involves fundamental and unavoidable challenges associated with the remoteness and size of the region, limited data availability, and incomplete monitoring networks. These expected challenges are further complicated by the fact that permafrost distribution throughout the
discontinuous permafrost zone is inherently defined as variable across space. Moreover, this heterogeneity is being further amplified as thermokarst is disturbed and thaw processes progress, whether through climate change or industrial expansion. These challenges introduce a unique opportunity to strengthen and build a better understanding of the relationships between landcover and permafrost that have been proposed given that landcover is much more visible and easily monitored. Specifically, monitoring changes to forest cover may provide a chance to simulate changes to underlying permafrost as these forests become analogously vulnerable through thaw progression and permafrost plateau collapse.

The relationship between landcover and permafrost, specifically where treed areas overlay permafrost plateaus while tree-free areas are permafrost-free, has been established and observed in the southern Northwest Territories but has not been rigorously tested (Baltzer et al., 2014; Quinton et al., 2011; Zoltai, 1971; Zoltai & Tarnocai, 1975). Much of this literature has been isolated to sites such as Scotty Creek given the longevity of the site’s operation and thus the length of record (Baltzer et al., 2014; Quinton et al., 2011). However, given that boreal peatlands have extensive range throughout northwestern Canada’s subarctic and discontinuous permafrost zone, relatively fewer studies have been completed to establish and confirm this relationship elsewhere. Documenting changes to landcover and permafrost at other boreal peatland sites, particularly further south, has been proposed as a method to corroborate and validate the work completed at sites like Scotty Creek. This research assesses the relationships that have been observed and proposed as potential methods of monitoring these landscapes by examining whether landcover can be used to predict the presence or absence of permafrost. Specifically, this study establishes the reliability of using the presence or absence of forest as a proxy for the presence or absence of permafrost beyond Scotty Creek. To do so, two sites were analyzed:
Scotty Creek, which has been widely studied and where many of these relationships were first observed, and Hossitl Creek, another boreal peatland site located at a more southerly latitude. This research first establishes how effective these proposed landcover classes are at predicting underlying permafrost and then connects those same relationships with broader landscape changes as observed through remote sensing.

3.2 Study Area

3.2.1 Boreal Peatlands

The global subarctic region, and thus much of Canada’s discontinuous permafrost zone, is largely dominated by boreal peatlands. Permafrost is a dominant characteristic of these boreal peatlands, and uniquely, even if climatic conditions such as air or soil temperature are individually unsuitable for permafrost, peat’s insulating properties allow for the ground to remain frozen (Beilman et al., 2001; Turetsky et al., 2007; Wright et al., 2009). This region is characterized by a patchwork landscape of boreal forest and two classes of wetland: channel fen and flat bog, each with unique hydrologic, edaphic and vegetative characteristics. Forested areas of these boreal peatlands have particular significance given that they are typically underlain by permafrost plateaus and have been proposed as a way of forecasting the location of permafrost (Baltzer et al., 2014; Quinton et al., 2011; Wright et al., 2009). Wetlands, both bogs and fens, have been used contrarily in these environments as a way of anticipating permafrost-free ground (Baltzer et al., 2014; Quinton et al., 2011; Wright et al., 2009).

Permafrost plateaus, also referred to as peat plateaus, are essentially mounds that remain perennially frozen for two or more consecutive years (Zoltai, 1971; Zoltai & Tarnocai, 1975). On the ground, they are distinguishable from the surrounding environment as they typically rise one to two metres above adjacent wetlands. However, when relying on remote sensing, the distinct
vegetation profile – most notably the presence of forests and their keystone species black spruce 
(*Picea mariana*), is most identifiable (Iwata et al., 2012; Quinton et al., 2003; Robinson & 
Moore, 2000). This is also the reason why forest cover specifically has been proposed as a way 
of monitoring the underlying permafrost plateaus. The characteristic and relatively dense 
vegetation cover also further contributes to peat’s ability to maintain thermokarst through 
decreasing incoming solar radiation, and by contributing organic matter (e.g. roots, needles, 
woody debris, etc.) to the thickening peat layer (Chasmer et al., 2011; Quinton et al., 2008; 
Robinson & Moore, 2000; Williams & Quinton, 2013).

### 3.2.2 Study Sites

This study was completed at two subarctic boreal peatland sites: Scotty Creek basin, 
Northwest Territories (61°18’N, 121°18’W; 283m above sea level) and Hossitl Creek basin, 
British Columbia (59°46’N, 120°42’W; 569m above sea level). Scotty Creek is located within 
the Liard River basin and has a mean annual air temperature of -3.1°C while Hossitl Creek has a 
mean annual air temperature of -2.2°C and is located within the neighbouring Petitot River basin 
(Figure 3.1). Both research sites are located within the discontinuous permafrost zone and are 
characterized by a patchwork of forested peat plateaus, where the presence of thick, insulating 
peat maintains underlying permafrost, while surrounding tree-free wetlands are typically 
permafrost free. However, despite the insulating properties associated with peat, evidence over 
recent decades has still shown a significant decrease in permafrost cover across the subarctic 
(Beilman & Robinson, 2003; Quinton et al., 2009; Baltzer et al., 2014). In many cases, this has 
manifested as a transition from forest- to wetland-dominated landscapes as plateaus collapse and 
forests are destabilized and inundated by water (Quinton et al., 2009; Baltzer et al., 2014). Scotty 
Creek ranged from 49-44% forest covered between 1970 and 2010, while Hossitl Creek was
between 42% and 40% treed over the study period. This transitioning and climatically sensitive environment provides an ideal opportunity to study how these visible changes to the surface may act as a meaningful indicator for the condition of the underlying permafrost.

Hossitl Creek, was identified via satellite imagery as a suitable boreal peatland site and although the two locations can be defined as typical boreal peatland sites, some differences were also noted. Firstly, Hossitl Creek had a less uniform vegetation assemblage than Scotty Creek. Both sites’ dominant tree species is black spruce as is regionally expected, however Hossitl Creek also had isolated areas of more mixed forest, notably the presence of white spruce (*Picea glauca*) and tamarack (*Larix laricina*) tree populations. Secondly, Hossitl Creek has a much more prominent industrial presence as compared to Scotty Creek, which is relatively less
impacted by oil and gas developments that dominate large areas of the Fort Nelson region of northeastern British Columbia. Thirdly, signs of peatland overmaturity were observed (i.e. fissures and cracks in plateau surfaces) at Hossitl Creek as described by Zoltai and Tarnocai (1975), which may indicate a predisposition to permafrost degradation and plateau collapse that is not occurring on the same scale at Scotty Creek. Finally, Hossitl Creek experienced a forest fire within the study period which introduced another factor that could impact landcover change over time beyond permafrost thaw acting as the dominant mechanism.

3.3. Methods

3.3.1 Remote Sensing Methods

For this analysis, panchromatic Worldview 1 imagery obtained in 2010 at both study sites was combined with 1970 and 1971 aerial photographs for Scotty Creek and Hossitl Creek, respectively. The historical imagery was georeferenced using multi-temporal stationary marks as tie points. Given the remoteness of the region and limited permanent anthropogenic features, seismic line intersections and distinct lake shore boundary forms were selected in each image (Chasmer et al., 2010). The georeferencing process used 30 tie points at each site and the residual errors upon completion were quantified through first order polynomial root mean square errors of 2.86 for Scotty Creek and 3.34 for Hossitl Creek. The adjusted historical aerial photographs (~1-1.5m resolution) and satellite imagery (0.3m resolution) were then subset to a 2.5-kilometer by 4-kilometer area, which was delineated using NAD 1983 Zone 10N over each study site.

Landcover classifications were then completed by manually digitizing the 10-square kilometer subsets in ArcGIS (ESRI, Redlands, California) into two classes: forest and wetland (bogs and fens), representing the landcovers that are thought to be indicative of permafrost and
permafrost-free ground, respectively. Areas classified as forest were defined as such given that plateau tree cover can range from fully forested (>70% tree cover) to wooded (30-70% tree cover) (Halsey et al., 1995; Quinton et al., 2009). Lakes, streams, seismic lines and drill pads were also digitized at both sites when applicable and all landcover types were classified and distinguished based on unique spectral signatures. To determine the amount of landcover change that occurred over the ca. 40-year study period, the total area of forested landcover was calculated for each image and areas of forest gain or loss were identified and enumerated. To focus on changes to landcover that could be attributed to permafrost thaw, areas that experienced forest loss or gain that could be confidently explained by forest-fires or industrial development were removed from these change detection calculations. These seemingly thaw-induced changes to the areal distribution of treed landcovers were then reported as net-forest loss between the historical and satellite imagery and were quantified as percentages for each site.

3.3.2 Field Methods

The presence or absence of permafrost, the impermeable boundary separating thawed and frozen soil layers, was measured and recorded at both sites using a two-metre graduated steel frost probe (Hayashsi et al., 2007). These permafrost field measurements were collected in areas at both sites that contained each dominant landcover: forest and wetland. This approach established a spatial pattern of permafrost distribution and enabled the evaluation of forest cover as a predictor of permafrost presence or absence. Two distinct and site-specific data collection approaches were used to organize and obtain frost table measurements for this study. Given the extent of existing data collection initiatives at Scotty Creek, a previously established grid was selected as the site for frost probe measurements to be completed. A 480 x 140m subset of a larger research plot (data not published) was used with georeferenced measurement points
located every 20m totaling 168 plot points (Figure 3.2). This Scotty Creek research plot contained 112 measurement points located on treed ground while 56 measurements were taken in tree-free wetlands during August 2014. A second, and more exploratory approach, was implemented at Hossitl Creek given that this site had not previously been studied or equipped for measurement. For this reason, two smaller-scale measurement campaigns were completed in October 2016 in order to more wholly incorporate and address site-specific factors, specifically differing forest densities and more variable vegetation assemblages. Permafrost presence or absence was recorded at 103 locations within the greater Hossitl Creek site where 80 measurements were recorded at forested locations and 23 measurements were taken on tree-free landcovers.

![Figure 3.2: Worldview satellite imagery showing locations of field data collection sites within the 10km² subsets.](image)

*Figure 3.2: Worldview satellite imagery showing locations of field data collection sites within the 10km² subsets.*
3.3.3 Statistical Analysis

The relationship between landcover and permafrost was assessed through the use of error matrices at each site. Each matrix enumerated the accuracy between predicted permafrost presence or absence and observed permafrost presence or absence using landcover as the explanatory mechanism. In this simple decision model, forest cover was used as the sole predictor for underlying permafrost and the tree-free wetlands were treated as predictors of permafrost-free ground. The results of the error matrices were then evaluated for overall predictive accuracy and misclassification rates. Additionally, Cohen’s Kappa was used to measure how well the classified performed as compared to chance. To further evaluate the results of this predictive tool, logistic regressions were performed on the data from each site. These results were reported as pseudo $R^2$ statistics (Nagelkerke and Cox & Snell) as well as a predictive probability measure to account for the odds ratio within the model. Finally, to evaluate the results of the remote sensing analysis, differences between the areal extent of forested plateaus between 1970 and 2010 were first compared using a paired-samples t-test to determine if significant change had occurred.

3.4 Results

3.4.1 Landcover as a Proxy for Permafrost

The presence or absence of permafrost was recorded across 168 sites in Scotty Creek basin, where 112 measurement points were located on treed ground and 56 measurements were taken in tree-free wetlands. As such, 112 sites were predicted from the remote sensing data to have underlying permafrost while the remaining 56 were assumed to be permafrost free. However, the true proportion of sites within each category was actually much more similar, with a total of 95 sites underlain by permafrost while 75 were found to be underlain by permafrost-
free ground (Table 3.1a). This predictive model, which uses landcover as the only control on the presence or absence of frozen ground, has an accuracy of 89.9% (Table 3.1b). Misclassifications were thus limited to 10.1% largely due to the fact that this model only experienced errors in one direction. This tool slightly overestimates the prevalence of permafrost (i.e. false positives or type I errors) beneath forested ground but there were no instances where tree-free landcovers were not indicative of permafrost-free ground (i.e. false negatives or type II errors).

Cohen’s Kappa works to define the difference between a model’s accuracy and the null error rate and was particularly important to include given that this tool relies on landcover as its only factor. Effectively, this model performs 74.8% above what would be expected if this classification was completed only by chance. Furthermore, two pseudo-$R^2$ statistics (Nagelkerke and Cox & Snell) were reported as methods of calculating the variation explained by this predictive tool. The amount of variation in the dependent variable (permafrost presence or absence) explained by landcover ranges from 56.2% to 75.0% depending on the method of assessment, and follows a well-established pattern in the literature (Baltzer et al., 2014; Quinton et al., 2011; Wright et al., 2009). In addition to these enumerations, a predicative probability statistic or odds ratio was also calculated establishing that forest cover is approximately 7 million times more likely to be underlain by permafrost than the surrounding wetlands at Scotty Creek.
Table 3.1: Scotty Creek (a) Confusion matrix of predicted permafrost presence or absence as per landcover type compared to ground-verified permafrost distribution. (b) Evaluation of model performance using landcover as the only control on permafrost presence or absence.

(a)  

<table>
<thead>
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<th></th>
<th>PREDICTED</th>
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<th></th>
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<tbody>
<tr>
<td></td>
<td>Permafrost</td>
<td>No Permafrost</td>
<td></td>
</tr>
<tr>
<td>ACTUAL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permafrost</td>
<td>95</td>
<td>0(^{\text{Type II}})</td>
<td>95</td>
</tr>
<tr>
<td>No Permafrost</td>
<td>17(^{\text{Type I}})</td>
<td>56</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>112</td>
<td>56</td>
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(b)  

<table>
<thead>
<tr>
<th></th>
<th>Evaluation:</th>
<th></th>
<th></th>
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<tr>
<td>Accuracy</td>
<td>0.899</td>
<td>Cohen’s Kappa</td>
<td>0.748</td>
</tr>
<tr>
<td>Misclassification Rate</td>
<td>0.101</td>
<td>Nagelkerke R(^2)</td>
<td>0.750</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cox &amp; Snell R(^2)</td>
<td>0.562</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Predictive Probability</td>
<td>7.652 x 10(^6)</td>
</tr>
</tbody>
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The results for Scotty Creek were largely as expected given the breadth of literature focused on this site. However, the Hossitl Creek site does not have the same record, prefacing the associated field data collection strategy. At this site 103 locations within the greater basin were selected for permafrost presence or absence sampling, where 80 measurements were recorded at forested locations and 23 measurements were taken on tree-free landcovers. As such, those 80 forested points were predicted to occur on frozen ground and the 23 were anticipated to be permafrost free. Much like Scotty Creek, the number of permafrost and permafrost-free sites were actually much more similar: of the 103 total points, 62 had permafrost and 41 did not (Table 3.2a). Despite clear differences in the predicted versus actual ground conditions, the model still performed with an accuracy of 74.8% with a misclassification rate of 25.2% (Table 3.2b). Using landcover as the only predictor for underlying permafrost at this more southerly site still over-predicts the pervasiveness of permafrost (i.e. false positives or type I errors) similarly to the model’s performance at Scotty Creek. However, the biggest difference between the two sites is that unlike at Scotty Creek, areas that are tree-free cannot always be presumed to be...
permafrost-free as well. This is evidenced by the fact that false negatives or type II errors have been newly introduced at this site.

Despite the fact that the predictive accuracy for this site is still reasonably high, Cohen’s Kappa only indicates that the model is performing 20.7% above what would be expected through chance, a significant drop from what was indexed at Scotty Creek. Furthermore, both modified $R^2$ statistics show a significant drop at this site indicating that landcover is a relatively poorer explanatory mechanism for any variability in subsurface permafrost condition as compared to Scotty Creek. Nagelkerke and Cox & Snell report the amount of variability explained by forest cover ranges down from 32.8% to 24.2%. Finally, forest cover at this site is still almost 19 times more likely to be underlain by permafrost than unforested areas as per the predictive probability odds ratio. However, given the four examples of permafrost observed beneath tree-free areas, wetlands cannot be assumed to be permafrost free with the same reliability as at Scotty Creek further north.

Table 3.2: Hossitl Creek (a) Confusion matrix of predicted permafrost presence or absence as per landcover type compared to ground-verified permafrost distribution. (b) Evaluation of model performance using landcover as the only control on permafrost presence or absence.

<table>
<thead>
<tr>
<th>ACTUAL</th>
<th>PREDICTED</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>Permafrost</td>
<td>No Permafrost</td>
</tr>
<tr>
<td>Permafrost</td>
<td>58</td>
<td>41 TypeII</td>
</tr>
<tr>
<td>No Permafrost</td>
<td>22 TypeI</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>23</td>
</tr>
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</table>

(b) EVALUATION:

- Accuracy 0.748
- Misclassification Rate 0.252
- Cohen’s Kappa 0.207
- Nagelkerke $R^2$ 0.328
- Cox & Snell $R^2$ 0.242
- Predictive Probability 18.730
3.4.2 Landcover Change

The remote sensing analysis over Scotty Creek indicates that the proportion of the 10km$^2$ subset occupied by forest in 1970 was 49%, which then decreased to 44% by 2010 (Figure 3.3a). A significant ($p<0.05$) net forest loss (as a proportion of forested area) over the 40-year period was observed and totaled 11.6% summing 547,846m$^2$. Net forest loss was also broken into its two components – loss and gain, both of which were found to be significant and equaled 11.8% and 0.2%, respectively. These landcover change patterns over this site appear to be fairly uniform as represented by the landcover change statistics, where small amounts of loss can be observed across most of the forested plateaus with only small and isolated areas of forest gain.

A landcover change detection was also completed over the 10km$^2$ subset of Hossitl Creek in northeastern BC. The original proportion of the site covered by forest in 1971 was 42%, which then decreased to 40% in the 2010 image (Figure 3.3b). A significant ($p<0.05$) net forest loss was also recorded at this more southerly site and was found to be 6.9%, or a net change of 152,939m$^2$ over the study period. It is important to note that while there was still a significant net forest loss, the two associated statistics; loss and gain, work to explain the seemingly lower rate of change. At the Hossitl Creek site a significantly higher amount of forest loss occurred totaling 16.3%, but this value was lowered given that significant gains of 9.4% also occurred over the time period. The forest loss at this site is not occurring nearly as uniformly or linearly as at Scotty Creek, as evidenced by the larger areas of loss as well as the areas of afforestation that are not occurring on the same scale at Scotty Creek.
Figure 3.3: Landcover change detection analysis over 10km² subset of (a) Scotty Creek, NWT and (b) Hossitl Creek, BC.
3.5 Discussion

Measuring peatland permafrost change has been identified as an increasingly important and urgent research topic due to the meaningful observed permafrost degradation throughout northwestern Canada’s discontinuous permafrost zone (Quinton et al., 2009; Zoltai, 1971; Zoltai & Tarnocai, 1975). Landcover, specifically the proposed relationship between tree cover and permafrost, has been used as a proxy for mapping permafrost distribution and loss in northern peatland environments (Baltzer et al., 2014; Quinton et al., 2011; Zoltai, 1971; Zoltai & Tarnocai, 1975). However, many of these studies have been relatively small-scale and isolated to areas where this relationship has already been well-established, as in the case of Scotty Creek (Baltzer et al., 2014; Quinton et al., 2011; Wright et al., 2009). This study aimed to test whether the relationships observed at Scotty Creek would also be found at the more southerly Hossitl Creek.

Using landcover as a predictive tool for determining the presence or absence of underlying permafrost was successful at Scotty Creek (accuracy of 89.9%). According to this result, changes in frost table across the landscape are primarily dependent on the changes between plateau forests and the surrounding wetland features. This was an expected result because permafrost at this site is known to be isolated to peat plateaus and has been a widely-described pattern in the literature (Baltzer et al., 2014; Quinton et al., 2011; Wright et al., 2009). The results at Scotty Creek indicated there were no outliers where permafrost was recorded beyond the forest boundaries as delineated by remote sensing. The reverse however, was not true as there were multiple instances where forested areas were not always underlain by frozen ground. Upon exploring the locations of these points, many were located on the edges or downward slopes of plateaus and in some instances, were found on forest patches that were not
elevated above the surrounding wetlands (and thus water table) at all (Baltzer et al., 2014; Chasmer & Hopkinson, 2017).

At Hossitl Creek in northeastern BC, landcover still works moderately well as a proxy for determining the distribution of permafrost across a landscape (accuracy of 74.8%). While permafrost presence or absence at this site is still largely conditional on landcover, there were more instances of misclassification compared to Scotty Creek. This was due to the fact that not only were there relatively more instances of missing permafrost below forested land, but there were also some instances where permafrost was found beneath tree free areas. In contrast to Scotty Creek, not all instances of false positives (i.e. predicting permafrost where there is none) could be easily attributed to their relative location within a forest. Of course, some of these misclassifications were located on the edges of plateaus or beneath forested areas that are level with the surrounding wetlands, but some plateaus also appeared to have no detectable permafrost despite still being elevated above the water table. Additionally, the instances of permafrost found beneath tree-free areas were isolated to this site and were found both in areas classified as bogs as well as on elevated plateau features that were tree free, introducing a new challenge to remote sensing-based landcover classification.

While the relationship between landcover and permafrost presence or absence begins to deteriorate moving south of Scotty Creek, it still appears to be a valuable tool for estimating the proportion of permafrost found at any given site. However, in the sample study, this predictive method was subject to slightly overestimating the amount of permafrost at each site given that not all areas delineated as forest occurred on permafrost. Conversely, wetlands or tree-free areas still largely appear to be a successful determinant of ice-free ground even with some instances of misclassification at Hossitl Creek. Landcover can still reliably be used to monitor permafrost
distribution however, this study proposes that in actuality, permafrost is likely overestimated by between 10-25% using this method.

Climate change and industrial development, both of which are occurring at an unparalleled rate in Canada’s cold regions, may introduce a new potential challenge to this method. Climate change in the boreal peatlands is most obviously present through less frozen ground and this process may be observed as a transition from forest to wetland dominated landscapes (Hayashi et al., 2004; Quinton et al., 2009). As permafrost thaws, the peat plateaus that house it begin to destabilize and eventually collapse and level with surrounding wetlands (Quinton et al., 2009; Quinton et al., 2011). These processes have been observed at both Scotty Creek and Hossitl Creek through net forest loss rates of 11.6% and 6.9% over the 40-year study period, respectively. However, Scotty Creek’s landcover change can be attributed to small but uniform amounts of loss occurring across the edges of most black spruce forested plateaus with only isolated areas of forest gain. Hossitl Creek is instead characterized by much more dramatic and rapid landcover change where both the areas of loss and gain are much more expansive. This could be due to a combination of factors including changes to climate, which is well described and recognized, or other influences such as industrialization, disturbance (i.e. the expansive fire in 1982), or overmaturatiion of peat, which was observed at Hossitl Creek (Beilman & Robinson, 2003; Quinton et al., 2003; Zoltai, 1993; Zoltai & Tarnocai, 1975).

Plateau-loss is occurring at an increasing rate and much faster than new peat can accumulate and form frost bulbs, as observed by measurements recorded in areas where reforestation had occurred but no permafrost had returned at either site (Jorgenson et al., 2010; Robinson & Moore, 2000; Turetsky et al., 2007). Additionally, these degradation methods are also typically characterized as positive feedback systems (Jorgenson et al., 2010; Robinson &
Moore, 2000; Turetsky et al., 2007). As more trees disappear from the landscape, not only will the landcover change but forest loss will also further expose the surface to solar radiation and any associated warming. In turn, this positive feedback has the added potential to accelerate plateau collapse and the loss of remaining tree cover; further exacerbating the landcover transition towards permafrost-free wetlands (Jorgenson et al., 2010; Robinson & Moore, 2000; Turetsky et al., 2007). This thaw-induced forest loss, as well as associated plateau overmaturity at Hossitl Creek, is most likely responsible for the majority of forest loss occurring at both sites whereas forest fire and industrialization are thought to have a less unidirectional impact (Baltzer et al., 2014; Beilman & Robinson, 2003; Quinton et al., 2011). Forest fire impacts can clearly cause forest loss if the fire intensity is great enough but over time, those lost stands can also be replaced assuming conditions are still suitable for forest reestablishment (Beilman & Robinson, 2003; Zoltai, 1993). Forest fire impacts were largely removed from this analysis in order to focus on landcover changes that could be attributed to other factors. Industrialization and other human developments can clearly cause notable forest loss through tree clearing for seismic lines, winter roads or drill pads. Despite removing forest loss from this analysis that could be confidently and directly attributed to new human activity over the study period, these clearings are often thought to increase drainage density and may assist in clearing water from the landscape in a similar way to fens and streams (Chasmer & Hopkinson, 2017; Connon et al., 2014; Quinton et al., 2003). New drainage patterns and higher connectivity, whether through an increase in wetland cover or industrialization, may lead to a drying trend across these landscapes potentially allowing for black spruce forests, which are water intolerant, to return once enough time has passed (Camill, 1999; Murphy et al., 2009; Ketteridge et al., 2013; Waddington et al., 2015).
While afforestation is not presently occurring on the same scale that thaw-induced deforestation is, and permafrost appears to have not returned to these newly forested areas, each introduces a new complication for using landcover as a proxy for underlying permafrost, which will only be exaggerated as these patterns continue and accelerate. Further work should be completed on whether lower latitude sites, such as Hossitl Creek, can be used as a potential analogue to represent future conditions for more northerly sites, such as Scotty Creek, as temperatures rise and the boundaries of permafrost zones shift northward. Additionally, the relationship between landcover and permafrost should be explored at more sites between Scotty Creek and Hossitl Creek to examine how representative each site is of boreal peatlands in northwestern Canada and the broader discontinuous permafrost zone.

3.6 Conclusions

This study identified two key conclusions. Firstly, landcover performed much more effectively as a proxy for underlying permafrost distribution at Scotty Creek than it did at Hossitl Creek. Secondly, landcover change at the Scotty Creek site in the southern Northwest Territories was significantly more uniform and unidirectional than at the Hossitl Creek site in northeastern British Columbia. Both of these conclusions highlight the need to explore the relationship between landcover and permafrost distribution across more sites throughout the boreal peatlands in order to determine how representative the patterns observed and established at Scotty Creek are of the broader region. Furthermore, determining permafrost distribution, condition, and rate of change is critical to better understanding these transitional and dynamic northern environments. These regions are becoming increasingly important to undergo further study as they are most urgently at risk from changes to climate as well as increasing industrialization and resource development. The need to advance predictive methods to better understand and more
economically determine permafrost distribution and change on a larger scale is becoming increasingly necessary given the pressing need to improve the monitoring and conservation of these environments.
CHAPTER 4.0: Conclusion

Canada’s subarctic and its boreal peatlands are inherently transitional and dynamic in nature. However, permafrost degradation has highlighted the urgency and challenge in studying these environments. Moreover, the remoteness and size of the region limits the depth of understanding of these environments as well as limits the scope of the locations where research can be conducted. This research aims to contribute to the understanding of permafrost thaw in Canada’s subarctic through the evaluation of remote sensing methodologies that measure and monitor landscape change.

While the general relationships and processes are well understood, particularly at the northern extent of the discontinuous permafrost zone, this research assists in developing and evaluating new and efficient strategies for monitoring permafrost thaw across this landscape. This research further offers a clear advantage through its ability to retain the detail and high-resolution results that are typical in single-site studies through the incorporation of remote sensing data alongside supporting fieldwork. Using both of these approaches across a broad range of sites also provides increased confidence in the value of remote sensing methods for future studies.

Monitoring large-scale landscape changes in Canada’s increasingly vulnerable cold regions is one of the most critical contributions of this research. Previous research in this field has largely been limited to the northernmost sites of the study region highlighted in this research, which has limited the findings to a specific region, and demonstrates how those sites are not representative of the entire adjoining regions. This research builds on our understanding that there are notable differences in the area of study despite relatively close geographic proximity, and reinforces the necessity for broader testing and studying boreal peatland landscapes across a
wide range of sites. The spatial range in this study is a critical component to not only addressing both research objectives but also to advancing the field as a whole. This research determined the amount and rate of permafrost thaw-induced landcover change at each area of interest, and also showed changes to these measurements across the large spatial gradient. Furthermore, this research established locations where landcover can be a useful proxy for the state of the underlying permafrost, as has been used in the northern sites, as well as where the relationship between permafrost and forest is less definite. Given the uniqueness and spatial heterogeneity of the subarctic boreal peatland environment, there remains a pressing need to analyze both of these opportunities across a wider range of sites in order to ensure studies can be produced that are representative of the entire region.

Detailed mapping and monitoring of permafrost environments indicates that significant degradation is occurring and climate appears to be the dominant control on this change. While this study addresses this concept, some limitations have also been identified. The first recognized limitation is due to a combination of geomatics issues. Firstly, historical air photos are afflicted with quality issues that can be problematic especially when a true orthorectification cannot be completed. Georeferencing was performed but it does not correct for issues of imaging perspective and topographic relief as reliably as the traditional orthorectification process would. This can further be compounded by inherent digitizing errors given the subjectivity of the approach and the limited fieldwork that was completed for this study. Defining the conditions required to categorize a landcover helps minimize these errors but manually digitizing these landcovers will always introduce variability in the results from user to user. Furthermore, there was some bias in site selection, as beyond having suitable remote sensing coverage, sites were only selected if they could confidently be characterized as boreal peatlands through satellite
imagery interpretation based on appearance and similarities to previously purchased imagery of Scotty Creek, NWT. Finally, further field data, especially across a wider variety of sites, would have been instrumental for both research objectives to help further solidify the relationship between landcover and permafrost distribution.

Determining permafrost distribution, condition, and rate of change, especially at a finer resolution, is critical to better understanding these transitional and dynamic northern environments. These regions are becoming increasingly important to study as they are most urgently at risk to changes in climate, which is only aggravated by increasing industrialization and resource development. The need to develop efficient and predictive methods to better determine permafrost condition and change on all spatial scales is essential given the pressing need to improve the monitoring and conservation of these environments. The approach in this study also highlights the importance of using remote and/or indirect predictive methods to research this area as arctic and subarctic field-data collection is burdened with cost and access limitations. To further enhance the understanding of the impact of these changes, there is a clear need to further acknowledge and study the permafrost variability across a wider range of sites. This is particularly important because the hydroclimatic conditions of the subarctic vary greatly, so local or even regional findings do not always apply to other sites given the area’s ingrained spatial variability.
CHAPTER 5.0: References


