The ecology and dynamics of ice wedge degradation in high-centre polygonal terrain in the uplands of the Mackenzie Delta region, Northwest Territories

by

Audrey Elizabeth Steedman
B.Sc., University of Calgary, 2008

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of

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in the School of Environmental Studies

Supervisory Committee

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Abstract

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Climate warming has the potential to alter the structure and function of Arctic ecosystems in ways that are not fully understood. Polygonal terrain is a widespread permafrost feature of Arctic landscapes that is likely to be impacted by warming ground temperatures. This is of particular relevance in the uplands in the Mackenzie Delta region, where high-centre ice wedge polygon fields comprise 10% of the terrestrial landscape, and mean annual ground temperatures have increased between 1 and 2°C over the last 40 years (Burn and Kokelj 2009). I used broad-scale airphoto analysis and fine-scale field studies to investigate the impacts and possible trajectories of ice wedge degradation in the upland tundra north of Inuvik, NWT. Field investigations were undertaken to characterize biotic and abiotic conditions and feedbacks in stable and degrading high-centre polygons. Field surveys were conducted along transects which crossed three polygon micropositions (centres, edges and troughs) and targeted a degradation sequence from stable troughs to ice wedge melt ponds. I measured surface microtopography, active layer depth, water depth, plant community composition, soil gravimetric moisture, late winter snow depth, and shallow annual ground temperatures. Field data showed that ice wedge degradation drove increases in soil moisture, standing water depth, ground surface collapse, ground temperature, and active layer thaw and snow pack compared to stable troughs. These changing abiotic conditions drove the shift from mesic upland tundra plant communities to unvegetated melt ponds. Interactions between abiotic and biotic factors in degrading troughs increase ground temperature and contribute to positive feedbacks for ice wedge degradation. Analysis of broad-scale factors affecting ice wedge degradation involved the mapping of high-centre polygon distribution across the study area and the distribution of ice wedge melt ponds using high-resolution aerial photographs from 2004. Recent changes in melt pond area were also mapped using imagery dating from 1972. Thermokarst activity in polygonal terrain adjacent to anthropogenic disturbances was also assessed. Polygon fields were more abundant and larger in the northern part of the study area, where ground temperature conditions were most favourable for ice wedge formation. Spatial variation in polygonal terrain density was also related to topography, drainage, and the distribution of lacustrine sediments. Melt pond mapping and assessment of thermokarst at anthropogenic disturbances showed that ice wedges at higher latitudes are more susceptible to degradation primarily because these areas are underlain by larger and more abundant ice wedges. Melt pond mapping confirmed that the polygonal fields north of 69.4°N have shown both large increases and decreases in area, and that polygons in the south have been relatively stable in recent decades. The increased thaw sensitivity of polygonal terrain at higher latitudes has implications for soil carbon dynamics, terrestrial ecosystems, and the planning and maintenance of infrastructure as air and ground temperatures continue to increase.

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Acknowledgments

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Dedication

This thesis is dedicated to my parents, Rob and Gillian, and to the Steedman, Barnett and Vander Wal families who have always supported, challenged and inspired me.

Chapter 1 – Introduction

Average global air temperatures have increased at a rate of 0.08 to 0.14 °C per decade from 1951 to 2012 (Stocker et al. 2013). Recent increases in air temperature at high latitudes have been more than double the global average (Hassol 2005; Serreze et al. 2000; McGuire et al. 2006). Climate models predict that future warming will continue to be amplified at high latitudes in the northern hemisphere, with increases of 3-5°C over Arctic land masses projected by the 2090s (Hassol 2005). Increased warming will be accompanied by increased evaporation and precipitation, with coastal areas of the Arctic projected to receive a 30% increase in winter and autumn precipitation by the end of the century (Hassol 2005).

Climate change has the potential to alter the structure and function of Arctic ecosystems in ways that are not fully understood (Hassol 2005; Serreze et al. 2000; McGuire et al. 2006). In Arctic ecosystems, disturbances associated with permafrost thaw (thermokarst) are one of the most dramatic manifestations of recent climate change. Changes in the frequency of thermokarst have been associated with increasing air and ground temperatures and create potential for rapid changes in Arctic vegetation (Jorgenson, Shur, and Pullman 2006; Burn and Kokelj 2009; Hassol 2005). In areas with continuous permafrost, observations of increased thermokarst include: ice wedge thaw pit development in Alaska (Jorgenson, Shur, and Pullman 2006), retrogressive thaw slump growth in the Mackenzie Delta region (Lantz and Kokelj 2008), and catastrophic lake drainage in the Old Crow Flats (Lantz and Turner, In Review). Interactions between slope position, soil texture, hydrology, and ground ice content influence the mode of permafrost degradation, and have distinct geomorphological and ecological consequences (Jorgenson et al. 2001). Ice-rich terrain is susceptible to subsidence upon thawing, resulting in the development of thermokarst terrain (Kokelj and Jorgenson 2013).

Polygonal terrain is a common type of patterned ground across the circumpolar Arctic that is underlain by large volumes of ground ice. This terrain type is particularly sensitive to thermokarst development. Ice wedges are created due to the thermal contraction cracking of the ground in winter. Meltwater infiltrates into the cracks and freezes, forming a vein of ice. Repetition of this process can lead to the growth of the ice wedge over thousands of years (Mackay 1984). Ice wedge growth causes the ground to deform and alters microtopography (Figure 1-1) (Mackay 1989). Polygonal terrain is the surface expression of an ice wedge network. Ice wedge polygons are frequently divided into high and low-centre polygons based on surface microtopography (Mackay 2000). Low-centre polygons are outlined by elevated ridges with a depression in the polygon centre. High-centre polygons are outlined by subsided troughs overlying the ice wedges, and have elevated centres. These variations in microtopography and abiotic conditions within the polygon and ice wedge trough are associated with distinct plant communities (Eisner and Peterson 1998; Vardy, Warner, and Aravena 1997; Peterson and Billings 1978; Peterson and Billings 1980; Minke et al. 2009).

High-centre polygons are considered to be indicative of past ice-wedge degradation (Mackay 2000) that can result from a deepening active layer due to disturbance or changes in hydrology. Degradation results in subsidence of the ice wedge trough that can hold standing water from ice wedge thaw and precipitation (Jorgenson, Shur, and Pullman 2006). These features have been called thermokarst pit or ice wedge melt ponds. Abrupt increases in ice wedge degradation have been identified in Alaska in recent decades and have been associated with a warming climate and increasing ground temperatures (Jorgenson, Shur, and Pullman 2006). Ice wedge degradation alters near surface hydrology, likely affecting soils and vegetation, local biodiversity, wildlife habitat, and creating the potential for landscape scale

Figure 1-1. High-centre ice wedge polygons in the uplands north of Inuvik in the Mackenzie Delta region. High-centre polygons are outlined by subsided troughs overlying the ice wedges, and have elevated centres. Photo: Audrey Steedman.

changes (Jorgenson, Shur, and Pullman 2006). However, little is known about the ecological conditions and feedbacks that characterize stable and degrading ice wedges in high-centered polygonal terrain. Additional research is also required to understand the regional extent of ice wedge degradation, recent changes in ice wedge degradation, and the ecological trajectories of degrading ice wedge troughs and melt ponds. For example, the accumulation of vegetation and organic matter in the trough is thought to stabilize degrading ice wedges by creating a thickened layer of insulation, which protects against further heat gain (Jorgenson, Shur, and Pullman 2006). However, conditions that prevent freezeback of the active layer such as latent heat introduced by ponded water (Nakano and Brown 1972) and increased snow accumulation (Zhang 2005) may also accelerate permafrost degradation, subsidence and trough deepening or expansion. To date, the ecological conditions and feedbacks associated with ice wedge degradation have not been well-characterized at a fine scale. In anticipation of further permafrost warming, research is required to understand the ecological dynamics of degrading polygonal terrain.

Ice wedges are extremely common in the Low Arctic, and their degradation has the potential to substantially alter ecosystem processes, including soil carbon storage (Lee et al. 2012; Tarnocai et al. 2009a), hydrology, and vegetation (Burn and Kokelj 2009; Jorgenson, Shur, and Pullman 2006). The nature of biotic and abiotic processes and feedbacks in high-centered polygons are also likely to vary at broad-scales where clear latitudinal differences in ice wedge abundance and size have been observed (Kokelj et al. 2014). Patterns in the distribution of melt ponds, and changes in their development in recent decades have not been studied at broad scales and this information is required to predict the conditions that will facilitate or constrain degradation.

The overarching goal of my MSc research is to understand the dynamics of ice wedge degradation at fine and broad scales. This research will focus on the upland tundra in the Mackenzie Delta region. It is estimated that in this region ice wedges occupy approximately 12 percent of the upper 4.5m of permafrost underlying this landscape, and up to 50 percent by volume of the top meter of ground in areas of polygonal terrain (Pollard and French 1980). Because the terrain is rich in ground ice, the landscape may be extremely susceptible to thermokarst resulting from ice wedge degradation. Ice wedge degradation is a of particular concern in the Mackenzie Delta region because ground temperatures have increased rapidly since 1970, with the uplands 1-2°C warmer than in 1970 (Burn and Kokelj 2009). The distribution of ice wedges in the region will likely result in significant infrastructure challenges for the construction and maintenance of the Inuvik – Tuktoyaktuk Highway and potential infrastructure for hydrocarbon exploration and transport.

In Chapter 2 of this thesis, I examine the following research question: **What are the fine-scale biotic and abiotic factors and interactions associated with ice wedge degradation in the Mackenzie Delta region uplands?** This study focuses on the relationships among abiotic and biotic factors in high-centre polygons fields in the upland tundra north of Inuvik, and characterizes the variability in physical and biological conditions in ice wedge troughs that have undergone varying degrees of degradation. This part of my field research involved ecological field surveys to analyze abiotic and biotic conditions in stable and degrading ice wedge troughs.

In Chapter 3 of this thesis, I explore the following research question: **What are the broad-scale factors influencing the characteristics and the spatial and temporal distribution of melt ponds in the Mackenzie Delta region uplands?** This chapter focuses on ice wedge melt ponds, examining their characteristics, spatial distribution, abundance, and change in surface area over time in the upland tundra north of Inuvik. To accomplish this, I used GIS methods to analyze high-centre polygonal terrain mapped using recent (2004) and historical (1972) aerial photographs.

In the final chapter of this thesis, I explore the implications of the findings presented in Chapters 2 and 3, provide an overall synthesis, and discuss possible avenues for further research. The remaining sections of this chapter provide critical context on the biophysical environment of the Mackenzie Delta region uplands, and some additional background on polygonal terrain.

Biophysical environment of the Mackenzie Delta region uplands

Glaciation, geology and surficial materials

The upland tundra east of the Mackenzie Delta was covered by the Laurentide ice sheet, which reached its maximum extent about 30, 000 years before present during the Wisconsinan glaciation (Aylsworth et al. 2000a). The Tuktoyaktuk Peninsula has been continuously ice-free for at least 13,000 years (Vardy, Warner, and Aravena 1997). The Inuvik area was covered by ice until about 15,000 years before present (Ritchie 1985). The bedrock underlying the Mackenzie Delta region is clastic and carbonate sedimentary rock (Burn and Kokelj 2009). Because the uplands in the Mackenzie Delta region are underlain by continuous permafrost, the surficial materials below the base of the active layer are generally frozen and contain ground ice. Much of the Mackenzie Delta region uplands has some cover of glacial moraine (till) over bedrock (Aylsworth et al. 2000a). This is a fine-grained till containing stones. Glaciolacustrine and lacustrine silt deposits are found at the former location of lake basins that have drained through the Holocene (Mackay 1992). These fine-grained deposits of silt and clay favour the formation of ground ice (Aylsworth et al. 2000a). The accumulation of peat can occur in low-lying areas with lacustrine sediments, and within depressions in moraine deposits. These frozen peatlands typically contain ice wedges (Kokelj et al. 2014). At the 1:100 000 scale, the majority of the Inuvik – Tuktoyaktuk gradient is mapped as being underlain by thick morainal deposits, with lacustrine and glaciofluvial deposits between Tuktoyaktuk and Husky Lakes (Aylsworth et al. 2000a). Numerous thermokarst basins that host peatlands developed on the Tuktoyaktuk Coastlands during a warm interval 13-8 thousand years ago (Murton 1996). In general these smaller patches of lacustrine sediments are not captured in mapping at this scale.

Soil

Cryosols are the dominant soils in the continuous permafrost zone in Canada, and cover approximately 92% of the soil area. The remaining areas contain alluvium and coarse-textured materials (Tarnocai and Bockheim 2011). The freezing and thawing of a moist or saturated active layer is believed to be the primary factor driving cryogenic processes. The movement of unfrozen soil water along thermal gradients (warmer to colder) can lead to the development of ice-lenses and frost heave, and thawing leads to settlement. It is believed that these processes drive cryoturbation and the formation of cryogenic soils (Tarnocai and Bockheim 2011). Mineral soils in the Mackenzie Delta region uplands generally show extremely active cryoturbation, with the exception of soils that developed on coarse-textured, sandy or gravelly material (Tarnocai 1973). Fine-grained mineral soils are common in hummocky terrain in this region (Kokelj et al. 2014).

Soils within polygonal peatlands are generally classified within the Organic Cryosol Great Group. These are organic soils that have developed from the accumulation of organic material. The cryogenic processes associated with this soil group are moderate cryoturbation and compaction due to the growth of ice lenses. The soil subgroups within the Organic Cryosol

Great Group are differentiated on the basis of the depth and degree of decomposition of the organic material (Tarnocai and Bockheim 2011).

Vegetation

The southern boundary of the study area is located approximately 12 km northeast of Inuvik, north of the limit of continuous forest, and is dominated by several forms of tundra. The transition from low subarctic open crown forest to high subarctic forest tundra occurs where trees become sparse (<0.1% cover) and are gradually replaced with open tundra (Timoney et al. 1992). At this transition, tall shrubs (100-400 cm) become the dominant vegetation, including *Alnus, Betula,* and *Salix*, as well as ericaceous shrubs (eg. *Ledum, Vaccinium*, etc.) (Lantz, Gergel, and Kokelj 2010). Tall-shrub dominated vegetation is also found on sandy sediments along river and stream channels and lake shores, as well as on gravelly lake shores (Corns 1974). Tall shrubs are gradually replaced by erect dwarf shrubs (<40 cm tall) with increasing latitude, and the tundra is characterized by dwarf shrub and sedge cover. Medium-shrub and low-shrub tundra are characterized by high cover from *Betula nana* and ericaceous shrubs such as *Vaccinium* spp., and are generally found on moist gentle slopes (Corns 1974). Trees are very uncommon in this zone, which includes lichen, tussock tundra, sedge meadows, and polygonal peatlands (Timoney et al. 1992).

Fire regime

Historically, tundra fires have been infrequent and limited in their intensity and magnitude. In 1968, a fire burned subarctic boreal forest and shrub tundra between Inuvik and Noell Lake (Mackay 1995). There is some evidence that tundra fires are becoming more widespread in the low Arctic as the climate warms (McCoy and Burn 2005; Flannigan and Vanwagner 1991).

Polygonal Terrain

Formation

The morphology of ice wedge polygons is variable, with a continuum of forms between low and high-centre terrain. Morphological variations in ice wedge polygons are thought to result from developmental processes that are related to the age and history of the feature (Mackay 2000; Peterson and Billings 1978). Although these transitions are not fully understood, several conceptual models have been developed that describe the processes involved and their effects on polygon morphology (Mackay 2000; Peterson and Billings 1978; Jorgenson, Shur, and Pullman 2006). During the development of an ice wedge network in a relatively flat area such as a drained lake basin, a low-centre polygon develops as a growing ice wedge deforms the surrounding materials, resulting in the development of elevated ridges that bound a low-lying ice wedge trough. This creates a ridge-lined depression, allowing water to pond (Mackay 2000). The transition from low-centre to high-centre morphology is not fully understood, but is thought to driven by several factors. The accumulation of peat within the polygon centre over time will elevate the centre relative to the troughs (Mackay 2000). The high-centre morphology can also result from the subsidence of ice wedge troughs following thaw. Mechanisms that affect soil moisture can lead to the development of a high-centre polygon by increasing the depth of thaw (Peterson and Billings 1978).

Vegetation in polygonal terrain

Distinct plant communities are associated with ice-wedge polygons (Eisner and Peterson 1998; Vardy, Warner, and Aravena 1997; Peterson and Billings 1978; Peterson and Billings 1980; Minke et al. 2009). The species composition of high-centre polygonal terrain described in the literature is variable, likely due to regional floristic differences. In low centres and troughs, hydrophilic sedges, such as *Carex aquatilis*, peat mosses (*Sphagnum* spp), and standing water are common. In polygon complexes near the Meade River, northern Alaska, drier plant communities that are at a mid to late successional stage may be characterized by *Eriophorum* spp, and by communities dominated by *Dryas integrifolia* and *Cassiope tetragona,* lichens and dwarf evergreen shrubs (Peterson and Billings 1980). In the uplands east of the Mackenzie Delta, low-lying ice wedge troughs have been characterized as having a richer species composition than the drier peat-dominated polygon centres (Corns 1974). Polygon centre communities are generally dominated by *Betula glandulosum*, *Rubus chamaemorus, Ledum decumbens, Vaccinium vitis-idaea* and lichen (Corns 1974). Ice wedge troughs are generally characterized by more hydrophilic species, including *Carex* spp, *Chamaedaphne calyculata* and *Sphagnum* spp (Corns 1974). Vegetation in high-centre polygonal terrain within the study area is characterized by sparse cover of high shrubs (*Salix* spp, *Alnus viridis*), abundant cover from low shrubs (*Ledum decumbens, Betula glandulosum*, *Vaccinium* and *Rubus* spp), grasses, and sedges, with patches of *Sphagnum,* and abundant lichen cover on drier polygon centres (Forest Management Institute 1975).

Studies of the stratigraphy, geochemistry, and the pollen, spore and macrofossil record of cores from ice wedge polygons have illustrated changes in vegetation communities associated with the evolution of ice wedge polygons in response to changes in climate and moisture (Eisner and Peterson 1998; Vardy, Warner, and Aravena 1997; Kienel, Siegert, and Hahne 1999; Ovenden 1982). A warmer than present climate during the early Holocene Milankovich insolation maximum began cooling 8000 years BP, and then cooled more rapidly around 4500-5000 years BP, resulting in the aggradation of permafrost and ice wedge development (Vardy, Warner, and Aravena 1997). Peat accumulation and changes in abiotic conditions likely influenced peatland hydrology and drove physical changes in polygon microtopography from low to high-centre morphology, and the resulting shifts in plant community composition identified in the peat record (Vardy, Warner, and Aravena 1997).

Chapter 2 – Impact of ice wedge degradation on vegetation composition, microtopography, active layer and ground temperatures in high-centre polygons in the uplands of the Mackenzie Delta region, Northwest Territories.

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4. AES and TCL conceived the study; AES, SVK, and TCL collected the data; AES analyzed the data; AES, SVK, and TCL wrote the manuscript.

Introduction

Recent increases in air temperature at high latitudes have been more than double the global average (Hassol 2005; Serreze et al. 2000; McGuire et al. 2006). In areas of continuous permafrost, warming has been accompanied by increased ground temperatures and shifts in the frequency of disturbances related to thawing ground ice, such as thaw slumps, active layer detachments and the development of ice wedge thaw ponds (Lantz and Kokelj 2008; Kokelj and Jorgenson 2013; Jorgenson, Shur, and Pullman 2006; Smith et al. 2010; Lewkowicz 1987). Ground-ice content in permafrost zones is a key determinant of terrain sensitivity to thermokarst, and ice rich landscapes are anticipated to be subject to significant terrain and ecological changes (Dyke et al. 1997; Kokelj and Jorgenson 2013). Ice wedge polygons are a form of ice-rich patterned ground that is likely to be particularly sensitive to changes in climate because large volumes of ice are close to the ground surface and are susceptible to subsidence upon thaw (Jorgenson, Shur, and Pullman 2006; Kokelj and Jorgenson 2013; Necsoiu et al. 2013; Kokelj et al. 2014). Polygonal terrain is a widespread feature of Arctic landscapes underlain by a network of ice wedges that form when thermal contraction cracks fill with water and freeze (Mackay 1989). Repeated cracking over periods of thousands of years results in ice wedge growth, deformation of adjacent sediments and alteration of microtopography. Along the Western Arctic Coast and across the circumpolar Arctic this terrain type hosts large volumes of near-surface ground ice (Mackay 1989; Mackay 2000). In the low Arctic, ice wedge networks typically develop in discrete patches of low-lying terrain such as drained lakes basins. Throughout this paper these discrete patches of polygonal networks are referred to as polygon fields.

Ice wedge polygons are classified (Mackay 2000) as high or low-centred based on their microrelief. Low-centre polygons are outlined by elevated ridges adjacent to the ice wedge troughs with a depression in the centre of the polygon. High-centre polygons consist of an elevated polygon centre outlined by low-lying troughs overlying ice wedges (Figure 2-1). High-centered polygons are indicative of older features that have undergone past ice-wedge degradation and subsidence to create a low-lying ice wedge trough (Mackay 2000). The continuum of polygon morphology from low to high-centre is shaped by several processes. After the formation of an ice wedge in the sediments of a drained lake bed, ice wedge growth results in ground deformation, with ridges adjacent and parallel to the ice wedge impeding drainage and impounding water in the polygon centre and in the troughs overlying the ice wedge (Mackay 2000; Morse and Burn 2013). The accumulation of peat in the polygon centre contributes to the formation of an intermediate-centred polygon (Mackay 2000). Further peat accumulation in the centre, sometimes in combination with trough formation from ice-wedge thermokarst contributes to the formation of a high-centre polygon (Mackay 2000).

In northern Alaska, increases in ice wedge degradation between 1982 and 2001 have been associated with a warming climate and increasing ground temperatures (Jorgenson, Shur, and Pullman 2006). Based on remote sensing analysis, Jorgenson et al. (2006) estimated that 10-30% of Arctic lowland landscapes may be extremely susceptible to thermokarst resulting from ice wedge degradation. Polygon terrain is sufficiently widespread in the Low Arctic (Kokelj et al. 2014) that even small increases in ice wedge degradation may significantly alter terrestrial ecosystem processes, including soil carbon storage (Lee et al. 2012; Tarnocai et al. 2009a), hydrology (Fortier, Allard, and Shur 2007), and vegetation (Burn and Kokelj 2009; Jorgenson, Shur, and Pullman 2006).

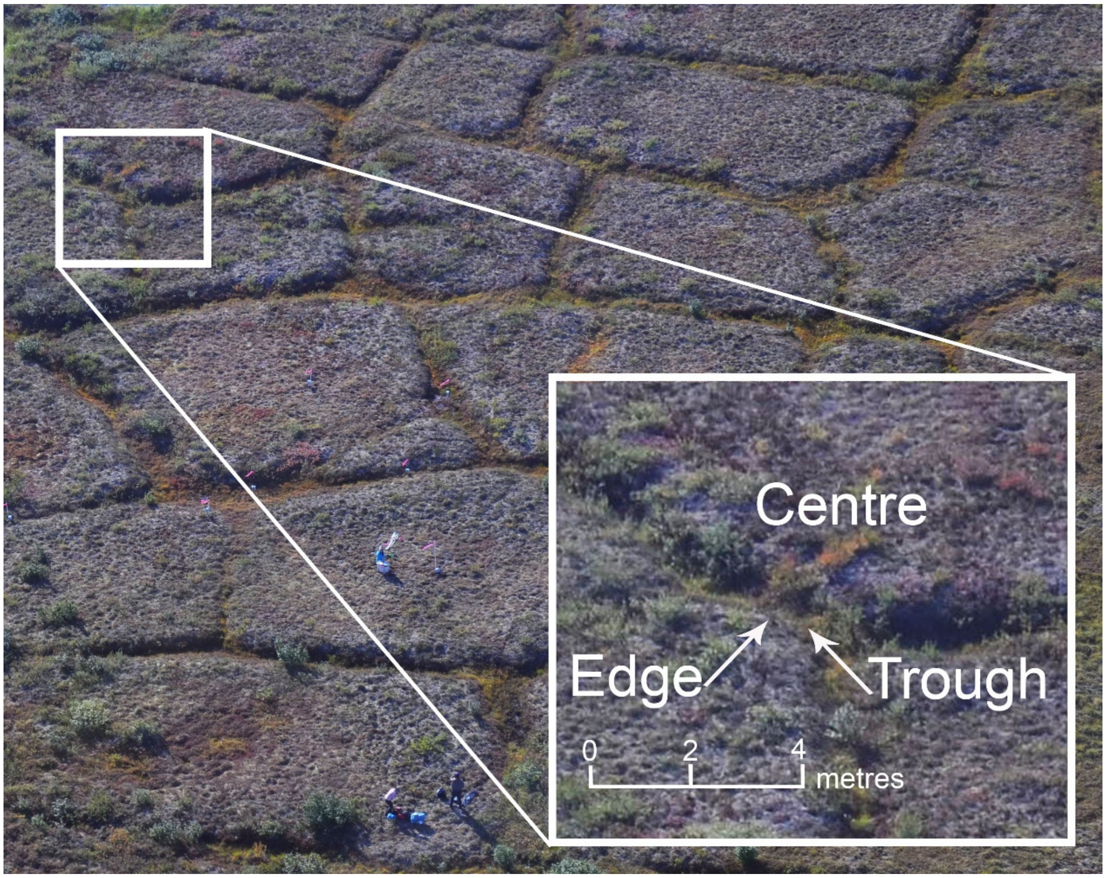


Figure 2-1. Photograph showing the centre, edge and trough microtopographical positions in a field of high-centre polygons.

To date, biotic and abiotic conditions in stable and degrading high-center polygons have not been investigated systematically or quantitatively, and little is known about the interactions among fine-scale factors such as microtopography, soil moisture, and vegetation cover, which may have an impact on ecological feedbacks influencing ground thermal regime following ice wedge degradation. Previous descriptive studies suggest that a soil moisture gradient associated with microtopography is the key determinant of plant community composition in polygonal terrain. Peterson and Billings (1978, 1980) show that wet polygon troughs are associated with hydrophilic vegetation (ex. *Sphagnum* spp, *Carex aquatilis*), whereas elevated polygon centres support the growth of upland tundra species (ex. lichens, ericaceous shrubs such as *Ledum groenlandicum, Vaccinium vitis-idaea*). Geomorphic processes influencing polygon morphology and topography, including aeolian erosion and deposition of sand, and erosion from flowing water, have also been linked to differences in soil moisture and vegetation composition in polygonal terrain (Peterson and Billings 1978; Peterson and Billings 1980). Analyses of the developmental history of polygonal peatlands from core samples also show that changes in permafrost and ground ice conditions drastically affect the ground surface topography and peatland hydrology, in turn affecting plant community composition (Vardy, Warner, and Aravena 1997; Eisner and Peterson 1998).

In other disturbances in permafrost environments such as thaw slumps (Lantz et al. 2009) and drilling mud sumps (Johnstone and Kokelj 2008), interactions between topography, vegetation cover, and snow accumulation create feedbacks that influence ground thermal conditions, surface stability and long term ecological trajectories. Similar feedbacks are expected to occur in degrading ice-wedge troughs, and may effectively enhance or limit further ice wedge degradation. Specifically, changes in soil moisture in polygonal terrain resulting from ice wedge degradation are likely to drive changes in plant community composition (Peterson and Billings 1978; Peterson and Billings 1980). Latent heat introduced by standing water from degraded ice wedges (Nakano and Brown 1972) and increased snow accumulation (Zhang 2005) in the deepening trough may also inhibit freezeback of the active layer and accelerate degradation (Kokelj et al. 2014). Alternatively, the accumulation of vegetation and organic matter in recently degraded troughs may insulate wedge ice from further degradation (Jorgenson, Shur, and Pullman 2006). Understanding the interactions of biotic and abiotic factors in both stable and degrading high-centre polygons is critical to predict the physical and ecological trajectories of Arctic peatlands as they respond to a changing climate. These trajectories will also be influenced by the configuration of the ice wedge, ie. size and depth. To date, the interactions among biotic and abiotic conditions have not been investigated in detail in stable and degrading high-centre polygons. In this study we[4] examine the relationships between abiotic and biotic factors in high-centre polygon fields in the upland tundra north of Inuvik, and characterize differences across a range of ice wedge degradation classes and microtopographical positions. Using this data we examine the hypotheses that:

1) Changes to polygon microtopography from ice wedge subsidence will be associated with increases in soil moisture and active layer thickness in ice wedge troughs.

2) The physical changes resulting from ice wedge degradation will drive changes in plant community composition.

3) Changes to biotic and abiotic conditions associated with ice wedge degradation will initiate feedbacks affecting the ground thermal regime.

Methods

Study area

The study area is the upland tundra north of Inuvik, NWT (Figure 2-2). The climate is characterized by a strong summer air temperature gradient with cooler temperatures near the coast (Burn 1997). Inland areas receive more annual precipitation, with a mean annual snowfall (1981-2010) of 159 cm at Inuvik, and 103 cm at Tuktoyaktuk (Environment Canada 2014).This climatic gradient strongly influences the transition from subarctic boreal forest to shrub tundra north of Inuvik (Timoney et al. 1992; Lantz, Gergel, and Kokelj 2010). This landscape is characterized by low rolling hills and is underlain by ice-rich continuous permafrost. Surficial materials consist predominantly of fine-grained tills deposited by the Laurentide ice sheet (Aylsworth et al. 2000b). The periodic drainage of tundra lakes throughout the Holocene has also produced extensive lacustrine plains which favour organic accumulation and development of peatlands (Mackay 1992). Ice wedges are extremely common in organic deposits (Kokelj et al. 2014), and it is estimated that in this region they occupy approximately 12 percent of the upper 4.5 m across the landscape, and up to 50 percent by volume of the top meter of ground in areas of polygonal terrain (Pollard and French 1980). The northward increase in the size and density of ice wedges in the region creates important context for the potential for landscape change resulting from thaw (Kokelj et al. 2014). The high density of ice wedges in the study area and their large size make this landscape particularly susceptible to thermokarst as a result of disturbance or climate warming (Burn and Kokelj 2009).

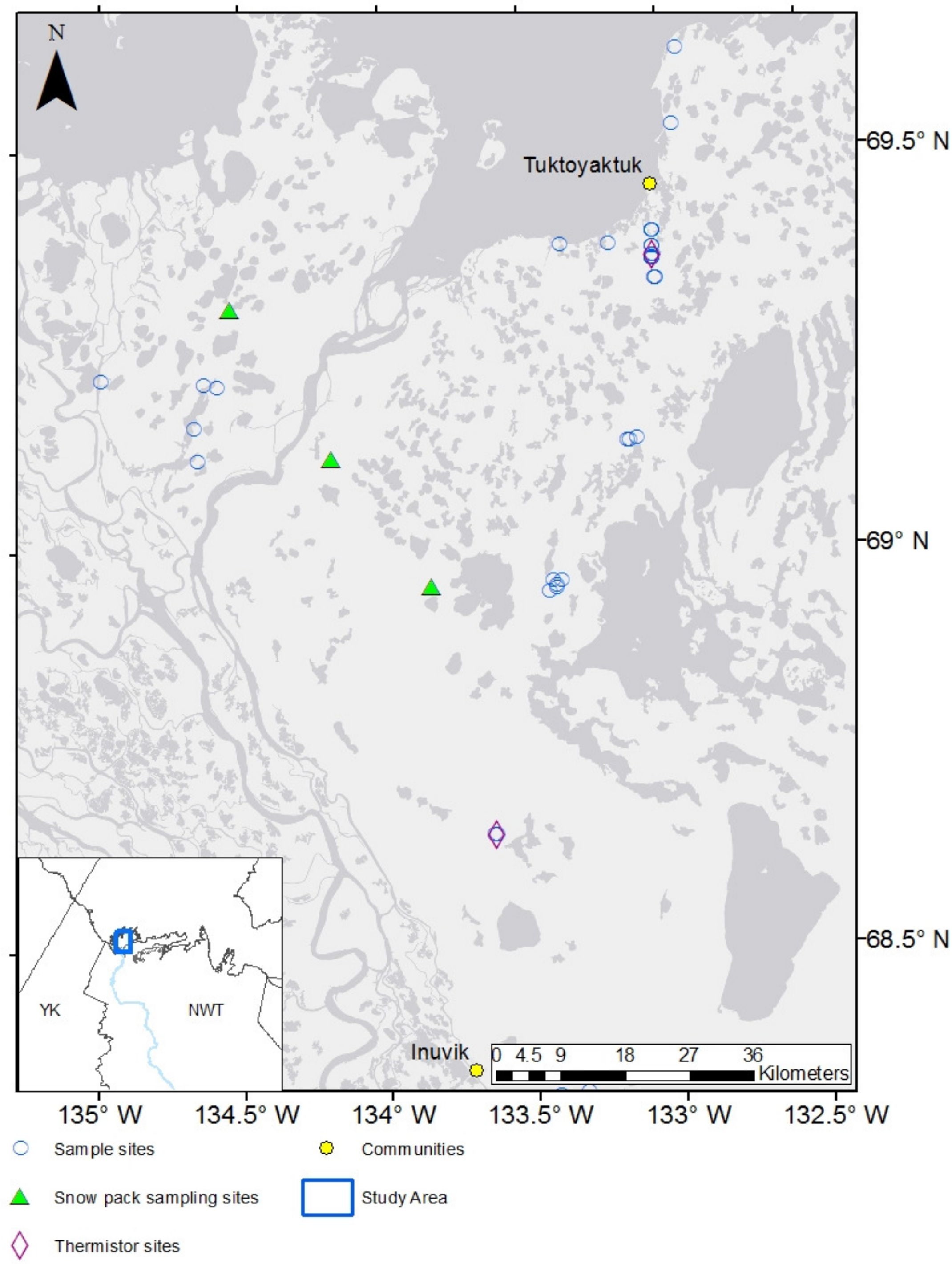


Figure 2-2. Map of the Mackenzie Delta region showing the sites where high-centre polygon fields were sampled in 2011 and 2012. Bodies of water greater than 100 ha in area are light grey. The blue box on the inset map at the bottom left shows the position of the of the study area in northwestern North America.

Field surveys

To examine the impacts of, and feedbacks initiated by ice wedge degradation in high-centre polygons, we conducted field surveys in the summers of 2011 and 2012. To identify polygon fields across the study area showing both stable features and those showing evidence of degradation, we used high-resolution airphotos captured in 2004 to select 23 sites (Figure 2-2). At each site we measured abiotic and biotic parameters at three microtopographic positions (polygon centres, polygon edges, and ice wedge troughs) and 4 wedge degradation classes using line transects and grids. Degradation classes were selected to represent the different stages of ice wedge degradation (Jorgenson, Shur, and Pullman 2006) and included: a) open water melt ponds (100% water cover), b) sparsely vegetated melt ponds (<50% vegetation cover with standing water), c) vegetated melt ponds (50% vegetation cover with standing water), and d) dry troughs without standing water (Figure 2-3). Throughout this paper these classes are abbreviated as follows: a) melt pond, b) very wet trough), c) wet trough, and d) mesic trough.

At each site we sampled between 1 and 8 troughs that included the range of thaw settlement and ponding present at the site. Transects were established running perpendicular to troughs and crossed the polygon trough and edge, and extended to the polygon centre. Data were collected at sample points located at 0.5 m intervals along each transect. Transects varied from 3.5 to 9 m in length depending on the geometry of each feature. Along each transect we measured: a) surface microtopography, b) active layer thickness, and c) pond depth. To measure microtopography we recorded the relative elevation of each sample point by measuring the distance between a level line and the surface of the ground or melt pond (Wright, Hayashi, and Quinton 2009). We measured thaw depth at each point by pushing a graduated steel probe into the ground to the depth of refusal. Active layer thicknesses were measured throughout the thaw

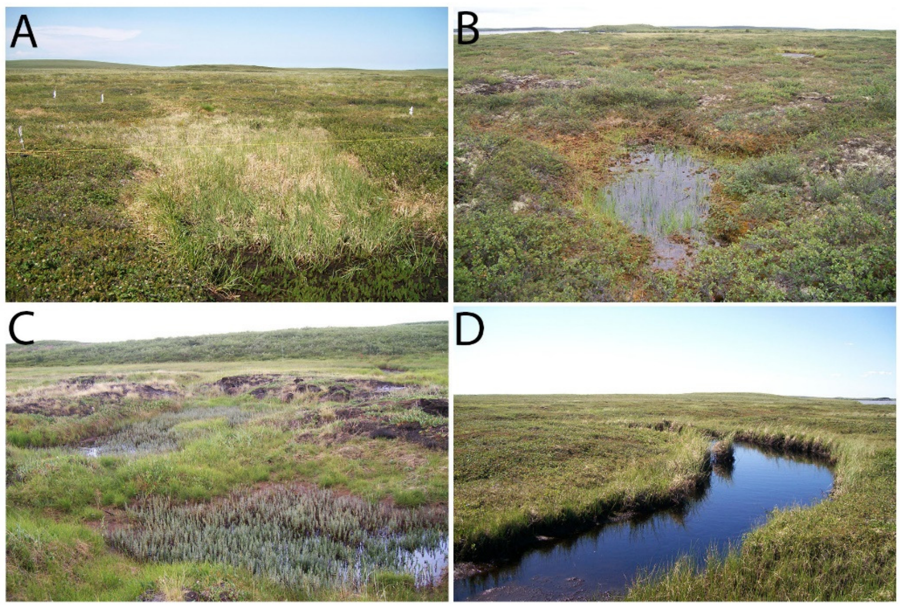


Figure 2-3. Photographs showing ice wedge troughs representative of the four degradation classes: a) mesic trough, b) wet trough, c) very wet trough, d) melt pond.

season and were standardized by adding a correction of 0.2 cm per day (Ovenden 1989) before September 15 of 2011 or 2012 to approximate maximum thaw depth. Water depth at each point was measured to the nearest centimetre using a ruler or tape measure, from the water surface to the top of sediments at pond bottom.

To characterize plant community composition along transects we visually estimated the cover of vascular plants inside 0.5 by 0.5m plots, by positioning quadrats over the centre, edge and trough of the selected polygon. Generally 3 to 4 plots were sampled along each transect to capture each of the three microtopographical positions. Percent cover was estimated for each species, with the exception of several genera (eg. *Salix, Carex*, *Sphagnum*) and two functional groups (non-*Sphagnum* moss, lichen).

To measure soil moisture, a composite sample of the active layer was collected at each vegetation plot using a trowel to collect soil from the top, middle and base of the soil profile. Wet and dry weights were measured in the laboratory to calculate gravimetric soil moisture on a wet weight basis ((weight of wet soil – weight of dry soil) / wet soil). Soil pH was measured by preparing a soil suspension with a 1:5 ratio of soil to distilled water. This mixture was stirred vigorously, and allowed to settle for 2 hours, before measuring the pH of the supernatant with an Oakton Model 510 pH metre (YSI Environmental 2006).

At each site, we also established a 10 by 10 m grid with 110 evenly spaced sample points covering an area of the polygonal field exhibiting varying stages of ice wedge degradation. At each point on this grid, the following variables were measured: a) the presence of all plant species/genera/functional groups at the point intercept, b) surface microtopography, c) active layer thickness, d) pond depth, and e) maximum vegetation height. At three randomly selected sampling points from each microtopographical position (centre, edge and trough), soil samples were collected and analyzed using the methods described above.

Late winter snow depth was measured at three sites in the Mackenzie Delta region uplands (Figure 2-2) in March 2007 and 2008. Measurements were taken using an avalanche probe pushed to base of the snow pack. At each site snow depth was measured at 2 to 6 polygon centres, edges and troughs. This sampling was conducted as a part of investigations of the frequency of ice wedge cracking (Kokelj et al. 2014).

Temperatures at the top of permafrost (T_p) were measured from August 2012 to August 2013 in polygon centres and ice-wedge troughs at two sites in the study area (Figure 2-3), in 3 of the four degradation classes (mesic, wet, pond) and polygon centres. Thermistors were attached to a PVC pipe installed into the permafrost (100 cm below the ground surface) using a water jet drill. Ground temperature measurements were made at two-hour intervals with thermistors (Onset Computing, HOBO™, TMC6-HD) connected to miniature data loggers (Onset Computing, HOBO™, U12-008). The temperature sensors had a range of –40 to 50 °C, an accuracy of ±0.25 °C and a precision of ±0.03 °C at 20°C. To calculate mean annual ground temperature, data from replicate thermistors were averaged (mesic (n=4), wet (n=4), pond (n=2), polygon centres (n=2)). For ground temperature time series, representative thermistors were analyzed. Freezeback duration was assessed as the period of time from September 15, 2012 to the date of the inflection point on the time series where a rapid decrease in temperature occurred.

Data analysis

To test for significant differences in biotic and abiotic factors among polygon micro-position and degradation class, we used SAS to run mixed effect models (Littell 2006). Mixed-effect models are particularly useful for unbalanced and spatially nested datasets collected in close spatial proximity along the same transect or at the same site (Buckley, Briese, and Rees 2003; Crawley 2007). In our models we treated micro-position and degradation class as fixed effects, and included random effects (site, or spatially nested site and transect). For snow depth data, the random effects (nested) were year and site. To assess the importance of random factors in our models for each biotic and abiotic variable, we tested their significance by removing terms one at a time, comparing the AICs of the models, and selecting the model with the lower AIC (Morrell 1998). Plant abundance data were grouped into the following functional groups: 1) tall shrubs (woody perennials greater than 1m tall), 2) dwarf shrubs (woody perennials less than 1 m tall), 3) forbs (non-woody flowering plants), 4) sedges (plants of the family Cyperaceae), 5) mosses, and 6) lichen. To meet the assumptions of normality and equal variance, functional group cover data were log transformed. To perform pairwise comparisons and identify significant differences among micro-position and degradation class, the LSMEANS procedure was used to conduct Tukey-Kramer adjusted multiple comparisons. To explore differences in plant community composition among micro-position and degradation class, we used PRIMER (version 6.1.10) to perform an NMDS ordination of a Bray-Curtis similarity matrix calculated from log transformed percent cover data. Each plot was used as a sample (n=319). ANOSIM (analysis of similarity) was used to test for significant differences in plant community composition among micro-position and degradation classes (Clarke 1993). SIMPER (similarity percentages) analysis was used to identify plant species that contributed most to the compositional similarities / dissimilarities of the microposition and degradation class (Clarke 1993). The “envfit” function in R was used to measure correlation of abiotic parameters with the NMDS ordination of plant community composition (Oksanen, Blanchet, and Roeland 2012).

Results

Abiotic factors

Differences in abiotic conditions were observed among degradation and microtopographical classes in high-centred polygonal terrain (Figure 2-4). Relative ground surface elevation decreased significantly from polygon centres through polygon edges and mesic ice wedge troughs (Figure 2-4a). Relative elevation among troughs also showed significant differences, with more degraded wedges exhibiting deeper troughs (Figure 2-5). The ground surface at troughs with ponds were more variable, but also had lower mean ground surface elevation than stable troughs. Maximum relief of high-centre polygons varied among sampling grids, with differences between maximum and minimum elevation ranging from 67.5 cm in an area with dry, shallow, less defined troughs (Figure 2-5A) to 107 cm in an area with wet, degraded troughs (Figure 2-5C).

Mean active layer thickness increased from polygon centres, towards edges and troughs with decreasing elevation of the terrain surface (Figure 2-4b). Active layers in the raised polygon centres were significantly shallower than all other micro-position and degradation classes. The mean active layer thickness beneath subsided areas with melt ponds was significantly greater than all other micro-position and degradation classes. Thaw depths among other microposition and degradation classes (edge, mesic trough, wet trough, very wet trough) were not significantly different from each other. Greater active layer thickness was also associated with subsided areas with high soil moisture and deep ponding. These relationships were also evident in the data obtained from in sampling grids (Figure 2-5). The thickest active

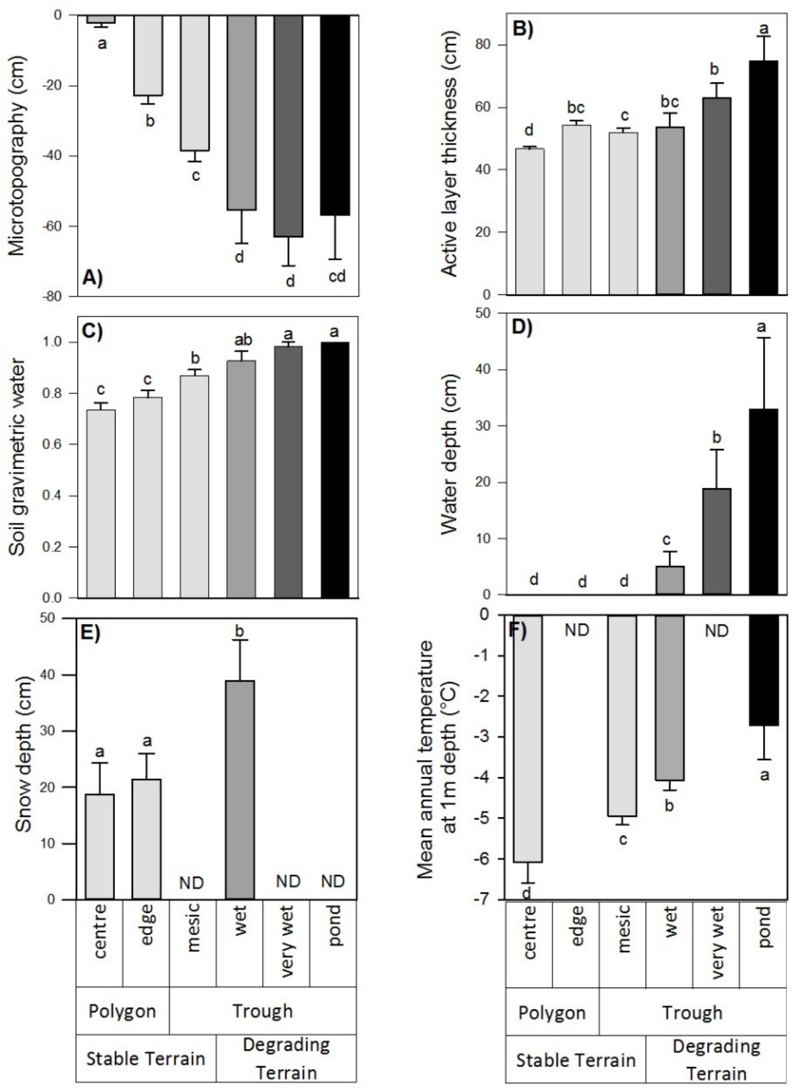


Figure 2-4. Abiotic variables measured in polygonal terrain, plotted by micro-position and degradation class. A) microtopography of the ground surface (cm), B) active layer thickness (cm), C) soil gravimetric water content, D) water depth (cm), E) snow depth (cm), and F) mean annual permafrost temperature 1m below ground surface (°C). The degradation class is shown on the x-axis progressing from driest to wettest (left to right). The microtopographical position is also indicated on the x-axis. Error bars show the 95% confidence intervals of the mean (untransformed). Bars with different letters are significantly different ($P < 0.05$, Tukey-Kramer multiple comparisons of least squares means).

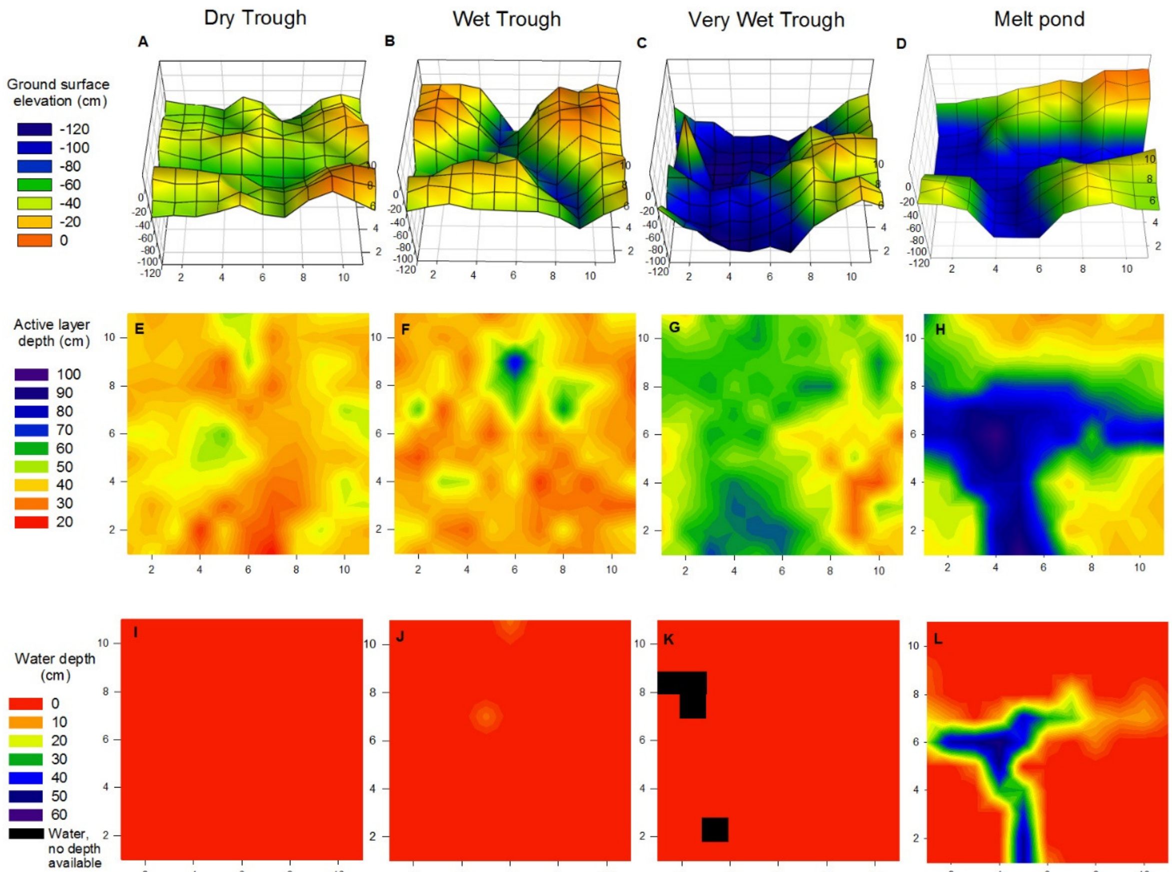


Figure 2-5. Sample grids showing typical examples of the four trough degradation classes. Grids from left to right are illustrative of: mesic troughs, wet troughs, very wet troughs, and melt ponds. Measurements were taken at 1m intervals within the grid, producing surface models of relative ground surface elevation (A-D), and contour models of active layer depth (E-H), and water depth (I-L). Water depth was not recorded at one location (K), only the presence or absence of water.

layers were generally measured within the trough in close proximity to areas of standing water, corresponding to lower relative elevation and higher soil moisture (Figure 2-5F-H). Beneath the drier stable troughs the permafrost table was often shallower than beneath the centres and edges, likely due to the close proximity wedge ice, and drier peat which has a low thawed thermal conductivity (Figure 2-5E). The dry site shown in Figure 2-5E also had the narrowest range of active layer depths within the grid (35 cm), whereas the largest range in active layer (65 cm) occurred at the melt pond grid with open standing water (Figure 2-5H).

Soil gravimetric water content increased from polygon centres through to edges and troughs (Figure 2-4c). Soil moisture at centre and edge were not significantly different, but all trough degradation classes had significantly higher soil moisture than centres and edges (Figure 2-4c). Water depth also increased significantly with degradation class (Figure 2-4d). Where water was present, it was shallowest in wet, densely vegetated troughs, and deepest but most variable in ponds. The melt pond degradation class was characterized by unvegetated standing water. The occurrence of deep standing water (ex. 55 cm in the sampling grid exemplifying the melt pond degradation class (Figure 2-5L)) was associated with deeper thaw and a subsided terrain surface overlying the degrading ice wedge (Figure 2-5D, H, L). At sites that lacked standing water (Figure 2-5I) or had small areas of vegetated, shallow standing water (Figure 2-5J), the spatial patterns of active layer depth and water depth did not strongly reflect the trough microtopography. This may result from the more ephemeral nature of shallow water, or from latent heat effects associated with shallow water that are not sufficient to promote strong positive feedbacks. Micro-relief was less-pronounced in these sites, and the trough depression (Figure 2-5A, B) was not reflected in the gridded active layer data (Figure 2-5E, F).

Mean snow depth increased from polygon centres towards edges and troughs (Figure 2-4e). Snow depth in troughs was significantly greater than on centres and edges, which were not significantly different from one another (Figure 2-4e).

Mean annual temperatures at the top of permafrost (T_p) and the timing of freezeback varied significantly among microtopographical position and degradation class (Figure 2-6). Mean annual temperatures at the top of permafrost (Figure 2-4f) increased across micro-position and degradation classes (Figure 2-4f), with the lowest temperatures at polygon centres (-6.1°C), and highest in melt ponds (-2.7°C). At Jimmy Lake, polygon centres reached a minimum average temperature of -12.5°C, with mesic troughs and wet troughs reaching an average temperature of approximately -10.9°C. At the Tuktoyaktuk site, polygon centres reached a minimum average temperature of -15.0°C, with wet troughs averaging -11.7°C, and melt ponds -9.6°C. In spring 2013, all microposition / degradation class T_p converged to a temperature between -1 and -2°C towards the end of May. The time series of shallow ground temperature showed that the timing of freezeback was delayed by 18-50 days in wet troughs and melt ponds, compared to mesic troughs. At both Jimmy Lake and Tuktoyaktuk, freezeback occurred first at polygon centres after 86 days (December 9, 2013). Freezeback in mesic troughs at Jimmy Lake occurred after 96 days, followed by wet troughs at both locations after about 114 days. Freezeback below melt ponds at the Tuktoyaktuk site occurred after approximately 146 days (February 8, 2013).

Plant functional group cover

Significant differences in plant functional group abundance were observed among polygon microposition and degradation classes (Figure 2-7). The abundance of most functional

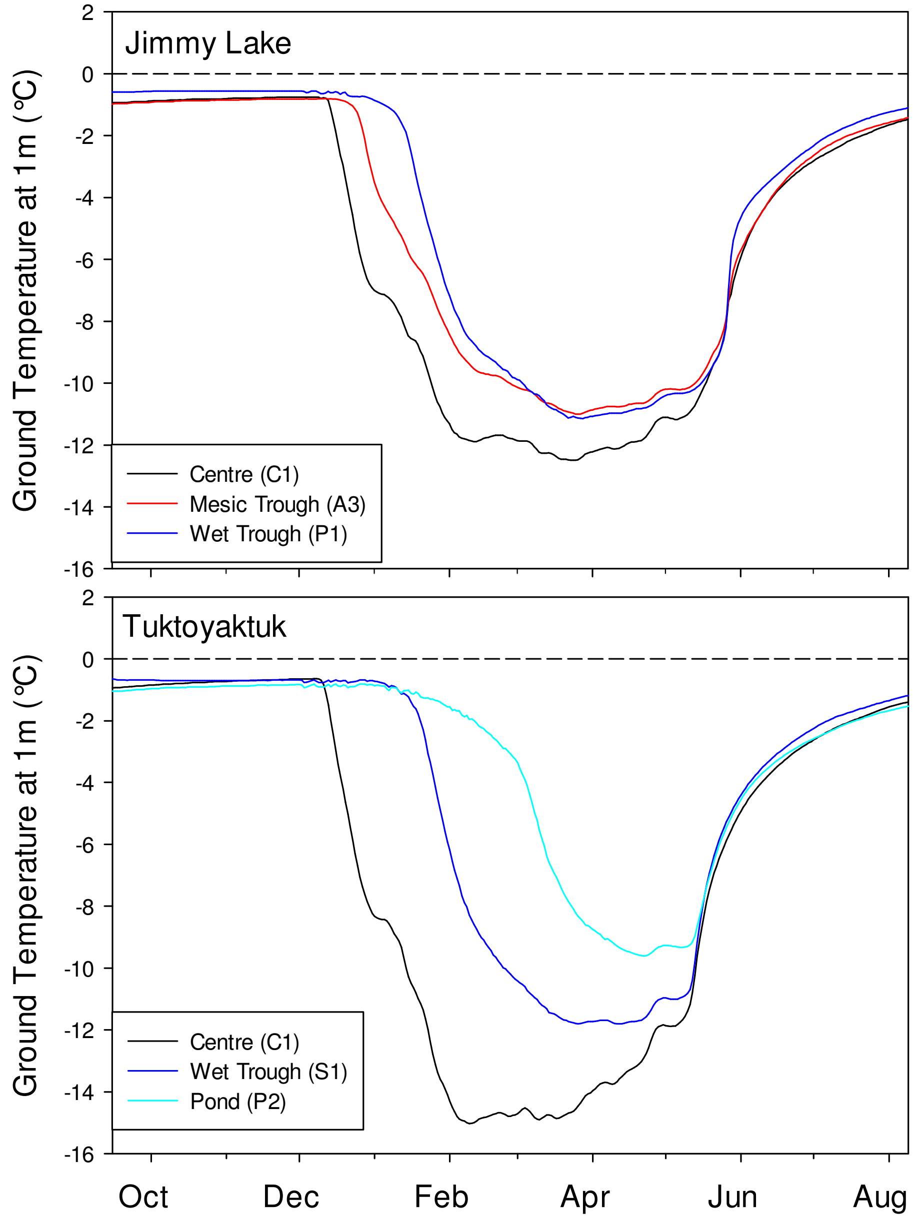


Figure 2-6. Temperatures at the top of permafrost (T_p) (1 metre depth) at Jimmy Lake (top) in a polygon centre, mesic trough and wet trough, and at Tuktoyaktuk (bottom) in a polygon centre, wet trough and melt pond. Line shows the daily mean temperatures. Ground temperatures were measured from October 2012 to August 2013.

groups decreased from higher to lower microposition, associated with increasing soil moisture and a deeper active layer. Most functional groups (tall shrubs, dwarf shrubs, forbs and lichen) and litter also had decreased cover with more advanced degradation class, associated with thicker active layers and lower lying surfaces with saturated soils or ponding. Although these trends were consistent among functional groups, many of the comparisons were not significant (Figure 2-7). Notable patterns across the microtopographical and degradation gradients include: 1) higher abundance of lichen at polygon centres (Figure 2-7E), 2) increased dwarf shrub and forb cover at polygon centres and edges (Figure 2-7B and 7C), and 3) increased cover of tall shrubs and litter at polygon edges (Figure 2-7A and 7G). The abundance of hydrophilic functional groups (sedges and moss) and bare peat increased from centre to trough, with increasing soil moisture. These functional groups also had decreased cover at more advanced degradation classes (Figures 2-7D, 7F, 7H), in association with greater ponding.

Plant community composition

Plant community composition varied significantly among microposition and trough degradation classes, and was correlated with strong abiotic gradients (soil moisture, active layer thickness, ground surface elevation, and pond depth) (Table 2-1). More than forty species of vascular plants were recorded in high-centre polygons (Table 2-2). The NMDS ordination (Figure 2-8) shows a clear separation of sites along the environmental gradients ranging from elevated (dry) polygon centres to subsided water filled troughs. Centres and mesic trough plots had overlapping but distinguishable community composition (R_{ANOSIM} = 0.443, Table 2-3), where community dissimilarity (66.5%) was driven by a greater abundance of lichen

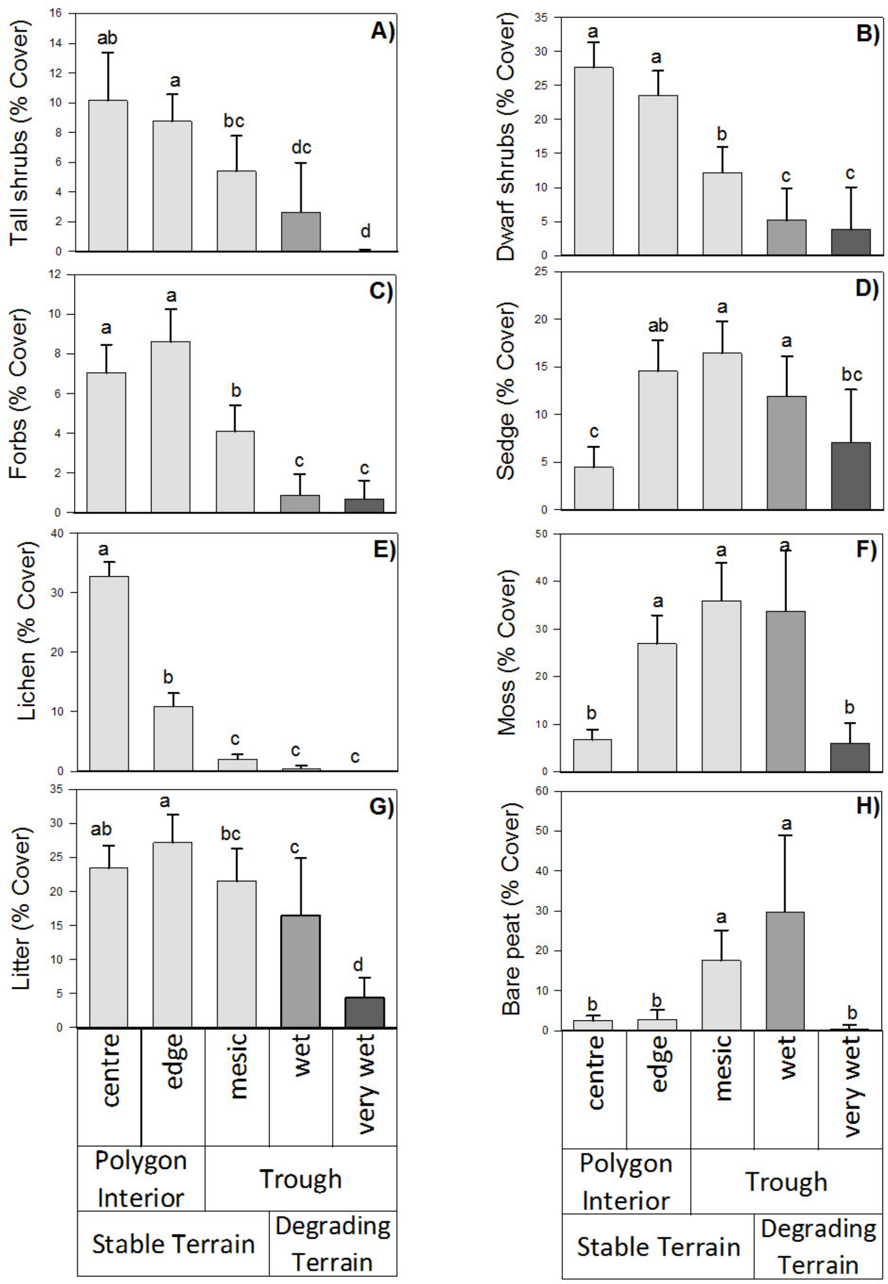


Figure 2-7: Biotic variables measured in polygonal terrain, plotted by degradation class and micro-position. Plots show percent cover of A) tall shrubs, B) dwarf shrubs, C) forbs, D) sedge, E) lichen, F) moss, G) litter, and H) bare peat. The degradation class is shown on the x-axis progressing from driest to wettest (left to right). The microtopographical position is also indicated on the x-axis. Error bars show the 95% confidence intervals of the mean (untransformed). Bars with different letters are significantly different (P < 0.05, Tukey-Kramer multiple comparisons of least squares means.

Table 2-1. Goodness of fit statistic (r^2) and p-values from envfit procedure performed in R to measure correlation of abiotic parameters with NMDS ordination of plant community composition.

Parameter	r^2	p-Value
Soil moisture	0.1178	0.0002
Active layer depth	0.1177	0.0002
Ground surface height	0.1231	0.0003
Water depth	0.2683	0.0001

Table 2-2. A partial list of vascular plants recorded in high-centre polygons, and their functional group.

Vascular Plant	Functional Group
Alnus viridis	tall shrub
Andromeda polifolia	dwarf shrub
Arctostaphylos alpina	dwarf shrub
Artemisia sp	dwarf shrub
Betula glandulosa	tall shrub
Callitriche sp	forb
Carex aquatilis	sedge
Carex physcocarpa	sedge
Carex lugens	sedge
Cassiope tetrandum	dwarf shrub
Chamaedaphne calyculata	dwarf shrub
Dryas octopetala	dwarf shrub
Empetrum nigrum	dwarf shrub
Epilobium angustifolium	forb
Epilobium palustre	forb
Eriophorum angustifolium	sedge
Eriophorum vaginatum	sedge
Hippuris tetraphylla	forb
Hippuris vulgaris	forb
Ledum decumbens	dwarf shrub
Myrica gale	dwarf shrub
Oxycoccus microcarpus	dwarf shrub
Pedicularis sp	forb
Petasites frigidus	forb
Picea glauca	coniferous tree
Pinguicula villosa	forb
Potentilla anserina	forb
Potetilla palustris	dwarf shrub
Pyrola chlorantha	forb
Ranunculus aquatilis	forb
Ranunculus hyperboreus	forb
Rubus chamaemorus	forb
Salix maccalliana	tall shrub
Salix glandulosa	tall shrub
Stellaria sp	forb
Tofieldia glutinosa	forb
Vaccinium uliginosum	dwarf shrub
Vaccinium vitis-idaea	dwarf shrub

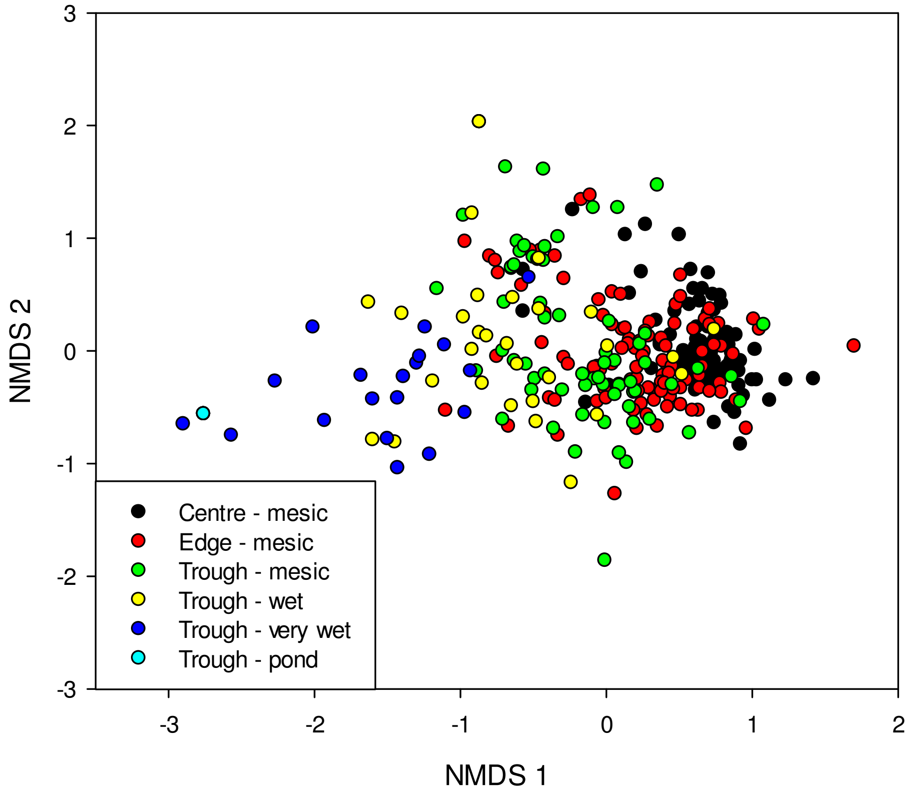


Figure 2-8: NMDS ordination plot of plant community composition in polygonal terrain. Each symbol shows the NMDS scores for a 0.25 m^2 vegetation plot on the first and second axes (n=319). Plots are grouped by microtopographical position and degradation class.

and *Ledum decumbens* on polygon centres, and a greater abundance of *Carex* and *Sphagnum* species in dry troughs (Table 2-4). Dry troughs had the lowest within-class similarity in community composition (36.92%, Table 2-5).

The community composition of the three vegetated trough classes were increasingly distinct from polygon centres along the degradation gradient. Trough classes associated with decreasing microtopography and increasing soil moisture, showed visible differences from centres and edges on the NMDS ordination (Figure 2-8). Very wet troughs were distinct (90.6% dissimilarity) from polygon centres (R_{ANOSIM} = 0.951), due to the greater abundance of water in the trough class, and the greater abundance of lichen, litter, and *Ledum decumbens* in polygon centres (Table 2-4). Wet densely vegetated troughs had overlapping but distinguishable community composition (R_{ANOSIM} = 0.678), and dissimilarity (72.7%) was driven by a greater abundance of lichen in polygon centres, followed by a greater abundance of water and bare peat in the trough class (Table 2-4). Wet, densely vegetated troughs had lower within group similarity, but were characterized by an assemblage of litter, water, *Carex* species, and bare peat (Table 2-5).

The largest difference in community composition among micro-position and degradation classes occurred between polygon centres and standing water troughs. Ponded troughs represent an advanced stage of ice-wedge degradation. The large difference between polygon centres and ponded troughs represents the two end-members along a moisture gradient in the NMDS ordination (Figure 2-8), characterized by a

Table 2-3. R_{ANOSIM} statistic for pairwise comparisons of the similarity in plant community composition among micro-position and degradation classes. R_{ANOSIM} values >0.75 indicate well separated groups, values between 0.5 and 0.75 describe overlapping but distinguishable groups, and values <0.25 represent groups that cannot be separated (Clarke and Gorley 2001). R_{ANOSIM} values >0.5 are followed by an asterisk.

	Trough - pond	**Trough - very wet**	**Trough - wet**	**Trough - mesic**	**Edge - mesic**
Centre-mesic	0.995*	0.951*	0.678*	0.443	0.137
Edge – mesic	0.988*	0.843*	0.431	0.16	
Trough - mesic	0.913*	0.596*	0.127		
Trough - wet	0.482	0.326			
Trough – very wet	-0.216				

Table 2-4: Results of the SIMPER analysis comparing plant community composition at six micro-topographic and degradation classes. The table shows the top four species (or species groups) that make the greatest contribution to the between-group Bray-Curtis dissimilarity for comparisons of interest. The mean cover (untransformed) of each species at the site types being compared is shown in the third and fourth columns. The last column shows cumulative dissimilarity associated with the species listed. Only comparisons with R_{ANOSIM} greater than 0.4 (Table 2-3) are included.

Sitetype 1	Sitetype 2	Species / Group	% Cover Sitetype 1	% Cover Sitetype 2	Dissimilarity (%)
Centre – mesic	Trough – pond	Water	1.0	100.0	21.45
		Lichen	18.5	1.0	34.73
		Litter	17.3	1.0	47.78
Total Dissimilarity	100	*Ledum decumbens*	7.5	1.0	56.83
Edge – mesic	Trough – pond	Water	1.0	100.0	20.49
		Litter	19.1	1.0	33.34
		Carex spp	5.1	1.0	40.64
Total Dissimilarity	100	*Ledum decumbens*	5.4	1.0	47.85
Trough – pond	Trough – mesic	Water	100.0	1.0	25.44
		Litter	1.0	11.7	38.18
		Carex spp	1.0	7.7	48.83
Total Dissimilarity	100	*Sphagnum* spp	1.0	6.7	57.7
Centre – mesic	Trough – very wet	Water	1.0	62.8	17.98
		Lichen	18.5	1.0	30.38
		Litter	17.3	3.0	39.55
Total Dissimilarity	90.6	*Ledum decumbens*	7.5	1.0	48.01
Edge – mesic	Trough – very wet	Water	1.0	62.8	18.02
		Litter	19.1	3.0	27.51
		Ledum decumbens	5.4	1.0	34.59
Total Dissimilarity	86.7	*Sphagnum* spp	4.3	2.6	41.64
Trough – very wet	Trough - mesic	Water	62.8	1.0	22.03
		Litter	3.0	11.7	32.26
		Sphagnum spp	2.6	6.7	41.79
Total Dissimilarity	84.7	*Carex* spp	2.0	7.7	50.95
Trough – wet	Trough - pond	Water	7.9	100.0	18.18
		Litter	9.6	1.0	32.29
		Bare peat	5.6	1.0	45.57
Total Dissimilarity	78.22	*Carex* spp	4.5	1.0	55.83
Centre – mesic	Trough – wet	Lichen	18.5	1.4	11.77
		Water	1.0	7.9	20.72
		Bare peat	1.6	5.6	28.99
Total Dissimilarity	72.7	*Ledum decumbens*	7.5	1.8	36.48
Edge – mesic	Trough – wet	Water	1.0	7.9	9.17
		Bare peat	1.3	5.6	17.56
		Sphagnum spp	4.3	4.2	25.63
Total Dissimilarity	68.5	Moss	3.5	4.3	32.95
Centre – mesic	Trough - mesic	Lichen	18.5	1.6	12.74
		Carex spp	1.8	7.7	21.47
		Sphagnum spp	1.1	6.7	29.87
Total Dissimilarity	66.5	*Ledum decumbens*	7.5	2.5	37.63

Table 2-5. Results of the SIMPER analysis characterizing plant community composition at six micro-position and degradation classes. The table shows the top four species (or species groups) that make the greatest contribution to the within-group Bray-Curtis similarity. The mean cover (untransformed) of each species is shown in the third column. The last column shows cumulative similarity associated with the species listed.

Class	Species / Group	% Cover	Similarity (%)
Centre – mesic	Litter	17.3	24.23
	Lichen	18.5	46.5
	Ledum decumbens	7.5	60.44
Percent similarity: 55.09	*Vaccinium vitis-idaea*	6.1	72.81
Edge – mesic	Litter	19.1	27.49
	Ledum decumbens	5.4	38.82
	Rubus chamaemorus	5.0	48.66
Percent similarity: 46.46	*Vaccinium vitis-idaea*	4.5	58.4
Trough - mesic	Litter	11.7	30.56
	Carex spp	7.7	53.82
	Sphagnum spp	6.7	67.12
Percent similarity: 36.92	Bare peat	2.6	73.2
Trough – wet	Litter	9.6	24.23
	Water	7.9	44.76
	Carex spp	4.5	58.63
Percent similarity: 38.16	Bare peat	5.6	71.68
Trough –very wet	Water	62.8	84.1
Percent similarity: 53.18	Litter	3.0	91.01
Trough – pond Percent similarity: 100	Water	100.0	100

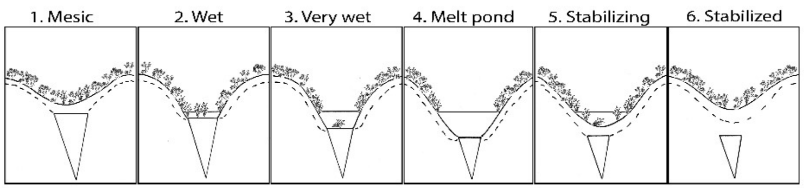
R_{ANOSIM} value of 0.995 (Table 2-2), which indicates almost non-overlapping groups. The largest contributor to this high dissimilarity was the complete water coverage for the trough class, and the absence of standing water from polygon centres (Table 2-4).

Results of the SIMPER analysis indicated that a small number of species, groups and cover classes contributed to dissimilarity between micro-position and degradation classes (Table 2-4) and similarity within each class (Table 2-5). The most important indicator species, groups, and cover classes were water, lichen, *Ledum decumbens*, *Carex, Sphagnum,* bare peat and litter. Polygon centres had the most homogeneous plant community composition of the vegetated classes with 55.1% similarity (Table 2-5), and were characterized by cover from litter, lichen, *Ledum decumbens, Vaccinium vitis-idaea, Rubus chamaemorus*, *Betula glandulosum*, and moss.

Discussion

Abiotic and biotic characteristics of stable high-centre polygons

Our field observations are consistent with the idea that topographic variation is a key determinant of biotic and abiotic conditions in high-centered polygonal terrain. Low lying polygon troughs had increased snow pack and soil moisture, deeper active layers, elevated ground temperatures, delayed freezeback and distinct (hydrophilic) plant community composition, whereas elevated polygon centres had low snow pack and soil moisture, a shallower active layer, lower minimum ground temperatures, earlier freezeback, and distinct mesic vegetation communities (Figure 2-9). These observations are also consistent with gradients anecdotally reported in the literature for high-centre polygons (Peterson and Billings 1978; Peterson and Billings 1980) and quantitatively for



	1. Mesic	2. Wet	3. Very wet	4. Melt pond	5. Stabilizing	6. Stabilized
Microtopography	Increasing micro-relief due to increasing subsidence ⟶				Higher micro-relief from accumulation of organic matter ⟶	
Active Layer	Increasing thaw depth ⟶				Decreasing thaw depth	
Surface water	None	Shallow water	Deeper water	Melt pond	Shallow water	None
Vegetation	Moist upland tundra vegetation	Hydrophilic species like *Carex* spp become more abundant	Sparse emergent vegetation, may have aquatic species	Unvegetated	Hydrophilic species like *Carex* spp become more abundant	Moist upland tundra vegetation
Snow pack	Increasing depth due to increasing micro-relief ⟶				Decreasing depth ⟶	
Ground temperatures	Increasing freezeback duration and MAGT ⟶				Earlier freezeback and decreasing minimum ground temperature ⟶	

Figure 2-9: Conceptual model of the key changes in biotic and abiotic conditions that are associated with ice wedge degradation. Stage 1 represents conditions in stable troughs. Stages 2-4 represent increasing ice wedge degradation resulting from positive feedbacks, based on this study. Stages 5-6 represent stabilization associated with positive feedbacks (Jorgenson et al 2006). The base of the active layer is represented by a dashed line. Key processes and changes are outlined below the diagram.

low-centre polygons (Minke et al. 2009; Zibulski et al. 2013; Donner 2007). Low magnitude topographic variation in permafrost environments exerts the major control over surface hydrology and soil moisture, and has strong influence on the active layer thickness, at a range of scales (Nelson et al. 1998). Recent fieldwork in low-centre polygons identified a correlation between lower relative elevation in troughs, and the increase in soil moisture and active layer depth (Minke et al. 2009). Moist organic soils have a high thermal conductivity compared to other soil types because of their high porosity, and the high heat capacity and thermal conductivity of water. As a result, low lying wet areas have enhanced thaw and deeper active layers (Nelson et al. 1998; Kokelj et al. 2014). Snow accumulation in troughs also slows ground heat loss in winter causing winter minimum T_p to be higher than in adjacent polygons. This is also consistent with other observations that variability in snow depth depends on microrelief (Smith 1975; Mackay 1993; Zhang 2005). The insulating properties of a thicker snowpack, higher soil moisture, and increased latent heat content also resulted in higher near-surface permafrost temperatures in troughs (Figure 2-6A).

The soil moisture gradient associated with microtopography was clearly the primary determinant of differences in plant functional group abundance and community composition. The species that were characteristic of trough community composition generally have a greater tolerance for saturated soil and standing water (Porsild and Cody 1980; Hauser 2006). The relationships between polygon microtopography, soil moisture and plant community composition have also been noted in high- and low-centre polygons across the circumpolar arctic (Eisner and Peterson 1998; Vardy, Warner, and

Aravena 1997; Peterson and Billings 1978; Peterson and Billings 1980; Minke et al. 2009; Zibulski et al. 2013; Donner 2007).

Abiotic and biotic characteristics and feedbacks in degrading high-centre polygons

Our field data show that the conditions created by ice wedge degradation reinforce feedbacks among topographic position, soil conditions, and vegetation, and influence ecological trajectories in this terrain type (Figure 2-9, panels 2-4). Seasonal heat flux, or the energy balance in the near surface of the ground as it relates to seasonal thawing and freezing of the active layer, is one of the key processes impacted by these changes. Seasonal heat flux is strongly influenced by the water content of soil, particularly the large amount of latent heat available in moist soils when freezing occurs (Kane et al. 2001). Ice wedge degradation was the result of changes to seasonal heat flux, as evidenced by higher ground temperatures and delayed freezeback in moist and waterlogged soils (Figure 2-5). An increase in soil moisture resulting from ice wedge thaw and drainage from surrounding polygons, and the deeper snow pack resulting from trough subsidence are key contributors to a longer duration for active layer freezeback and warming permafrost in ice wedge troughs. Increasing soil moisture and snow pack influence ground thermal conditions in degrading troughs in several ways. During the summer, soil saturation can result in a deeper active layer because of the high heat capacity of water and thermal conductivity of saturated organic soils relative to dry organic soils (Hinzman et al. 1991). Melt ponds are effective heat sinks due to the high heat capacity of water, and may accelerate convective heat flow in summer. During the winter, our data show that increased soil moisture in degrading troughs is associated with a prolonged zero-curtain effect, as the release of the latent heat of fusion in saturated soil maintains permafrost temperatures close to 0°C and delays freezeback (Hinkel et al. 2001; Outcalt, Nelson, and Hinkel 1990; Kokelj et al. 2014). The longer duration for freezeback decreases the amount of time for conductive heat loss. These changes create a positive feedback for increases in ground temperature, with an increase in active layer thickness promoting further degradation of ice wedges, subsidence and ponding.

Snow depth is one of the primary factors influencing ground thermal regime in cold regions (Zhang 2005) because increasing snow pack decouples air and ground surface temperatures in winter and contributes to delayed freezeback. Subsidence of the ice wedge trough can promote snow accumulation above degrading ice wedges. In conjunction with soil moisture, an increase in snow thickness contributes to the thermal disturbance that drives ice wedge degradation (Figure 2-4E). Our observations are consistent with other studies showing similar relationships between microrelief, deeper snowpack and subsidence (Smith 1975; Sturm and Holmgren 1994; Kokelj et al. 2014). Up to an optimal depth of about 40 cm, increasing snow pack acts as a heat sink for the underlying ground because of its low thermal conductivity and high latent heat from melting, with each 5-15 cm of snow resulting in an average 1°C increase in mean annual ground temperature (Zhang 2005). Mean trough snow depth (38.9 cm) exceeded average polygon centre snow depth by 20 cm, likely contributing to warmer annual ground temperature at the ground surface, and the deeper active layer and observed subsidence. Unpublished data collected at our sites (Kokelj and Lantz) also show that more subsided troughs hold a deeper snowpack, also contributing positive feedbacks for further ice wedge degradation.

Our field data are also supported by recent thermal modelling of the effects of increasing soil moisture and snow pack in organic soils in both warm and cold permafrost (Kokelj et al. 2014). Modelling demonstrated that saturation of the active layer and doubling of the snow pack were associated with an increase in the duration of active layer freezeback and higher ground temperatures (Kokelj et al. 2014), relationships which were both evident in the field data, where related increases in moisture and snow depth in troughs modified ground thermal conditions.

Our observations are also consistent with the conceptual model proposed by Jorgenson et al. (2006) that shows the accumulation of water in degrading ice wedge troughs increases ground temperatures and promotes further degradation. The negative correlations between ground surface elevation and active layer thickness and moisture reported here have also been observed in low-centre polygonal terrain (Minke et al. 2009; Donner 2007; Zibulski et al. 2013). The thermal sensitivity of organic soils to the effects of increasing soil moisture and snow depth may have important implications for the ecological trajectory of high-centre polygonal terrain. Under conditions of increasing air temperature and snow accumulation, terrain with saturated organic soil will be the most sensitive to permafrost degradation (Kokelj et al. 2014). In warm permafrost settings, a saturated active layer and deep snow pack has been found to prevent freezeback, with unfrozen saturated soil persisting throughout the winter, both in the field and in thermal modelling (Kokelj et al. 2014).

Abiotic conditions altered by ice wedge degradation strongly influenced trough vegetation communities. As soil moisture increased, hydrophilic species such as sedges and sphagnum moss became more abundant. Degradation was also accompanied by the replacement of vegetated ground cover with water, the replacement of less water-tolerant functional groups with those that are more hydrophilic, and the development of water-logged bare peat. The loss of upland tundra vegetation as a result of ice wedge degradation and the development of water-logged troughs likely also acts as a feedback to the process of ice wedge degradation because the ground cover characteristics of tundra communities influence surface albedo and impact ground thermal conditions (Loranty, Goetz, and Beck 2011). The albedo of water is significantly lower than tundra vegetation (Weller and Holmgren 1974), and the loss of tundra vegetation to standing water associated with ice wedge degradation may contribute to positive feedbacks. However, albedo-related affects are likely secondary relative to the influence of water and snow depth on freezeback.

Ecological trajectories of degrading ice wedge polygons

The long-term ecological trajectories of degrading ice wedges have not been well characterized. Over longer time scales, vegetation succession, peat development and a lowering of the water table are thought to increase thermal stability by creating an increasingly thick and elevated layer of insulating organic material above the ice wedge, protecting it from further heat gain (Jorgenson, Shur, and Pullman 2006). The initial stages of revegetation have been described for shallow ponds in thermokarst lake basins. These sites are first colonized by productive fen vegetation, such as grasses and *Eriophorum* spp., which is then succeeded by *Carex aquatilis* dominated communities, later replaced by ericaceous shrubs and birch (Jones et al. 2012). Similar sequences of vegetation establishment have been described in paleoecological studies of the development and dynamics of ice wedge polygon fields (de Klerk et al 2011). This successional trajectory is central to the process of terrestrialization and peatland development in drained thermokarst lake basins and shallow thermokarst ponds (Jones et al. 2012; Payette et al. 2004), and may also play a role in melt pond stabilization.

Data on litter abundance from this study suggest that the accumulation of vegetation and organic matter (Figure 2-9, panels 5-6) may drive negative feedbacks that prevent further increases in ground temperature and limit ice wedge degradation. Similar processes have also been identified in other forms of thermokarst in ice-rich terrain (Kokelj and Jorgenson 2013; Jorgenson, Shur, and Pullman 2006). Pairwise comparisons of degrading trough classes showed that litter was generally more abundant in the drier class, suggesting that its accumulation over time in stabilizing troughs may be an important driver of this process. In addition, the three vegetated trough classes (mesic troughs, wet troughs, and very wet troughs) had relatively low within class similarity in plant community composition (37-53%). This low similarity in plant community composition suggests that these sites are a mix of successional stages that reflect the continuum of abiotic conditions across the ice wedge degradation sequence. It is possible that the abiotic and biotic conditions characterizing mesic troughs are representative of the stable state that will be reached by currently degrading ice wedge troughs, as their community composition is similar to the successional endpoint that has been described for the terrestrialization of shallow ponds.

Changes in the thermal regime brought about by revegetation or lowering of the water table could potentially allow permafrost to aggrade, buffering against further degradation. Jorgenson et al. (2006) observed ground ice indicative of permafrost aggradation over ice wedges that had previously undergone degradation and stabilization, and aggrading permafrost above the ice wedge was a characteristic of advanced stabilization in their ice-wedge degradation classification.

Subregional biophysical differences in climate, frequency of thermal contraction cracking, and ice wedge size have contributed to variation in the process of ice wedge degradation and stabilization at north and south ends of the study area. At the northern field sampling sites (Tuktoyaktuk), wedge ice in mesic troughs was encountered just below the permafrost table. This implies that previous thaw was arrested prior to the development of a melt pond, possibly due to a colder permafrost setting, or cooling effects from adjacent polygon centres. At more southern sites (Jimmy Lake), several mesic troughs that were evaluated were underlain by truncated wedges. This indicates that the ice wedge had previously undergone more advanced thaw, but the processes of degradation and stabilization that occurred are unclear. For example, a melt pond may have developed that was later infilled with organic material, or improved drainage directed surface water out of the trough. Alternatively, peat accumulation and collapse may have filled the trough at the same time as wedge degradation. Because polygonal peatlands typically occur in flat areas, subtle differences in topography resulting from heave or subsidence may have a profound effect on drainage. Feedbacks influencing site hydrology and ecosystem processes are associated with a high degree of variability in the rate and magnitude of the development of other types of thermokarst disturbances (Kokelj and Jorgenson 2013). However, evidence of spatial variation in the distribution of melt ponds, and in the change in melt pond area in recent decades suggests that in addition to fine-scale processes, subregional biophysical differences that influence ice wedge size and depth also influence melt pond dynamics.

The time scale required for thermal stabilization and terrestrialization of melt ponds is unclear. On decadal scales, ecological processes that drive positive feedbacks and promote further ice wedge degradation may predominate in some parts of our study area. Melt ponds north of 69.4°N in the uplands showed the most dynamic changes in area, including large increases in area in recent decades (Chapter 3). The consequences of further ice wedge degradation would likely include deeper thermokarst troughs with more surface water, the formation of interconnected networks of melt ponds (Negandhi et al. 2013), and depending on site-specific hydrological conditions, the formation of gullies along ice wedge troughs through the process of thermal erosion (Fortier, Allard, and Shur 2007). The regional spatial pattern described in Chapter 3 of this thesis suggests that large melt ponds are not likely to persist over longer time scales (centuries), or develop in a cyclical manner with repeated cycles of degradation, melt pond development and stabilization. In high-centre polygons in the south of the study area that have undergone more advanced past degradation, and have a thicker organic layer overlying the wedge, melt ponds are less abundant and less dynamic in response to recent warming. This suggests that if melt ponds developed previously, they have generally not persisted on a century time-scale, and that previously degraded ice wedges are less susceptible to thaw under current climate conditions due to an insulating organic layer.

However, the long term trajectory of individual ice wedge melt ponds has not been studied at any scale, and further work is necessary to understand the feedbacks that influence ice wedge degradation. Given the range of possible trajectories following ice wedge degradation, additional monitoring is necessary to elucidate the processes and feedbacks that are involved.

Implications for environmental change

High-centre polygonal terrain is a form of patterned ground in which fine-scale variation in biotic and abiotic conditions is repeated across the landscape. Other examples of patterned ground include earth hummocks (Kokelj, Burn, and Tarnocai 2007), and sorted and unsorted circles (Walker et al. 2011). Patterned ground features in permafrost environments create strong, small scale heterogeneity in biotic and abiotic characteristics. Ice wedge degradation and the resultant ecological feedbacks can alter the relative proportion of different physical and biological elements that characterize these repeating units, which on a landscape scale may impact tundra ecological processes. Understanding the formation and dynamics of the repeating microenvironments associated with patterned ground and their impact on soil carbon, water, and nutrient dynamics requires additional study (Walker et al. 2011).

Increased ice wedge degradation is expected to occur with increasing air and ground temperatures across the circumpolar Arctic, as is the rate and magnitude of thermokarst disturbances in general (Kokelj and Jorgenson 2013). Over the past thirty years (1972-2004), the northernmost portion of the study area has shown a net increase in melt pond area, resulting from a combination of increases and decreases in melt pond area within individual polygon fields (Chapter 3). The field data presented here indicates that this increase in the proportion of melt ponds has likely been accompanied by broad scale ecological change. For example, changes in the distribution of surface water and vegetation composition associated with ice wedge degradation will likely impact the quality and availability of wildlife habitat. The habitat heterogeneity of degrading polygonal terrain has been found to be favourable for some waterfowl species, and the expansion of melt ponds, increased biomass of aquatic invertebrates and plants, and potential increase primary and secondary productivity, could benefit many bird species (Martin et al 2008). Our field data also suggest that terrestrial productivity is decreasing in troughs as conditions become increasingly waterlogged and vegetation cover is replaced by standing water. However, this may be counteracted by increased productivity in polygon centres from shrub proliferation (Fraser et al. 2014). Overall, the long-term effects and magnitude of habitat change due to ice wedge degradation are unclear, as are effects on birds and terrestrial mammals. Changes in arctic vegetation communities, particularly decreases in the availability of lichen which may result from ice wedge thermokarst and other climate-driven changes in moisture, could impact the quality of caribou habitat (Joly, Jandt, and Klein 2009). As with other forms of permafrost thaw, ice wedge degradation will influence soil carbon dynamics with the potential for feedbacks to the global climate system (Kokelj and Jorgenson 2013).

Conclusion

Physical changes resulting from thermokarst processes in ice wedge troughs drive ecological change. Our data are consistent with the notion that variation in microtopography is the primary control of biotic and abiotic conditions in stable high-centered polygonal terrain, and that soil moisture gradients associated with microtopography were the primary determinant of differences in plant functional group abundance and community composition. Conditions created by ice wedge development and degradation drive feedbacks among topographic position, soil conditions, and vegetation and are likely to influence ecological trajectories in this terrain type. Ice wedge degradation increases soil moisture in troughs, promoting positive feedbacks to potentially further ice wedge degradation by increasing latent heat content in saturated peat and by decreasing ground heat flux in winter through greater snow accumulation in subsided troughs. Processes contributing to positive feedbacks include increasing depth of active layer thaw, trough subsidence, increasing depth of standing water, an increasing depth of snow pack. These physical changes altered trough vegetation, with degradation resulting in the replacement of vegetated ground cover with water, the replacement of less water-tolerant functional groups with those that are more hydrophilic, and the development of water-logged bare peat. The loss of upland tundra vegetation to water also contributes to positive feedbacks due to albedo-related thermal effects. Although increased ice wedge degradation is expected to occur with increasing air and ground temperatures both in the Mackenzie Delta region uplands and across the circumpolar Arctic, it is likely that vegetation development or changes in hydrology may punctuate degradation with periods of stabilization. Additional research is needed to characterize the long-term thermal and ecological trajectories of melt ponds and degrading ice wedges.

Chapter 3 – Spatiotemporal variation in high-centre polygons and ice wedge melt ponds in the uplands of the Mackenzie Delta region, Northwest Territories.

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4. AES and TCL conceived the study; AES, SVK, and TCL collected the data; AES analyzed the data; AES, SVK, and TCL wrote the manuscript.

Introduction

Recent increases in air temperatures at high latitudes will alter the structure and function of Arctic ecosystems in ways that are not fully understood (Hassol 2005; Serreze et al. 2000; McGuire et al. 2006). Across the Arctic, warming air temperatures have been accompanied by widespread increases in ground temperatures and changes in the frequency of disturbances associated with the thawing of ice-rich permafrost (thermokarst)(Kokelj and Jorgenson 2013; Smith et al. 2010). Thermokarst disturbances occur in permafrost regions when the melting of ice-rich soils causes the loss of structural integrity and the collapse of the ground surface. Generally, the potential for thermokarst disturbance is higher in terrain with greater ground ice content (Kokelj and Jorgenson 2013). In areas of continuous permafrost, increasing ground temperatures have been associated with increased rates of ice wedge thaw in polygonal peatlands (Jorgenson, Shur, and Pullman 2006), and increased rates of retrogressive thaw slump growth (Lantz and Kokelj 2008). Thermokarst disturbances strongly influence hydrology, soils, topography, snow pack, and sediment and nutrient flux (Kokelj et al. 2005; Kokelj, Zajdlik, and Thompson 2009). As such, changes in their frequency will drive important changes in ecosystem structure and function (Jorgenson, Shur, and Pullman 2006; Lantz et al. 2009; Grosse et al. 2011).

Polygonal terrain is an extremely widespread feature of Arctic landscapes and is likely to be impacted by warming ground temperatures. Polygonal terrain is the surface manifestation of an underlying ice-wedge network that develops through thermal contraction cracking (Mackay 1989). Repeated cracking, infilling with spring meltwater, and freezing over thousands of years of contributes to ice wedge growth and alters microtopography. Polygonal networks are one of the most common forms of massive ground ice and in the low Arctic and subarctic environment they tend to occur in organic deposits because these soils favour thermal contraction cracking over fine-grained mineral soils (Kokelj et al. 2014). Greater thermal stress is generated in saturated organic soils because of greater rates of cooling and lower minimum temperatures, which are associated with the high thermal contraction coefficient of ice, and the higher volumetric water content of organic compared to mineral soils (Kokelj et al. 2014).

Ice wedge polygons are classified as high or low-centred, based on the micro-position of the terrain adjacent to the wedge ice (Mackay 2000). Low-centre polygons are outlined by elevated ridges that bound a trough that overlies the ice wedge, and with a depression in the polygon centre. High-centre polygons consist of an elevated centre outlined by subsided troughs overlying ice wedges. Polygonal terrain is sensitive to terrain modification because the wedge, which consists of pure ice is typically located near the top of permafrost (Jorgenson, Shur, and Pullman 2006). High-centered polygons are thought to be indicative of older features that have undergone past ice-wedge degradation (Mackay 2000).

An increase in active layer thickness caused by increasing air and ground temperatures or surface disturbance can result in ice wedge degradation and thaw subsidence leading to the development of melt ponds (Figure 3-1) (Jorgenson, Shur, and Pullman 2006; Kokelj and Jorgenson 2013). These small waterbodies (<1000 m^2) develop following ice wedge thaw and are known as melt ponds or thermokarst pits. Melt ponds are associated with recent ice wedge degradation and are readily identifiable

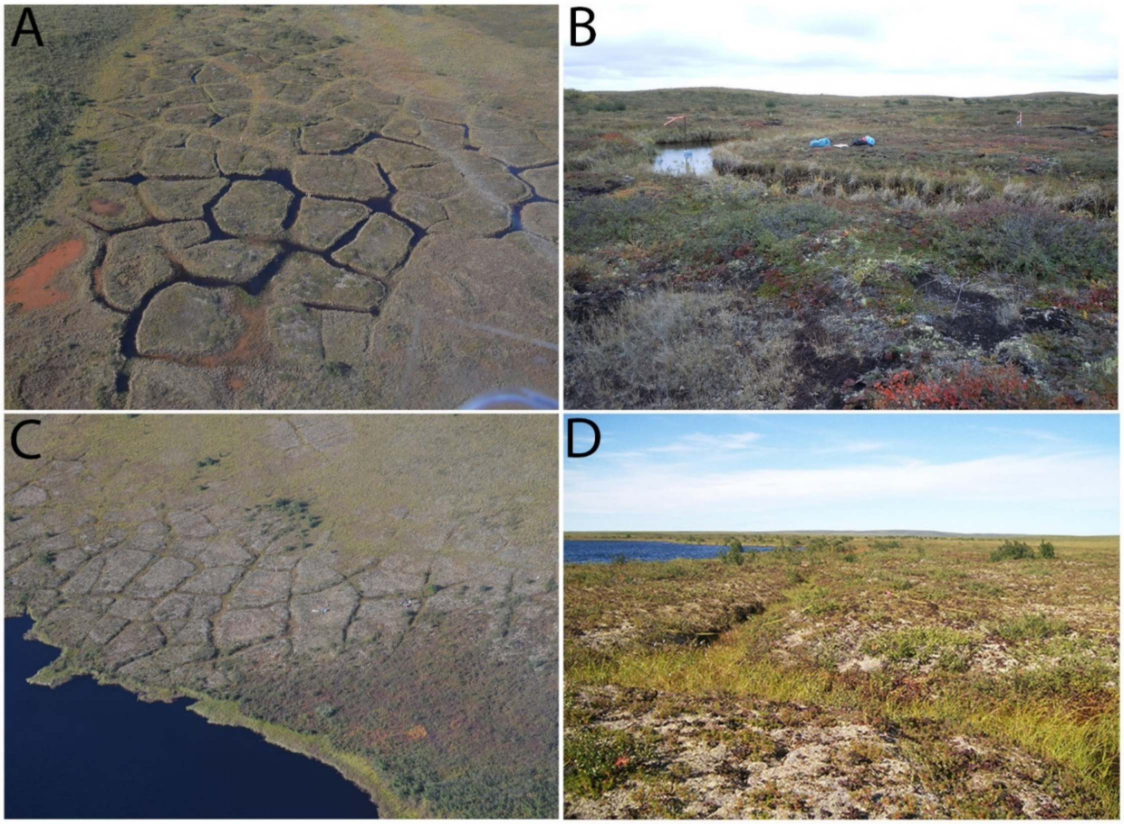

Figure 3-1. Oblique aerial photos of polygon fields near Tuktoyaktuk (A&B: 69.366°N, -133.034°W) and Jimmy Lake (C&D: 68.646°N, -133.63°W). Large melt ponds are visible in the polygon field near Tuktoyaktuk (A&B). The polygon field near Jimmy Lake is characterized by vegetated ice wedge troughs, visible in the ground photo as a band of grassy vegetation in the foreground (D).

on historical and recent aerial photographs as small water bodies overlying the edges and corners of high-centre ice wedge polygons (Jorgenson, Shur, and Pullman 2006). As such, melt ponds have been used as an indicator of ice wedge degradation, and have been mapped using remotely-sensed imagery to quantify changes over time (Jorgenson, Shur, and Pullman 2006). A recent analysis of a time series of remotely sensed images of Arctic coastal plain in northern Alaska showed an abrupt increase in the area and density of ice wedge melt ponds between 1989 and 1998, which was associated with a 2-5 °C increase in mean annual ground temperature (Jorgenson, Shur, and Pullman 2006). Jorgenson et al. (2006) estimated that 10- 30% of Arctic lowland landscapes may be extremely susceptible to thermokarst resulting from this form of ice wedge degradation.

Since terrain susceptibility to thermokarst involves interactions among multiple factors (ground ice content, climate, hydrology, and vegetation, etc.) (Kokelj and Jorgenson 2013), it is unclear if polygonal terrain in other regions will be equally susceptible to change. Overall, very little is known about landscape-scale spatial variation in the size, density, and growth of melt ponds. In the upland tundra north of Inuvik, a strong North-South climate gradient is associated with significant differences in ice wedge abundance, and size (Kokelj et al. 2014). In this region, ice wedge abundance and size increase with the frequency of thermal contraction cracking, which is positively associated with the northward decline in snow depth, shrub density and ground temperature (Kokelj et al. 2014). Latitudinal variation in ground ice conditions and soil properties likely also influence the process of ice wedge degradation. In areas where ice wedges are abundant and large, there is likely to be greater potential for physical change as a result of terrain subsidence. Areas with large volumes of wedge-ice in the near-surface also create potential for strong positive feedbacks to degradation that involve the accumulation of standing water. In areas where ice wedges are smaller, less abundant, and have undergone past degradation, there is less potential for physical change to the ground surface, and strong positive feedbacks to degradation are less likely to occur.

Landscape level variation in near-surface ground ice conditions suggests that polygonal terrain may not respond in a uniform manner to increasing air and ground temperatures. However, where ice wedges are large and occur immediately beneath the active layer, even small increases in thaw depth have the potential to significantly alter terrestrial ecosystem processes, including soil carbon storage (Lee et al. 2012; Tarnocai et al. 2009a), near surface hydrology, and vegetation (Burn and Kokelj 2009; Jorgenson, Shur, and Pullman 2006). Consequently, understanding regional variation in the susceptibility of this terrain type to degradation is a prerequisite to accurate predictions of ecological change that may be associated with warming ground temperatures. In this study we[4] focused on ice wedge melt ponds, examining their spatial distribution, abundance, and change in surface area over time in the upland tundra north of Inuvik.

Methods

Study Area

The study area is the upland tundra north of Inuvik (Figure 3-2). This landscape is within the zone of continuous permafrost and is characterized by low rolling hills and thousands of tundra lakes (Burn and Kokelj 2009; Heginbottom, Dubreuil, and Harker 1995). Surficial materials consist of morainal deposits characterized as fine-grained till

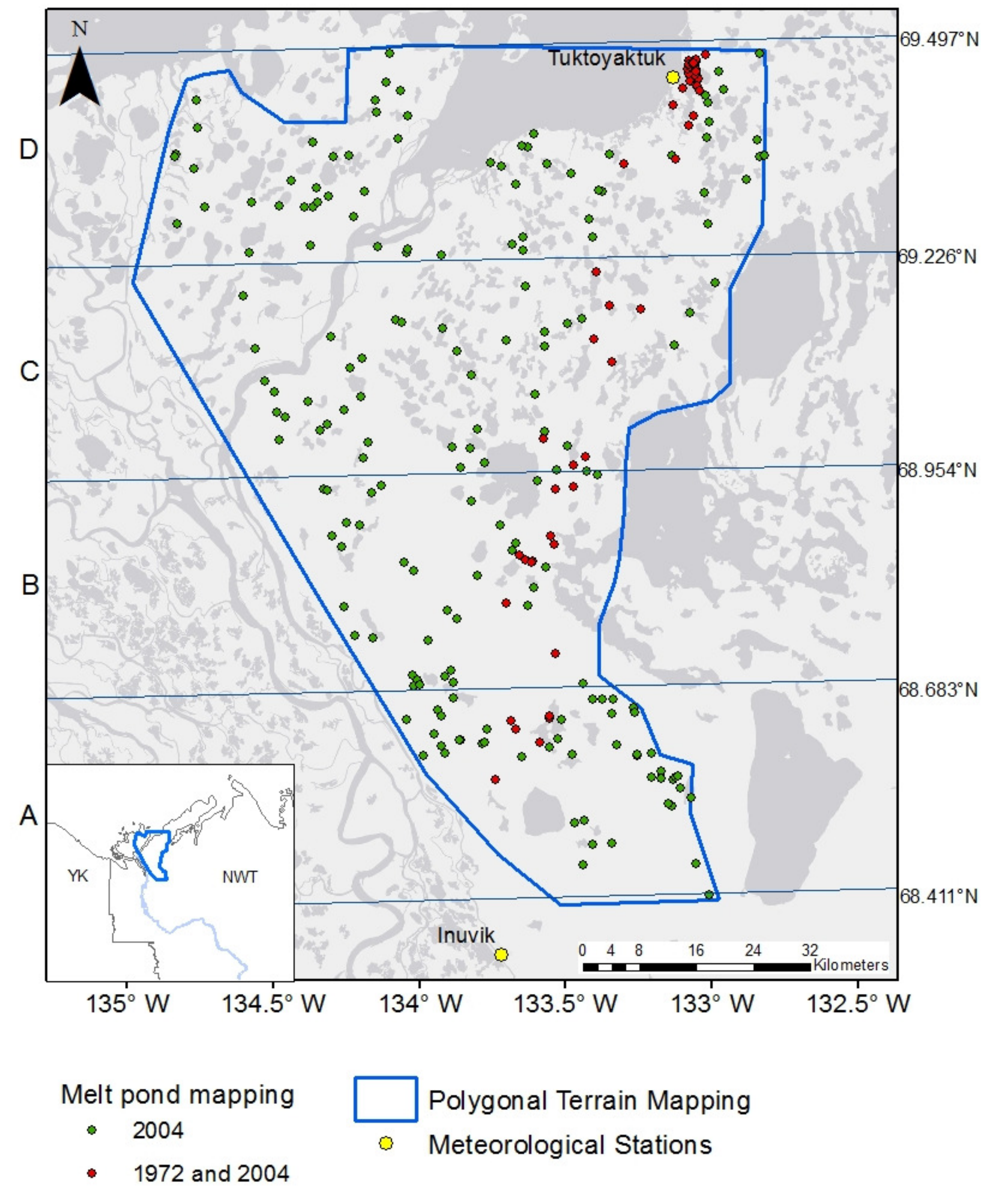

Figure 3-2. Map of the study area in the upland tundra between Inuvik and Tuktoyaktuk. The blue outline shows the area where airphotos were used to map more than 22,000 polygon fields. Locations where polygon fields were assessed for melt ponds are shown by green (2004 mapping) and red points (1972 and 2004 mapping). The lines across the study area show the four latitudinal zones used in the analysis (A-D). The inset at the bottom left shows the location of the study area in northwestern North America, and the Mackenzie River.

with stones that were deposited during the Wisconsinan glaciation (Aylsworth et al. 2000b). Peatlands have developed in the extensive lacustrine deposits of the region, which became widespread due to the drainage of lakes throughout the Holocene (Mackay 1992; Murton 1996). Lacustrine deposits typically host well developed polygonal terrain because following lake drainage, permafrost aggrades into the newly exposed lake bottom sediments and thermal contraction cracking can occur (Mackay and Burn 2002; Kokelj et al. 2014). Ice wedges are extremely common in areas with organic deposits, and it is estimated that in some areas they comprise up to 50 percent by volume of the top meter of ground in areas of polygonal terrain (Pollard and French 1980).

The regional climate in the study area is characterized by an air temperature gradient that is strongest in the summer, with cooler temperatures towards the coast (Burn 1997). Inland areas receive more annual precipitation, with a mean annual snowfall (1981-2010) of 159 cm at Inuvik, and 103 cm at Tuktoyaktuk (Environment Canada 2014). The climatic gradient across the region influences the transition from subarctic boreal forest to shrub tundra north of Inuvik (Timoney et al. 1992; Lantz, Gergel, and Kokelj 2010). Mean annual ground temperatures in the Mackenzie Delta region uplands have increased between 1 and 2°C during over the last 40 years (Burn and Kokelj 2009). Increasing ground temperatures are of particular concern because of the high density of ice wedges in the region and the potential for thermokarst (Kokelj et al. 2014).

Polygonal terrain mapping

To map the distribution of high-centre polygons across the study area we used airphotos captured in August 2004 as part of the Mackenzie Valley Air Photo Project

(NWT Geomatics). These 1: 30,000 scale images have an effective pixel size of 0.5 m. Polygonal terrain was mapped by manually delineating the boundaries of all areas dominated by high-centre polygons greater than 100 m^2 using ArcGIS 9.3 and 10.0. In total, we used this method to map more than 22,000 areas of polygonal terrain. Throughout this paper these discrete areas of polygonal terrain are referred to as polygon fields. To map the density of high-centered polygonal terrain across the study area we used the kernel density feature in Spatial Analyst (ArcGIS 10.1).

Melt pond mapping

To map the regional distribution of melt ponds in the Mackenzie Delta region uplands, a subset of the polygon fields delineated in the region were assessed in more detail. One hundred and eighty three polygon fields (>5000 m^2) were randomly selected from the mapped population of polygon fields across the study area. An additional 54 polygon fields were randomly selected from a portion of the study that overlapped with 1972 airphoto coverage (see below). Polygon fields that were within 500 m of tundra fires or drilling mud sumps were not chosen. In each polygon field, all melt ponds larger than 1 m^2 were hand delineated in ArcGIS 9.3 -10 using the 2004 airphotos. To emphasize the contrast between standing water and other land-cover types, airphotos were viewed as RGB composites with a standard deviation stretch calculated using the entire airphoto. In total, over 2500 melt ponds were mapped across the study area. When mapping was completed we used the data to calculate the following parameters: a) total melt pond area per polygon field, and b) proportion of standing water [total melt pond area / polygon field area]. To assess the spatial patterns of melt pond area, proportional melt pond areas in each field were mapped across the study area. To examine latitudinal changes in these parameters we divided the study area into four zones spanning equal latitudinal ranges: 1) 68.411-68.68249°N, 2) 68.6825-68.9539°N, 3) 68.954-69.22549°N, and 4) 69.2255-69.497°N (Figure 3-2). To test for significant differences in the characteristics of melt ponds and polygon fields among latitudinal zones we used one-way Analysis of Variance. To meet the assumptions of normality, data were log transformed. Tukey's Honestly Significant Different Test (95% family-wise confidence level) was used to perform pairwise comparisons of means in cases where the ANOVA was significant at the 95% confidence level.

To examine recent changes in melt pond area, 54 polygon fields that were mapped on airphotos from 2004 were also mapped using 1972 imagery. High resolution (1:12,000) greyscale images from July were obtained from the National Air Photo Library (NAPL), georeferenced, then used to digitize features. These images have an effective pixel size of 0.29 m. Melt ponds on 1972 images were mapped in the same manner as those on the 2004 images. Our initial analysis included 31 polygon fields randomly chosen from the entire study area. However, following a preliminary analysis showing that melt ponds were more dynamic in the northern portion of the study area, we randomly selected another 23 melt ponds from this part of the region. To assess changes in melt pond area between 1972 and 2004, we used map data to calculate the change in proportional melt pond area per polygon field [(melt pond area $_{2004}$ – melt pond area $_{1972}$)/polygon field area].

Assessment of ice wedge thermokarst at anthropogenic disturbances

Thermokarst activity in polygonal terrain adjacent to anthropogenic disturbances was also assessed in the study area. One hundred and nine sites that were disturbed and abandoned at least 10 years ago were assessed using the 2004 airphotos. The majority of these sites were hydrocarbon exploration leases where an exploratory well was drilled, and drilling muds and other materials were disposed in a sump excavated in the permafrost that was capped with excavated materials (Johnstone and Kokelj 2008). The majority of these sites were abandoned in the 1970s and 1980s (Aboriginal Affairs and Northern Development Canada and Technical Advisory Group 2009). To assess the level of ice wedge degradation, airphoto interpretation and ground-level photographs were used to classify each of the sites into three categories of thermokarst: 1) no evidence of ice-wedge subsidence; 2) evidence of minor or moderate subsidence due to ice wedge degradation; and 3) evidence of extreme surface subsidence due to ice wedge degradation. The 109 disturbances we assessed were categorized into four latitudinal zones that roughly corresponded to those used in the previous analysis (see *Melt Pond Mapping*) and chi-square tests were used to test for significant differences among latitudinal zones in the proportion of sites impacted by different thermokarst levels (1, 2, or 3). The alpha value of 0.05 was adjusted using the Bonferroni correction for 6 pairwise comparisons among latitudinal zones.

Precipitation data

To assess the potential influence of interannual variation in precipitation on melt pond dynamics, historical precipitation data from meteorological stations in Tuktoyaktuk and Inuvik were examined for the years 1958 to 2006. Total annual rain and snow from 1958 to 2006, and mean annual precipitation over this period were plotted for each location. To fill in months of missing data, precipitation data from the "Inuvik A" meteorological station (68.3°N, -133.48°W, 67.7 m elevation) was supplemented with data from the "Inuvik UA" station (68.32°N, -133.52°W, 103.2 m elevation) for 1996, 2004, 2006, and July-December, 1995. At Tuktoyaktuk, precipitation data from 1958-1993 was from the Tuktoyaktuk meteorological station (69.45°N, -133°W, 18.3 m elevation), and the "Tuktoyaktuk A" station (69.43°N, -133.03°W, 4.3 m elevation) provided data for 2000-2006.

Results

Polygon field mapping and kernel density

Mapping across the Mackenzie Delta region uplands identified 48 million hectares of high-centre polygonal terrain, representing 10% of the terrestrial study area. Polygon fields were more abundant in the northern part of the study area (north of 68.88°N) where the proportion covered ranged from 0 – 37% of the landscape (Figure 3-3). South of 68.88°N there was a marked decrease in the density of polygon fields, with the proportional area occupied ranging from 0-12% (Figure 3-3). In the southern portion of the study area, the highest density of polygonal terrain occurred on the boundary between the North and South Caribou Hills (69.03° N, 134.49° W). The northward increase in the density of polygonal terrain was accompanied by an increase in the mean size of polygon fields (Figure 4a). The average area of polygon fields in the two southernmost latitudinal zones were not significantly different from each other, but north of 68.95°N the average area of polygon fields increased significantly with latitude (Figure 4a, $p<0.05$).

Patterns of ice wedge density corresponded with several of the physiographic subdivisions defined by Rampton (1988) (Figure 3-3). The physiographic subdivisions

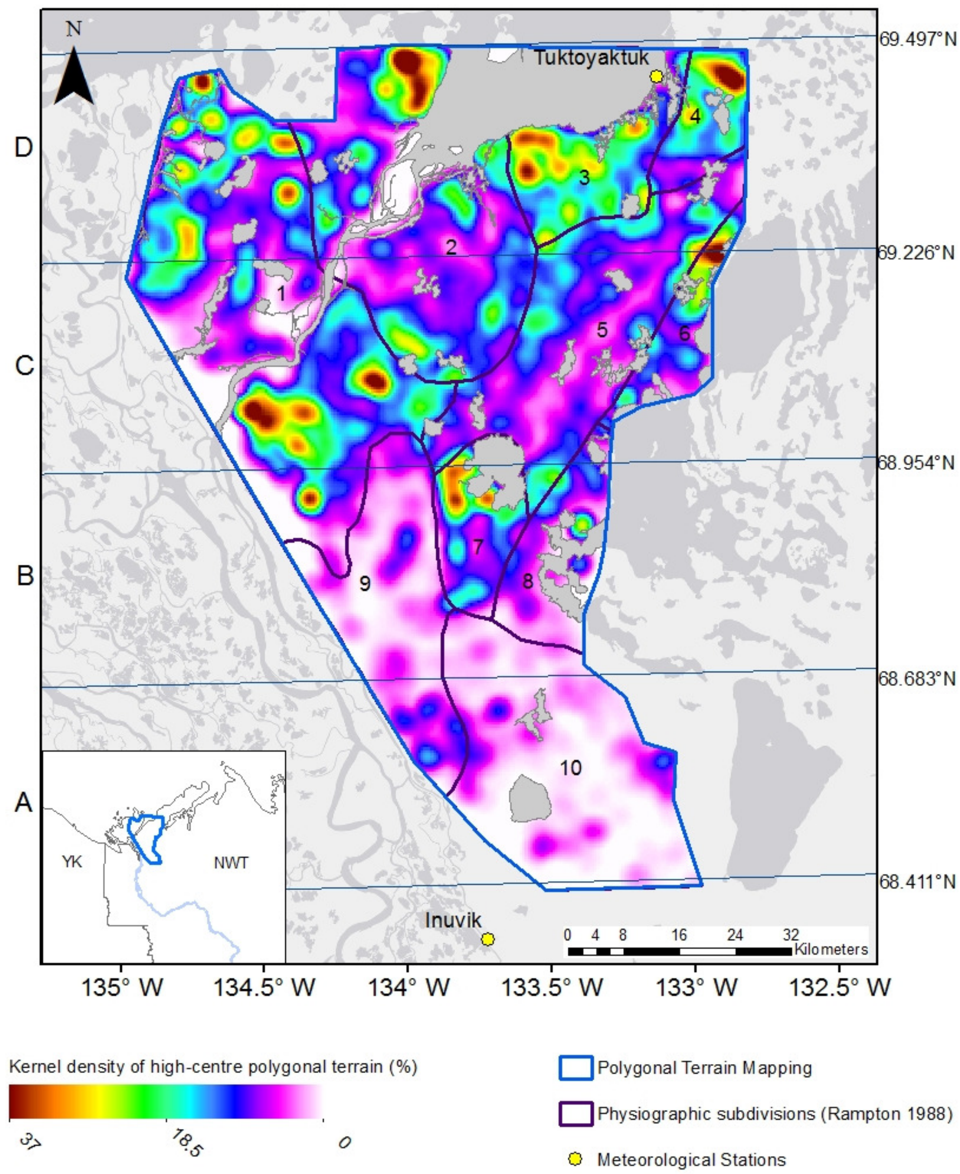

Figure 3-3. Density of high-centre polygonal terrain in the study area. The map shows the proportion of the landscape (0-1) that is occupied by high-center polygons. The lines across the study area show the four latitudinal zones used in the analysis (A-D). Lakes larger than 5,000,000 m^2 are displayed within the study area boundary. Physiographic subdivisions defined by Rampton (1988) are also displayed: 1) Tununuk Low Hills, 2) Kittigazuit Low Hills, 3) Kugmallit Plain, 4) Low Involuted Hills, 5) West Tuk Peninsula Axis, 6) Eskimo Lakes Fingerlands, 7) Parsons Lake Plains, 8) Eskimo Lakes Pitted Plains, 9) North Caribou Hills, 10), South Caribou Hills. The inset at the bottom left shows the location of the study area in northwestern North America, and the Mackenzie River.

with a low density of polygonal terrain were generally in the southern part of the study region, including the North Caribou Hills (range: 0 – 12.7%; mean: 3.2%) and South Caribou Hills (range: 0 – 11.9%; mean: 1.7%). Topography in the Caribou Hills (30-200 mASL) is controlled by bedrock, which is generally overlain by well-drained tills. In this physiographic unit, small lacustrine deposits are limited to drainages (Ecosystem Classification Group 2012). The density of polygonal terrain was generally higher in the northern part of the study area (0-80 mASL), where lacustrine basins were more abundant (Ecosystem Classification Group 2012). Areas with a high density of polygonal terrain appearing yellow, orange and red (approximately 22-37 %), generally showed a close spatial correspondence with low lying lacustrine deposits (Rampton 1987). The highest mean polygonal terrain density was located in the Low Involuted Hills (range: 4.2 – 34.9 %; mean: 13.4%) and Eskimo Lakes Fingerlands (range: 0.2 – 33.8%; mean: 10.6%). The next highest densities were located in the Parsons Lake Plain (range: 0 – 27.6%; mean: 9.8%), Tununuk Low Hills (range: 0-32.1%, mean: 8.9%), and Kugmallit Plain (range: 0 – 28.7%; mean: 8.2%). The Kittigazuit Low Hills generally had an intermediate mean density (7.8%), but contained the highest maximum density within the study area (range: 0 – 36.9 %) along the northeast coast of Richards Island. Relatively low densities within the northern part of the study area were located in the hilly landscapes of the West Tuk Peninsula Axis (range: 1.8 – 24.5%; mean: 7.7%) and the Eskimo Lakes Pitted Plain (range: 0 - 20%; mean: 5%). Areas with a low density of polygonal terrain appear as white and purple on the density scale (approximately 0-5%), and show close spatial correspondence with areas of higher elevation (Mackenzie Valley Air Photo Project, Digital Elevation Model UTM 08, 2006).

Melt pond mapping, 2004

Mapping of ice wedge melt ponds using airphotos from 2004 was completed for 237 polygon fields across the study area. In total, 2846 melt ponds were mapped. Individual melt pond size ranged from 1 to 898 m^2 across the study area. Average individual melt pond size consistently increased with latitude, but the differences were not significant (Figure 3-4b). Total melt pond area per polygon field ranged from 0 to 3086 m^2 across the study area, with the highest area observed in the most northerly zone (236 m^2). The mean area in the northernmost zone was significantly greater than the remaining latitudinal zones, which were not significantly different from one another (Figure 3-4c). The proportional melt pond area (Figure 3-4d) was also greatest in the northernmost zone (0.68%), and was significantly greater than the remaining latitudinal zones, which were not significantly different from one another. Mapping the proportional melt pond area per polygon field (Figure 3-5) also revealed two areas with a high density of melt ponds. The Tuktoyaktuk area (69.456° N, -133.05° W) and the boundary between the North and South Caribou Hills area (69.034° N, 134.49° W) both showed numerous polygon fields with a relatively high proportion of melt ponds (Figure 3-5).

Historical comparison

Fifty four of the polygon fields that were examined for melt ponds using 2004 imagery were also examined using 1972 imagery, and increases and decreases in melt pond area were observed (Figures 3-6 and 3-7). A plot of the change in proportional melt

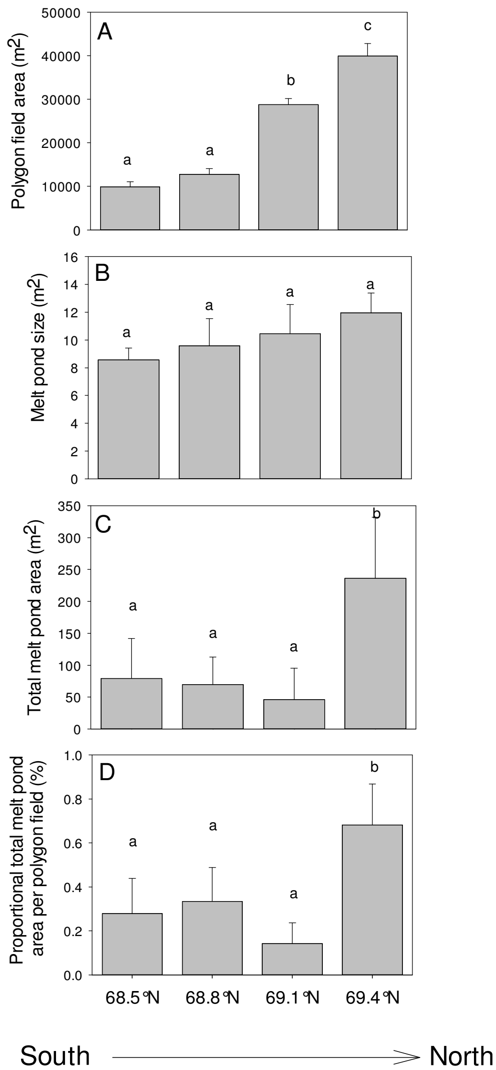

Figure 3-4. Polygon field and melt pond characteristics by latitudinal zone (2004). A) polygon field area (m^2), B) individual melt pond size (m^2), C) total melt pond area per polygon field (m^2), D) average proportional melt pond area (%). The midpoint of each latitudinal zone is indicated below each bar, and the northernmost zone is on the far right. Bars show means and error bars represent the 95% confidence intervals of the mean (untransformed). Means that are significantly different ($P < 0.05$, ANOVA and Tukey's HSD test) are indicated by different letters.

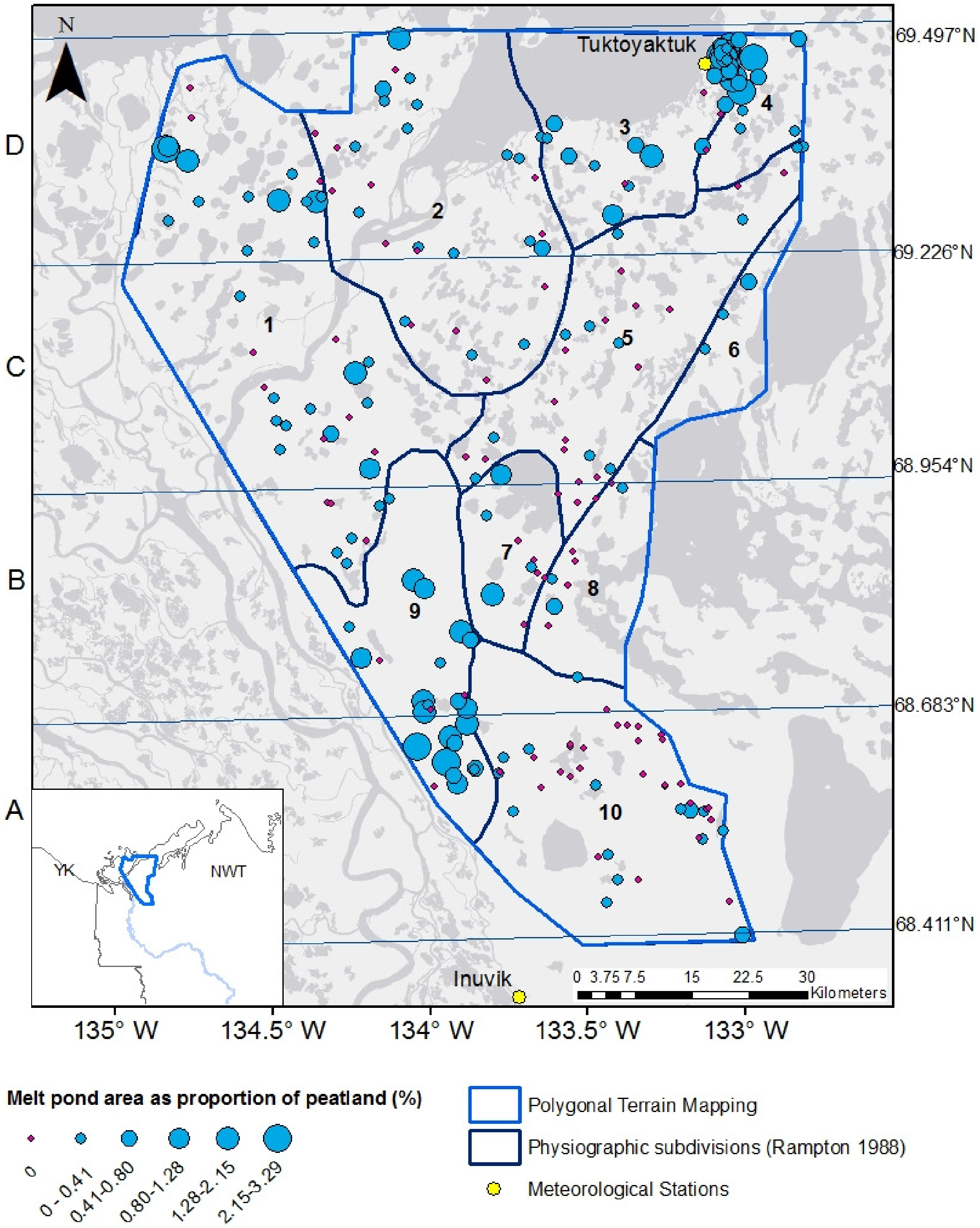

Figure 3-5. Map showing the percentage of selected polygon field occupied by melt ponds. The lines across the study area represent the four latitudinal zones used in the analysis (A-D). The inset at the bottom left shows the location of the study area in northwestern North America, and the Mackenzie River.

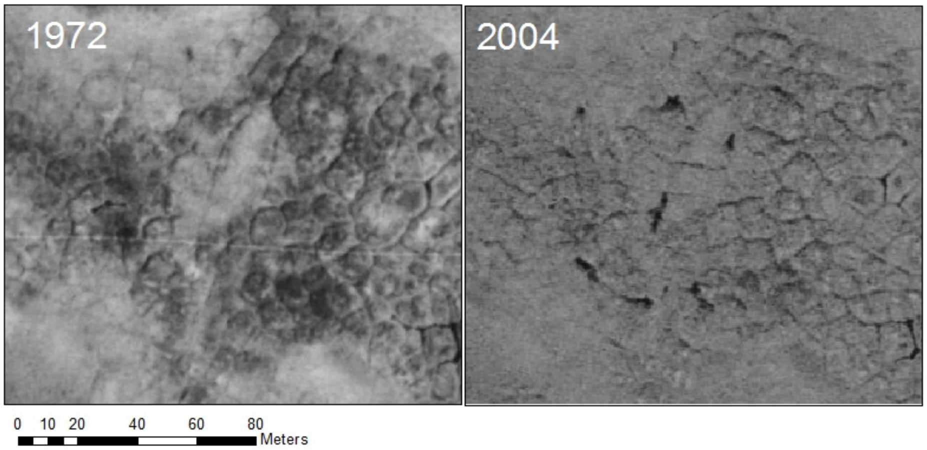

Figure 3-6. An example of a polygon field showing an increase in melt pond area from 1972 to 2004.

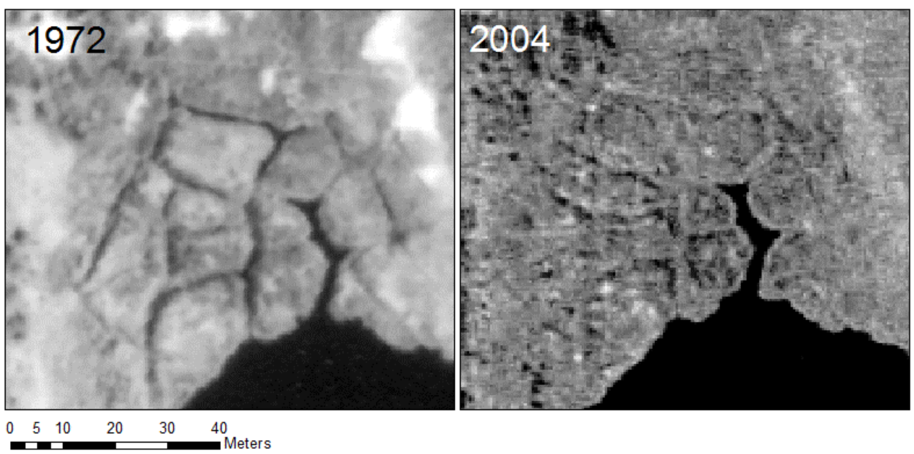

Figure 3-7. An example of a polygon field showing a decrease in melt pond area from 1972 to 2004.

pond area from 1972 to 2004 shows that many of the areas mapped did not have increased ice wedge ponding (Figure 3-8). South of 69.4°N nearly half of polygon fields showed no net change in proportional melt pond area (13 of 27), and the remainder showed net increases or decreases less than 0.35% of the field area. Conversely, north of 69.4°N, nearly half of polygon fields mapped showed increases or decreases greater than 0.35% (13 of 27), with the largest increase (3.74%), and largest decrease in proportional melt pond area (2.20%) occurring in the northernmost latitudinal zone in the study area. Overall, ice wedge degradation from 1972 to 2004 resulted in a net increase of 1444 m^2 of open water, representing a 0.09% increase of the total area assessed for change. The net change in melt pond area from 1972-2004 south of 69.4°N was a 721m^2 loss, whereas north of 69.4°N there was a gain of 2165m^2, changes of -0.07% and 0.38% respectively.

Assessment of ice wedge thermokarst at anthropogenic disturbances

Of the 109 anthropogenically disturbed sites that were assessed, 32 showed no evidence of ice-wedge subsidence (level 1), 44 showed evidence of minor or moderate subsidence due to ice wedge degradation (level 2), and 33 showed evidence of extreme surface subsidence due to ice wedge degradation (level 3). Comparing the severity of subsidence by latitude showed that severe subsidence at anthropogenically disturbed sites was significantly more common in the northern part of the study area (Table 3-1, Figure 3-9). Eleven anthropogenic disturbances were located within the southernmost latitudinal zone and all showed no evidence of ice-wedge subsidence (level 1). Disturbed sites within the two central latitudinal zones exhibited minor or moderate subsidence due to ice wedge degradation (level 2), or no subsidence (level 1). Within the northernmost

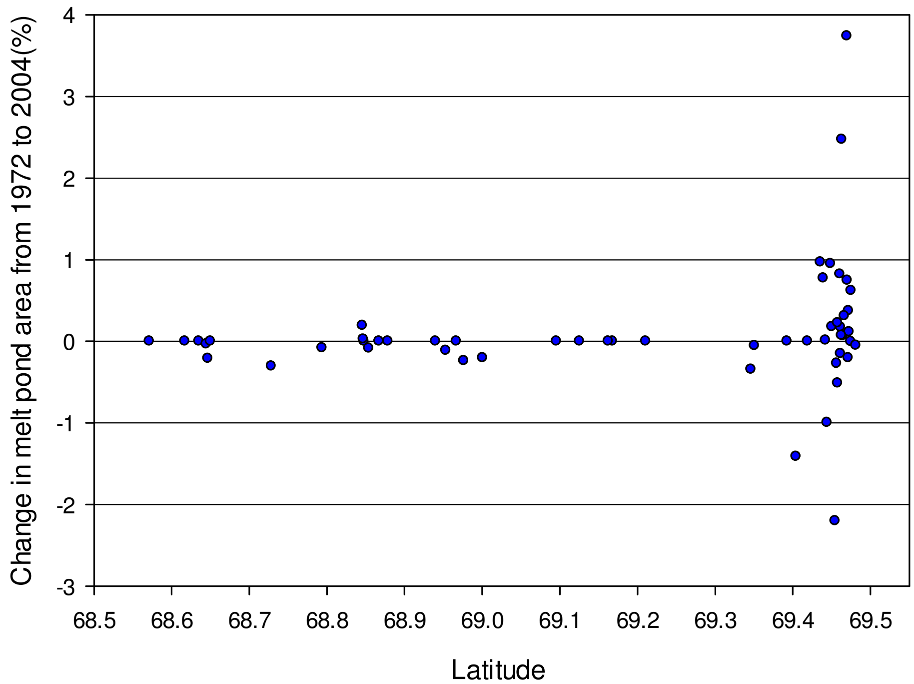

Figure 3-8. Change in melt pond proportional area per polygon field from 1972 to 2004 (%).

Table 3-1: Assessment of subsidence due to ice wedge degradation at anthropogenic disturbances in the tundra north of Inuvik. Chi-square analysis indicated that the proportion of ice wedge subsidence levels were not equal between all latitudinal zones ($p < 0.001$). The southernmost latitudinal zone was characterized by a higher than expected proportion of sites showing no ice wedge subsidence, whereas the northernmost zone had a higher than expected proportion of sites showing extreme subsidence ($p<0.01$).

Latitudinal Zone	**No subsidence (Level 1)**	**Minor to moderate subsidence (Level 2)**	**Extreme subsidence (Level 3)**	**Total**
A) 68.37-68.68°N	11	0	0	11
B) 68.68-68.95°N	6	11	2	19
C) 68.95-69.23°N	12	12	3	27
D) 69.23-69.69N	3	21	28	52
Total	32	44	33	109

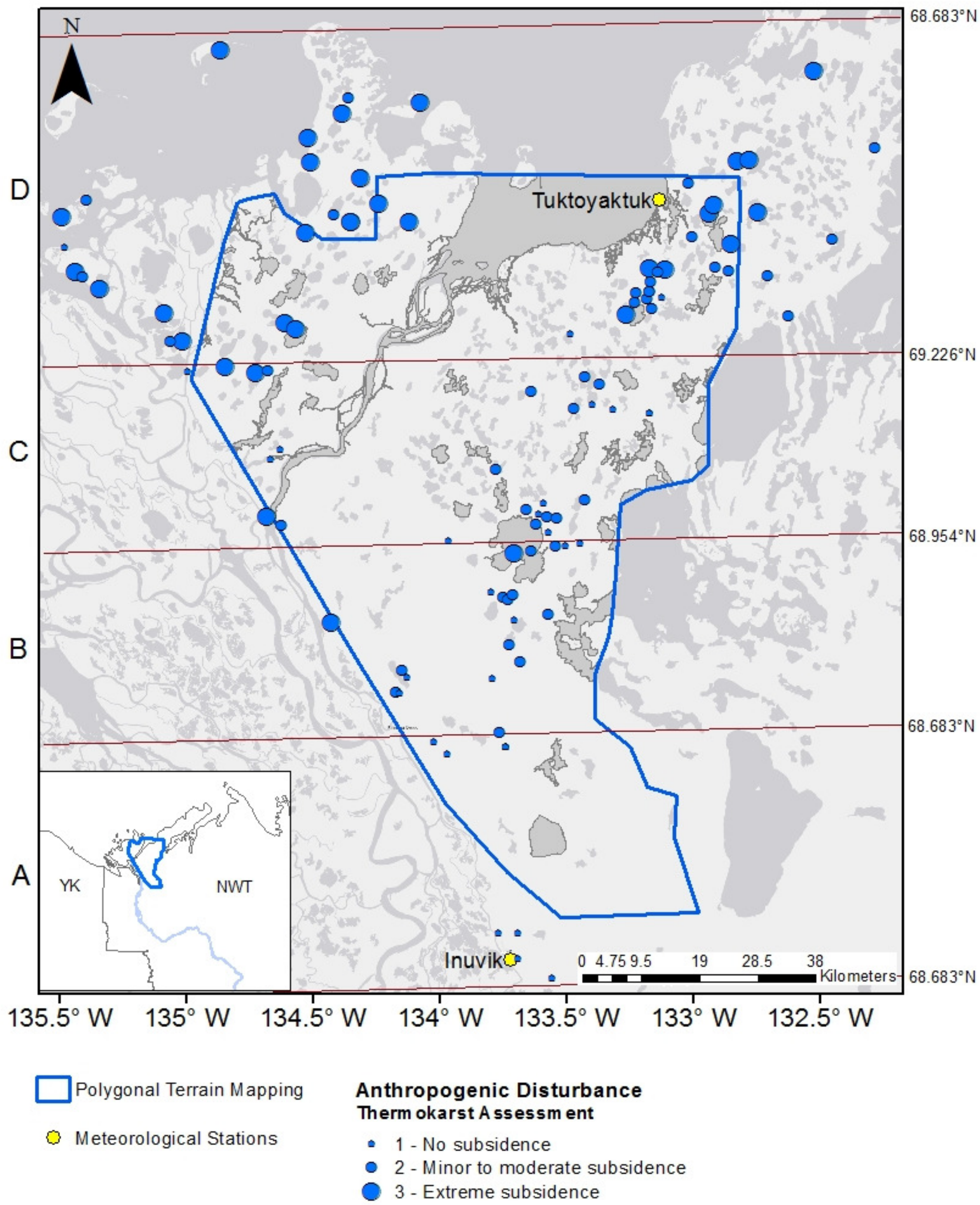

Figure 3-9: Sites of anthropogenic disturbance assessed for subsidence due to ice wedge degradation. The majority of these disturbances are drilling mud sumps that were abandoned in the 1970s and 1980s. Three levels of thermokarst were categorized: 1) no evidence of ice-wedge subsidence; 2) evidence of minor or moderate subsidence due to ice wedge degradation; and 3) evidence of extreme surface subsidence due to ice wedge degradation. The inset at the bottom left shows the location of the study area in northwestern North America, and the Mackenzie River.

latitudinal zone extreme subsidence (level 3) was common (54% of sites). Chi-square analysis of the whole dataset indicated that the proportion of ice wedge subsidence levels were not equal between all latitudinal zones ($p < 0.001$). The southernmost latitudinal zone was characterized by a higher than expected proportion of no ice wedge subsidence. The central latitudinal zones were characterized by higher than expected proportions of no, minor or moderate subsidence. The northernmost zone was characterized by a higher than expected proportion of extreme subsidence ($p < 0.01$).

Precipitation data

Inuvik

From 1958 to 2006, mean annual precipitation in Inuvik was 252.0 mm. Mean annual rainfall was 115.9 mm and total snowfall was 178.1 cm (Figure 3-10a). Mean summer temperature (May – August) over this time period was 8.85 °C (Environment Canada 2007). In 1972, all measures of precipitation were above the long term average. Annual precipitation was 340.1 mm, with annual rainfall of 150.1 mm, and annual snowfall of 247.1 cm. The mean summer temperature of 8.58°C was also comparable with the long term average. In 2004, the annual precipitation of 215.5 mm was slightly below average, with annual rainfall of 83.4 mm, and annual snowfall of 246.0 cm. The mean summer temperature of 9.65°C was higher than the long term average.

Tuktoyaktuk

From 1958 to 2006, mean annual precipitation in Tuktoyaktuk was 137.5 mm. Mean annual rainfall was 72.3 mm, and mean annual snowfall was 72.6 cm (Figure 3-10b).

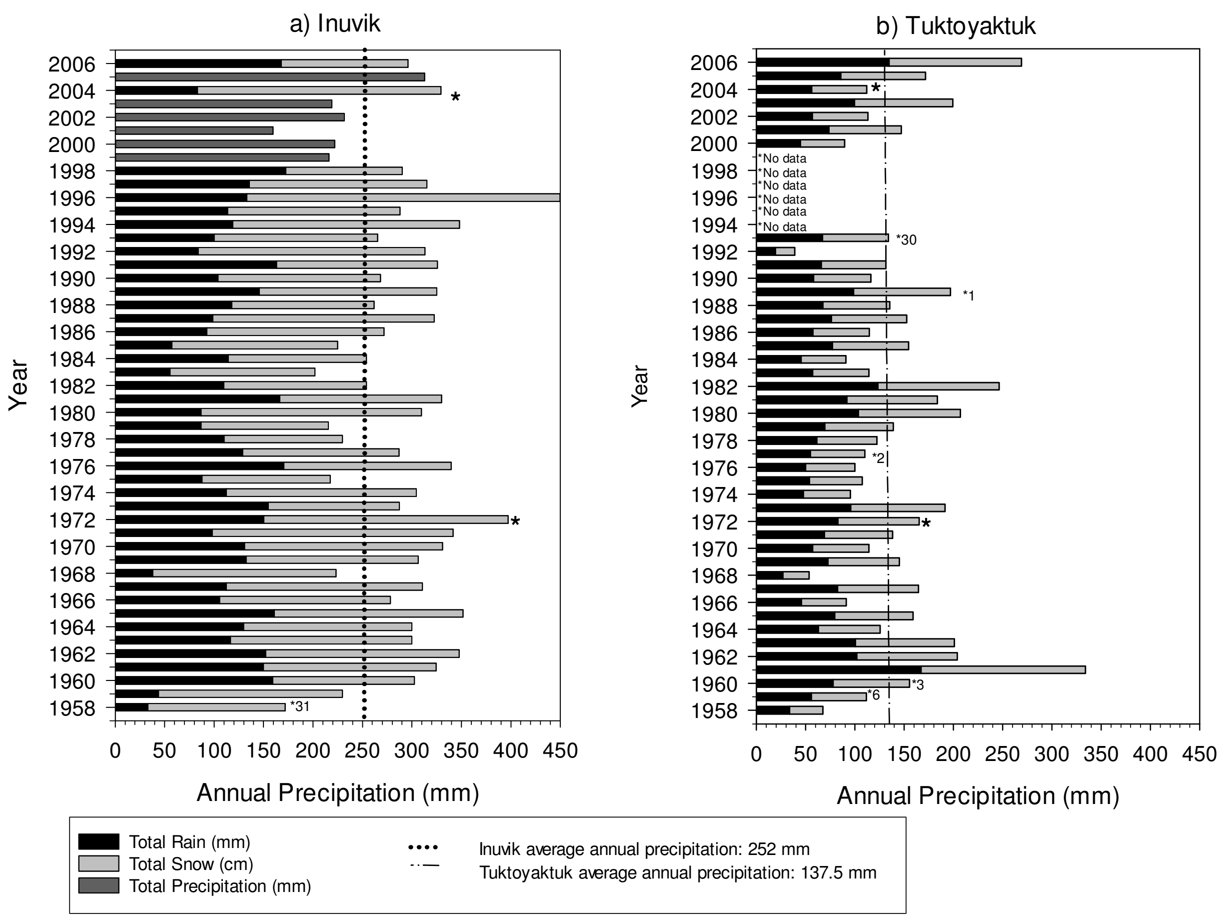

Figure 3-10. Annual precipitation from 1958 to 2006 for a) Inuvik, and b) Tuktoyaktuk. Total annual rain and snow are plotted, and mean annual total precipitation from 1957 to 2007 is indicated with a vertical line. Years in which airphotos of the study area were examined to map ice wedge melt ponds (1972 and 2004) are indicated with an asterisk. The number of days of missing data annually is 0 unless otherwise indicated to the right of the bar.

Mean summer temperature (May – August) over this time period was 5.32°C (Environment Canada 2007). In 1972, the annual precipitation of 153.4 mm was above the long term average, with annual rainfall of 82.6 mm, and annual snowfall of 70.7 cm. The mean summer temperature of 4.91°C was below the long term average. In 2004, the annual precipitation of 130.0 mm was slightly below average, with annual rainfall of 56.0 mm, and annual snowfall of 151.3 cm. The mean summer temperature of 5.55°C was comparable with the long term average.

Discussion

Spatial variation in polygonal terrain in the Mackenzie Delta region uplands

The increased abundance and size of polygon fields in the northern part of the study region was associated with a higher abundance of terrain conducive to their growth at northern latitudes, and ground thermal conditions conducive to thermal contraction cracking (Kokelj et al. 2014). Lacustrine sediments in drained lake basins favour the accumulation of peat and the formation of ground ice, including ice wedges (Aylsworth et al. 2000b). Coarse-scale mapping in the study region shows that lacustrine sediments are more common with increasing latitude (Kokelj et al. 2014). In the physiographic units north of 69°N, smaller drained lake basins are also twice as abundant and one-and-a-half times larger than in the southern part of the study area (Marsh et al. 2009).

Our observation that polygon fields are more abundant and larger in the northern part of the study area is also consistent with recent work showing that ice wedge size increases with latitude where colder ground temperatures facilitate more frequent ice wedge cracking (Kokelj et al. 2014). Thermal contraction cracking and ice-wedge development is controlled by the rate and magnitude of ground cooling in winter, which is related to air temperature and augmented by snow depth, vegetation cover, and soil properties (Mackay 1993; Kokelj, Pisaric, and Burn 2007; Kokelj et al. 2014). Precipitation decreases with increasing latitude in the study region, with a steep gradient in average annual snowfall (1981-2010) between Inuvik (159 cm) and Tuktoyaktuk (103 cm). Lower snow cover at more northern sites results in lower ground temperatures that also favour ice wedge cracking and growth (Kokelj et al. 2014). At sites in the southern part of the study area, deeper snow inhibits ground heat loss resulting in warmer ground temperatures in winter (Kokelj, Pisaric, and Burn 2007; Kokelj et al. 2014). The density of tall shrubs also increases southwards across the treeline, which contributes to warmer ground temperatures by capturing snow (Palmer et al. 2012; Sturm et al. 2005).

Geophysical variation among physiographic subdivisions likely also contributed to observed differences in the density of polygonal terrain. Differences in elevation, topography, surficial geology, and their influence on drainage patterns and waterbody development vary spatially in the study area, and correspond with differences in the density of polygonal terrain (Figure 3-3). The northern part of the study area towards the Tuktoyaktuk coastlands contains a higher density of polygonal terrain because this area is low-lying, poorly drained, and has greater coverage of lacustrine sediments formed following lake drainage (Ecosystem Classification Group 2012; Rampton 1987). This is most evident at the boundary between the relatively well-drained Caribou Hills, which contains a lower density of polygonal terrain, and the poorly-drained, lower-relief physiographic subdivisions to the north, which contain a higher density of this terrain type (Figure 3-3). High mean polygonal terrain density in most subdivisions within the

Tuktoyaktuk Coastal Plain ecoregion was associated with poorly drained areas underlain by lacustrine sediments (Rampton 1988). Areas in the northern part of the study area that were characterized by a low density of polygonal terrain included the Eskimo Lakes Pitted Plain and the West Tuk Peninsula Axis. These areas were characterized by increased topographic variation, better drainage and a lower proportion of peatlands (Mackenzie Valley Air Photo Project, Digital Elevation Model UTM 08, 2006, Rampton 1988).

Throughout the study area, low densities of polygonal terrain were associated with the location of ice-contact and morainal deposits including eskers, kames, kettles, and outwash plains (Rampton 1987). These areas are generally concentrated in the southern portion of the study area where morainal deposits host a low density of lakes (Ecosystem Classification Group 2012) (Figure 3-3). In the southern part of the study area, the only area with a high density of polygonal terrain is located in part of the South Caribou Hills dominated by poorly drained depressions that resemble ancient lacustrine basins (Rampton 1988). These areas favour the development of organic soils and peatlands.

The mapping of polygonal terrain completed in this study represents the finest scale mapping of organic deposits in the Mackenzie Delta region uplands that has been conducted to date. High-centre polygon fields occupy 10.04% of the terrestrial study area. Since these organic deposits host a large volume of ground ice they are particularly susceptible to thermokarst from disturbance, changes in hydrology or climate warming.

Potential for change increases with latitude

Contemporary melt pond mapping and thermokarst assessments following anthropogenic disturbance show that polygons at higher latitudes are more susceptible to degradation. The total and proportional melt pond area, and subsidence following disturbance all increased dramatically north of 69.4°N. Larger and more abundant ice wedges in the north of the study area, plus shallower active layer thickness result in a higher volume of ice in closer proximity to the surface (Kokelj et al. 2014). This increases the susceptibility of polygon fields to ponding following active layer deepening or disturbance. In the south of the study area, small ice wedges are typically truncated below the base of the contemporary active layer and may be less susceptible to thermokarst (Kokelj, Pisaric, and Burn 2007; Kokelj et al. 2014).

Recent changes in melt pond area provide additional evidence that the northern part of the study area is more susceptible to ice wedge degradation. Comparisons of melt pond area between 1972 and 2004 indicated that polygonal fields south of 69.4°N have shown little to no net change, whereas those north of 69.4°N have shown large increases and decreases in area. North of 69.4°N the magnitude of change ranged from 0-3.7% of the polygon field area, which represented losses and gains ranging from 120m^2 to 970m^2 respectively. Combined with the observation that the majority of anthropogenic disturbances in the northernmost part of the study area showed extreme ponding, these findings clearly indicate that ice wedges are more susceptible to degradation and thermokarst with increasing latitude.

It is likely that the northern part of the study area exhibited both increases and decreases in melt pond area from 1972 to 2004 because the degradation of near-surface wedge ice can alter peatland hydrology resulting in both ponding and the drainage of surface water. Across the Tuktoyaktuk coastlands, rapid or catastrophic lake drainage can also occur when the erosion of ground ice leads to the creation of a new outlet channel in ice-rich permafrost (Marsh et al. 2009; Mackay 1992; Mackay 1988). The recent expansion of lakes in continuous permafrost as a result of thermokarst processes has also been identified in Siberia (Smith et al. 2005). In areas of continuous permafrost in northern Alaska, large lakes decreased in number and area between 1950 and 2007 as a result of lateral drainage (Jones et al. 2011). These changes in tundra water bodies highlight the complexity of permafrost hydrology in a warming environment, and underscore the difficultly in identifying mechanisms associated with changes in tundra water body size and abundance (Smith et al. 2005). Our observations are consistent with these findings and suggest that many of the same factors may be driving increases and decreases in ice wedge melt ponds area in high-centre polygon fields. It is also possible that decreases in melt pond area could have resulted from feedbacks limiting melt pond growth and decreasing the surface area of open water visible on airphotos. It has been suggested that after ice wedge degradation produces a melt pond, aquatic vegetation growth, peat accumulation and permafrost aggradation can reduce ponding and prevent further degradation (Jorgenson, Shur, and Pullman 2006). Observed decreases in melt pond area support the idea that melt ponds may be a transitory feature.

Our observation that net increases in melt pond area between 1972 and 2004 were restricted to the northern part of the study area suggests that ponding resulted from ice wedge degradation and not increased precipitation and seasonal ponding. If melt pond changes were driven by increased precipitation, uniform increases would be expected across the study area. Furthermore, our analysis of historical climate data shows that the net increase in open water melt ponds occurred despite lower than average total precipitation in 2004. The patterns we observed are also opposite of changes in the area of large lakes on the Tuktoyaktuk Peninsula, which were driven by changes in cumulative precipitation. Lake surface area increased from 1978 to 1992, and decreased from 1992 to 2001 in response to increases and decreases in precipitation, respectively (Plug, Walls, and Scott 2008).

The magnitude of recent ice wedge degradation in the Mackenzie Delta region uplands is considerably lower than reported in similar studies in Alaska. Jorgenson et al. (2006) and Necsoiu et al. (2013) reported that melt ponds occupy between 3- 4.4% of the polygon fields mapped. In the Mackenzie Delta region uplands, on average melt ponds occupied 0.368% and never exceeded more than 3.92% of mapped polygon fields. These contrasts highlight the importance of studying inter and intraregional variation in melt pond dynamics.

Spatial variation in ice wedge degradation

Hotspots of melt pond development and polygonal terrain density at the boundary of the North and South Caribou Hills, and around Tuktoyaktuk, indicate that subregional variation in soil, surficial materials and hydrology also has a strong influence on ice wedge dynamics (Figures 3-3, 3-5). Areas with a large expanses of melt ponds likely coincided with areas of polygon terrain where lower snow cover and cooler ground temperatures contributed to larger ice wedges closer to the ground surface. It is likely that these areas may be more susceptible to melt pond development.

Implications for environmental change

The potential for ice wedge ponding due to increasing temperatures differs across the study area. In the portion of the study area south of 69.4°N, polygon fields showed minimal net change in melt pond area despite regional increases in air and ground temperature (Burn and Kokelj 2009). North of 69.4°N, increases in open water melt pond area of 0.38% between 1972 and 2004 indicate that this part of the study area is highly susceptible to increasing air and ground temperatures. If we assume that a similar increase occurred across the entire study area north of 69.4°N, it is likely that approximately 216, 095 m^2 of open water melt ponds may have developed due to ice wedge degradation. The higher proportion of extreme thermokarst at historic drilling sumps in the northernmost latitudinal zone suggests that human disturbances in polygonal terrain in the northern part of the study will be most susceptible to ice wedge degradation. The short and long-term environmental implications of widespread ice-wedge ponding in this portion of the study area and across the circumpolar Arctic requires additional investigation. Loss of tundra vegetation driven by increases in open water is likely to initiate a positive feedback promoting additional degradation. The lower albedo and high heat capacity of water are likely to contribute to lateral heat transfer, degrading wedges and resulting in additional permafrost thaw and altered peatland hydrology (Quinton and Baltzer 2013; Wright, Hayashi, and Quinton 2009). The process of melt pond stabilization is not well characterized, but it is possible that vegetation development may limit melt pond growth and reduce the long-term effects of ice wedge degradation.

Our data show that ice wedge degradation varies at both the regional and fine scale. Variation in melt pond dynamics evident from airphotos indicates that further investigation into fine-scale factors that promote or limit further ice wedge degradation is required. One limitation of the approach used here is that tracking changes in the total melt pond area per polygon field does not capture the dynamics of individual melt ponds over time. Tracking individual melt ponds through time would allow exploration of the drivers of melt pond formation and revegetation. Understanding the ecological implications of ice wedge degradation due to future warming and development is important because polygonal terrain (high- and low-centre) comprises a large portion of this study region (12.45%), and the low Arctic as a whole. This terrain type contains large stores of carbon that are likely to be released as methane and carbon dioxide with increasing temperature (Schuur et al. 2008). Understanding the impact of melt pond formation and changing hydrology on these processes will be particularly important.

Conclusions

Spatial

Landscape variation in the distribution of high-centre polygonal terrain is related to the distribution of organic deposits in the region. Large lacustrine basins and small organic deposits in old lake beds are more common throughout the lower-lying, poorly drained physiographic regions in the northern part of the study area. The increased water content and thermal properties of these organic deposits favour thermal contraction cracking and ice wedge development. Northern sites are also characterized by lower air and ground temperatures, shallower snow pack, and lower density of shrubs, which result in more frequent thermal contraction cracking, contributing to an increased density and size of polygonal fields.

Temporal

Recent changes in melt pond area and thermokarst at historical anthropogenic disturbances show that terrain at higher latitudes is more susceptible to ponding resulting from ice wedge degradation. The increased thaw sensitivity of polygonal terrain at higher latitudes has implications for the planning and maintenance of infrastructure in the region, particularly in light of the potential for ongoing oil and gas exploration, and construction of the Inuvik-Tuktoyaktuk highway through regions with abundant polygonal terrain. Significant variation in polygonal terrain density and melt pond development among physiographic units also indicates that there are fine-scale factors influencing ice wedge dynamics and thermokarst in the Mackenzie Delta region uplands, including topography, drainage and surficial deposits.

Chapter 4 – Conclusion

Recent climate warming has been associated with an increased frequency of disturbances from permafrost thaw in the circumpolar north (Jorgenson and Osterkamp 2005; Kokelj and Jorgenson 2013). These changes affect ground stability, terrestrial and aquatic ecosystems, and soil carbon cycling (ACIA 2005; Serreze et al. 2000; Jorgenson, Shur, and Pullman 2006; Kokelj and Jorgenson 2013; Lantz and Kokelj 2008; Necsoiu et al. 2013; Negandhi et al. 2013; Marsh et al. 2009). The overall goal of my MSc research was to investigate the dynamics of ice wedge degradation at fine and broad scales, focussing on a study area in the upland tundra north of Inuvik, NWT. The conditions and feedbacks associated with ice wedge degradation have not been well-characterized at either a regional or fine scale, and further research is required to understand the ecological dynamics of degrading polygonal terrain, in anticipation of further permafrost warming.

This thesis explored two research questions, each of which was addressed in separate chapters. In Chapter 2, research was undertaken to answer the following question: What are the fine-scale biotic and abiotic factors and interactions associated with ice wedge degradation in the Mackenzie Delta region uplands? Three hypotheses were examined: 1) Changes to polygon microtopography from ice wedge subsidence will be associated with increases in soil moisture and active layer thickness; 2) The physical changes resulting from ice wedge degradation will drive changes in plant community composition, and 3) Changes to biotic and abiotic conditions associated with ice wedge degradation will initiate feedbacks affecting seasonal heat flux. In Chapter 3, research was undertaken to answer the following question: What are the broad-scale factors influencing the spatial and temporal distribution of melt ponds in the Mackenzie Delta region uplands?

The field investigations described in Chapter 2 of this thesis characterized biotic and abiotic conditions in stable and degrading high-centre polygons, and investigated ecological feedbacks influencing ground thermal regime following ice wedge degradation. Surveys were conducted at 23 sites that had stable and degrading high-centre polygons in the upland tundra north of Inuvik, NWT. Field sampling involved transects crossing three polygon micropositions (polygon centres, edges and troughs) and targeting four trough degradation classes representing a degradation sequence from stable troughs to ice wedge melt ponds. I measured surface microtopography, active layer depth, water depth, plant community composition, soil gravimetric moisture, late winter snow depth, and shallow annual ground temperatures across polygon microposition and degradation classes. High-centre polygonal terrain was characterized by abiotic gradients of decreasing ground surface elevation and increasing soil moisture, active layer depth, and shallow ground temperatures across polygon microposition. These gradients are consistent with the control microtopographic variation exerts over surface hydrology and local active layer thickness in permafrost environments. Field data indicated that these gradients drive differences in plant community composition between micropositions in stable terrain, with significant differences in the abundance of indicator species associated with different moisture regimes (ex. lichen, *Sphagnum* spp). More advanced levels of ice wedge degradation were associated with increases in soil moisture, standing water depth, ground surface collapse, active layer and snow pack compared to stable troughs, and created positive feedbacks for further degradation, including delayed freezeback and increasing ground temperatures. These changing abiotic conditions in troughs were associated with a shift from mesic upland tundra plant communities, to an increasing abundance of hydrophilic species, to unvegetated standing water in ice wedge melt ponds. Interactions between abiotic and biotic processes in degrading troughs directly and indirectly increased ground temperature, and contributed to positive feedbacks driving continued ice wedge degradation.

In Chapter 3 I analyzed the distribution of high-centre polygon fields, and the distribution of ice wedge melt ponds using high-resolution aerial photographs taken in 2004. Historical melt pond distribution at a subset of the mapped polygon fields was assessed using aerial photographs from 1972. Thermokarst activity in polygonal terrain adjacent to historical anthropogenic disturbances was also documented using airphotos, and precipitation data from meteorological stations in Tuktoyaktuk and Inuvik was examined for the years 1958 to 2006. GIS investigations showed that polygon fields are more abundant and larger in the northern part of the study area, where lacustrine sediments are more abundant and conditions for thermal contraction cracking are more favourable. Spatial variability in the density of polygonal terrain also corresponded to physiographic subdivisions of the study region (Rampton 1988). This highlights that the differences in topography, drainage, and abundance of lacustrine sediments are important broad-scale controls on the distribution of polygonal terrain.

Contemporary melt pond mapping and thermokarst assessments following anthropogenic disturbance showed that ice wedges at higher latitudes are more susceptible to degradation, with large increases in the severity of thermokarst north of 69.4°N, due primarily to the presence of larger and more abundant ice wedges. Comparisons of melt pond area between 1972 and 2004 showed that polygonal fields south of 69.4°N have exhibited little to no net change, whereas those north of 69.4°N have shown large increases and decreases in area. Spatial variability in the change in melt pond area, and lower than average total precipitation in 2004 suggests that these changes resulted from ice wedge degradation and not increased precipitation.

Together these chapters provide insight into the factors driving ice wedge degradation at multiple spatial scales in the Mackenzie Delta region uplands. At the regional-scale ice wedge degradation is not occurring uniformly, but is concentrated in the north of the study area, where there is a higher density of lacustrine deposits and polygonal terrain, and the greater abundance of larger ice wedges. Subregionally, areas of high melt pond proportion were found in the south of the study area where poorly-drained topography and lacustrine deposits were present, and ground ice conditions were likely similar to those in the north of study area. At fine scales, the variability in ice wedge trough characteristics within short distances in the same and adjacent polygon fields indicates that fine-scale environmental conditions also influence susceptibility to thaw and the process of degradation. Ice wedges in close proximity showed variable stages of degradation, ranging from stable mesic troughs to open-water melt ponds, and fine-scale biotic and abiotic characteristics varied significantly within short distances. Localized changes in soil moisture and microtopography within a degrading ice wedge trough initiate feedbacks that influence ground thermal conditions and the trajectory of degradation, in combination with changes in active layer depth, snow pack, and changes in plant community composition. These findings suggest that both broad and fine-scale factors influence the dynamics of ice wedge degradation. Variability in ground ice conditions, including differences in ice wedge abundance, size, and proximity to the ground surface, result in polygonal terrain with variable susceptibility to thaw under current climatic conditions at a broad scale. However, fine-scale biotic and abiotic conditions strongly influence the trajectories of melt pond development and stabilization through feedbacks that influence ground thermal conditions.

My thesis research also provides information on temporal aspects of melt pond dynamics: a snapshot of current conditions, changes in recent decades, and information on the future trajectories of polygonal terrain in response to permafrost warming and anthropogenic disturbance. In the south of the study area, past degradation from warmer temperatures and more frequent fires has repositioned the top of the remaining ice wedge below the contemporary position of the permafrost table, insulating it from further thaw. The observed stability of ice wedges in the southern part of the study area in response to recent temperature increases suggests that these sites represent the longer-term trajectory of recently degraded polygonal terrain in the north. Current warming at northern sites may set ice wedges on a similar trajectory. However, it is unclear if melt ponds developed and stabilized in the past in the south of the study area, or whether degradation ever progressed to melt pond development. If the development of melt ponds in the north of the study area is in fact a new phenomenon that occurs in areas with large ice wedges under the current and warming climatic conditions, then the trajectories of these features may be novel.

The field component of this research demonstrated that the biotic and abiotic conditions in degrading ice wedge troughs alter seasonal heat flux and drive positive feedbacks to further degradation. Ice wedge degradation increases soil moisture, subsidence, and snowpack, resulting in delayed freezeback and higher ground temperatures. Jorgenson et al. (2006) speculated that degrading ice wedges are quickly stabilized by processes of organic matter accumulation and the aggradation of permafrost above degraded ice wedges, which will require further investigation across the bioclimatic gradient in the Tuktoyaktuk coastlands.

Polygonal terrain is expected to continue to thaw with further increases in ground temperature. Understanding the dynamics of ice wedge degradation is a key part of understanding environmental change in permafrost environments. With likely increases in the rate of degradation, polygonal peatlands in the Mackenzie Delta region uplands and across the circumpolar Arctic may play an increasingly important role in global carbon cycling. Long-term ecological impacts to peatland ecosystems from ice wedge degradation are only partly understood, and along with carbon flux require further study given the potential magnitude of effects. My thesis research has identified several areas of research that should be explored in more detail.

One area that requires additional investigation is the melt pond dynamics of low-centred polygons. Necsoiu et al. (2013) documented the transition of a predominantly low-centred polygon field to one dominated by high-centre polygons, a process that occurred relatively rapidly between 1978 and 2005 and was characterized by the redistribution of surface water from polygon centres to troughs. This type of morphological change was not observed between 1972 and 2004 in the 54 polygon fields that were examined using high-resolution imagery. However, my analysis focussed on polygon fields with well-defined high-centre polygons and likely excluded polygons that may have undergone this kind of transition. Further work with high-resolution air photos focussing on the northern part of the study area where low-centre terrain is more prevalent (Lantz et al. 2014) would likely yield additional insights into ice wedge dynamics.

Increased ice wedge degradation is expected to occur with increasing air and ground temperatures and further work is necessary to understand the feedbacks that influence ice wedge degradation, and the ecological implications. The long term physical and ecological trajectories of melt ponds have not been studied. Data obtained in this study regarding the processes involved in limiting or promoting further ice wedge degradation were inferred from biotic and abiotic conditions in degrading and stable terrain measured at a single point in time. This work has provided some insight into the dynamics of ice wedge degradation and predictive information for future trajectories, and should be followed with long-term monitoring and experimental manipulations. Future research should monitor changes in existing melt pond characteristics with increasing ground temperatures, and quantify potential changes in the rate of melt pond development using the 1972 and 2004 airphotos and field data (2011/2012) as a reference point. Using a combination of remote sensing and field studies, physical changes in melt pond size (surface area and depth), connectivity with other troughs, hydrology, and processes of revegetation should be monitored on an annual basis. Long-term (10 year) monitoring of vegetation change in polygonal peatlands, particularly the expansion of tall shrubs and reductions in lichen cover, will be important because of the high density of this terrain type in the region, and the implications of changes in lichen abundance on the quality of caribou winter habitat.

One of the most pressing avenues of future research relates to carbon flux in degrading polygonal terrain. The northern circumpolar region holds an estimated 50% of the world's below-ground organic soil carbon (Tarnocai et al. 2009b), and increasing air temperatures have the potential to change this carbon sink to a source of greenhouse gases. The role of ice wedge degradation in the carbon cycle, and the magnitude of this contribution and its feedbacks to the global climate system have not been characterized. Ongoing research in the University of Victoria Arctic Landscape Ecology group is quantifying carbon emissions along an ice wedge degradation gradient, and investigating carbon lability in deep and shallow peat. Information on the abundance of polygonal terrain and extent of recent ice wedge degradation presented in this thesis will allow data on carbon emissions to be scaled-up across the region. Characterizing the rate and form of carbon emissions from degrading polygonal terrain is of particular importance given the high density of this feature in the region, and across the circumpolar Arctic.

Studies of tundra ponds have indicated that carbon cycling in shallow water is influenced by complex interactions between environmental conditions and microbial activity, with increasing temperatures and exposure to sunlight intensifying microbial turnover of organic carbon (Laurion and Mladenov 2013). The mechanisms driving these changes, and the icrobial communities involved in the breakdown of soil organic carbon in polygonal peatlands require additional investigation. Previous studies of the microbial gene pool in Arctic soils show that the metabolic potential for decomposition of soil organic carbon is similar to that found in warmer climates (Tveit et al. 2013). However, further study of saturated soils in polygonal terrain, including melt ponds, is needed to understand microbial processes and carbon cycling in this terrain type. Fields studies could target soils along a degradation gradient, as well as melt ponds.

A study of peat stratigraphy overlying stable and degrading ice wedges and nearby polygon centres across the bioclimatic gradient could be undertaken to better characterize the long-term dynamics of ice wedge degradation and stabilization and provide examples of past and current degradation. At stable and degrading ice wedges, peat cores could be collected to characterize vegetation dynamics above the ice wedge using techniques like pollen and plant macrofossil identification, radiocarbon dating, and isotope analysis. These investigations could help elucidate past episodes of ice wedge degradation, and the role that peat accumulation and vegetation succession played in thermally stabilizing the ice wedge trough. This type of investigation could also provide information on the timing of past degradation and allow inferences about environmental conditions to be made, providing context for current degradation in response to increasing ground temperatures. This approach has been used to study several peatlands in the Mackenzie Delta region (Vardy, Warner, and Aravena 1997; Vardy 1997).

Ground-ice rich terrain like high-centre polygons will continue to be impacted by increasing ground temperatures and anthropogenic disturbances. Variation in recent melt pond dynamics and variation in biotic and abiotic factors associated with ice wedge degradation described in this thesis suggest that trajectories may not be simple. Analysis of changes in individual melt ponds using airphotos combined with field sampling is likely needed to provide more information on the persistence of these features, and to predict future landscape-scale ecological changes and feedbacks to global carbon cycling.

The increased thaw sensitivity of polygonal terrain at higher latitudes has implications for the planning and maintenance of infrastructure (eg. minimizing thermal disturbance from surface disturbance and altered hydrology, dealing with ice wedge degradation and subsidence). The cumulative effects of disturbance on ground-ice rich landscapes like the uplands in Mackenzie Delta region may require careful study and management.

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