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Spatio-Temporal Variation in High-Centre Polygons and Ice-Wedge Melt Ponds, Tuktoyaktuk Coastlands, Northwest Territories

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ABSTRACT

High-centred polygonal terrain is a widespread feature of Arctic landscapes that is sensitive to increasing ground temperatures because of its high ground-ice content. Understanding spatial variation in the distribution and sensitivity of high-centred polygonal terrain is important for predicting landscape change. In the Tuktoyaktuk Coastlands, Northwest Territories, Canada, mean annual ground temperatures in permafrost have increased between 1 and 2°C over the last 40 years and high-centred polygonal terrain comprises about 10 per cent of the terrestrial landscape. To investigate factors affecting the distribution and potential degradation of ice wedges, we mapped high-centred polygonal terrain and ice-wedge melt ponds, and documented ice wedge related thermokarst at anthropogenic disturbances using 2004 aerial photographs. Historical melt pond distribution was assessed using 1972 aerial photographs. The density of polygonal terrain (up to 37%) was significantly higher in the northern than the southern part of the study area, where more abundant lacustrine sediments and lower ground temperatures have favoured ice-wedge development. Larger proportional melt pond area (0.68%), increases in pond area (up to 3.74%) and a higher frequency of major thermokarst activity following anthropogenic surface disturbance (54%) suggest that high-centred polygonal terrain in the northern part of the study area is more susceptible to degradation than in the southern part.

KEY WORDS: polygonal terrain; thermokarst; remote sensing; air photos; peatlands; ice wedge

INTRODUCTION

Across the Arctic, rising air temperatures have been accompanied by increases in permafrost temperatures and thermokarst activity (Kokelj and Jorgenson, 2013; Lantz and Kokelj, 2008; Lantz and Turner, 2015; Smith *et al.*, 2010). Thermokarst affects permafrost terrain when the thawing of ice-rich soils causes the loss of structural integrity and the collapse of the ground surface. Thermokarst disturbances strongly influence hydrology, soils, topography, snow pack, and sediment and nutrient flux to lakes and streams (Fortier *et al.*, 2007; Kokelj *et al.*, 2014). As such, an increase in their frequency will drive important landscape changes and influence the structure and function of northern ecosystems (Jorgenson *et al.*, 2006; Lantz *et al.*, 2009; Grosse *et al.*, 2011).

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Polygonal ice-wedge networks are common throughout areas of continuous permafrost (Lachenbruch, 1962). Since modern ice wedges are typically encountered near the top of permafrost, polygonal terrain is particularly susceptible to thermokarst (Jorgenson *et al.*, 2006). Ice wedges can develop in a range of surficial materials due to thermal contraction cracking of the ground in winter and infilling of the crack with meltwater to form a vein of ice. Repeated cracking may cause large ice wedges to develop (Leffingwell, 1915; Lachenbruch, 1962; Mackay, 1984, 1989). In low-lying, flat areas, polygonal terrain is often conspicuous because the microtopography is not obscured by slope processes (Mackay, 1995). In flat terrain, polygons can be classified based on their microrelief (Mackay, 2000; French, 2007). In low-centre polygons, a central depression is outlined by elevated ridges that bound a trough overlying the ice wedge. High-centre polygons consist of an elevated centre surrounded by subsided troughs overlying partially degraded ice wedges. In this paper, we focus on the high-centred polygonal terrain associated with relatively flat, poorly drained lacustrine deposits of the

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Tuktoyaktuk Coastlands (Mackay, 1989; Kokelj *et al*., 2014), where environmental conditions have led to the development of peat (Zoltai and Tarnocai, 1975; Vardy *et al*., 1997).

High-centre polygons are generally considered to be degradational features that originated as low-centre polygons (Mackay, 2000). An increase in active-layer thickness in high-centred polygonal terrain caused by rising air and ground temperatures, surface disturbance, or changes in hydrology can result in further ice-wedge thaw and surface subsidence. In poorly drained areas, water can accumulate in troughs, which may promote further degradation involving collapse of the outer edges of the polygon centres and lateral enlargement of the pond (Necsoiu *et al*., 2013; Jorgenson *et al*., 2006). These small waterbodies are referred to as melt ponds (Figure 1) and are readily identifiable on aerial photographs. As such, change in melt pond area, mapped with remotely sensed imagery, has been used as an indicator of ice-wedge degradation over time. A recent analysis of a time series of remotely sensed images of the Arctic Coastal Plain in northern Alaska showed an abrupt increase in the area and density of ice-wedge melt ponds, which was associated with a 2–5°C increase in mean annual ground temperature since the 1980s (Jorgenson *et al*., 2006). The authors estimated that 10 to 30 per cent of Arctic lowland landscapes may be extremely susceptible to thermokarst driven by ice-wedge degradation.

Even small increases in thaw depth have the potential to significantly alter polygonal terrain, influencing soil carbon storage (Lee *et al*., 2012; Tarnocai *et al*., 2009), near-surface hydrology, vegetation (Fortier *et al*., 2007; Jorgenson *et al*., 2006) and infrastructure (Nelson *et al*., 2002). However, the physical sensitivity of polygonal terrain is likely to vary with spatial patterns in ice-wedge size, thermal regimes, topography, surficial geology and climate (Kokelj *et al*., 2014). Consequently, it is likely that polygonal terrain will respond in a non-uniform manner to increasing air and ground temperatures.

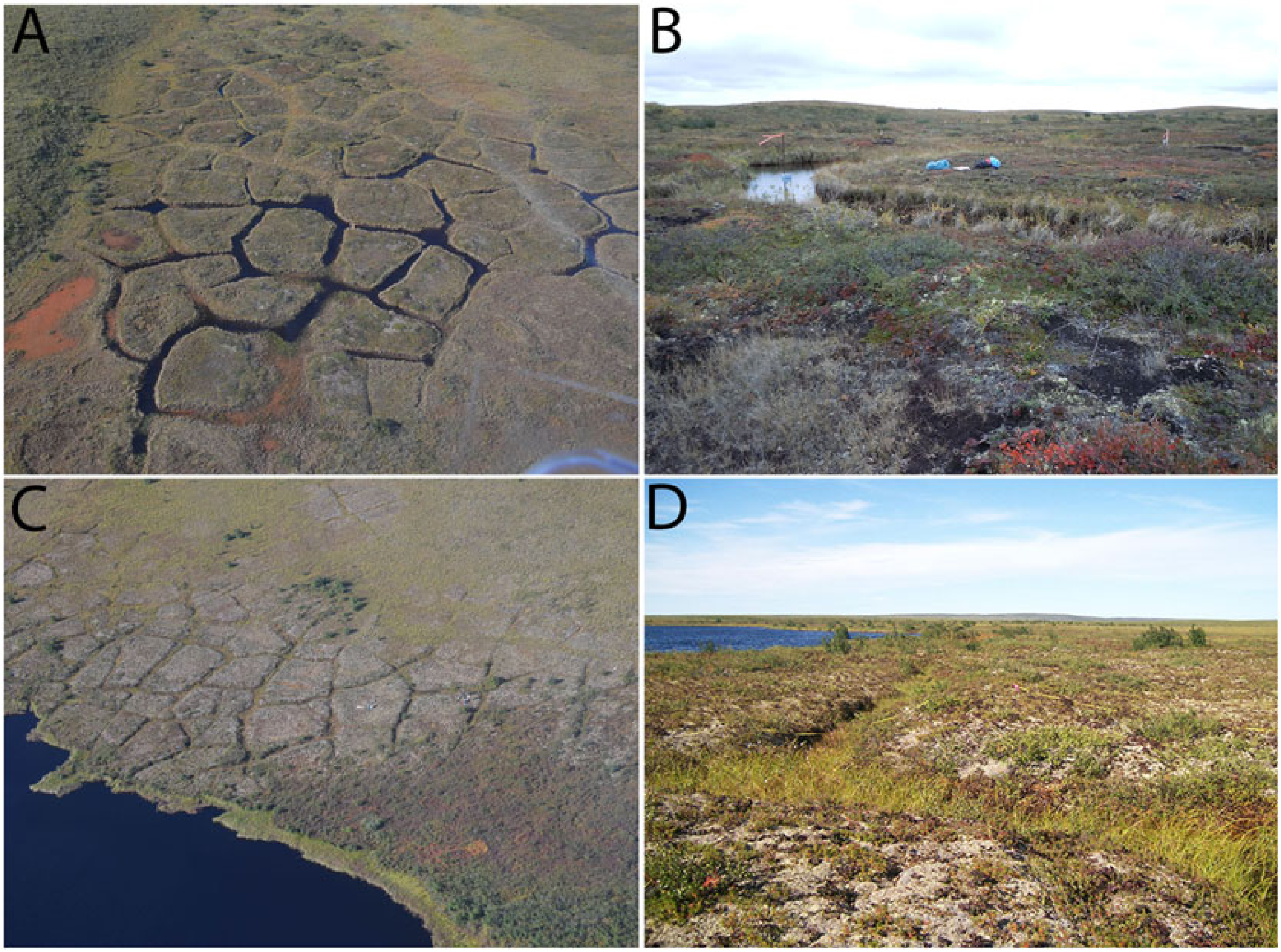

Figure 1 Oblique aerial photographs of high-centred polygon fields near (A, B) Tuktoyaktuk (69.366°N, 133.034°W) and (C, D) Jimmy Lake (68.646°N, 133.63°W). Large melt ponds are visible in the polygon field near Tuktoyaktuk (A, B). The polygon field near Jimmy Lake is characterised by vegetated ice-wedge troughs, visible in the ground photograph as a band of grassy vegetation in the foreground (D). This figure is available in colour online at wileyonlinelibrary.com/journal/ppp

In the Tuktoyaktuk Coastlands and northern Anderson Plain, a steep north-south gradient in air and permafrost temperatures results in the northward increase in the frequency of thermal contraction cracking, ice-wedge size and the abundance of polygonal terrain (Kokelj *et al.*, 2014). We suggest that variation in ice-wedge characteristics, in conjunction with local physiography and hydrology, influence the potential for terrain modification resulting from ice-wedge thaw. In this study, we focused on high-centred polygonal terrain and associated ice-wedge melt ponds, because it is the dominant form of polygonal terrain in the region. Throughout this paper, we refer to discrete areas of polygonal terrain as polygon fields. On the basis of regional variations in terrain physiography (Rampton, 1988), permafrost temperatures (Burn and Kokelj, 2009) and ice-wedge characteristics (Mackay, 1989, 2000; Kokelj *et al.*, 2014), we make the following hypotheses:

1. A northward increase in the proportion of the landscape covered by high-centred polygonal terrain is associated with the distribution of low-lying lacustrine basins.
2. Polygon fields in the northern part of the study area, underlain by larger ice wedges, are characterised by more extensive surface ponding than polygon fields in the southern part of the study region.
3. Change in melt pond area, and melt pond development associated with anthropogenic disturbance is greatest in the northern part of the study region, where ice wedges are largest and most abundant.

To test these hypotheses, we mapped the spatial distribution of high-centred polygonal terrain and examined the abundance and change in surface area of melt ponds between 1972 and 2004. To examine the potential influence of climate (air and ground temperatures) and regional variation in terrain attributes (surficial geology and topography), we examined our findings using latitudinal zones that bisect the regional climate gradient and the physiographic subdivisions defined by Rampton (1988).

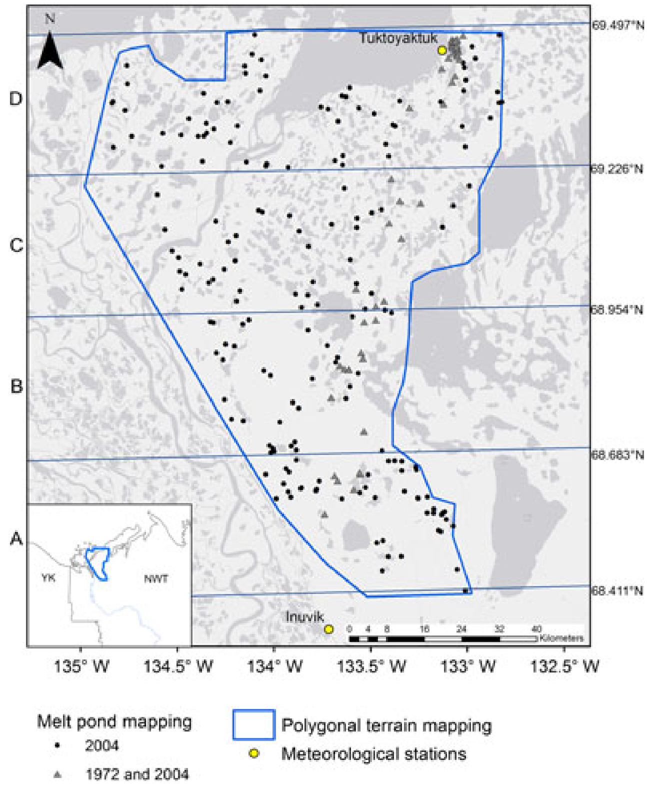

Figure 2 Map of the study area in the Tuktoyaktuk Coastlands. The outlined area shows where aerial photographs were used to map more than 22 000 polygon fields. Locations where polygon fields were assessed for melt ponds are shown as black circles (2004 mapping, n = 183) and grey triangles (1972 and 2004 mapping, n = 54). 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 Canada, and the Mackenzie River. NWT = Northwest Territories; YK = Yukon. This figure is available in colour online at wileyonlinelibrary.com/journal/ppp

STUDY AREA

Our study area, between the communities of Inuvik and Tuktoyaktuk, is located primarily in the Tuktoyaktuk Coastlands, but extends into the Anderson Plain (Figure 2). This area is within the continuous permafrost zone and is characterised by low, rolling hills and plains, inset with thousands of tundra lakes (Burn and Kokelj, 2009). Laurentide glacial ice covered the entire study area and remained in the southern part of the region during the Sitidgi Stade, as late as *c.* 13 000 ^{14}C years BP (Rampton, 1988). The area was ice-free shortly thereafter (Duk-Rodkin and Lemmen, 2000). A climate warmer than present during the early Holocene was associated with the development of regional thaw unconformity (Burn, 1997) and widespread thermokarst and the initiation of thaw lakes (Rampton, 1988; Murton, 1996). Gradual regional cooling commenced around 8000 ^{14}C years BP due to lower solar insolation (Ritchie, 1985) and more than 100 km of coastal retreat since the early Holocene (Burn, 1997). The influence of glaciation and periglacial processes throughout the Holocene has contributed to the present-day landscape of the Tuktoyaktuk Coastlands.

Advance and retreat of the Laurentide Ice Sheet have influenced landscape form, the distribution of surficial deposits, the formation of ground ice, and the nature and extent of thermokarst activity across the study region (Rampton, 1988; Murton, 1996; Mackay and Burn, 2002; Kokelj *et al.*, 2014). Surficial materials in the study area consist mostly of glacial deposits, including till moraine, till blanket and glaciofluvial materials (Rampton, 1988). Slope and thermokarst deposits occur in many areas, and lake drainage has produced widespread lacustrine basins, which are most extensive in the northern part of the study region (Rampton, 1988; Marsh *et al.*, 2009). A cold climate during the Holocene following Laurentide deglaciation has sustained permafrost hundreds of metres thick, preserving massive ground ice bodies and leading to the development of ice wedges and polygonal terrain. Rampton (1988) divided our study area into physiographic subdivisions on the basis of surficial geology and physiography. Physiographic subdivisions in the Tuktoyaktuk Coastlands and Anderson Plain defined by Rampton (1988) are shown in Figure 3. Hereafter, we refer to the area shown in Figures 2 and 3 as the Tuktoyaktuk Coastlands.

The regional climate in the study area is characterised by an air temperature gradient that is steepest in summer, with cooler temperatures towards the coast (Burn, 1997). The mean annual air temperatures for 1971–2000 at Tuktoyaktuk and Inuvik were -10.2°C and -9.0°C, respectively (Environment Canada, 2014). Inland areas receive more annual precipitation than coastal areas, with a mean annual snowfall (1981–2010) of 159 cm inland at Inuvik, and 103 cm at Tuktoyaktuk on the coast (Environment Canada, 2014). The climatic gradient across the region is associated with a transition from open spruce woodlands to upright shrub tundra in the southern part of the region and then to dwarf shrub and tussock tundra in the north, near the coast (Timoney *et al.*, 1992; Lantz *et al.*, 2010a). Ground temperatures decrease northwards, largely in association with a thinner snow cover in the north. In undisturbed terrain, near-surface mean annual ground temperatures (2003–07) ranged from -3 to -4°C in the south of the study area, to -6 to -7°C in the north (Burn and Kokelj, 2009). Mean annual ground temperatures have increased by 1 to 2°C since the mid-1960s (Burn and Kokelj, 2009). Active-layer thickness in high-centred polygonal terrain near Inuvik (68.3617°N) between 1999 and 2008 ranged from 45 to 65 cm. Farther north on Richards Island (69.1998°N), the depth of thaw in high-centred polygonal terrain during the same period was 35 to 55 cm (Burn and Kokelj, 2009). Anthropogenic disturbances in the study area include drilling of exploratory hydrocarbon wells and disposal of drilling muds and other materials in sumps excavated in the permafrost (Johnstone and Kokelj, 2008), mainly during the 1970s and 1980s (Aboriginal Affairs and Northern Development Canada and Technical Advisory Group, 2009).

Ice wedges are abundant in the Tuktoyaktuk Coastlands and may comprise up to 50 per cent (by volume) of the top metre of permafrost in some areas (Pollard and French, 1980). Ice wedges and polygonal terrain are found on hillslopes (Mackay, 1995) and in flat terrain (Mackay, 2000). However, polygonal terrain is most conspicuous in the latter setting, where ice wedges have developed following the aggradation of permafrost into lacustrine sediments exposed by the drainage of lakes throughout the Holocene (Mackay, 1992; Murton, 1996). Since the age of the lacustrine surfaces may differ significantly, the time available for the development of ice wedges in those post-glacial deposits may vary. Nevertheless, Kokelj *et al.* (2014) found that ice-wedge size and abundance increased northward in association with lower ground temperature and thermal conditions conducive to thermal contraction cracking. In tall shrub tundra in the southern part of our study region, polygonal terrain was found only in association with organic deposits, and ice-wedge tops were typically less than 2 m wide (Kokelj *et al.*, 2014). Further north in dwarf shrub tundra, ice wedges were present in both peatlands and fine-grained mineral soils, although wedges were typically larger and more abundant in peatlands. Drilling indicated that some ice wedges in organic deposits near Tuktoyaktuk exceeded 3 m width at the top of permafrost (Kokelj *et al.*, 2014). In this paper, we examine regional variation in high-centred polygonal terrain, which generally occurs in low-lying, flat or gently sloping terrain, where environmental conditions limiting the decomposition of organic matter facilitate the accumulation of peat (Murton, 1996; Vardy *et al.*, 1997).

METHODS

Polygon Field Mapping

Polygonal terrain in the 7941 km^2 study area was digitised on-screen by viewing georeferenced orthomosaics. These images were captured from 5 to 28 August 2004 as part of the Mackenzie Valley Airphoto project and have an effective pixel size of 0.5 m (NWT Centre for Geomatics, 2008). Polygonal terrain was mapped by manually digitising the boundaries of all areas greater than 0.01 ha dominated by polygons using ArcGIS (versions 9.3 and 10.0, Esri, Redlands, California, USA). Each polygon field was also classified as high-centre or low-centre by inspecting the photographs. In instances where polygon fields consisted of both high and low-centred terrain, we recorded the dominant morphology. Since polygon fields with poor surface expression are not detectable by visual inspection of aerial photographs, our mapping excludes polygons on hillslopes. As such, our analysis focuses on the distribution of high-centre polygon fields, predominantly associated with low-lying, flat terrain. To map the per cent of the landscape covered by high-centre polygons across the study area, we used the kernel density feature in Spatial Analyst (ArcGIS version 10.1), set to the default parameters: a search radius of 2.97 km (approximately 7 km^2) and a cell output size of 356.3 m.

Melt Pond Mapping

To map the regional distribution of melt ponds in the study area, we assessed a subset of the digitised polygon fields. One hundred and eighty-three polygon fields ($>$5000 m^2 in size and located $>$ 500 m from past tundra fires or drilling mud sumps) were randomly selected from the mapped population of polygon fields. An additional 54 polygon fields were selected from a portion of the study area that overlapped with 1972 aerial photograph coverage (see below). In each polygon field, all visible melt ponds larger than 1 m^2 were manually digitised in ArcGIS using the 2004 aerial photographs. To emphasise the contrast between standing water and other land-cover types, aerial photographs were viewed as red, green and blue (RGB) composites with a standard deviation stretch calculated using the entire aerial photograph. More than 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) the proportion of standing water (total melt pond area/polygon field area). To examine the relationship between the distribution and characteristics of melt ponds and the summer air temperature gradient in the study area, we divided the mapped area into four latitudinal zones spanning equal distances: (1) 68.411–68.683°N; (2) 68.683–68.954°N; (3) 68.954–69.226°N; and (4) 69.226–69.497°N.

To examine recent changes in melt pond area, we mapped 54 polygon fields on aerial photographs from 2004 that were also mapped using images from 16 to 28 July 1972. These high-resolution (1:12 000) greyscale images were obtained from the National Air Photo Library, georeferenced and used to digitise features. The images have an effective pixel size of 0.29 m. Melt ponds on the 1972 images were mapped in the same manner as those on the 2004 images. Initial analysis included 31 polygon fields randomly chosen within the latitudinal zones. 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 polygon fields within this part of the study area. 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 Near Anthropogenic Disturbances

Thermokarst activity in terrain impacted by anthropogenic disturbances was also assessed in the study area, using 109 disturbed sites identified from the 2004 aerial photographs. The majority of these sites are exploratory hydrocarbon leases and were disturbed at least 10 years prior to aerial photograph acquisition. To evaluate evidence of terrain modification resulting from ice-wedge degradation, aerial photographs and ground-level photographs were used to classify each site using three categories: (1) no evidence of ice-wedge degradation; (2) evidence of localised, minor to moderate ice-wedge degradation; and (3) evidence of widespread, major ice-wedge degradation. Categories were based on the intensity of impact and the aerial extent of disturbance. In our classification, sites in category 1 showed no evidence of ice-wedge trough formation or ponding. Sites in category 2 showed evidence of minor to moderate ice-wedge degradation, which affected less than 10 per cent of the lease. Degrading ice wedges at these sites are equivalent to stage 3 described by Jorgenson *et al*. (2006), which indicates some evidence of subsidence and shallow standing water over the troughs of a degrading ice-wedge network. Sites classified as category 3 showed evidence of major ice-wedge degradation, which impacted more than 10 per cent of the lease area. These sites had thermokarst intensity that is comparable to Jorgenson *et al*.'s stage 4, where at least some of the degrading ice wedges are characterised by deep, water-filled pits (Jorgenson *et al*., 2006).

Data Analysis

To examine regional variation in the distribution of high-centred polygonal terrain, we calculated the mean per cent cover of polygonal terrain by latitudinal and physiographic zone (Figure 3). To explore variation in the per cent cover of polygonal terrain and elevation, we used ArcGIS to calculate the mean elevation of each grid cell where we calculated the kernel density of polygonal terrain (proportion of the landscape covered). We also calculated the elevation and per cent cover of dominant surficial materials (Rampton, 1987) in each of these zones (Tables 1 and 2). To test for significant differences in the characteristics of melt ponds and polygon fields among latitudinal zones, we used one-way ANOVA. Data were log transformed to meet the assumption of normality. Tukey's honestly significant different test (95% family-wise confidence level) was used to perform pairwise comparisons of means. To examine the spatial patterns of proportional melt pond area in each polygon field, these data were mapped across the study area. We tested the hypothesis that the intensity of ice-wedge degradation is greater at anthropogenically disturbed sites in the northern part of the study area by grouping the 109 disturbed sites that we assessed into four latitudinal zones that corresponded to those used in the previous analysis (see the Melt Pond Mapping subsection). Chi-square tests were used to test for significant differences in the proportion

Table 1 Average summer temperature, elevation (mean, standard deviation and range), per cent cover of high-centred ice-wedge polygon fields (% HCPF) calculated using the kernel density function, the per cent cover based on the mapped surface area, and dominant surficial materials by latitude zone (Rampton, 1987, 1988).

Latitude zone	Average summer temperature[a]	Elevation mean ± standard deviation (m asl)	Elevation range (m asl)	Kernel density of HCPF		% HCPF by latitude zone	Dominant surficial materials	
				Range (%)	Mean (%)		Primary	Secondary
(A) 68.411–68.683°N	9.6°C	108.1 ± 35.7	7–246	0–11.3	2.2	2.1	Till (83%)	Lacustrine (6%)
(B) 68.683–68.954°N	8.8°C	88.0 ± 57.6	0–257	0–28.3	5.3	5.7	Till (47%)	Glaciofluvial (30%)
(C) 68.954–69.226°N	8.0°C	27.6 ± 18.5	0–162	0–33.8	8.5	8.7	Till (37%)	Glaciofluvial (31%)
(D) 69.226–69.497N	7.2°C	14.7 ± 11.8	0–75	0–36.9	11.1	11.1	Till (42%)	Lacustrine (28%)

[a]Mean summer temperature (June–August) in each zone was estimated using the regression equation presented in Lantz *et al*. (2010b).

Table 2 Elevation mean, (standard deviation and range), per cent cover of high-centred ice-wedge polygon fields (% HCPF) calculated using the kernel density function, the per cent cover based on the mapped surface area, and dominant surficial materials by physiographic subdivisions of the Tuktoyaktuk Coastlands (Rampton, 1987, 1988).

Physiographic subdivision number (Figure 3)	Physiographic subdivision area	Elevation mean ± standard deviation (m asl)	Elevation range (m asl)	Kernel density of HCPF (%)		% HCPF by physiographic subdivision	Dominant surficial materials	
				Range	Mean		Primary	Secondary
1	Tununuk Low Hills	23.7 ± 20.2	0–141	0–32.1	8.9	10.2	Till (40%)	Glaciofluvial (28%)
2	Kittigazuit Low Hills	22.0 +/- 12.5	0-75	0-36.9	7.8	9.0	Till (70%)	Glaciofluvial (13%)
3	Kugmallit Plain	8.5 +/- 6.2	0-49	0-28.7	8.2	14.5	Lacustrine (65%)	Till (17%)
4	Low Involuted Hills	13.0 +/- 8.5	0-55	4.2-34.9	13.4	13.6	Till (48%)	Lacustrine (44%)
5	West Tuk Peninsula Axis	31.0 +/- 15.3	0-96	1.8-24.5	7.7	7.8	Glaciofluvial (54%)	Lacustrine (24%)
6	Eskimo Lakes Fingerlands	7.4 +/- 7.4	0-49	0.2-33.8	10.5	10.2	Till (40%)	Glaciolacustrine (19%)
7	Parsons Lake Plain	47.1 +/- 15.1	26-133	0-27.6	9.8	10.8	Lacustrine (49%)	Till (21%)
8	Eskimo Lakes Pitted Plain	33.1 +/- 30.5	0-131	0-20.0	4.9	5.7	Till (42%)	Glaciofluvial (32%)
9	North Caribou Hills	141.1 +/- 43.7	17-257	0-12.7	3.2	3.3	Till (73%)	Colluvial (18%)
10	South Caribou Hills	103.6 +/- 34.0	12-217	0-11.9	1.7	1.6	Till (80%)	Colluvial (10%)

of sites characterised by various intensities of ice-wedge thaw (categories 1, 2 or 3) among latitudinal zones. The alpha value of 0.05 was adjusted using the Bonferroni correction for six pairwise comparisons among latitudinal zones.

RESULTS

Polygon Field Mapping and Kernel Density

Mapping across the study area identified 60 246 ha of polygonal terrain, comprising 12.5 per cent of the terrestrial study area. Fields dominated by high-centre polygons were more common than those dominated by low-centre polygons, with 92 per cent of mapped polygon fields classified as high centre and comprising 10 per cent of the terrestrial study area. Only 8 per cent of mapped polygon fields were classified as low centre, and these comprised 2.5 per cent of the terrestrial study area. High-centred polygonal terrain was present in most surficial units mapped by Rampton (1987), but was most abundant in morainal (36%), lacustrine (33%) and glaciofluvial (22%) deposits (Figure 3, Table 3). In our mapping of the Tuktoyaktuk Coastlands, high-centred polygonal terrain is almost invariably associated with low-lying and low-relief areas, most of which are wetlands or underlain by lacustrine deposits (Figure 5) (Murton, 1996; Vardy *et al*., 1997). The regional surficial geology map compiled by Rampton is at a scale of 1: 500 000 and the resolution is insufficient to capture the numerous small areas of lacustrine terrain which host the majority of the high-centre polygons. Since drained lakes are larger and more abundant in the northern part of the study area (Marsh *et al*., 2009), coarse-scale mapping likely underestimates the area of lacustrine sediments in some of the northern physiographic zones (Table 1).

The per cent of the landscape covered by polygonal terrain increased northward by latitudinal zone (Table 1; Figure 3). The cover of polygonal terrain was highest in the northern part of the study area (north of 68.88°N), where the area covered ranged from 0 to 37 per cent of the landscape (Figure 3). South of 68.88°N, there was a marked decrease in the coverage of polygon fields, with the proportional area occupied ranging from 0 to 11.3 per cent (Figure 3). The northward increase in the per cent cover 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 did not differ significantly, but north of 68.95°N the average area of polygon fields increased significantly with latitude (Figure 4A, $p < 0.05$).

The spatial distribution of high-centre polygons was also associated with the physiographic subdivisions defined by Rampton (1988) (Figure 3; Table 2). The subdivisions with a low coverage of polygonal terrain generally occurred in the southern part of the study region, including the North Caribou Hills and South Caribou Hills. Topography in the Caribou Hills is controlled by bedrock, overlain by well-drained tills. In this physiographic unit, lacustrine deposits are not a dominant surficial material (Table 1). In the

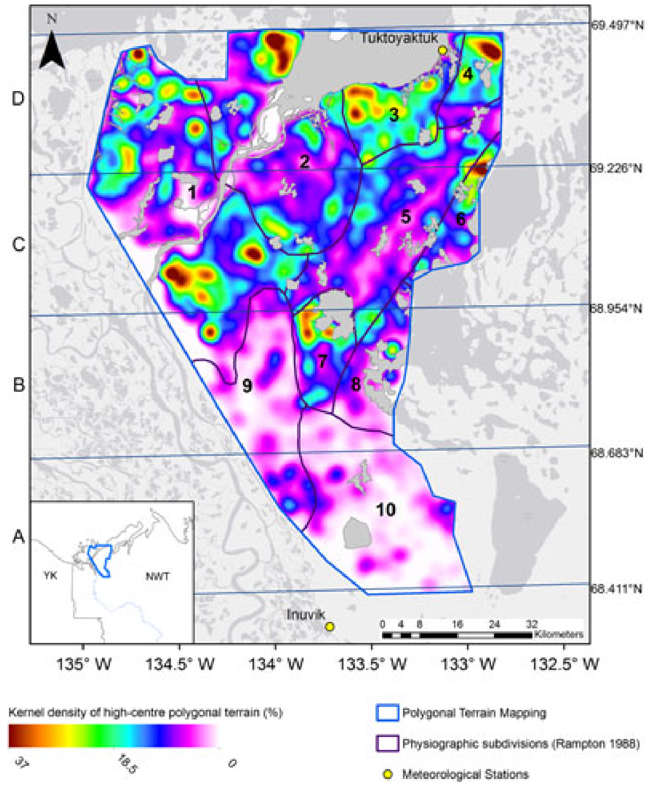

Figure 3 Kernel density of high-centred polygonal terrain in the study area. The map shows the proportion of the landscape (0–37%) that is occupied by high-centre polygons. The lines across the study area distinguish the four latitudinal zones used in the analysis (A–D). Lakes larger than 500 ha are 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 Plain; (8) Eskimo Lakes Pitted Plain; (9) North Caribou Hills; (10) South Caribou Hills. The inset at the bottom left shows the location of the study area in northwestern Canada, and the Mackenzie River. NWT = Northwest Territories; YK = Yukon. This figure is available in colour online at wileyonlinelibrary.com/journal/ppp

southern portion of the study area, the highest per cent coverage of polygonal terrain occurred on the boundary between the North and South Caribou Hills (68.63°N, 134.49°W). The coverage of polygonal terrain was generally higher in the northern part of the study area (Table 3; Figure 3). Lower elevations within the Tuktoyaktuk Coastlands, typically characterised by lacustrine plains, were associated with a higher per cent area occupied by high-centred polygonal terrain (Figure 5).

Melt Pond Mapping 2004

Mapping of ice-wedge melt ponds using 2004 aerial photographs 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.

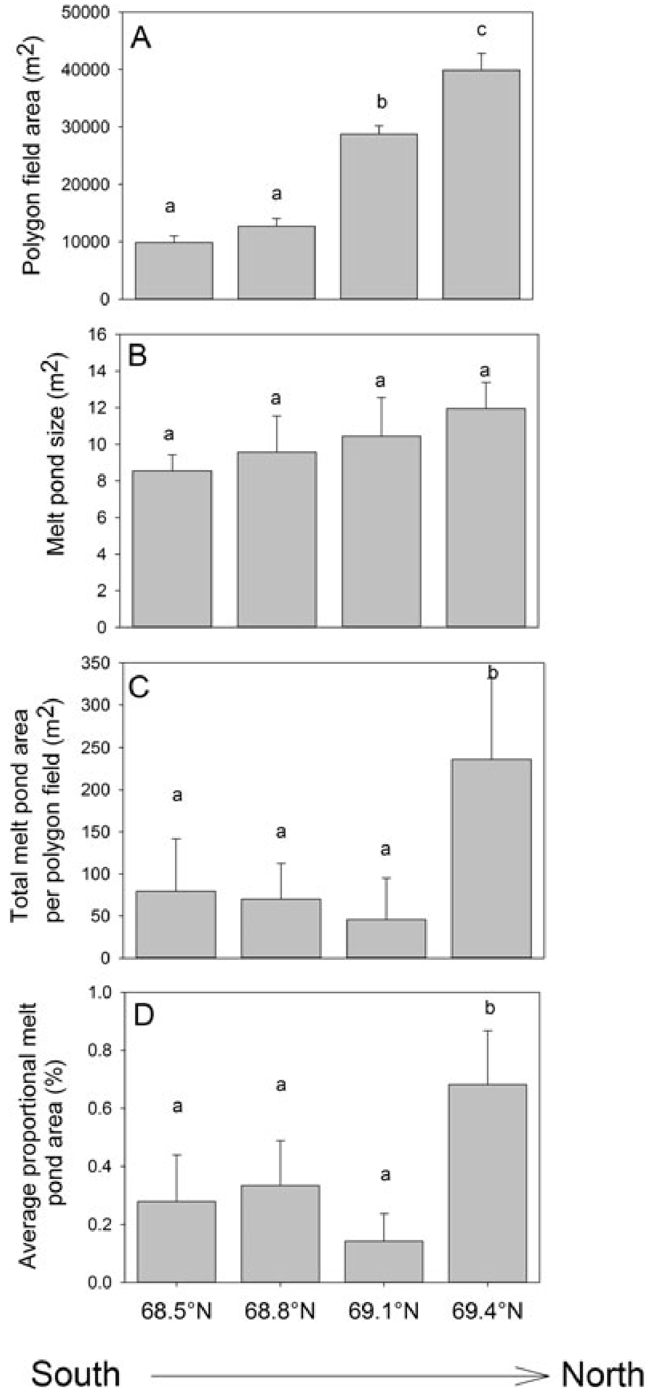

Figure 4 Polygon field and melt pond characteristics by latitudinal zone (2004): (A) mean individual polygon field area (m^2); (B) mean individual melt pond size (m^2); (C) total melt pond area per polygon field (m^2); (D) average proportional melt pond area (%). The midpoint of each latitudinal zone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

Table 3 Evidence of terrain modification due to ice-wedge degradation at sites impacted by anthropogenic disturbances.

Latitudinal zone	No degradation (category 1)	Minor to moderate degradation (category 2)	Major degradation (category 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) 69.23–69.69°N	3	21	28	52
Total	32	44	33	109

Chi-square analysis indicated that the proportion of ice-wedge degradation categories were not equal between all latitudinal zones ($p < 0.001$). The southernmost latitudinal zone was characterised by a significantly higher proportion of sites showing no ice-wedge degradation, whereas the northernmost zone had a significantly higher proportion of sites showing extreme degradation ($p < 0.01$).

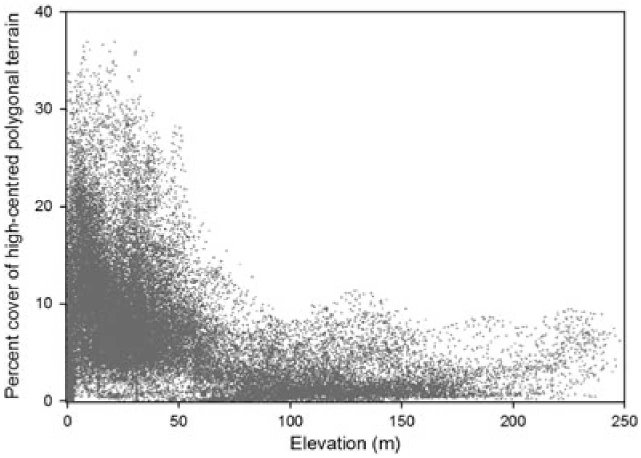

Figure 5 Scatter plot showing the relationship between elevation and the per cent of the landscape covered by high-centred polygonal terrain in the study area.

Average individual melt pond size consistently increased with latitude, but the differences were not significant (Figure 4B). Total melt pond area per polygon field ranged from 0 to 3086 m^2, with the highest average area observed in the most northerly zone (236 m^2). The mean melt pond area in the northernmost zone was significantly greater than the remaining latitudinal zones, which were not significantly different from one another (Figure 4C). The proportional melt pond area (Figure 4D) was also greatest in the northernmost zone (0.7%), and was significantly greater than in the remaining latitudinal zones, which were not significantly different from one another. Mapping the proportional melt pond area per polygon field (Figure 6) 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 (68.63°N, 134.49°W) both showed numerous polygon fields with a relatively high proportion of melt ponds (Figure 6).

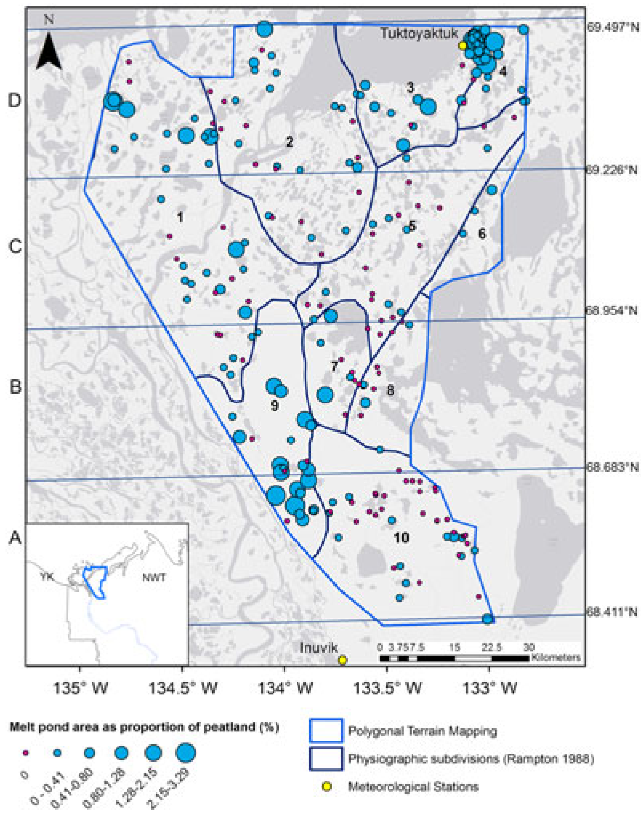

Figure 6 Map showing the proportion of each polygon field occupied by melt ponds. The lines across the study area distinguish the four latitudinal zones used in the analysis (A–D). The inset at the bottom left shows the location of the study area in northwestern North America, and the Mackenzie River. See Figure 3 for physiographic subdivisions. NWT = Northwest Territories; YK = Yukon. This figure is available in colour online at wileyonlinelibrary.com/journal/ppp

Historical Comparison

Fifty-four of the polygon fields examined for melt ponds using 2004 imagery were also examined using 1972 imagery, and increases and decreases in melt pond area were observed (Figures 7 and 8). A plot of the change in proportional melt pond area from 1972 to 2004 shows that many of the areas mapped did not show an increase in ice-wedge ponding (Figure 9). South of 69.4°N nearly half of the polygon fields (13 of 27) showed no net change in proportional melt pond area, and the remainder showed net increases or decreases less

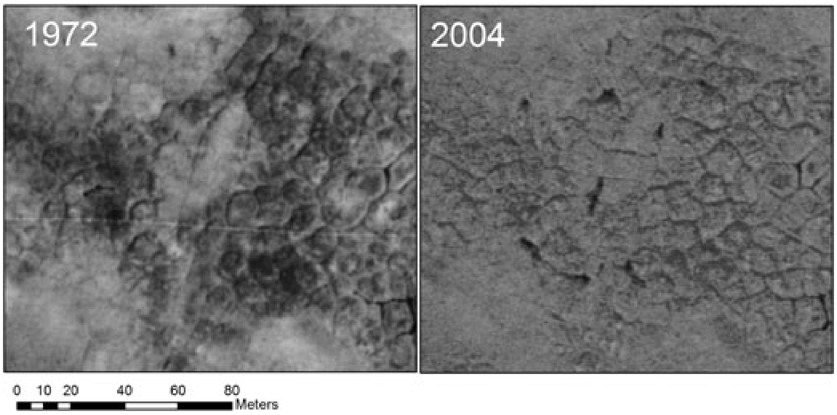

Figure 7 An example of a high-centred polygon field (69.472°N, 132.973°W) showing an increase in melt pond area from 1972 to 2004.

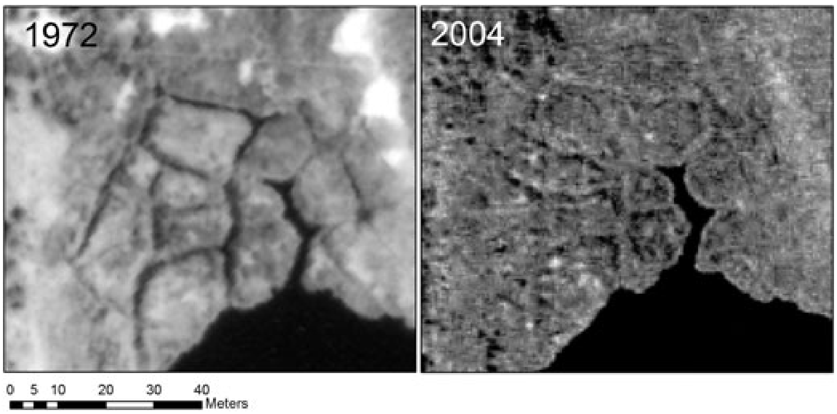

Figure 8 An example of a high-centred polygon field (69.444°N, 132.951°W) showing a decrease in melt pond area from 1972 to 2004.

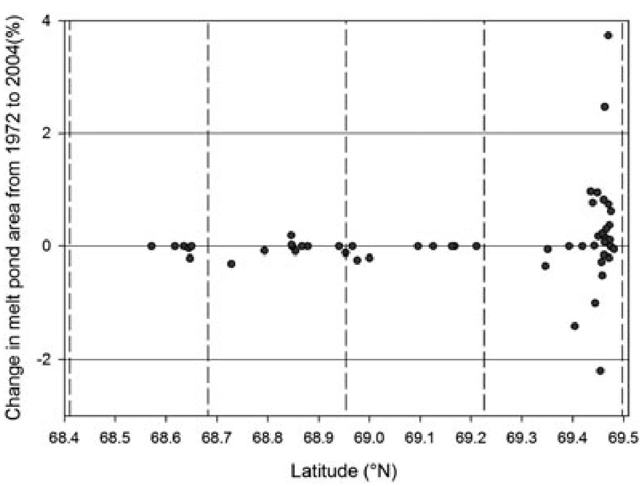

Figure 9 Change in proportional melt pond area per polygon field from 1972 to 2004 (%). Boundaries of the four latitudinal zones are shown as dashed lines.

than 0.35 per cent of the field area. Conversely, north of 69.4°N, nearly half of the polygon fields mapped showed increases or decreases greater than 0.35 per cent (13 of 27). The largest increase (3.74%) and largest decrease in proportional melt pond area (2.20%) occurred 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 per cent increase within the total area assessed for change. The net change in melt pond area from 1972 to 2004 south of 69.4°N was a 721m^2 loss, whereas north of 69.4°N there was a gain of 2165m^2, which represent changes of 0.07 per cent and 0.38 per cent, respectively.

Ice-Wedge Thermokarst Near Anthropogenic Disturbances

Of the 109 anthropogenically disturbed sites assessed, 32 showed no evidence of ice-wedge degradation (category 1), 44 showed evidence of minor or moderate ice-wedge degradation (category 2) and 33 showed evidence of major ice-wedge degradation (category 3). Thermokarst driven by ice-wedge degradation at anthropogenically disturbed sites was significantly more common in the northern part of the study area (Table 3; Figure 10). Eleven areas of anthropogenic disturbance were located within the southernmost latitudinal zone and all showed no evidence of ice-wedge subsidence (category 1). Most disturbed sites within the two central latitudinal zones exhibited minor or moderate subsidence due to ice-wedge degradation (category 2), or no subsidence (category 1). Within the northernmost latitudinal zone, major subsidence (category 3) was most common (54% of sites). Chi-square analysis of the whole data-set indicated that the proportions of ice-wedge subsidence categories were not equal between all latitudinal zones ($p < 0.001$). The southernmost latitudinal zone was characterised by a significantly higher proportion of sites with no ice-wedge subsidence. The central latitudinal zones were characterised by significantly higher proportions of no, minor or moderate subsidence. The northernmost zone was characterised by a higher than expected proportion of sites with major subsidence ($p < 0.01$).

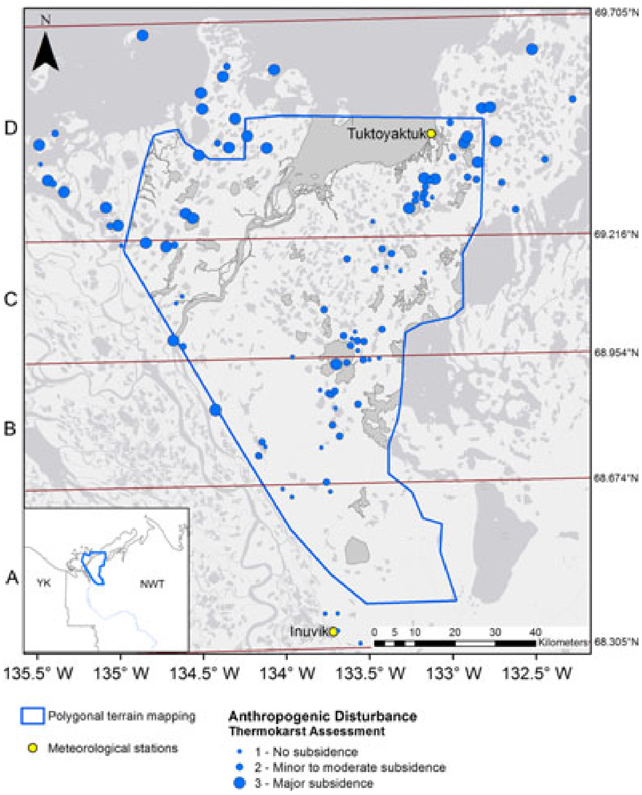

Figure 10 Sites of anthropogenic disturbance assessed for subsidence due to ice-wedge degradation. The majority of these disturbances are historical oil and gas leases from the 1970s and 1980s. The lines across the study area distinguish the four latitudinal zones used in the analysis (A–D). Three categories of thermokarst are shown: (1) no evidence of ice-wedge degradation; (2) evidence of minor or moderate subsidence due to ice-wedge degradation; and (3) evidence of major 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. NWT = Northwest Territories; YK = Yukon. This figure is available in colour online at wileyonlinelibrary.com/journal/ppp

DISCUSSION

Spatial Distribution of Polygonal Terrain in the Tuktoyaktuk Coastlands

The greater density and size of high-centre polygon fields in the northern part of the study area are partly due to an increase in the dominance of terrain conducive to ice-wedge growth. Drained lake basins dominated by lacustrine deposits are more common in the northern part of the study area (Rampton, 1987; Marsh *et al.*, 2009) and this terrain type favours the accumulation of peat and the formation of ice wedges (Aylsworth *et al.*, 2000; Kokelj *et al.*, 2014). Kokelj *et al.* (2014) showed that the contrasting physical properties of peat and mineral soils influence the distribution of wedge ice across the study area. The high coefficient of thermal contraction in saturated organic soils explains why ice wedges are common in organic deposits throughout the study area, but largely absent in fine-grained soils in the southern portion of the study area. In the south, polygonal terrain is restricted to organic deposits, which are limited by the extent of low-lying lacustrine terrain and wetlands. The study region is also characterised by a steep climate gradient, and variation in ground temperature accounts for the large contrasts in ice-wedge conditions across a relatively small latitudinal gradient. Our observation that polygon fields are more abundant and larger in the northern part of the study area (Figure 4A) is also consistent with recent work showing that a latitudinal increase in thermal contraction cracking and ice-wedge size is associated with a northward decline in ground temperatures and snow cover (Kokelj *et al.*, 2014). Thermal contraction cracking and ice-wedge development are 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 *et al.*, 2007, 2014).

Differences in the density of polygonal terrain among physiographic subdivisions (Rampton, 1988) may also be attributed to variation in surficial geology, elevation and drainage patterns (Figure 3; Table 2). Physiographic zones in the northern part of the study area contain a high density of polygonal terrain because this area is low-lying, poorly drained and has greater coverage of lacustrine sediments and small drained lake basins (Ecosystem Classification Group, 2012; Rampton, 1987; Marsh *et al.*, 2009). The three physiographic zones with the highest percent cover of mapped polygon fields have lacustrine deposits covering over 40 per cent of their areas, are low in elevation and have low relief. A comparison of polygonal terrain density and elevation also shows that high densities of high-centre polygon fields are limited to low-lying areas (Figure 5). The effect of topography is most evident at the boundary between the relatively well-drained Caribou Hills, which contains a low 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). High densities of polygonal terrain in most subdivisions within the Tuktoyaktuk Coastal Plain ecoregion were associated with poorly drained areas with a higher abundance of lacustrine sediments (Rampton, 1988). Regions of the study area that were characterised by a low density of polygon fields were associated with increased topographic variation, better drainage and the absence of lacustrine deposits as a dominant surficial deposit (Table 2; Figures 3 and 5). Throughout the study area, low densities of high-centred polygonal terrain were associated with ice contact and morainal deposits, including eskers, kames, kettles and outwash plains (Rampton, 1987). In the southern part of the study area, the only area with a high density of polygonal terrain is located in part of the North Caribou Hills dominated by poorly drained depressions that resemble ancient lacustrine basins (Rampton, 1988).

Spatial and Temporal Variation in Ice-Wedge Degradation

Mapping of modern melt ponds and thermokarst assessments following anthropogenic disturbance show that ice-wedge polygons at higher latitudes in the Tuktoyaktuk Coastlands are more susceptible to degradation. The total and proportional melt pond area, and subsidence following disturbance were all greatest north of 69.4°N. It is likely that lower air and permafrost temperatures in the north of the study area have facilitated the development of large ice wedges truncated by the base of the active layer (Kokelj *et al*., 2014), which, in conjunction with poor drainage, makes polygonal fields here highly susceptible to thaw subsidence, pond development and enlargement due to disturbance or climate-driven permafrost warming. In the southern part of the study area, small ice wedges are often truncated below the base of the modern active layer and may be less susceptible to topographic modification by thermokarst (Kokelj *et al*., 2007, 2014).

Recent changes in melt pond area provide additional evidence that the northern part of the study area is more susceptible to terrain modification as a result of ice-wedge degradation. The majority of anthropogenic disturbances in the northernmost part of the study area also showed evidence of major subsidence and ponding. In contrast, there was little to no evidence of ice-wedge degradation at southern sites. Together, these findings clearly indicate that the large ice wedges in the north make this area more susceptible to terrain alteration as a result of ice-wedge degradation. The limited evidence of ice-wedge thaw at anthropogenic sites in the south is also consistent with the notion that ice wedges are less common there.

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 pond growth or drainage (Raynolds *et al*., 2014). Decreases in melt pond area may also have resulted from feedbacks limiting melt pond growth and inhibiting thermokarst development. It has been observed that after ice-wedge degradation produces a melt pond, aquatic vegetation growth, peat accumulation and permafrost aggradation can reduce ponding and may prevent further degradation (Jorgenson *et al*., 2006).

The magnitude of recent ice-wedge degradation in the study area is considerably lower than reported in studies of Alaskan tundra. Jorgenson *et al*. (2006) and Necsoiu *et al*. (2013) reported that melt ponds occupy 3–4.4 per cent of the polygon fields mapped. In a highly disturbed part of the Alaskan North Slope, Raynolds *et al*. (2014) reported that ice-wedge thermokarst had affected 12.5 per cent of high-centred polygonal terrain. In the Tuktoyaktuk Coastlands, on average, melt ponds occupied 0.368 per cent and never exceeded 3.29 per cent of mapped polygon fields. All of these studies examined the abundance of melt ponds within relatively homogeneous areas of polygonal terrain. However, our study was conducted within a larger and more variable area in terms of topography, drainage, surficial deposits and climate. These contrasts highlight the high degree of variation in the response of ice-rich landscapes to a changing climate.

Implications for Environmental Change

The potential for permafrost degradation due to increasing temperatures, changing hydrology or disturbance differs across the Tuktoyaktuk Coastlands. 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 temperatures (Burn and Kokelj, 2009). North of 69.4°N, an increase in open-water melt pond area of 0.38 per cent between 1972 and 2004 indicates greater terrain sensitivity than in areas to the south. If we assume that a similar increase occurred across the entire study area north of 69.4°N, over 200 000 m^2 of open-water melt ponds may have developed due to ice-wedge degradation. Significant terrain modification due to ice-wedge degradation at most historic oil and gas exploration leases in the northernmost latitudinal zone indicates that this landscape is underlain by large ice wedges and terrain sensitivity is high in comparison with the southernmost part of the study region (Figure 10). The increased thaw sensitivity of polygonal terrain at higher latitudes has implications for infrastructure in the region, including the construction and maintenance of the Inuvik-Tuktoyaktuk highway, potential oil and gas exploration and development activities, and the long-term integrity of historical infrastructure.

CONCLUSIONS

High-centred polygonal terrain occupies about 10 per cent of the land area of the Tuktoyaktuk Coastlands. Spatial pattern in the density of polygonal terrain is related to both physiographic and climatic variability in the study area. The higher density of high-centred polygonal terrain in the northern part of the study area and several central physiographic zones was associated with the greater abundance/extent of lacustrine terrain, and lower ground temperatures and thinner snow pack.

High-centre polygons in the northern portion of the Tuktoyaktuk Coastlands (e.g. Low Involuted Hills, Eskimo Lake Fingerlands) are more susceptible to degradation and thermokarst because the underlying wedges are large and close to the ground surface. Melt ponds were significantly larger and occupied a greater proportion of polygon fields in the northernmost latitudinal zone than those in the southern part of the study region. North of 69.4°N, we also observed large increases and decreases in melt pond area between 1972 and 2004, resulting in a net increase of 1444 m^2 of open water (0.09% of the total area assessed for change). At anthropogenic disturbances in the northernmost latitudinal zone, major terrain modification due to ice-wedge thaw was observed at 54 per cent of the sites, but was not observed at any disturbed sites in the most southern latitudinal zone.

AUTHOR INFORMATION

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

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