Permafrost degradation adjacent to snow fences along the Dempster Highway, Peel Plateau, NWT

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ABSTRACT
The long-term ground thermal effects of a snow fence in continuous permafrost (Fence 1) were examined on Peel Plateau, west of Fort McPherson, NWT. Active-layer thicknesses and vegetation changes were also described at three additional fences (Fences 2-4). The fences were erected in the early 1980s, so present environmental conditions represent the effects of over 30 years of modification to snow conditions. We observed increased snow cover, active-layer thickness (ALT), and moisture content at Fence 1, which have combined to prevent winter freezeback, so that a talik now exists at the site. ALTs were statistically related to distance from the fence at flat sites, but not at sites of slope ≥5° with good drainage.

RÉSUMÉ
Les effets thermaux à long terme d'une clôture de neige située dans le pergélisol continu (Fence 1) ont été examinés sur Plateau Peel, à l'ouest du Fort McPherson, TNW. Des changements d'épaisseur du mollisol et de la végétation près de trois clôtures additionnelles ont aussi été décrits (Fences 2-4). Les clôtures ont été érigées au début des années 1980, par conséquent les conditions environnementales actuelles représentent les effets des modifications des conditions de la neige sur plus de 30 ans. Nous avons observé une augmentation de la couverture de neige, de l'épaisseur du mollisol, et de la teneur d'humidité à Fence 1, dont les effets combinés ont empêché le regel de l'hiver, ce qui a eu pour conséquence de créer un talik à ce site. L'épaisseur du mollisol a été statistiquement reliée à la distance à partir de la clôture sur les sites plats, mais pas sur les sites où la pente est ≥5° avec du drainage.

1 INTRODUCTION

Snow fences are common engineering structures throughout cold regions. They are typically constructed to reduce snow accumulation and increase visibility at infrastructure by reducing wind velocity and promoting snow deposition near the fence (Freitag and McFadden 1997). Snow fences are economic because their construction cost is easily recuperated by reducing expenditures on snow removal (Tabler 1991). In flat ground, snow fences with a porosity of 50 % placed perpendicular to the prevailing wind may trap snow within a distance of 15H in the upwind direction and 30H in the downwind direction, where H is the height of the snow fence (Tabler 1991, Fig. 9).

In permafrost regions, snow fences alter the ground thermal regime because they trap blowing snow, limiting ground heat loss and prolonging active-layer freeze back. As a result, near-surface ground temperatures in winter are considerably higher near snow fences (Mackay 1978, 1993; Hinkel et al. 2003; Kurunaratne and Burn 2003; Hinkel and Hurd 2006; Burn et al. 2009). Over time, the warming effect on the ground may cause subsidence if ice-rich permafrost degrades (e.g. Hinkel and Hurd 2006). While snow fences may solve issues of local snow accumulation and visibility, they may become problematic if the thermal regime in ice-rich terrain is disturbed. For example, in Kaktovik, Alaska, the construction of a snow fence to reduce snow accumulation in the village has caused a network of ice-wedge polygons to degrade. The subsidence around the fence has created the potential for a stream to form along the structure, which might drain an adjacent lake – the town's source of drinking water (Nolan 2010).

Past research has identified the ground thermal effects of enhanced snow accumuation at fences (Mackay 1978, 1993; Hinkel et al. 2003; Kurunaratne and Burn 2003; Hinkel and Hurd 2006; Burn et al. 2009; Lafrenière et al. 2013), and reported on ground subsidence and vegetation changes near the structures over several years following their erection (e.g. Hinkel and Hurd 2006; Burn et al. 2009; Johansson et al. 2013). However, to our knowledge, none have examined longer-term (multi-decadal) effects of snow fences in different topographic settings.

In an applied context, these topics should be explored near highways because snow fences may initiate thermokarst processes in close proximity to the road embankment. Infrastructure managers may benefit from an understanding of the long-term response of permafrost to these installations, to help plan future projects. Therefore, the objectives of this study were to (1) examine ground thermal effects of a long-standing snow fence along the Dempster Highway on Peel Plateau, west of Fort McPherson, NWT, and (2) describe resulting active-layer thicknesses and vegetation changes near this fence, and at three additional snow fences in the region.

2 BACKGROUND

Snow cover is the most important local control on ground temperatures in the continuous permafrost zone (Mackay and MacKay 1974; Zhang 2005). The latent heat content of the active layer also influences the freezeback period and resulting permafrost temperatures. Complex relations exist between snow cover, ground thermal conditions, active layer soil moisture, and vegetation in tundra environments (e.g. Sturm et al. 2001; Kokelj et al. 2010; Morse et al. 2012). For example, winter ground temperatures commonly rise as tall shrubs establish and trap snow, causing an increase in active-layer thickness (ALT) (Sturm et al. 2001). However, ALT may thin over time as the shrub canopy develops (e.g. Mackay and Burn 2002; Blok et al. 2010), despite relatively high winter ground temperatures (Gill et al. 2014).

2.1 Study area

The study was conducted along the Dempster Highway on Peel Plateau and in Richardson Mountains, between the Yukon/NWT border and Peel River (Figure 1). The region is in the continuous permafrost zone. The Dempster Highway is an all-season gravel road that connects the communities of Fort McPherson, Tsiigehtchic, and Inuvik, NWT to southern Canada. The highway is important to the communities because it facilitates the flow of goods and services and supports regional tourism. The Dempster Highway transportation corridor is currently being extended to connect with the Beaufort Sea coast at Tuktoyaktuk.

The Peel Plateau region has a continental climate with long, cold winters and short, cool summers. The mean annual air temperature (1987-2006) is -7.0 °C at the Fort McPherson airport, the nearest long-term meteorological station, which was in operation until 2007. Total annual precipitation averages 295 mm, with 148 mm falling as rain (Environment Canada 2012). Precipitation falls mostly in late summer and early fall. The dominant winter winds blow from the north.

The substrate on Peel Plateau consists of fine-grained, glacially-derived sediments underlain by marine shale and siltstone bedrock (Norris 1984). In Richardson Mountains, near-surface sediments mostly consist of discontinuous till and colluvial deposits (Fulton 1995).

Permafrost temperatures in the tundra environment on Peel Plateau are relatively high (~-2 °C) partly due to strong winter air temperature inversions (O'Neill et al. 2015). In addition, permafrost is characteristically ice-rich in the near surface, and may contain massive ground ice at depth (Kokelj et al., 2013; Lacelle et al. 2015). As a result, permafrost is sensitive to disturbances that affect the surface energy balance.

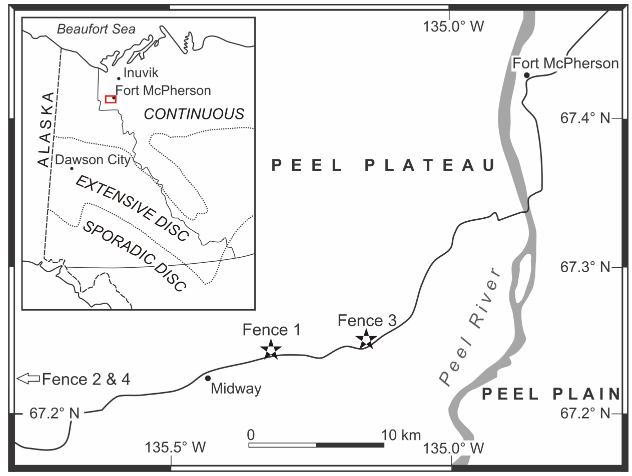

Figure 1. Location of study sites. Fences 2 and 4 are at approximately 67.179°N 135.776°W and 67.104N 136.096W, respectively, in Richardson Mountains.

3 METHODS

3.1 Study design and sites

In 2012-2014, snow depth, ALT, shallow ground temperatures, ground surface topography, and vegetation were examined at a snow fence (Fence 1; Figure 2) located on Peel Plateau, adjacent to the Midway emergency airstrip. ALT and vegetation heights were measured at three other snow fences (Fences 2-4) in the region, to capture these conditions in a range of topographic settings. Fence 1 was in a poorly-drained peatland (Figure 2). The ground near the fence was saturated, and wetland vegetation dominated near the fence. Fence 2 was on a 20°, well-drained tundra slope in Richardson Mountains. Fence 3 was in relatively flat, shrubby ground, but was well drained in comparison with Fence 1. Fence 4 was on a well-drained tundra slope (5°) in Richardson Mountains. The fences were erected in the early 1980s, and are approximately 1 m high.

3.2 Field measurements and analyses

Snow depths were measured at Fence 1 by probing in March 2013 and 2014 every 2 m along a 40 m transect normal to Fence 1, to characterize snow accumulation near the fence. ALTs were estimated by probing along the transect in August 2012, 2013, and 2014, with probes of either 150 or 175 cm length, to determine whether the snow fence had caused near-surface permafrost degradation. ALTs were also estimated by probing at Fences 2-4, typically every 2 m along transects that ran 50 m from either side of the structures. Some transects were shorter than 50 m because of the proximity of the fences to the road embankment. Two transects were established at Fence 4 because of the structure's considerable length.

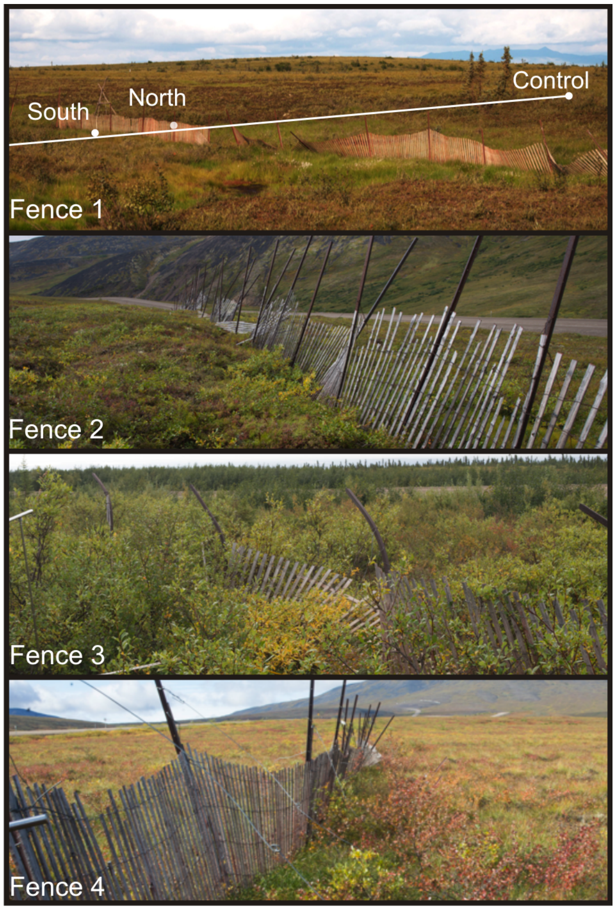

Figure 2. Field sites in summer 2014. Locations of the transect (line) and shallow thermistor arrays (dots) are shown for Fence 1.

Ground temperatures were monitored with shallow thermistor arrays at three locations at Fence 1 (Figure 2), to compare conditions near the fence with those in undisturbed terrain. The South and North instruments were beside the fence. The Control instrument was placed in nearby undisturbed terrain, 25 m upwind of the fence in the direction of prevailing winter winds (N). The arrays consisted of thermistors (HOBO TMC6-HA/D) placed at 5 and 100 cm depth, and attached to data loggers (HOBO H08-006-04), which recorded temperatures every 2 hours. The thermistors have a reported accuracy of ±0.25 °C over a measurement range of -40 to 50 °C, and about ±0.45 °C precision with the logger used.

The ground surface profile along the transect at Fence 1 was surveyed in summer 2012 with an optical level. Dominant vegetation species were recorded along the transect. Vegetation height was measured along the transects at Fences 2-4 to examine the effect of the fences on shrub vegetation. Vegetation heights were not measured at Fence 1 because low sedges, not shrubs, dominated there.

The Spearman rank correlation test was used to examine associations between ALT and vegetation height and distance from the snow fences. All statistical tests were conducted at the 0.05 significance level.

4 RESULTS

4.1 Fence 1

4.1.1 Snow depths

Snow was much deeper in 2013 than in 2014 on Peel Plateau (O'Neill et al. 2015). Consequently, snow depths near Fence 1 in 2013 were up to 150 cm, while further from the structure they were <1 m. In 2014, snow depths near the fence were about 1 m, and at either end of the transect ranged from about 30 – 80 cm (Table 1; Figure 3). Though the depths were varied between the two years of measurement, snow depths near the fence were consistently greater (Table 1; Figure 3).

4.1.2 Ground temperatures

Annual mean ground temperatures (AMGT) were higher near Fence 1 than at the control site. On the south side of Fence 1, AMGT at 100 cm depth was 0.6 °C in 2012-2013 (Table 2), but the instrument was inundated with melt water in 2014, so a value for the second year could not be determined.

Table 1. Active-layer thickness (ALT) and snow depths along the transect at Fence 1, 2012-2014. The date format is MM/DD/YYYY.

Dist. (m)	ALT (cm)			Snow depth (cm)	
	08/16/ 2012	*08/14/ 2013*	*08/08/ 2014*	*04/19/ 2013*	*04/25/ 2014*
0	61	44	49	74	72
2	50	47	52	92	70
4	60	43	45	102	71
6	67	61	37	105	72
8	63	77	40	116	89
10	78	90	50	137	89
12	88	100	60	145	107
14	97	120	92	150	96
16	114	130	105	142	97
18	110	155	150+	143	101
20	150+	175+	150+	143	97
22	100	175+	150+	140	100
24	150+	175+	132	139	106
-------------------------Fence-------------------------					
26	150+	175+	150+	141	101
28	130	125	150+	139	100
30	140	140	150+	138	85
32	110	128	133	135	48
34	80	129	60	95	38
36	62	41	57	90	33
38	70	66	50	88	33
40	55	70	48	87	38

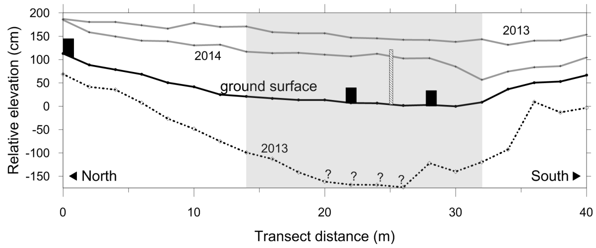

Figure 3. Cross-section of Fence 1 showing the ground surface, snow depths, and active-layer thicknesses along the transect. The gray shading represents sedge-dominated vegetation. Thermistor arrays are shown as black rectangles.

On the north side, AMGT at 100 cm depth was 0.1 and 0.0 °C in 2012-2013 and 2013-2014, respectively. At the control site, AMGT at 100 cm depth was lower (-0.8 and -1.1 °C) in each of the two years of record. Temperatures near the ground surface (5 cm depth) remained high (> -2 °C) during both winters beside Fence 1, but reached considerably lower values (< -8 °C) at the control site (Figure 4).

In summer, ground temperatures at 5 cm at the control site are consistently lower than at the sites beside the fence (Figure 4). This is likely due to the contrasting moisture and surface vegetation conditions, discussed below.

Table 2. Annual mean ground temperatures (AMGT) at 5 cm and 100 cm (bold) at the snow fence and control site in 2012-2014. Minimum temperatures are shown in brackets beside the annual means.

Instrument	$AMGT_5$ (°C)		$AMGT_{100}$ (°C)	
	2012-13	*2013-14*	*2012-13*	*2013-14*
South	2.2 (-1.4)	n/a (-2.4)	0.6 (-0.2)	n/a (-0.6)
North	1.8 (-1.5)	1.3 (-2.4)	0.1 (-0.6)	0.0 (-0.6)
Control	-0.2 (-4.8)	-1.3 (-8.9)	-0.8 (-1.5)	-1.1 (-3.4)

4.1.3 Active-layer thickness and ground subsidence

ALTs were considerably greater near Fence 1 than near the ends of the transect (Table 1, Figure 3). In each year, the thaw depth near the fence extended below the maximum length of the measurement probes, so the greatest ALTs could not be determined. The mean (2012-2014) ALTs at points further than 15H (~15 m) from the fence was 65 cm in the upwind (N) direction, and within 15H, the mean was 141 cm. The transect only extended 15 m beyond the fence in the downwind direction, due to the proximity of the highway embankment. However, ALTs on the south side of the fence were also greater than in the control areas (Figure 3).

During active-layer probing in August 2014, a thin (5-10 cm) frozen layer was encountered near the fence at a depth of about 50 cm. This frozen layer was penetrated with the probe, and underlain by unfrozen ground, indicating that a talik now exists near the fence.

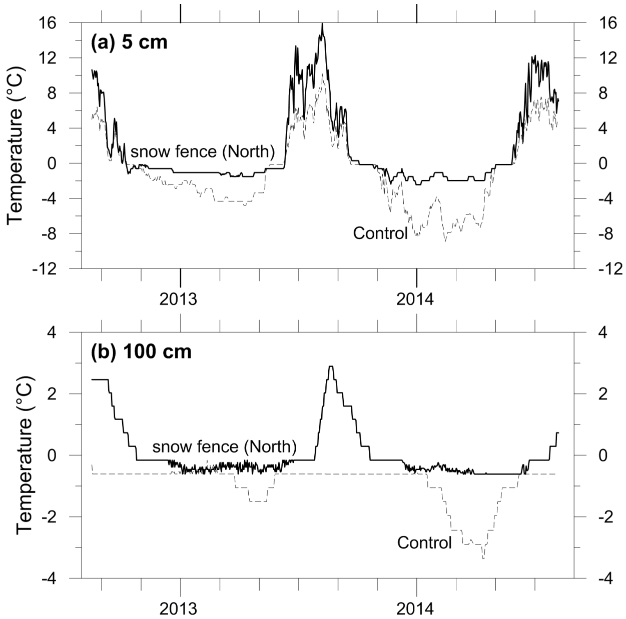

Figure 4. Ground temperatures at (a) 5 cm and (b) 100 cm depth near the snow fence and at the control site.

The ground around Fence 1 has subsided noticeably as a result of the disturbed thermal conditions and active-layer deepening. We estimate that the subsidence is about 50 cm (Figure 3). As a result, the ground is much wetter around the fence from water accumulation in subsided areas (Figure 2).

4.2 Active-layer thickness and topography

There was a significant negative correlation ($\rho = -0.20$, $p < 0.01$, $n = 164$) between ALT and the distance from Fences 1-4 (Figure 5). However, the effect of the snow fences on the active layer was not consistent among the fences, but varied with topography. ALTs at the flattest sites (Fences 1 and 3) were statistically associated with distance from the fences ($\rho = -0.59$, $p < 0.01$, $n = 47$), but not at sites on sloping ground (Fences 2 and 4, Figure 5, $\rho = -0.13$, $p = 0.15$, $n = 117$).

4.3 Vegetation

Two distinct vegetation responses were observed near the snow fences. First, the vegetation community has changed at Fence 1 from shrub-tundra species to wetland vegetation (Figure 2). At the control site in undisturbed tundra, cloudberry (*Rubus chamaemorus*) and mosses dominated vegetation cover, with some low-lying shrubs such as dwarf-birch (*Betula glandulosa*), cranberry (*Vaccinium vitis-idaea*), and Labrador tea (*Rhododendron*

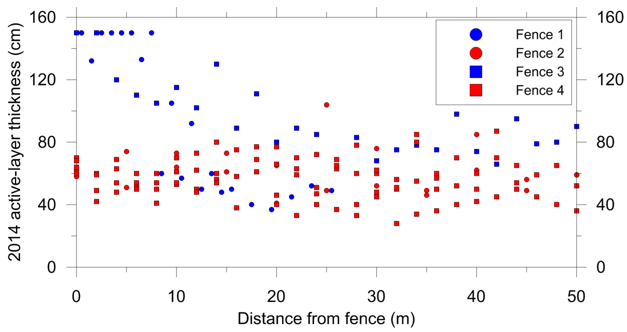

Figure 5. Active-layer thicknesses along transects at all fences in 2014. The blue data points are from sites on flat ground and the red points are from sites on slopes.

subarcticum) also present. However, vegetation beside the fence consisted mostly of moisture-tolerant sedges (*Carex* spp.), with limited cover of cloudberry, dwarf-birch, mosses, and willows (*Salix* spp.). The second vegetation response observed was a change in shrub structure at Fences 2-4. Pooled data of vegetation height was significantly and negatively correlated ($\rho = -0.22$, $p < 0.01$, $n = 142$) with the distance from the fences (Figure 6), indicating that tundra shrubs have increased in height near Fences 2-4.

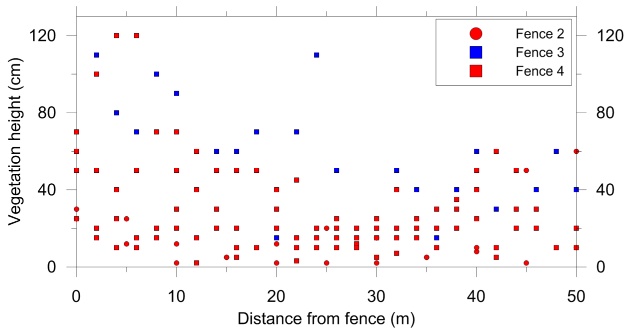

Figure 6. Vegetation heights along transects at Fences 2-4. The blue data is from the site in flat ground and the red data are from sites on slopes.

5 DISCUSSION

5.1 Long-term permafrost degradation and thermokarst initiation at Fence 1

Considerable snow cover was present in late winter at Fence 1. O'Neill et al. (2015) placed an iButton array at Site 1 and observed that deep (> 90 cm) snow cover accumulates around the structure by early November, limiting heat loss early in the freezing season.

Near-surface ground temperatures were higher near Fence 1 than at the nearby control site, and above 0 °C on an annual basis. Seasonally, winter ground surface temperatures (5 cm depth) were considerably higher near the fence due to the insulating effect of deep snow cover, but also due to release of latent heat throughout the freezing season (Figure 4). In summer, ground temperatures at 5 cm depth were also typically higher near the fence than at the control site. This may occur since the saturated ground near the fence has a higher thermal conductivity than the dryer organic material at the control site. Johansson et al. (2013) also observed this effect in northern Sweden at snow fences in a peatland.

The active layer is considerably thicker near the fence than at the control site, and appears to have increased by at least 1.25 m. This increase in ALT has resulted in an estimated 50 cm of ground surface subsidence, presumably from the thaw of near-surface ground ice.

Subsidence around the fence has caused moisture to accumulate, and there has been a shift from shrub-tundra vegetation to moisture-tolerant species. These long-term effects of the snow fence have caused a talik beneath Fence 1, indicated by probing in summer 2014. The ground beneath the snow fence now likely acts as a heat source to degrade adjacent permafrost year-round.

In summary, the thermal disturbance from increased snow cover at Fence 1 has caused substantial permafrost degradation and ground subsidence. These effects have been amplified by poor drainage and saturated ground at the site.

5.2 Active-layer thickness, topography, and vegetation response

At Fences 1 and 3, in relatively flat ground, ALTs were thicker near the fences than at other sites surveyed. No similar systematic effects were observed in sloping terrain at sites 2 and 4 (Figure 5). This may be because water, either from thawed ground ice or precipitation, is able to drain away and does not increase the latent heat content of the active layer that must dissipate during freeze back. However, this should be investigated further, as the number of fences examined was limited, and ground ice conditions were unknown at Fences 2-4. There appeared to be some ground subsidence at Fences 2-4, though not nearly to the extent observed in the wet environment at Fence 1.

Higher shrubs were observed in proximity to the structures at Fences 2-4 (Figure 2, Figure 5). This suggests that the snow fences enhance shrub growth, likely due primarily to protection from wind abrasion in winter within the snow pack, and to changed ground thermal, active layer, moisture, and nutrient conditions (e.g. Sturm 2001). However, at Fence 1, the significant depression around the fence and associated saturated conditions has instead caused establishment of sedge vegetation. Therefore, it appears that snow fences in well-drained terrain are generally an anthropogenically-induced source of shrub enhancement for tundra, but at poorly-drained sites, they may cause a shift in vegetation community. The observation of shrub enhancement near infrastructure in the region is similar that observed by Gill et al. (2014) beside the Dempster Highway embankment.

6 SUMMARY AND CONCLUSIONS

(1) A snow fence in operation for ~30 years alongside the Dempster Highway in the continuous permafrost zone has

caused deep snow accumulation, which has resulted in permafrost degradation.

(2) Active-layer thicknesses are significantly greater near fences in flat ground, but are similar to undisturbed tundra at fences on slopes, presumably because water is able to drain away in sloped areas.

(3) Vegetation has responded to disturbed conditions near snow fences. Increased shrub growth has occurred at well-drained sites, while sedges now dominate the vegetation cover at a poorly-drained site.

(4) Shallow ground temperatures (5 cm) remain higher near the fence than at the control site for most of the summer, likely due to higher thermal conductivity in the saturated ground near the structure.

The results of this investigation highlight the effect of anthropogenic disturbance on thermokarst initiation in tundra of the continuous permafrost zone, and potential unforeseen effects of snow fences near linear transportation infrastructure, particularly in poorly drained areas. Snow fences should, if possible, be placed in well-drained terrain to minimize permafrost degradation.

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