Field measurements of permafrost conditions beside the Dempster Highway embankment, Peel Plateau, NWT

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ABSTRACT
Permafrost conditions were examined adjacent to the Dempster Highway road embankment on Peel Plateau, NWT. Ground temperatures recorded in 2013-14 at five sites at the embankment toe and at two control sites are presented. Annual mean temperatures near 5 m depth ranged between -2.2 and 0.0 °C at the embankment toe, and were -1.8 and -2.6 °C at control sites. Permafrost has degraded near the road at four sites. Thaw depths at degrading sites were typically >1 m, but < 1 m in the undisturbed tundra of the region. High ground temperatures at road sites were associated with deep snow accumulation. Numerical modelling should be used to explore the effects of snow compaction or removal to reduce ground temperatures.

RÉSUMÉ
Les conditions du pergélisol ont été analysées près des remblais de l'autoroute Dempster sur le Plateau Peel, TNO. Les températures du pergélisol enregistrées en 2013-14 proviennent de cinq sites situés en pied de remblai et de deux sites témoins. Les températures moyennes annuelles mesurées à environ 5 m de profondeur varient entre 2.2 et 0.0 °C aux sites localisés en pied de remblai et entre -1.8 et -2.6 °C aux sites témoins. Une dégradation du pergélisol a été observée à quatre sites près de la route. La profondeur de dégel aux sites, où il y a dégradation, est habituellement >1 m, comparativement à < 1 m dans la toundra non perturbée. Les températures élevées du pergélisol mesurées en pied de remblai sont dues à une importante accumulation de neige. Il serait intéressant d'avoir recours à la modélisation numérique pour mieux comprendre les effets du compactage et du déneigement pour refroidir les températures du sol.

1 INTRODUCTION

Recently, the western Arctic of North America has been one of the most rapidly warming environments on Earth (Serreze et al. 2000; Burn and Kokelj 2009). Permafrost temperatures in the region have responded to rising air temperatures, increasing by more than 2 °C at some sites in the past few decades (Smith et al. 2010). This warming has led to increases in active-layer thickness (ALT) and the thaw of near-surface ground ice. Thaw of ice-rich permafrost causes ground subsidence and may damage infrastructure. Continued climate warming is a clear threat to infrastructure in circumpolar regions (Nelson et al. 2002).

Irrespective of climate change, degradation of permafrost may occur near infrastructure that traps snow, thereby limiting winter ground cooling (e.g., Darrow 2011). Built structures may also disrupt natural drainage networks, causing water to accumulate, and increasing the amount of latent heat that must dissipate before ground cooling can occur below 0 °C (Andersland and Ladanyi 2004; de Grandpré et al. 2012). Along northern highways, these problems may be particularly pronounced, because the road embankment acts as a windbreak, promoting snow accumulation (Auerbach et al. 1997; Fortier et al. 2011). At the same time, the elevated permafrost table in the embankment may inhibit drainage.

The Dempster Highway is the only all-season road to Canada's western Arctic. Communities in the Mackenzie Delta region rely on the highway for transportation, goods and services, and tourism. The Dempster Highway has gained importance since 2011 as Inuvik now relies on tanker loads of propane for power generation. In addition, construction of the $300M Inuvik-Tuktoyaktuk Highway, begun in 2013-14, is an important northern development project that will link the Dempster Highway with the Beaufort Sea at Tuktoyaktuk, NWT.

Despite the practical and political importance of the road transportation network in the western Arctic, and significant investment by territorial and federal governments in maintenance and new construction projects, field measurements of permafrost conditions along roads have not been available until recently. Given the projected increases in air temperatures, baseline data on permafrost conditions near roads in the region is needed to enable modelling of future conditions near roadways, and inform effective maintenance.

In this paper, we present ground temperatures measured at five tundra sites along the Dempster Highway on Peel Plateau, NWT. The sites were installed in 2012. Four long-term monitoring sites were also installed along the highway in Yukon and NWT in 2013-14, to measure permafrost conditions at the centreline, toe, and away from the embankment (Idrees et al. 2015). Together, these studies are the first to report on permafrost conditions along this important transportation route (Burn et al. 2015).

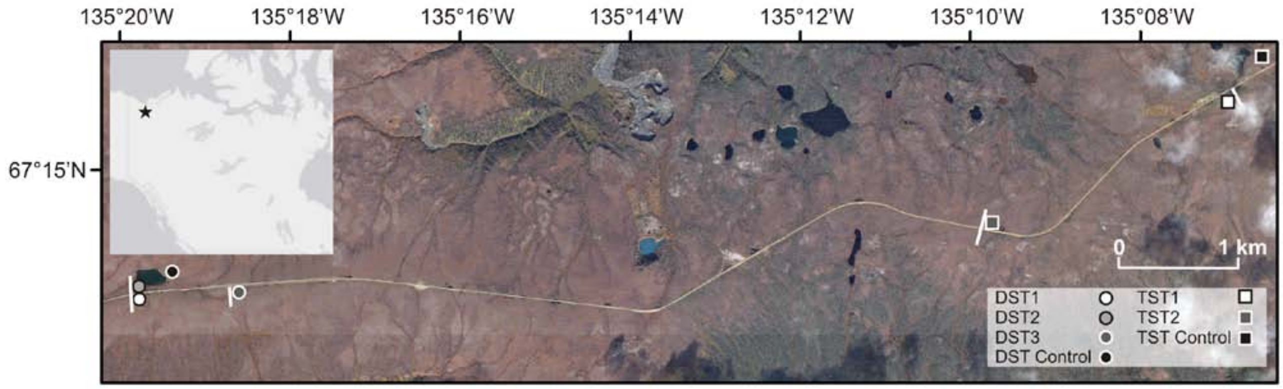

Figure 1. Location of study sites in dwarf-shrub tundra (DST) and tall shrub tundra (TST) on Peel Plateau. Snow depth transects are marked by white lines.

Figure 2. The Dempster Highway on Peel Plateau. Shrubs have proliferated near the embankment (see Gill et al. 2014).

Here, we present the effect of snow accumulation on the thermal regime by comparing conditions near the road with nearby undisturbed sites. The objectives of this paper are to (1) characterize permafrost conditions near the toe of the Dempster Highway road embankment on Peel Plateau, NWT, (2) assess the thermal influence of snow and moisture accumulation along the roadway, and (3) compare ground thermal conditions at the embankment toe with undisturbed tundra.

2 STUDY AREA

Study sites were located along the Dempster Highway in continuous permafrost on Peel Plateau, west of Fort McPherson, NWT (Figure 1). Peel Plateau consists of rolling terrain (Figure 2), incised by steep-sided valleys draining eastward toward Peel River. The climate in the region is subarctic and continental, characterized by long, cold winters and short, cool summers. The mean annual air temperature at Fort McPherson (1987-2006) is -7.0 °C, however, strong winter temperature inversions cause annual mean air temperature to be higher on Peel Plateau than in the lowlands near the village (O'Neill et al. 2015). Total annual precipitation in the area averages 295 mm, with 148 mm falling as rain (Environment Canada 2012). Precipitation is typically heaviest in late summer and early fall.

Peel Plateau was glaciated during the late-Wisconsinan (Fulton 1995), and is covered by moraine, glaciolacustrine, and glaciofluvial deposits. These predominantly fine-grained deposits overlie Lower Cretaceous marine shale and siltstone bedrock (Norris 1984). The sediments on Peel Plateau are characteristically ice-rich, and massive ice is commonly present at depth (Kokelj et al. 2013; Lacelle et al. 2015). Permafrost temperatures on Peel Plateau in undisturbed tundra are about -2 °C (O'Neill et al. 2015).

The Dempster Highway opened for traffic in 1979. The embankment height ranges from about 1 m to 2.5 m, but may be higher on sloping ground. Current permafrost conditions near the road reflect the effects of over 35 years of disturbance from road construction and operation. The portion of the highway on Peel Plateau has required significant maintenance in response to permafrost-related problems, and has recently been rehabilitated at a cost of $65M.

3 METHODS

3.1 Site selection

Five sites were selected for monitoring ground temperatures near the road and two were chosen as control sites in undisturbed terrain (Figure 1, 3). Three of the road sites and one control site were in dwarf-shrub tundra (DST) on upper Peel Plateau. The two other road sites and the second control site were in tall-shrub tundra (TST) at lower elevation. The road sites were selected to encompass a range of snow and moisture conditions. Therefore, road sites were placed adjacent to both low and high embankments, where the amount of snow trapping differs and moisture conditions appeared dissimilar. Areas of high moisture content were identified qualitatively by ponding within 5 m, and the growth of *Equisetum* spp. Conditions at each road site are summarized in Table 1.

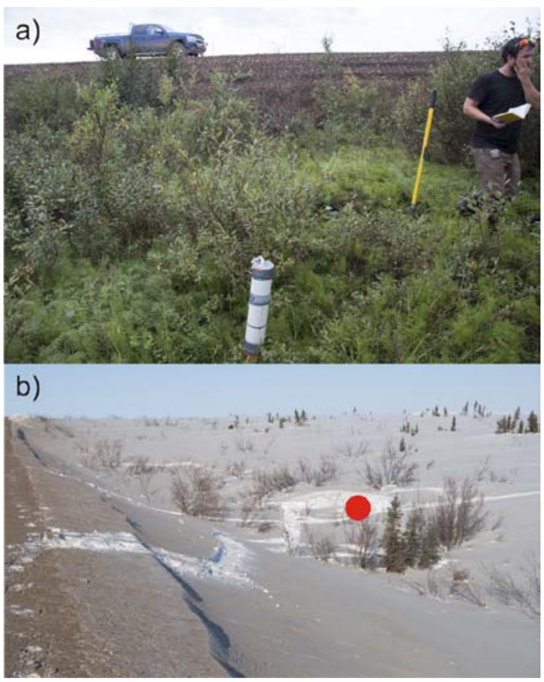

Figure 3. Site TST2 near the highway embankment showing a) the thermistor cable installation and embankment in summer, and b) snow accumulation in winter. Note than many of the tall shrubs are covered by deep snow in winter. The red dot indicates the location of the thermistor cable.

Table 1. Embankment height (High > 2 m, Low < 2 m), presence of standing water, and occurrence of *Equisetum* spp. at each road site.

	DST1	DST2	DST3	TST1	TST2
Embankment	High	Low	Low	Low	High
Ponding(Y/N)	N	N	Y	N	N
Equisetum(Y/N)	Y	N	Y	Y	Y

3.2 Field measurements

Paired deep and shallow thermistor cables were installed at the five road sites in 2012 between 5 to 10 m from the embankment toe (Figure 3) to characterize the ground thermal regime in the active layer and permafrost. Two additional deep cables were installed at the control sites in 2013. Deep thermistor cables were drilled by water jet and cased in 1” steel pipes that were filled with silicone oil. The deep cables were installed up to 8.5 m depth with thermistors (YSI44033, YSI Inc., Yellow Springs CO, USA) spaced at 1 m intervals, except for the DST control site, which had variable thermistor spacing. The thermistors are accurate to ±0.1 °C. The maximum depth of water jet drilling varied due to rock clasts encountered in the boreholes. The ground temperatures were recorded every four hours on RBR XR-420 T8 data loggers (Richard Brancker Research Ltd., Ottawa ON), which have a reported precision of <0.00005 °C. In this paper, we report annual mean ground temperature (T_G) from the sensor nearest 5 m depth for 2013-14, when all instruments were in operation.

The shallow cables consisted of two thermistors (HOBO TMC6-HD/HA, Onset, Bourne MA, USA) attached to a dowel and placed in the ground at 0.05 m (surface) and 1 m depths. Data were recorded every two hours on either HOBO H08-006-04 or U12-006 loggers with an accuracy of ±0.25 °C. The measurement precision is 0.45 °C with the H08 logger and 0.02 °C with the U12. Data from the 0.05 m sensor were used to characterize the annual mean surface temperature (T_S) at the road sites. T_S was not determined for control sites because there were no shallow cables there.

Active-layer thickness (ALT) or thaw depth was estimated at each site in mid-late August 2013-14 either by probing with a 1.5 m graduated steel rod, or by examining the temperature envelope obtained from the deep cable if the thaw depth exceeded the length of the probe. Since the control sites were installed in summer 2013, ALTs are only available from August 2014.

Late-winter snow depths were measured at each site to characterize snow accumulation beside the road embankment and at control sites. Five snow depths were measured with a graduated probe within 1 m of each instrument in March 2013-15, and the five values were averaged to estimate snow depth at the instrument. Snow depths were also measured in 2015 every metre along six 50-m transects perpendicular to the embankment, to examine spatial patterns of snow accumulation with distance from the road (Figure 1). Six additional transects were established along the road in 2015 in forest at lower elevation on Peel Plateau, to compare snow accumulation along the embankment between the vegetation types.

Snow pits were excavated at most sites in March 2013 and 2014, and at all sites in 2015. The snow density was determined for each 0.1 m interval in the snow pit by weighing a 100 cm^3 sample. The densities were averaged to obtain a value for the entire snowpack. The snow cover thermal conductivity (λ_s) was estimated using (Sturm et al. 1997; eq. 7):

$$\lambda_S = 10^{(2.650\rho - 1.652)} \qquad [1]$$

Table 2. Annual mean ground temperatures near 5 m depth (T_G), at the surface (T_S), and active-layer thickness (ALT) or thaw depth, late-winter snow depth (March), and snow thermal resistance at the seven study sites. The T_S ranges reported for the control sites are from nearby sites in undisturbed tundra (O'Neill et al. 2015), as there were no shallow cables at the control sites.

	DST1	DST2	DST3	DST Control	TST1	TST2	TST Control
Distance from embankment (m)	5	6	7	150	5	8	50
T_G(°C)	-1.3	-2.2	-0.7	-1.8	-0.7	0.0	-2.6
T_S (°C)	1.6	-1.6	1.8	-0.5 to -3.4	2.1	1.3	-1.8 to -1.9
ALT/thaw depth (m)	1 - 1.5*	0.9	3*	0.7	2.5*	5*	0.6
Snow depth (m)	1.2 - 1.7	0.4 - 0.8	0.9 - 1.8	0.4 - 0.8	0.9 - 1.4	1.1 - 2.2	0.4 - 0.5
Snow thermal resistance (m^2 K W^{-1})	7 - 11	4 - 5	8 - 10	4 - 7	11 - 14	10 - 13	3 - 5

*estimated from ground temperature envelope.

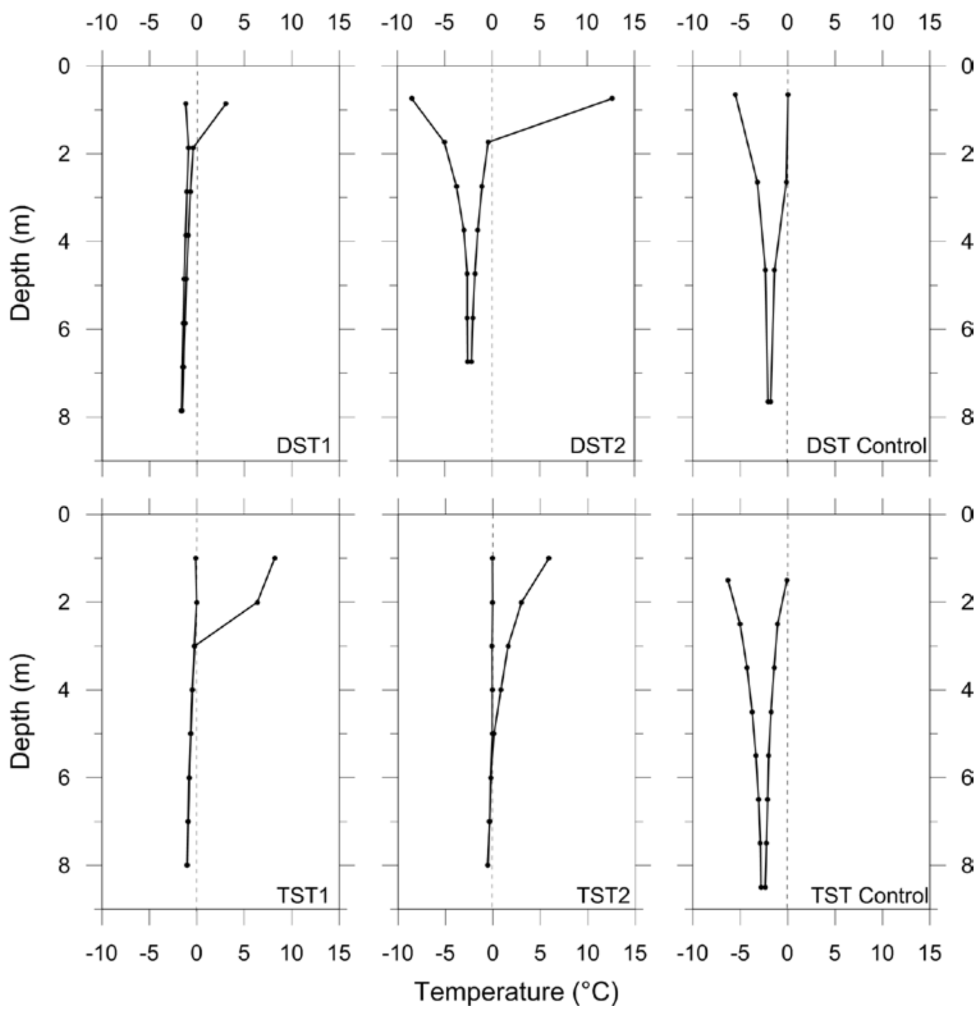

Figure 4. Temperature envelopes for all sites in 2013-14. The dots on the lines indicate the position of thermistors. Note that DST3 is not plotted here.

where ρ is the average snow cover density. Following this, the snow cover thermal resistance (R_s, m^2 K W^{-1}) was estimated with (Lunardini 1981, p. 43, eq. 3.9):

$$R_S = H / \lambda_S \quad [2]$$

where H is the snow depth. We used the average snow depth measured around each instrument for H, because this represents the snow conditions influencing the thermal regime at the installation.

4 RESULTS

4.1 Ground temperatures

Annual mean ground temperatures (T_G) near 5 m depth at the road sites were between 0.5 and 2.5 °C higher than at the control sites, except at DST2 (Table 2). T_G ranged from 0.0 to -2.2 °C at the road sites, and were -1.8 and -2.6 °C at the DST and TST control sites, respectively. T_G at control sites were consistent with those measured by O'Neill et al. (2015). Ground temperature at DST2 was -2.2 °C, similar to those observed at the control sites. Three of the road sites had T_G > -1.0 °C. Annual mean surface temperatures were >0 °C at all road sites except DST2, and ranged from 1.3 to 2.1 °C. At DST2, T_S was -1.6 °C (Table 2).

There was a large variation in ALT/thaw depth at road sites, from 0.9 to ~5 m (Table 2). At the DST and TST control sites, the ALTs were 0.7 and 0.6 m, respectively, however, these depths were measured on August 8, so maximum thaw depth was likely not reached by that date. Probing in August 2014 revealed thin frozen layers between 0.5 and 0.6 m depth underlain by unfrozen ground at several sites near the road embankment. These sites were at TST2, at a monitoring site on Peel Plateau described in Idrees et al. (2015), and at a snow fence near the embankment (O'Neill and Burn 2015). This indicates that taliks have developed in some places near the embankment.

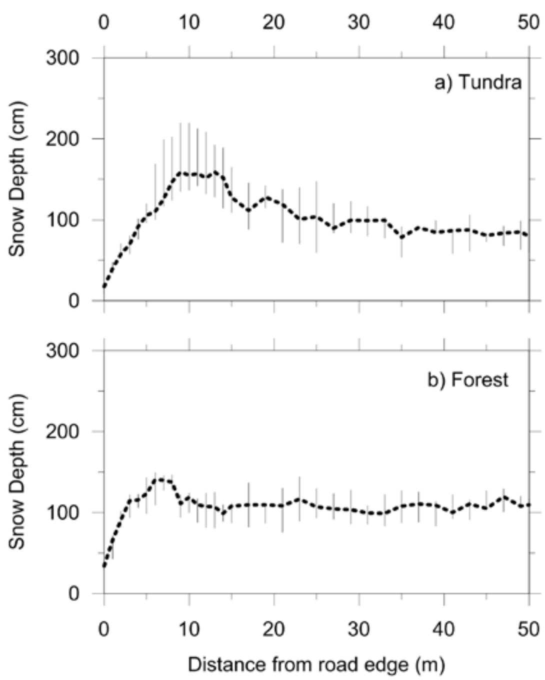

Figure 5. Snow accumulation measured every metre (n = 50 for each transect) in March 2015 at a) six tundra and b) six forest transects. The dashed line is the median from the transects, and the vertical lines represent the interquartile range.

Deep snow accumulated annually along the road embankment. Snow depths at all road sites except DST2 were commonly > 1 m, and measured up to 2.2 m. These depths are considerably greater than at control sites and DST2, which ranged from 0.4 to 0.8 m (Table 2). The effect of the road embankment on snow accumulation in tundra is illustrated with the data collected along transects in 2015 (Figure 5). In tundra, snow accumulation was enhanced between about 5 and 15 m from the roadside, and then decreased with distance from the embankment (Figure 5a). In contrast, there was no pronounced change in snow depth away from the embankment in forest, and snow depths were similar over the length of the transects (Figure 5b).

5 DISCUSSION

Higher ground temperatures were observed near the toe of the road embankment than at control sites, except at DST2, which was distinct from all other road sites (Table 2). The thermal disturbance to permafrost is primarily associated with deeper snow cover resulting from wind deposition along the embankment (Table 2; Figure 5). The average snow cover thermal resistance at road sites other than DST2 was 10.3 m^2 K W^{-1}, while at control sites it was 4.6 m^2 K W^{-1}. DST2 had an average snow cover thermal resistance of 4.7 m^2 K W^{-1} (Table 2), similar to the control sites.

The step-change increase in snow cover following embankment construction has resulted in increased active-layer thickness at all sites except DST2. For example, the measured ALTs at control sites suggest that ~4 m of permafrost has degraded at TST2 (Figure 4). The thaw of near-surface permafrost at four of the five road sites is corroborated by the temperature envelopes, which are in disequilibrium (Figure 4), by probing, which indicated taliks in some locations near the road, and by T_S values >0 °C.

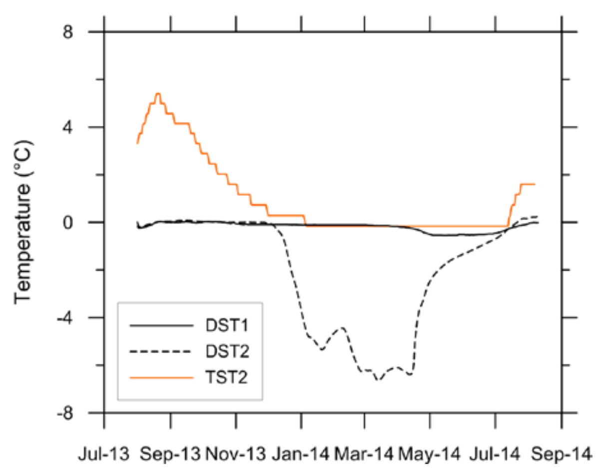

Figure 6. Ground temperatures at 1 m depth at three road sites. For clarity, data from the other road sites are not plotted because they are similar to DST1 and TST2.

Near-surface ground temperatures measured at 1 m depth at the shallow cables were near 0 °C the entire freezing season, indicating that winter ground cooling does not occur at the degrading road sites (Figure 6). The thermal data and deep surface thaw observed in this study help explain recent maintenance challenges along the embankment on Peel Plateau, where significant fill material has been placed beside the road to stabilize thawing. Ground thawing of several metres, as observed at TST2, could cause significant subsidence in this ice-rich environment and lead to such issues.

At DST2, snow cover was similar (0.4 to 0.8 m) to that observed in undisturbed tundra on Peel Plateau (O'Neill et al. 2015). This is likely due to the embankment at this site being relatively low (~1 m in height). The ground surface slopes upward away from the road, so that the site is exposed to dominant winter winds. Consequently, snow does not accumulate as at the other road sites, resulting in permafrost temperatures and ALTs similar to control sites (Table 2). This finding indicates that site-specific topographic characteristics are important in determining susceptibility to permafrost degradation along linear transportation infrastructure in tundra terrain.

It was not possible to rigorously examine the thermal effects of soil moisture due to the sample size, but some insight may be gained from our field observations. TST2 had the highest T_G (0.0 °C), likely because of a deep snow cover (Table 2) and relatively high soil moisture content, indicated by thick *Equisetum* plant cover (Figure 3a). TST1 and DST3 had the next highest T_G (-0.7 °C). DST3 was the wettest site, due to the presence of standing water and *Equisetum* plants, but snow depths and thermal resistance were lower than at TST2. TST1 had high snow cover thermal resistance, but was likely not as wet as DST3, as there was no standing water there. DST1 had the lowest T_G of the degrading road sites (-1.3 °C) despite relatively thick snow cover. This is likely because the site was on a slope, and had only sparse *Equisetum* cover, indicating drier soil conditions. In summary, moisture conditions are likely important due to their influence on the latent heat content of the active layer. However, differences in timing and magnitude of snow accumulation along the embankment presently complicate any partitioning of the effects of snow vs. moisture. Additional ground temperature, snow, and soil moisture measurements along the highway, in conjunction with numerical modelling, may enable future investigations of these effects to be examined quantitatively.

6 SUMMARY AND CONCLUSIONS

The results of this study provide some of the only field measurements of permafrost conditions adjacent to the Dempster Highway. The following conclusions may be drawn:

(1) Permafrost is degrading at four of five study sites near the toe of the embankment. Annual mean ground temperatures near 5 m depth at the degrading sites were between -1.3 and 0.0 °C, in comparison with -1.8 and -2.6 °C at two control sites in undisturbed tundra.

(2) High ground temperatures are associated with thick, insulating snow cover that accumulates along the embankment.

(3) Enhanced snow accumulation near the embankment toe is pronounced in both dwarf- and tall-shrub tundra, due to wind redistribution, but not where the road passes through forest.

These results highlight the importance of step-changes in snow conditions on the thermal stability of ground in this environment, where ground temperatures are within a few degrees of 0 °C. As a next step in this research, the potential of removing or compacting snow to reduce ground temperatures will be examined using numerical simulations. The compounding effects of moisture and changes to surface organic cover may also be explored.

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