Impacts of variations in snow cover on permafrost stability, including simulated snow management, Dempster Highway, Peel Plateau, Northwest Territories

<table>
<thead>
<tr>
<th>Journal:</th>
<th>Arctic Science</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuscript ID</td>
<td>AS-2016-0036.R2</td>
</tr>
<tr>
<td>Manuscript Type:</td>
<td>Article</td>
</tr>
<tr>
<td>Date Submitted by the Author:</td>
<td>12-Apr-2017</td>
</tr>
<tr>
<td>Complete List of Authors:</td>
<td>O’Neill, Hugh; The University Centre in Svalbard, Arctic Geology</td>
</tr>
<tr>
<td></td>
<td>Burn, Chris; Carlton University, Geography and Environmental Studies</td>
</tr>
<tr>
<td>Keyword:</td>
<td>permafrost, infrastructure, thermal regime, highways, snow cover</td>
</tr>
</tbody>
</table>
Impacts of variations in snow cover on permafrost stability, including simulated snow management, Dempster Highway, Peel Plateau, Northwest Territories

H.B. O’Neill¹,²*, C.R. Burn¹

¹Department of Geography and Environmental Studies, Carleton University, Ottawa, Canada
²Department of Arctic Geology, The University Centre in Svalbard, Longyearbyen, Norway

*Corresponding author:
H.B. O’Neill
The University Centre in Svalbard (UNIS)
Svalbard Science Centre
P.O. Box 156
N-9171 Longyearbyen
Norway
brendan.oneill@unis.no

C.R. Burn
Department of Geography and Environmental Studies
Carleton University
1125 Colonel By Dr.
Ottawa ON, K1S 5B6
Canada
Christopher.burn@carleton.ca
ABSTRACT

Permafrost conditions were examined near the Dempster Highway embankment on Peel Plateau, Northwest Territories. Ground temperatures were recorded in 2013-15 at five sites at the embankment toe and at two sites in undisturbed (control) tundra. Annual mean ground temperatures at approximately 5 m depth ranged from -2.2 to 0.0 °C at the embankment toe, and were -1.8 and -2.6 °C at control sites. Permafrost is degrading beside the road at four of five sites. Thaw depths are greater at the embankment toe, where deep snow accumulates, than in undisturbed tundra. A numerical model was used to examine the influence of varying snow cover properties on the ground thermal regime. Simulations indicated that delaying the onset of deep (1 m) snow accumulation and/or prolonging the duration of the same total accumulation accelerates removal of latent heat from the active layer, increases sensible ground cooling, and results in reduced thaw depth. Furthermore, reducing snow depth and increasing snow density may rapidly raise the permafrost table, lower ground temperatures at the embankment toe, and cool permafrost at depth over several years. In consequence, mechanical snow removal and/or compaction should be investigated as an active management strategy for mitigating permafrost degradation in ice-rich settings.

KEYWORDS: Permafrost, infrastructure, highways, thermal regime, snow cover
INTRODUCTION

The western Arctic of North America has been one of the most rapidly warming environments on Earth over the past few decades (Burn and Kokelj 2009). Permafrost temperatures in the region have responded to rising air temperatures, increasing by more than 2 °C at some sites since the 1970s (Smith et al. 2010). This warming has led to increases in active-layer thickness and thaw of near-surface ground ice (Burn and Kokelj 2009; Raynolds et al. 2014). Thaw of ice-rich permafrost causes ground subsidence and may damage infrastructure. Continued climate warming will pose serious challenges to owners and operators of infrastructure in circumpolar regions (Nelson et al. 2002).

Permafrost degradation may occur irrespective of climate change near infrastructure that traps snow, thereby limiting winter ground cooling (e.g., Darrow 2011; Fortier et al. 2011). Infrastructure embankments may also disrupt natural drainage networks, causing water to accumulate and increasing the amount of latent heat that must dissipate during freeze back of the active layer before further ground cooling may occur (Andersland and Ladanyi 2004; de Grandpré et al. 2012). These problems may be particularly pronounced along northern highways, because the road embankment acts as a windbreak and promotes snow accumulation (Auerbach et al. 1997), while the elevated permafrost table in the embankment may inhibit drainage, causing ponding at the embankment toe and increasing the potential for thaw subsidence there.

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, Northwest Territories. The portion of the highway on Peel Plateau (NWT km 30 – 69) has required significant maintenance in response to permafrost-related problems, and has recently been rehabilitated.

Despite the practical and political importance of the road transportation network in the western Canadian Arctic and significant investment by territorial and federal governments in maintenance and new construction projects, field measurements of permafrost conditions along the Dempster Highway have not been reported until recently (Gill et al. 2014; Burn et al. 2015; Idrees et al. 2015). Given projected increases in air temperatures over the next few decades, baseline data on permafrost conditions near roads in the region are needed to calibrate modeling of present conditions at the road and of the anticipated effects of climate change. Such modeling may inform effective maintenance.

In this paper, ground temperatures measured at five tundra sites along the Dempster Highway on Peel Plateau are presented and compared with conditions at two sites in undisturbed tundra. The present ground thermal conditions at the sites are examined with transient numerical simulations and the effect of altering snow properties is investigated to build on data presented in O’Neill et al. (2015a). 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 were the first to report on permafrost temperatures in and adjacent to the embankment of this important transportation route, though Gill et al. (2014) presented shallow ground temperatures (0.1-1.0 m) from some sites near the roadside.
The specific objectives of this paper are to (1) characterize permafrost conditions near the toe of the Dempster Highway road embankment on Peel Plateau, (2) recreate disturbed conditions near the road with a numerical model that allows the simulation of snow accumulation and ablation, (3) examine the sensitivity of the thermal model to changes in the snow accumulation regime, and (4) simulate the effect of active snow management, i.e., limiting snow depth and/or increasing snow density through mechanical compaction, to determine whether it may be an effective strategy to restrict or prevent permafrost degradation in sensitive areas.

BACKGROUND

Numerous passive techniques have been developed to mitigate the disturbance to permafrost near embankments. These include thermosyphons, air convection embankments, heat drains, snow/sun sheds, and high-albedo surfaces (Doré et al. 2016). Field measurements and simulations of the effectiveness of these techniques have been widely reported from infrastructure in various regions (e.g., Lepage et al. 2012; Qin and Zhang 2013; Darrow and Jensen 2016; Dumais and Doré 2016). There has been less investigation of active mitigation techniques, such as the removal of snow to increase the heat flux out of the ground in winter. Lepage et al. (2012) found that snow ploughing on a section of the Alaska Highway in Yukon, Canada, was effective in stabilizing the heat intake into the embankment toe after three years. In the first winter of ploughing, cooling of up to several degrees occurred in the embankment shoulder to a depth of about 3 m (Lepage and Doré 2010). However, longer-term thermal effects of repeated snow manipulations at road embankments have not been reported. The technique has potential because it requires no construction of stationary infrastructure as with many passive
techniques (Lepage and Doré 2010), and thus may be targeted at sections of embankment in areas where the ground is ice rich and sensitive to degradation.

For confidence in simulations of snow clearing and/or compaction to address objective (4), it is necessary to reproduce present thermal conditions near the embankment in transient simulations that begin at the time of the construction. Relatively few investigations have simulated the transient disturbance to permafrost at infrastructure. Typically, these have focused on reproducing ground temperatures at and around road embankments, and projecting future degradation under climate warming scenarios (Alfaro et al. 2009; Fortier et al. 2011; Darrow 2011; LeBlanc et al. 2014; Flynn et al. 2016). The ground surface boundary condition in these studies was defined using air temperatures modified by empirical transfer functions (n-factors) for the freezing and thawing seasons. Freezing season n-factors summarize the effect of heat transfer through the snow cover over the entire freezing period, or at shorter time intervals (e.g., Karunaratne and Burn 2003; Leblanc et al. 2014). Using another approach, Kokelj et al. (2010) employed a one-dimensional surface energy balance model to define ground thermal conditions for transient simulations of northern drilling-mud sumps.

In contrast with the above studies, Smith and Riseborough (2010) used a model that allows the timing and physical properties of snow cover to be explicitly defined in a simulation of permafrost disturbance at a pipeline right-of-way in the Northwest Territories. This study uses the same modeling approach so that the snow cover properties (timing, density, depth) can be manipulated individually and their effects examined directly. The surface temperature of the ground or snow surface is determined by n-factors from the air temperature, but heat flow in the ground and through the snow pack is simulated numerically.
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 towards 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 (Environment Canada 2012). 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. 2015b), but there is no long-term record of the Peel Plateau climate. Total annual precipitation at Fort McPherson 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. 2015b).

The Dempster Highway opened for traffic in 1979, so permafrost conditions near the road reflect the effects of over 35 years of disturbance from road construction and operation. The embankment height ranges from about 1 m to 2.5 m, but may be higher on sloping ground. Due to the unsuitable fine-grained and ice-rich surface materials in the region, the embankment was built of relatively dry quarried sandstone and shale, which was packed to break down the large fractions before being topped with a gravel driving surface (Huculak et al. 1978).
FIELD METHODS

Site selection

Five sites were selected for ground temperature measurements near the road and two were chosen as control sites in undisturbed terrain (Figure 1). 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 slightly 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 differed and moisture conditions appeared dissimilar. Areas of higher moisture content were identified qualitatively by water pooling within 5 m of the site, and the presence of moisture-tolerant *Equisetum* spp. Conditions at each road site are summarized in Table 1.

Measurements

*Ground temperatures*

Paired deep and shallow thermistor cables were installed at the five road sites in 2012 between 5 to 10 m from the embankment toe to characterize active-layer and permafrost temperatures (Figure 2). Two additional deep cables were installed at the control sites in 2013. Boreholes for deep thermistor cables were drilled by water jet and cased in 1” steel pipes that were filled with silicone oil to restrict free convection and ensure effective thermal contact with the ground. The deep cables were installed up to 8.5 m depth with sensors (YSI44033, YSI Inc., Yellow Springs, CO) 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. Ground temperatures were recorded every four hours on RBR XR-420 T8 data loggers (Richard Brancker Research Ltd., Ottawa, ON), and averaged to obtain daily values. Here 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 Corp., Bourne, MA) 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 was 0.45 °C with the H08 logger and 0.02 °C with the U12. The data were averaged to obtain daily values. 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, but are reported at a number of other undisturbed sites in O’Neill et al. (2015b).

**Thaw depth**

The maximum late-summer thaw depth was either estimated at each site in early-late August 2013 and 2014 by probing to refusal with a graduated steel rod, or by examining the temperature envelope obtained from the deep cable if the thaw depth exceeded the length of the probe. For manual probing, five measurements were obtained within a radius of 1 m from the instrument and the average of these values is reported. Since the control sites were installed in summer 2013, thaw depths at these sites are only available from August 2014.

**Snow conditions**
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 along six 50-m transects perpendicular to the embankment, to examine spatial patterns of snow accumulation with distance from the road (Figure 1). Measurements were every metre within 15 m of the road, and every 2 m between 15 and 50 m. 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 ($\lambda_s$, W m$^{-1}$ K$^{-1}$) was estimated using (Sturm et al. 1997, Eq. 7):

$$\lambda_s = 10^{(2.650\rho-1.652)}$$

where $\rho$ is the snow cover density in g cm$^{-3}$. Following this, the snow cover thermal resistance ($R_s$, m$^2$ K W$^{-1}$) was estimated with (Lunardini 1981, Eq. 3.9):

$$R_s = \frac{\Delta H}{\lambda_s}$$

where $\Delta H$ is the snow thickness. Snow depth in the $R_s$ calculation was defined as the average snow depth measured around each instrument, because this best represents the snow conditions influencing the thermal regime at the installation.

**NUMERICAL SIMULATIONS**
Numerical simulations of ground temperatures were conducted using TONE, a one-dimensional finite-element thermal model (e.g., Oelke et al. 2003; Riseborough 2007; Smith and Riseborough 2010). TONE is similar to the model used in Goodrich (1982), but provides improved accounting of total latent heat (Smith and Riseborough 2010). TONE was used to obtain ground temperatures in simulations that accounted for the accumulation and ablation of a snow pack. The numerical simulations addressed objectives 2-4 of this paper.

**Ground materials and element spacing**

No detailed stratigraphic data were available from the study sites, but general substrate characteristics were observed during water-jet drilling, and during shallow core drilling elsewhere on Peel Plateau. Thus, we employed a simplified model substrate profile for most simulations, consisting of a 0.1 m thick layer of saturated peat underlain by 49.9 m of saturated, fine-grained mineral soil. The exception was a simulation of thermal conditions in the road centreline, which included a 2-m thick layer of low moisture content coarse-grained material (i.e., the embankment) overlying 48 m of fine-grained mineral soil. Thermal properties of materials are shown in Table 2. Temperature-dependent conductivity and unfrozen water content curves are presented in Figure 3. TONE calculates the frozen and unfrozen heat capacities using an arithmetic mean of soil constituent heat capacities (e.g., Burn 2004, Eq. 3.3.5), while temperature-dependent thermal conductivities are determined by Kersten’s method for dry soils (see Farouki 1981, p. 45), or by using an equation for composite material in wet ground developed by Johansen (1975) (Burn 2004, Eq. 3.3.3). Element spacing was 0.02 m near the surface and increased with depth to a maximum spacing of 2 m at 50 m depth - the bottom of the simulation.
Initial temperature profile

The initial ground thermal profile was intended to represent conditions prior to construction of the Dempster Highway in the late 1970s. A 1000-year spin-up was run to establish an equilibrium ground temperature profile. The surface boundary condition was the median air temperature from three years of measurement, modified by a thawing season $n$-factor (0.7) calculated from ground surface temperatures in undisturbed tundra on Peel Plateau at a site described in O’Neill et al. (2015b) about 700 m from the DST control deep cable (see Figure 1). The seasonal value was used for snow-free conditions. When the ground was covered by snow, the snow surface temperature and air temperature were identical ($n = 1$). The Peel Plateau daily air temperatures were reduced slightly on a seasonal basis based on observed warming at Inuvik between 1950-80 and 1980-2010 to account for recent climate warming in the region. Differences in mean seasonal temperatures (summer, autumn, winter, spring) for the two time periods were subtracted from the measured daily air temperatures from Peel Plateau. Data from Inuvik were used for this correction because the records from Fort McPherson are insufficiently complete. No climate data have been collected from Peel Plateau prior to this study. All calculations were in daily time steps. The lower boundary condition was a constant heat flux of 0.05 W m$^{-2}$, a value that has been used successfully in other simulations of the ground thermal regime in the western Arctic (Burn and Zhang 2009).

Transient simulations

Simulation initialization and boundary conditions
Transient simulations aimed to reproduce (i) present thermal conditions in undisturbed tundra at the DST control site, (ii) the disturbances observed at the five deep cables near the toe of the road embankment, and (iii) conditions at the road centreline. The model was run for 35 years to simulate the evolution of the thermal regime in 1980-2015.

For all simulations, the initial ground temperature profile was from August 1st of the 1000 year spin-up. The ground or snow surface temperature was driven using the median of three years’ air temperature measurements (2012-14) from the air temperature sensor on Peel Plateau described in O’Neill et al. (2015b) (Figure 1). For (i) and (ii), snow cover was modelled using a linear accumulation with a constant density of 250 kg m$^{-3}$; it was assumed for (iii) that the road centerline remained clear of snow each winter. Snow density was based on average late-winter conditions measured in the field. Snow cover was initially specified to begin on the first day of freezing conditions (September 24), however these values were adjusted slightly for each site to try to calibrate the resulting thaw depths and ground temperatures with field conditions (Table 3). The snow commencement dates used in the simulations are within the dates of snow arrival observed in the field, as described below.

The time to reach maximum snow depth at each site was specified from a minimum of 30 days (TST2) to a maximum of 120 days (DST1). These accumulation regimes correspond to maximum snow depths being reached between late-October and late-January. The rapid accumulation at TST2 is reasonable for this topographic setting, as O’Neill et al. (2015b) observed deep snow accumulation within a few weeks of freezing temperatures at a snow fence and at the base of a steep tundra slope, and the high embankment at TST2 is comparable to these sites. Snow accumulation up to the snow-holding capacity of tundra vegetation is commonly reached early in winter in the western Arctic, after one or two storms (e.g. Morse et al. 2012, Fig.
4). Snow cover in flat terrain is commonly assumed to accumulate over the freezing season with the square root of time (e.g., Zhang 1993; Riseborough 2007; Smith and Riseborough 2010) so that most of the snow cover is established within the first few months of the freezing season. The linear accumulation specified for the sites in this study represents a similar regime, though snow cover is slightly lower early in the season in the linear case compared with a parabolic function.

The maximum snow depth for each site was specified as the median value of three late-winter snow measurements from the field, rounded to the nearest 0.25 m (Table 3). For example, measured snow depths at DST1 were 1.24, 1.00, and 1.70 m in 2013, 2014, and 2015, respectively, so the maximum snow depth in the DST1 simulation was 1.25 m. Snow ablation at the end of winter occurred at a rate of 1.5 kg m\(^{-2}\) per degree-day (e.g., Smith and Riseborough 2010).

When snow was absent, the ground surface freezing \(n\)-factor had a value of 1.0. However, for the embankment, a freezing \(n\)-factor of 0.9 was used (Andersland and Ladanyi 2004; Darrow 2011). When present, the snow surface had an \(n\)-factor of 1.0. For each site in simulations for (i) and (ii), thawing-season \(n\)-factors were calculated using measured air temperatures, and ground temperatures recorded at 0.05 m depth at the shallow cables. The embankment was assigned a thawing \(n\)-factor of 1.1 (e.g., Darrow 2011).

**Examining the effect of the snow accumulation regime at the embankment toe**

Additional 35-year transient conditions were simulated to examine the effect of the snow initiation date and the number of days taken to establish maximum snow cover for conditions representative of the embankment toe. Maximum snow depth was set as 1.0 m and the thawing \(n\)-factor to 0.7 for all cases to isolate the influence of the snow timing parameters. A 1.0 m snow
pack was specified as this represents an intermediate value of snow accumulation measured at the embankment toe sites (Table 3). The parameters for each simulation are shown in Table 4.

Snow management simulations

Further transient simulations examined the effect of limiting snow depth and increasing snow density to mimic potential mechanical snow management at the embankment toe.

Three scenarios (M1-M3) began with the initial (undisturbed) temperature profile and simulated ground temperatures over 35 years. These scenarios represent the effect of long-term snow management immediately following embankment construction. The maximum snow cover was set to 0.3 m, and density varied to account for mechanical compaction during the snow removal process (Table 5). The maximum snow depth was set to 0.3 m to allow a base for machinery operation without significant disturbance to the ground surface. The maximum snow density simulated was 400 kg m$^{-3}$, which is attainable after only two passes of a snow roller (Abele 1990, Figure 51).

An additional three scenarios (M4-M6) began with the disturbed conditions simulated at TST2 after 35 years, and the model was run for 10 years with the same depth and densities as M1-M3 (Table 5). These simulations represent the potential effect of future snow management activities at disturbed sites where significant permafrost degradation has already occurred.

RESULTS

Field measurements

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 6, Figure 4). $T_g$ 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. (2015b) at similar sites. Annual mean ground temperature at DST2 was -2.2 °C, similar to the values for 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 6). Curvatures of the annual mean ground temperature envelopes indicate that permafrost is presently degrading at all road sites except DST2 (Figure 4).

**Thaw depths**

There was a large variation in thaw depth at road sites, from 0.9 to 5.3 m. Thin frozen layers were encountered near the road embankment at three sites during probing in August 2014 between 0.5 and 0.6 m depth, and were underlain by unfrozen ground. 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 2017). This indicates that taliks have developed in some places near the embankment. At the DST and TST control sites, the August thaw depths were 0.7 and 0.6 m, respectively (Table 6). However, thaw depths at control sites were measured on August 8 in 2014, so maximum thaw was likely not reached by that date.

**Snow conditions**

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 6). Snow thermal resistance was greater at road sites than at control sites, except at DST2 where the values were similar to those for control sites (Table 6). The median snow thermal resistance for all road site snow pits was 9.6 m$^2$ K W$^{-1}$ (n=13). A Mann-Whitney U test indicated that the median at control sites was significantly lower (4.5 m$^2$ K W$^{-1}$; n=4, p=0.02). The high thermal resistances at road sites were due to greater snow depths beside the embankment, as average snow pack densities for the road sites (230-350 kg m$^{-3}$, n=13) were statistically indistinguishable (Mann-Whitney U) from those at the control sites (230-270 kg m$^{-3}$, n=4, p=0.11).

The effect of the road embankment on snow accumulation in tundra is illustrated with the data collected along transects in 2015. 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, presumably due to a lack of wind redistribution (Figure 5b).

The annual start date of a continuous winter snow cover at road sites was estimated by examining ground temperatures from the thermistors at 0.05 m depth. Snow was assumed to cover the ground when the diurnal variation in surface temperature dropped below 1 °C and persisted below this value (Burn and Zhang 2009; O’Neill et al. 2015b). Snow cover began to accumulate at all the road sites between September 11 and October 17 in 2012-14 (Table 6).

Simulation results
The initial temperature profile from the spin-up conducted to establish conditions representative of undisturbed tundra in the 1970s is shown in Figure 6. The annual mean temperature at 5 m depth was -2.9 °C. This is lower than measured at the control sites (DST control: -1.8 °C; TST control: -2.6 °C), due to the cooler climate prevailing at that time (Burn and Kokelj 2009).

*Reproducing conditions near the embankment*

The model generally reproduced present annual mean ground temperatures at the toe of the embankment, though the performance varied between sites and at different depths (Figure 7). The differences between measured and modeled $T_g$ values (5 m depth) were between 0.1 °C (TST2) and 0.9 °C (DST1). The median difference between measured and modeled temperatures at all thermistor depths for the five embankment toe sites was between 0.1 °C (TST2) and 0.9 °C (DST1). In most cases, the differences in temperature decreased with depth, except for DST1 (Figure 7).

Temperatures from the road centreline simulation were compared with measured values from the highway monitoring site on Peel Plateau presented in Idrees et al. (2015). Annual mean temperatures within the embankment were simulated reasonably well, with a median difference for the top four thermistors of 0.5 °C (Figure 7f). Below 2 m, the difference between measured and modeled values increased gradually with depth. This is likely due to lateral heat flow from the warm ground adjacent to the embankment, which is not accounted for in the 1-d simulation. Conditions at the DST control site were closely reproduced (Figure 7g), with the median difference between measured annual mean temperatures from all thermistor depths and modeled values being 0.1 °C.
Measured and modeled ground surface temperatures between 2012-15 (0.05 m depth) are presented for four sites in Figure 8. The influence of lower snow depths in winter 2013-14 is apparent from the measured values at DST2. Modeled values do not capture the interannual variation as the snow conditions and air temperatures did not vary between years through the simulations. Thus, in some years the winter ground surface temperatures were reproduced closely (e.g. TST1 in 2013-14), while in others (DST2 in 2013-14) there were differences of about 10 °C. However, at the four degrading sites at the embankment toe (DST1&3, TST1&2), measured and modeled winter ground surface temperatures were similar.

There are several systematic characteristics exhibited by the modeled ground surface temperatures. Snow cover thawed later in the simulations than in the field at all sites in every year, suggesting bias in parameterization of the snow melt factor. This is apparent from the onset of positive ground surface temperatures, which occurred between April and June depending on the snow depth (Figure 8). Modeled summer surface temperatures were also commonly lower than measured temperatures, by up to nearly 10 °C, at DST1&2, and TST1.

Three indices of model performance for time series analyses are presented in Table 7 for the measured and modeled surface temperatures (Figure 9). The definitions and significance of these indices are widely reported in statistical source material (e.g., Adhikari and Agrawal 2013). The indices are included to enrich the assessment of model performance in characterizing the ground surface thermal regime. Root mean square errors (RMSE) of modelled daily ground surface temperatures were between 1.5 °C (TST2) and 4.2 °C (DST2), and mean absolute errors (MAE) were between 1.1 and 3.0 °C for the same sites, respectively (Table 7). The higher errors at DST2 are due to the interannual variation in snow depth causing significant differences in daily winter surface temperatures there. The RMSE values are higher than the MAE values.
because the statistic is weighted towards large errors. Mean error (ME) values were between -0.1 °C (TST2) and 0.9 °C (DST1). The positive MEs at DST1, DST2, and TST1 indicate that measured temperatures were typically higher than the simulated values, which is likely due to the systematically lower values produced by the model in summer (Figure 9). ME values are lower than MAE, particularly for DST2, because the statistic conceals large positive and negative errors by offsetting them.

There was some variation in the ability of the simulations to reproduce measured thaw depths (Table 6, Figure 7). Among all sites, the median difference between measured and modeled thaw depth was 0.3 m. There was a maximum difference of 0.9 m for TST1, and a minimum of 0.1 m for DST2 and DST3. In general, the simulations at sites with colder ground and little snow (DST2, Embankment, DST control) best reproduced measured thaw depths, with a median difference of 0.2 m at these three sites (Figure 7). However, it should be noted again that thaw depth was measured on August 8 at DST2 and DST control, when thawing was likely not at maximum, which may have contributed to some of the difference between measured and modeled values. The implications of the differences between measured and modeled temperature and thaw depths are discussed below.

**Snow accumulation regime simulations**

The S1-S6 simulations examined the thermal effect of changing the starting date for snow accumulation and its rate (see Table 4). Results from year 35 of the simulations are shown in Figures 10-12.

S1 and S2 demonstrate the effect of a short delay in snow commencement on winter ground temperatures and, most notably, the resulting thaw depth. The two-week delay in S2
allowed significant heat evacuation from the active layer, which is apparent from the initial cooling and persistence of lower surface temperatures throughout the freezing season (Figure 10a). A result of this heat loss early in the freezing season was reduced thaw depth by year 35 in S2 (2.6 m) compared to S1 (4.4 m) (Table 4). A talik nearly formed by year 35 in S1, indicated by the closing of the 0 °C isotherms shortly prior to downward thawing from the surface (Figure 10b). Freezeback in S1 took about 5 months longer than in S2. Summer thaw commenced at the same rate in S1 and S2, but as ground just below 0 °C was encountered between 1 and 4 m depth in S1, thawing progressed more rapidly. Differences in $T_g$ between S1 and S2 were small, because the greater heat extraction in S2 was occupied in phase change rather than in cooling by sensible heat (Figure 10c, Table 4).

S3 and S4 demonstrate the influence of a longer period of snow accumulation. The greater number of days to maximum snow depth had a relative effect of lowering ground surface temperatures and thaw depth. However, the difference in ground surface temperature between S3 and S4 occurred later than in S1 and S2, because snow initiated on the same day in the former scenarios. The thaw depth was 1.1 m less in the S4 scenario than in S3, and freezeback was completed about two months earlier (Figure 11, Table 4). Downward thaw from the surface in summer began at similar rates, but increased in July and August in S3 as warmer ground was encountered at depth (Figure 11b,c). As in S1 and S2, there was little difference in $T_g$ between S3 and S4 because heat exchange was mainly occupied by phase change in the near surface rather than in sensible heating or cooling.

S5 and S6 highlight the combined effects of a delayed snow commencement and longer snow accumulation. The primary difference between these scenarios and S1-S4 is a more pronounced sensible cooling of the ground, both at the surface and at depth, and resulting
shallower thaw depths (Figure 12). Surface temperatures reached near -4 °C in S6, which
facilitated significant winter heat loss as the latent heat requirement, characterized by the
unfrozen water content curve, was mostly satisfied (Figures 3, 11c). The sensible cooling of the
ground in S5 and S6 caused ground thawing to be similar in both simulations, with little
difference in thaw penetration timing or magnitude (Figure 12c). This is indicative of a threshold
between simulations like S1-S4 and S5-S6 where thaw depths are controlled predominantly by
the winter snow regime (S1-S4) rather than summer conditions (S5, S6).

Snow manipulation simulations

The M1-M6 simulations examined the effect of limiting the accumulation of snow at the
embankment toe and increasing the snow pack density to simulate potential mechanical snow
management. M1-M3 simulated 1980-2015 temperatures with three different snow densities,
assuming snow depth was limited to 0.3 m each year for the 35 years since embankment
construction. M4-M6 examined 10-year future responses to depth and density manipulations of
the present disturbed thermal conditions simulated for TST2 (see Table 5).

M1-M3 demonstrate the effect on ground temperatures of limiting snow accumulation
and increasing snow density immediately following embankment construction (Figure 13). M1
resulted in ground temperatures slightly lower than the DST control site. When the density of the
snow cover was increased to 400 kg m\(^{-3}\) in M3, mean annual ground temperature at 5 m depth
was reduced to -4.8 °C after 35 years, compared to -1.8 °C for the DST control simulation
(Figure 13). The active-layer thicknesses after 35 years in M1-M3 were 1.0, 0.9, and 0.8 m,
respectively, similar to values for undisturbed tundra.
M4-M6 demonstrate the response of disturbed conditions to snow management over 10 years. The M4-M6 manipulations rapidly decreased ground temperatures and thaw depths from the disturbed conditions simulated at TST2 (Figure 14). After 10 years, $T_g$ was reduced by up to 4.4 °C (M6, Figure 14). The reduction in ground temperatures was rapid in the initial years following snow management. To illustrate, annual mean ground temperature profiles for years 2, 5, and 8 in M6 are plotted in Figure 15. Ground cooling reached about 4 m depth by the second year, 8 m by year 5, and 17 m by year 8. Thaw depth decreased from nearly 5.0 m in the first year to <1.5 m in the second year of the M4-M6 simulations, and to about 1.0 m after 10 years (Figure 16), indicating the reduction in depth to permafrost.

The results from M1-M6 suggest that even shorter-term (e.g., several year) snow management efforts may serve to effectively cool near-surface ground temperatures, refreeze taliks, and prevent thaw of ice-rich permafrost at the embankment toe. Longer-term activities may cool permafrost to significant depths and thus provide added thermal stability.

**DISCUSSION**

**Field conditions**

Higher ground temperatures were observed near the toe of the road embankment than at control sites, except at DST2, where the embankment made little change in snow cover. The thermal disturbance to permafrost is primarily associated with deeper snow cover resulting from wind deposition along the embankment. 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$^{-1}$, and 4.7 m$^2$ K W$^{-1}$ at DST2.
The increase in snow cover following embankment construction has resulted in increased thaw depths at all sites except DST2. For example, the measured thaw depths at control sites suggest that >4 m of permafrost has degraded at TST2. The thaw of near-surface permafrost at four of the five road sites is corroborated by the temperature profiles, which are in disequilibrium, by probing, which indicated taliks at some locations near the road, and by $T_s$ values at these sites >0 °C.

Ground surface temperatures measured at the shallow cables were near 0 °C throughout the freezing season, indicating that winter ground cooling does not occur at the degrading road sites. 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, may 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. 2015b). 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 the dominant northerly winter winds. Consequently, snow does not accumulate as at the other embankment toe sites, resulting in permafrost temperatures and thaw depths similar to control sites. This finding indicates that site-specific topographic characteristics are important in determining susceptibility to permafrost degradation along linear transportation infrastructure in tundra terrain.

**Simulations of field conditions**
In general, the 35-year disturbance simulations reproduced conditions observed in the field. Modeled ground temperatures were close to measured values at depths of 0-8 m. Simulated ground surface temperatures (0.05 m depth) after 35 years of disturbance closely matched measured values from the shallow cables, and reproduced seasonal patterns, particularly for the four sites with degrading permafrost. The largest absolute differences between measured and modeled ground surface temperatures on individual days occurred in the thawing season, except at DST2, where differences were also sometimes large in winter. The large differences in some freezing season surface temperatures at DST2 are attributable to the low snow accumulation in 2013-14. There was no interannual snow variation in the model, so in years with abnormal snow accumulation, differences at DST2 are pronounced due to the thin snow cover characteristic of the site. In contrast, the other road sites are less affected by seasonal differences in snow depth because the influence of changes in snow depth is diminished in snow packs more than 50 cm thick (Smith 1975), and the surface temperature is constrained by the latent heat released during seasonal ground freezing.

Modeled thaw depths at sites with little snow were in close agreement with those measured in the field, and the presence of a talik, indicated by probing at TST2, was also simulated. There was general agreement regarding thaw depth at the embankment toe sites, with a median difference between modeled and measured values of 0.35 m. However, there were relatively large differences in measured and modeled thaw depths at TST1 (0.9 m) and TST2 (0.4 m). This is likely because ground temperatures at these sites were very close to 0 °C, and thaw-depth prediction is made difficult under this condition because of the phase change associated with small changes in temperature (e.g., LeBlanc et al. 2014). This observation may
limit the utility of such simulations for predicting the depth to permafrost in degrading permafrost.

**Simulation limitations**

Differences between measured and modeled values may be associated with several necessary simplifications in the simulations. First, no long-term air temperature record exists for Peel Plateau, and it was not possible to accurately produce a synthetic record using temperatures from Inuvik, because the long-term nature of the winter air temperature inversions between the plateau and lowlands is unknown (O’Neill et al. 2015b). As a result, air temperatures were simulated using median values from three years (2012-14) of measurements on Peel Plateau, and these may not reflect air temperatures over the entire period of the transient simulation (1980-2015). For example, air temperatures in 2012-14 at Inuvik were about 1 °C higher than in 1980-2015.

Second, the model assumed a constant snow accumulation regime, so any interannual effects or long-term precipitation trends were not captured. Third, the site-specific \( n_t \) values used characterized the present-day conditions at the shallow cables. These represent the best available information on the relation between air and ground surface temperatures in the thawing season. However, these do not account for interannual or shorter time scale variations in summer surface conditions that strongly control ground surface temperatures on a given day. In addition, proliferation of shrubs and changes to soil moisture near the embankment toe have likely caused an evolution of \( n_t \) over time since embankment construction (Gill et al. 2014; Cameron and Lantz 2016). These factors were not included in the model. Fourth, the initial equilibrium temperature profile was the same for all sites. This likely resulted in the differences in annual ground temperatures observed at DST1. Near-surface ground temperatures were reproduced closely, but
differences increased with depth, with measured values lower than those simulated, suggesting that this site may have had lower initial ground temperatures than specified in the model. This point indicates that the assigned initial ground thermal profile is an important consideration, particularly if permafrost temperatures at depth are of interest. Earlier iterations of transient simulations with different initial ground temperatures indicated that thaw depths at the most disturbed sites are also sensitive to the initial thermal conditions. Fifth, material properties used in the simulation were a simplification of field conditions, and did not account for ground subsidence effects from the thaw of near-surface ground ice.

Finally, simulations did not include the effects of lateral heat flow. The ground thermal conditions near the road are the result of three-dimensional heat transfer processes (LeBlanc et al. 2014). This simplification was apparent in the simulation of temperatures at the road centreline, where modeled values were much lower at depth than measured in the field, because lateral heat flow from the warm ground at the embankment toe was not included. Nonetheless, the agreement between modeled and field conditions is remarkable and gives confidence in the simulations. The coincidence of the temperature profiles is due to the thermal inertia provided by the latent heat requirements of thawing permafrost. For transient conditions, the efficacy of latent heat in reducing variation in ground temperatures increases with depth due to reduction in amplitude of the annual temperature cycle.

**Implications and future directions**

Measurements at the Dempster Highway embankment toe suggest permafrost is degrading in settings that are favourable to deep snow accumulation (Darrow 2011; Fortier et al. 2011; Lanouette et al. 2015). The thaw of ice-rich permafrost beside the Dempster Highway
embankment on Peel Plateau is already an ongoing maintenance challenge, and future climate warming may exacerbate the problem. The agreement between measured and modeled temperatures at the embankment toe allows future simulations to examine the effects of climate amelioration. The ground surface temperatures from the TONE model may be implemented as boundary conditions in two-dimensional simulations of permafrost conditions near infrastructure as in Smith and Riseborough (2010), using commercially available models such as TEMP/W (GeoStudio, Calgary, AB). This would allow consideration of lateral heat flow between the embankment and surrounding terrain. The present literature on this topic has applied air temperature increases to the ground thermal regime using $n$-factors, but the TONE model also enables potential changes in precipitation (snow) to be considered explicitly.

Future investigations on permafrost near infrastructure embankments would benefit from a longer-term baseline dataset on snow accumulation regimes. Snow accumulation and ablation at the embankment may be monitored directly using time-lapse photography and snow stakes (Farinotti et al. 2010; Parajka et al. 2012), with sonic range sensors, or inferred using thermistors mounted at increments above the ground surface (Lewkowicz 2008; Lanouette et al. 2015). A catalogue of such data would allow increased confidence when assigning snow accumulation parameters in models, as interannual variability over longer timespans could be quantified. Given the sensitivity of the modeled thaw depths to initial conditions and parameterization, modeling of future permafrost degradation at infrastructure could then employ a probabilistic approach based on measured distributions of field conditions.

From a practical standpoint, the modeling in S1-S6 and M1-M6 suggests that snow management techniques that delay, limit, or densify snow accumulation near the embankment toe could be a maintenance option to ensure longer-term stability at sites where permafrost thaw
threatens the embankment integrity. This would facilitate more rapid ground cooling during the critical freezeback period, resulting in a reduction in thaw depth and protection of underlying ice-rich ground. This agrees with observations in a field experiment by Lepage et al. (2012) of reduced ground temperatures in the initial years following snow clearing. The short-term effects of snow manipulation on the thermal regime could be further explored in the field by instrumenting a site and compacting snow cover at regular intervals, and tracking snow depth and density changes over the winter. Snow compaction may have a double effect of facilitating conductive heat loss through the snow pack, and limiting ground thaw in summer due to a longer snow ablation period (e.g., Keller et al. 2004). For future snow removal or compaction experiments at the embankment toe, it is critical that the surface organic material on the natural ground remain intact, and thus a minimum snow cover depth should be established for the specific equipment used.

CONCLUSIONS

The measurement and modeling of permafrost conditions near the Dempster Highway road embankment on Peel Plateau has led to the following conclusions:

(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. A talik was measured at the site with the deepest snow by probing in summer, and simulated with a 1-dimensional numerical model.
(2) High ground temperatures are associated with a thick, insulating snow cover that accumulates along the embankment. Enhanced snow accumulation near the embankment toe is pronounced in tundra, due to wind redistribution, but not where the road passes through forest.

(3) A one-dimensional numerical model that incorporated the accumulation and ablation of a snow pack closely reproduced ground temperatures at embankment toe sites. Thaw depths were reasonably reproduced, but differences were larger at sites with ground temperatures near 0 °C, highlighting the difficulty of modeling thaw depth precisely in degrading permafrost.

(4) A delay in the onset of deep (1 m) snow accumulation for a short period (e.g. two weeks) and/or an extension in the duration of snow accumulation allows the evacuation of latent heat from the active layer, facilitates sensible cooling of the ground, and significantly decreases thaw depths.

(5) Limiting the depth and increasing the density of snow cover at the embankment toe significantly reduced temperatures and thaw depths in modeling simulations of the most disturbed site. Active snow management should be explored further as a potential maintenance activity along thaw sensitive sections of northern transportation infrastructure.
ACKNOWLEDGEMENTS

This project has been supported by the NWT Cumulative Impact Monitoring Program, the Northern Scientific Training Program of Aboriginal Affairs and Northern Development Canada, the Natural Sciences and Engineering Research Council of Canada, the Aurora Research Institute, the W. Garfield Weston Foundation, the Tetlit Gwich’in Council and Transport Canada. Field assistance from Steven Tetlichi, Clifford Vaneltsi, Abraham Snowshoe, John Itsi, Christine Firth, Adrian Gaanderse, Jeff Moore, Blair Kennedy, Marcus Phillips, Emily Cameron, Krista Chin and Dominique Hill is greatly appreciated. Helpful comments, which improved the paper, were received from S.A. Wolfe and S.V. Kokelj. We thank the editors and two reviewers for their careful examination of the manuscript during the review process, and for comments which led to improvements in the paper.

REFERENCES

Abele, G. 1990. Snow roads and runways. U.S. Army Cold Regions Research and Engineering Laboratory Monograph 90-3, Hanover, NH.


Northwest Territories. Paper 705. In Proceedings, 68th Canadian Geotechnical Conference and
7th Canadian Permafrost Conference, 21-23 September 2015, Quebec City, QC, Canadian
Geotechnical Society, Richmond, BC. 8 p. Available at http://carleton.ca/permafrost/wp-
content/uploads/705.pdf

Cameron, E.A., and Lantz, T.C. 2016. Drivers of tall shrub proliferation adjacent to the
11. DOI: 10.1088/1748-9326/11/4/045006

Darrow, M.M. 2011. Thermal modeling of roadway embankments over permafrost. Cold
Regions Science and Technology 65(3): 474–487. DOI: 10.1016/j.coldregions.2010.11.001

embankment (ACE) with thermal berm over ice-rich permafrost, Lost Chicken Creek, Alaska.
Cold Regions Science and Technology 130:43–58. DOI: 10.1016/j.coldregions.2016.07.012

Doré, G., Niu, F., and Brooks, H. 2016. Adaptation of transportation infrastructure built on

embankment enhanced by heat advected in groundwater. Canadian Journal of Earth Sciences
49(8): 953–962. DOI: 10.1139/e2012-018

Environment Canada (2012), *Climate Data Online*, available at [http://climate.weather.gc.ca/index_e.html#access](http://climate.weather.gc.ca/index_e.html#access) [31 January 2012].


Farouki, O.T. 1981. Thermal properties of soils. Cold Regions Research and Engineering Lab Monograph 81-1, Hanover NH.


Canadian Geotechnical Society, Richmond, BC. 8 p. Available at:


http://dx.doi.org/10.3189/172756404781815310


10.1016/j.coldregions.2010.04.009

Kokelj, S.V., Lacelle, D., Lantz, T.C., Tunnicliffe, J., Malone, L., Clark, I.D., and Chin, K.S. 2013. Thawing of massive ground ice in mega slumps drives increases in stream sediment and


Lepage, J.-M., and Doré, G. 2010. Experimentation of mitigation techniques to reduce the effects of permafrost degradation on transportation infrastructures at Beaver Creek experimental road site (Alaska Highway, Yukon). In Proceedings of the 63rd Canadian Geotechnical Conference, 12-16 September 2010, Calgary, AB. Canadian Geotechnical Society, Richmond, BC. 526-533


FIGURE AND TABLE CAPTIONS

Figure 1: Location of instruments on Peel Plateau along the Dempster Highway (black line). Snow depth transects are marked by dashed lines (not to scale). The asterisk indicates the position of the air and shallow ground temperature sensors (O’Neill et al. 2015b) from which data were used in modeling simulations (see text). The inset is modified from Burn (1994, Figure 1), and permafrost zones are after Heginbottom et al. (1995).

Figure 2: The DST2 and TST2 instrument locations. DST2 is the least disturbed, located near a low embankment and exposed to winds that carry snow away. TST2 is adjacent to a high embankment where vegetation and moisture conditions have changed as a result of deep snow accumulation.

Figure 3: Thermal conductivity and unfrozen water content characteristic curves for the three materials in the simulations. The frozen thermal conductivity of the coarse embankment material is less than the unfrozen conductivity because of the very low moisture content (e.g., Farouki, 1981, p. 45).
Figure 4: Temperature envelopes from the deep cables in 2013-14 at embankment toe sites and control sites. The dots on the lines indicate the position of thermistors. Note that DST3 is not plotted here.

Figure 5: Snow accumulation measured in March 2015 at (a) six tundra and (b) six forest transects. The dots are the median depths from the transects, and the vertical lines represent the interquartile ranges.

Figure 6: Temperature envelope (annual maximum, minimum, and mean values) for the equilibrium spin-up used as the initial condition in subsequent 35-year transient simulations. Measured air temperatures on Peel Plateau were reduced based on the record from Inuvik to represent cooler conditions in the late 1970s, when the road was constructed. The annual mean temperature at 5 m depth was -2.9 °C, and active-layer thickness was 1.0 m.

Figure 7: Measured (dots) and modeled (solid line) annual mean ground temperatures for sites at the embankment toe, at the road centreline (measured values from Idrees et al. (2015)), and for the DST control site. The solid horizontal line is the modeled thaw depth after 35 years, and the dashed horizontal lines are the measured values from Table 6. Maximum snow depths used in the simulations are shown under each site label.

Figure 8: Measured (solid) and modeled (dashed) ground surface temperatures (0.05 m depth) between 2012-2015 for sites at the embankment toe. Note that DST3 is not plotted here.

Figure 9: Modeled vs. measured ground surface temperatures (0.05 m depth) at sites near the embankment toe between 2012-15 (same data as Figure 8). The ellipse in (a) encompasses values when the modeled snowpack was still ablating but the ground was free of snow in the field. Note that DST3 is not plotted here.

Figure 10: (a) simulated ground surface temperatures (0.05 m depth), (b) positions of the 0 °C isotherm, and (c) temperature envelopes for simulations S1 and S2. In S1, snow began to accumulate on the first day of freezing conditions; in S2, snow accumulation began 14 days after freezing conditions. In both simulations, snow reached its maximum depth (1.0 m) after 30 days of accumulation. The simulations commence on August 1 and results are shown for year 35.

Figure 11: (a) simulated ground surface temperatures (0.05 m depth), (b) positions of the 0 °C isotherm, and (c) temperature envelopes for simulations S3 and S4. In S3, the maximum snow depth (1.0 m) is reached after 90 days; in S4, the maximum snow depth (1.0 m) is reached after 120 days. Snow commenced on the first day of freezing conditions in both simulations. The simulations commence on August 1 and results are shown for year 35.

Figure 12: (a) simulated ground surface temperatures (0.05 m depth), (b) positions of the 0 °C isotherm, and (c) temperature envelopes for simulations S5 and S6. In these simulations, snow commenced 14 days following freezing conditions; in S5, the maximum snow depth (1.0 m) is reached after 90 days, and in S6, the maximum snow depth (1.0 m) is reached after 120 days. The simulations commence on August 1 and results are shown for year 35.
Figure 13: Simulated annual mean ground temperatures for year 35 of the M1-M3 snow manipulation scenarios (see Table 5). The initial temperature conditions in the simulations were the undisturbed conditions in Figure 6. The results are plotted with simulated conditions after 35 years for the DST control site (e.g., Figure 7g).

Figure 14: Simulated annual mean ground temperatures for year 10 of the M4-M6 snow manipulation scenarios (see Table 5). The initial temperature conditions in the simulations were from year 35 of the TST2 embankment toe simulation in Figure 7e.

Figure 15: Simulated annual mean ground temperatures for years 2, 5, and 8 of the M6 snow manipulation scenario (see Table 5). The initial temperature conditions in the simulations were from year 35 of the TST2 embankment toe simulation in Figure 7e.

Figure 16: Simulated thaw depths (0 °C isotherm) over ten years for the M4-M6 snow manipulation scenarios (see Table 5). The initial temperature conditions in the simulations were from year 35 of the TST2 embankment toe simulation in Figure 7e.

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

Table 2: Properties of materials used in the simulations. $\lambda_f$ and $\lambda_t$ are the frozen and thawed thermal conductivities (W m$^{-1}$ K$^{-1}$) calculated using Kersten’s method (e.g., Farouki 1981) and an equation developed by Johansen (1975). $\theta_v$ is volumetric water content (m$^3$ m$^{-3}$); the value for the mineral soil is the porosity for Mayo silty clay from Smith and Tice (1988), while the value for peat is from Smith and Riseborough (2010). The value for the embankment is representative of dry conditions within the coarse material. $C_f$ and $C_t$ are the frozen and thawed heat capacities (J m$^{-3}$ K$^{-1}$), and are based on an arithmetic mean of the soil constituent heat capacities (e.g., Burn, 2004, eq. 3.3.5).

Table 3: Snow parameters and $n$-factors from field measurements used to simulate present ground thermal conditions at the embankment toe sites, undisturbed (control) tundra, and the road centreline. Snow initiation refers to the number of days between the onset of freezing surface temperatures and snow cover commencement.

Table 4: Parameterizations for six snow accumulation simulations. Snow initiation refers to the number of days after freezing air temperatures that snow accumulation commences. Resulting $T_g$ (5 m depth), $T_s$, and thaw depths from year 35 of the simulations are also presented.

Table 5: Parameterizations for six snow management simulations that varied snow density (kg m$^{-3}$). Snow initiation refers to the number of days after freezing air temperatures that snow accumulation commences. All $n_i$ values were 0.7, as in S1-S6. The initial temperature profile for M1-M3 is from the undisturbed simulation (Und., Figure 6). Resulting $T_g$ (5 m depth), $T_s$, and thaw depths from the final year of the simulations are also presented.
Table 6: Annual mean ground temperatures near 5 m depth ($T_g$), at the surface ($T_s$), and thaw depths, late-winter snow depth (March), snow thermal resistance, and snow arrival dates (written as S/O dd; where S = Sept., O = Oct., dd = day) at the seven field sites. The $T_s$ ranges and snow arrival dates reported for the control sites are from nearby sites in undisturbed tundra (O’Neill et al., 2015b), as there were no shallow cables at the control sites.

Table 7: Root mean square error (RMSE, °C), mean absolute error (MAE, °C), and mean error (ME, °C) of modeled daily ground surface temperatures (0.05 m depth) at four sites at the Dempster Highway embankment toe. All indices are based on n=730 (2 years) daily measurements. The calculations were conducted using the hydroGOF package in R (http://www.rforge.net/hydroGOF/).
Table 1

<table>
<thead>
<tr>
<th></th>
<th>DST1</th>
<th>DST2</th>
<th>DST3</th>
<th>TST1</th>
<th>TST2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Embankment</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Ponding (Y/N)</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td><em>Equisetum</em> (Y/N)</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Material</th>
<th>$\lambda_f$</th>
<th>$\lambda_t$</th>
<th>$\theta_v$</th>
<th>$c_f$</th>
<th>$c_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral</td>
<td>2.4</td>
<td>1.3</td>
<td>0.51</td>
<td>1.9E+06</td>
<td>3.0E+06</td>
</tr>
<tr>
<td>Peat</td>
<td>1.3</td>
<td>0.5</td>
<td>0.75</td>
<td>1.9E+06</td>
<td>3.6E+06</td>
</tr>
<tr>
<td>Embankment</td>
<td>1.4</td>
<td>1.7</td>
<td>0.10</td>
<td>1.5E+06</td>
<td>1.7E+06</td>
</tr>
</tbody>
</table>

Table 3

<table>
<thead>
<tr>
<th></th>
<th>DST1</th>
<th>DST2</th>
<th>DST3</th>
<th>TST1</th>
<th>TST2</th>
<th>DST control</th>
<th>Centreline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max snow (m)</td>
<td>1.25</td>
<td>0.5</td>
<td>1.5</td>
<td>1</td>
<td>1.75</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>Snow initiation</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>10</td>
<td>0</td>
<td>7</td>
<td>n/a</td>
</tr>
<tr>
<td>Days to max snow</td>
<td>120</td>
<td>100</td>
<td>90</td>
<td>90</td>
<td>30</td>
<td>90</td>
<td>n/a</td>
</tr>
<tr>
<td>$n_t$</td>
<td>0.62</td>
<td>0.78</td>
<td>0.67</td>
<td>0.77</td>
<td>0.70</td>
<td>0.70</td>
<td>1.10</td>
</tr>
</tbody>
</table>

Table 4

<table>
<thead>
<tr>
<th></th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. snow</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Snow initiation</td>
<td>0</td>
<td>14</td>
<td>0</td>
<td>0</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Days to max. snow</td>
<td>30</td>
<td>30</td>
<td>90</td>
<td>120</td>
<td>90</td>
<td>120</td>
</tr>
<tr>
<td>$n_t$</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>$T_g$</td>
<td>-0.1</td>
<td>-0.3</td>
<td>-0.2</td>
<td>-0.3</td>
<td>-0.5</td>
<td>-0.9</td>
</tr>
<tr>
<td>$T_s$</td>
<td>1.9</td>
<td>1.5</td>
<td>1.6</td>
<td>1.4</td>
<td>1.0</td>
<td>0.4</td>
</tr>
<tr>
<td>Thaw depth (m)</td>
<td>4.4</td>
<td>2.6</td>
<td>3.2</td>
<td>2.1</td>
<td>1.2</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Table 5

<table>
<thead>
<tr>
<th></th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
<th>M6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation duration</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Initial T profile</td>
<td>Und.</td>
<td>Und.</td>
<td>Und.</td>
<td>TST2</td>
<td>TST2</td>
<td>TST2</td>
</tr>
<tr>
<td>Max. snow (m)</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Snow initiation</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Snow density</td>
<td>250</td>
<td>300</td>
<td>400</td>
<td>250</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>Days to max. snow</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>$T_g$</td>
<td>-2.2</td>
<td>-3.7</td>
<td>-5.7</td>
<td>-0.3</td>
<td>-1.9</td>
<td>-4.1</td>
</tr>
<tr>
<td>$T_s$</td>
<td>-0.9</td>
<td>-2.5</td>
<td>-4.8</td>
<td>-0.4</td>
<td>-2.1</td>
<td>-4.5</td>
</tr>
<tr>
<td>Thaw depth (m)</td>
<td>1.0</td>
<td>0.9</td>
<td>0.8</td>
<td>1.1</td>
<td>1.0</td>
<td>0.9</td>
</tr>
</tbody>
</table>
Table 6

<table>
<thead>
<tr>
<th></th>
<th>DST1</th>
<th>DST2</th>
<th>DST3</th>
<th>DST Control</th>
<th>TST1</th>
<th>TST2</th>
<th>TST Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from embankment (m)</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>150</td>
<td>5</td>
<td>8</td>
<td>50</td>
</tr>
<tr>
<td>Td (°C)</td>
<td>-1.3</td>
<td>-2.2</td>
<td>-0.7</td>
<td>-1.8</td>
<td>-0.7</td>
<td>0.0</td>
<td>-2.6</td>
</tr>
<tr>
<td>Ts (°C)</td>
<td>1.6</td>
<td>-1.6</td>
<td>1.8</td>
<td>-0.5 to -3.4</td>
<td>2.1</td>
<td>1.3</td>
<td>-1.8 to -1.9</td>
</tr>
<tr>
<td>Thaw depth (m)</td>
<td>0.9</td>
<td>3.4</td>
<td>0.7</td>
<td>3.0</td>
<td>5.3</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Snow depth (m)</td>
<td>1.2</td>
<td>0.4</td>
<td>0.9</td>
<td>0.4 - 0.8</td>
<td>0.9</td>
<td>1.1</td>
<td>0.4 - 0.5</td>
</tr>
<tr>
<td>Snow thermal resistance (m² K W⁻¹)</td>
<td>7 - 11</td>
<td>4 - 5</td>
<td>8 - 10</td>
<td>4 - 7</td>
<td>11 - 14</td>
<td>10 - 13</td>
<td>3 - 5</td>
</tr>
<tr>
<td>Snow arrival date</td>
<td>S16</td>
<td>S17</td>
<td>S17</td>
<td>S11</td>
<td>S26</td>
<td>O17</td>
<td></td>
</tr>
</tbody>
</table>

*estimated from ground temperature envelope; superscripts 2, 3, 4 indicate 2012, 2013, and 2014, respectively.

Table 7

<table>
<thead>
<tr>
<th>Statistic</th>
<th>DST1</th>
<th>DST2</th>
<th>TST1</th>
<th>TST2</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE</td>
<td>1.7</td>
<td>4.2</td>
<td>2.1</td>
<td>1.5</td>
</tr>
<tr>
<td>MAE</td>
<td>1.2</td>
<td>3.0</td>
<td>1.4</td>
<td>1.1</td>
</tr>
<tr>
<td>ME</td>
<td>0.9</td>
<td>0.8</td>
<td>0.9</td>
<td>-0.1</td>
</tr>
</tbody>
</table>

\[
RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (S_i - O_i)^2}
\]

\[
MAE = \frac{1}{N} \sum_{i=1}^{N} |S_i - O_i|
\]

\[
ME = \frac{1}{N} \sum_{i=1}^{N} (S_i - O_i)
\]
Figure 1. Location of instruments on Peel Plateau along the Dempster Highway (black line). Snow depth transects are marked by dashed lines (not to scale). The asterisk indicates the position of the air and shallow ground temperature sensors (O’Neill et al. 2015b) from which data were used in modeling simulations (see text). The inset is modified from Burn (1994, Figure 1), and permafrost zones are after Heginbottom et al. (1995).
Figure 2. The DST2 and TST2 instrument locations. DST2 is the least disturbed, located near a low embankment and exposed to winds that carry snow away. TST2 is adjacent to a high embankment where vegetation and moisture conditions have changed as a result of deep snow accumulation.
Figure 3. Thermal conductivity and unfrozen water content characteristic curves for the three materials in the simulations. The frozen thermal conductivity of the coarse embankment material is less than the unfrozen conductivity because of the very low moisture content (e.g., Farouki, 1981, p. 45).
Figure 4. Temperature envelopes from the deep cables in 2013-14 at embankment toe sites and control sites. The dots on the lines indicate the position of thermistors. Note that DST3 is not plotted here.
Figure 5. Snow accumulation measured in March 2015 at (a) six tundra and (b) six forest transects. The dots are the median depths from the transects, and the vertical lines represent the interquartile ranges.
Figure 6. Temperature envelope (annual maximum, minimum, and mean values) for the equilibrium spin-up used as the initial condition in subsequent 35-year transient simulations. Measured air temperatures on Peel Plateau were reduced based on the record from Inuvik to represent cooler conditions in the late 1970s, when the road was constructed. The annual mean temperature at 5 m depth was -2.9 °C, and active-layer thickness was 1.0 m.
Figure 7. Measured (dots) and modeled (solid line) annual mean ground temperatures for sites at the embankment toe, at the road centreline (measured values from Idrees et al. (2015)), and for the DST control site. The solid horizontal line is the modeled thaw depth after 35 years, and the dashed horizontal lines are the measured values from Table 6. Maximum snow depths used in the simulations are shown under each site label.
Figure 8. Measured (solid) and modeled (dashed) ground surface temperatures (0.05 m depth) between 2012-2015 for sites at the embankment toe. Note that DST3 is not plotted here.
Figure 9. Modeled vs. measured ground surface temperatures (0.05 m depth) at sites near the embankment toe between 2012-15 (same data as Figure 8). The ellipse in (a) encompasses values when the modeled snowpack was still ablatting but the ground was free of snow in the field. Note that DST3 is not plotted here.
Figure 10. (a) simulated ground surface temperatures (0.05 m depth), (b) positions of the 0 °C isotherm, and (c) temperature envelopes for simulations S1 and S2. In S1, snow began to accumulate on the first day of freezing conditions; in S2, snow accumulation began 14 days after freezing conditions. In both simulations, snow reached its maximum depth (1.0 m) after 30 days of accumulation. The simulations commence on August 1 and results are shown for year 35.
Figure 11. (a) simulated ground surface temperatures (0.05 m depth), (b) positions of the 0 °C isotherm, and (c) temperature envelopes for simulations S3 and S4. In S3, the maximum snow depth (1.0 m) is reached after 90 days; in S4, the maximum snow depth (1.0 m) is reached after 120 days. Snow commenced on the first day of freezing conditions in both simulations. The simulations commence on August 1 and results are shown for year 35.
Figure 12. (a) simulated ground surface temperatures (0.05 m depth), (b) positions of the 0 °C isotherm, and (c) temperature envelopes for simulations S5 and S6. In these simulations, snow commenced 14 days following freezing conditions; in S5, the maximum snow depth (1.0 m) is reached after 90 days, and in S6, the maximum snow depth (1.0 m) is reached after 120 days. The simulations commence on August 1 and results are shown for year 35.
Figure 13. Simulated annual mean ground temperatures for year 35 of the M1-M3 snow manipulation scenarios (see Table 5). The initial temperature conditions in the simulations were the undisturbed conditions in Figure 6. The results are plotted with simulated conditions after 35 years for the DST control site (e.g., Figure 7g).
Figure 14. Simulated annual mean ground temperatures for year 10 of the M4-M6 snow manipulation scenarios (see Table 5). The initial temperature conditions in the simulations were from year 35 of the TST2 embankment toe simulation in Figure 7e.
Figure 15. Simulated annual mean ground temperatures for years 2, 5, and 8 of the M6 snow manipulation scenario (see Table 5). The initial temperature conditions in the simulations were from year 35 of the TST2 embankment toe simulation in Figure 7e.
Figure 16. Simulated thaw depths (0 °C isotherm) over ten years for the M4-M6 snow manipulation scenarios (see Table 5). The initial temperature conditions in the simulations were from year 35 of the TST2 embankment toe simulation in Figure 7e.