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Impacts of shrub removal on snow and near-surface thermal conditions in permafrost terrain adjacent to the Dempster Highway, NT, Canada

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Abstract

The Peel Plateau, NT, Canada, is an area underlain by warm continuous permafrost where changes in soil moisture, snow conditions, and shrub density have increased ground temperatures next to the Dempster Highway. In this study, ground temperatures, snow, and thaw depth were monitored before and after tall shrub removal (2014). A snow survey after tall shrub removal indicated that snow depth decreased by a third and lowered winter ground temperatures when compared with control tall shrub sites. The response of ground temperatures to shrub removal depended on soil type. The site with organic soils had cooler winter temperatures and no apparent change in summer temperatures following shrub removal. At sites with mineral soil, moderate winter ground cooling insufficiently counteracted increases in summer ground heat flux caused by canopy removal. Given the predominance of mineral soil along the Dempster, these observations suggest tall shrub removal is not a viable short-term permafrost management strategy. Additionally, the perpendicular orientation of the Highway to prevailing winter winds stimulates snow drift formation and predisposes the site to warmer permafrost temperatures, altered hydrology, and tall shrub proliferation. Subsequent research should explore the effectiveness of tall shrub removal at sites with colder winter conditions or different snow accumulation patterns.

Key words: tall shrub removal, permafrost, Arctic, climate change, infrastructure

Introduction

Air temperatures in Canada's western Arctic have increased more than twice as fast as the global average (ACIA 2005; IPCC 2019) and are driving significant changes to permafrost conditions (Burn and Kokelj 2009; Romanovsky et al. 2010; Smith et al. 2010) and ecological processes (Camill 1999; Kimball et al. 2007; Zhang et al. 2008; Natali et al. 2011). The impacts of climate change on permafrost conditions are mediated by broad-scale differences in regional climate, surficial geology, ground ice content, hydrology, ecology, and site-scale differences in soil type, moisture, and snow conditions (Smith and Riseborough 1996; Kokelj and Burn 2005; Jorgenson et al. 2010; Smith et al. 2010; Kokelj et al. 2017*a*). Site-scale variation in snow, vegetation, and soil conditions influences the magnitude of the offset between air and ground surface temperatures by altering heat transfer (Goodrich 1982; Kanigan et al. 2009; Johansson et al. 2013), intercepting solar radiation (Marsh et al. 2010), and affecting soil moisture and latent heat capacity of the soil (Williams and Smith 1989). The magnitude of temperature differences between the surface of the ground and the top of the permafrost can also depend on soil type due to differences in thermal conductivity of frozen versus thawed organic and mineral soils (Burn and Smith 1988; Romanovsky and Osterkamp 1995; Smith and Riseborough 2002). Site conditions and their impacts on ground surface temperatures play an increasingly important role in ground heat flux as permafrost temperatures approach 0 °C (Smith and Riseborough 2002; Karunaratne and Burn 2004; Shur and Jorgenson 2007; Holloway and Lewkowicz 2020), and comparing differences between freezing and thawing n-factors at different locations can help understand the relative importance of site factors on ground and permafrost surface temperatures.

The Peel Plateau is an ice-rich permafrost environment in northwestern Canada, where winter air temperature inversions and relatively deep snow raise ground temperatures relative to conditions in shrub tundra at similar latitudes (O'Neill et al. 2015*b*; Kokelj et al. 2017*b*). The mean annual ground temperatures (MAGTs) on the Peel Plateau are comparable to those typically encountered approximately 200 km to the south (O'Neill et al. 2015*b*). These regional climate factors make this landscape sensitive to disturbances that impact ground heat flux.

The Dempster Highway is an all-season road that connects southern Canada to the Beaufort Delta region. At the Peel Plateau, the roadbed consists of a raised gravel embankment. Measures to reduce the impact of the Highway on permafrost conditions include construction that minimized disturbance to organic surface material, in addition to the raised embankment. Despite these measures, several studies have shown evidence of roadside permafrost thaw in areas where increased snow cover has compounded the effects of rising air temperature (Gill et al. 2014; O'Neill et al. 2015*a*; O'Neill and Burn 2017). The disruption of natural drainage by the road embankment and thaw subsidence has also altered drainage patterns, increasing soil moisture adjacent to the road (Cameron and Lantz 2016). Deeper snow packs and greater soil moisture increase the temperature of permafrost because saturated conditions raise the latent heat content of the soils (Romanovsky and Osterkamp 2000), while snow inhibits ground heat loss (Goodrich 1982; Zhang 2005*a*; Kokelj et al. 2014).

The impacts of the road on soil moisture and nutrients have also altered the vegetation adjacent to the Dempster Highway. Tall shrub proliferation has been observed across the Peel Plateau, but has been more rapid and extensive adjacent to the Dempster Highway than at sites distant from the road (Cameron and Lantz 2016). Previous research in this region indicates that increases in tall shrub cover have contributed to permafrost thaw beside the road by increasing snow depth in areas of dense tall shrub vegetation (Gill et al. 2014). This is consistent with research at other sites showing that increased snow depth associated with shrub proliferation (Mackay and Burn 2002; Sturm 2005) can alter the timing of snow melt (Marsh et al. 2010; Wilcox et al. 2019), increase winter ground temperatures and thaw subsidence (Gill et al. 2014; Pelletier et al. 2019), inhibit ground heat loss (Sturm 2005; Myers-Smith et al. 2011*a*), and increase soil nutrient availability (Schimel et al. 2004; Buckeridge and Grogan 2008).

Although this "shrub–snow–permafrost" feedback has received considerable attention, some evidence suggests that nature of these interactions likely vary among biophysical regions and with landscape context. Research by Gill et al. (2014) along the Dempster Highway and Sturm (2005) near Council, Alaska shows that tall shrub proliferation can increase both summer and winter ground temperatures when compared with non-shrubby areas. Conversely, Myers-Smith et al. (2011*b*) and Marsh et al. (2010) show that ground temperatures beneath shrub canopies are cooler in the summer compared to areas of open tundra on Herschel Island, Yukon, and near Trail Valley Creek north of Inuvik, NT, respectively. Blok et al. (2010) and Cameron and Lantz (2016) have also shown that tall shrub proliferation can result in thinner active layers in both northeastern Siberia and next to the Dempster Highway, though modelling work by Way and Lapalme (2021) suggests that winter warming from relatively deep snow has greater impact on ground temperatures than summer shading from vegetation. Increasing thaw depths and permafrost degradation have also been observed at northeastern Siberian tundra sites following shrub (*Betula nana*) removal (Blok et al. 2010; Nauta et al. 2015).

In this study, we use a field-based approach to explore the relative impacts of vegetation, snow, and soil type on near-surface thermal conditions on the Peel Plateau, where different categories of shrub cover include tall shrub, dwarf shrub, and cut tall shrub at sites with both organic and mineral soils. We employ a shrub removal experiment to explore the impacts of roadside shrub proliferation on near-surface ground temperatures adjacent to the Dempster Highway in the Peel Plateau Region of the Northwest Territories (NWT). Specifically, we test the hypothesis that removing shrub thickets, which have developed adjacent to the road since 1975, will decrease winter snowpack, resulting in decreased ground temperatures and thaw depths. Several years of data demonstrate inter-annual variation in air temperatures and snow depth that contextualize this manipulation experiment to provide (1) real-world field conditions associated with tall shrub manipulation to inform permafrost modelling experiments and (2) insight into the potential application of vegetation removal as a management strategy to maintain permafrost integrity adjacent to roads.

Materials and methods

Study area

This research was conducted along a 14 km stretch of the Dempster Highway where it crosses the Peel Plateau in the NWT (Fig. 1). The Dempster Highway was built between 1959 and 1979 and follows the height of land along the eastern foothills of the Richardson Mountains before descending to the Peel River near the community of Fort McPherson (Fig. 1). Elevation across the study area ranges from 150 to 600 m above sea level, and manipulation sites have elevations that range from 320 to 440 m above sea level. With the exception of several deeply incised creeks, the Peel Plateau has a rolling topography (Kokelj et al. 2017*c*).

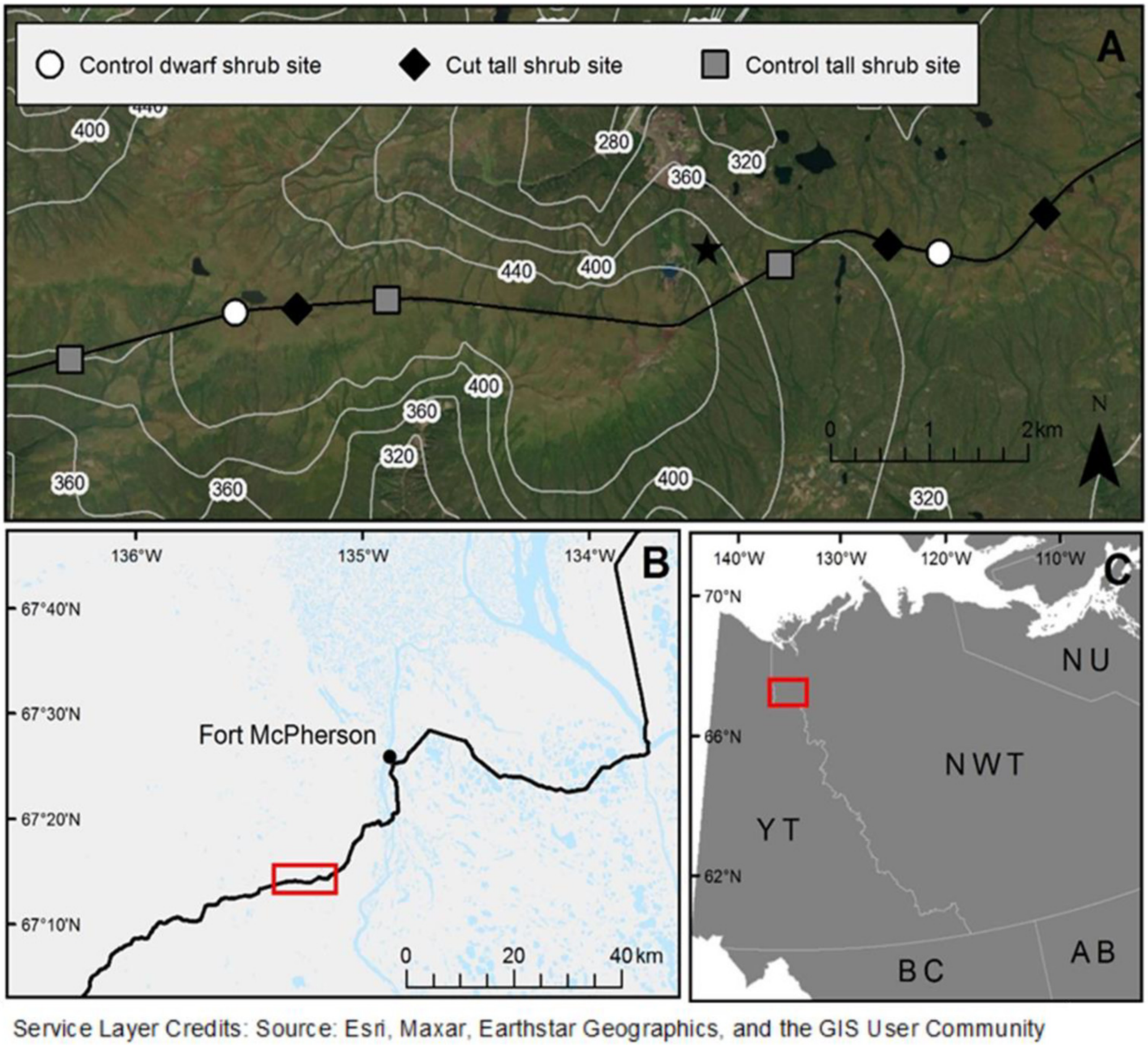
Surficial materials

Across the Peel Plateau, glacio-fluvial, glacio-lacustrine, and morainal sediments from the Late Wisconsinan (Fulton 1995; Roots et al. 2006) overlie Cretaceous sandstones, marine shale, and siltstone bedrock (Norris 1985). This area is dominated by earth hummocks and soils are classified as largely Turbic Cryosols (Tarnocai 2004). This glaciated landscape is underlain by ice-rich continuous permafrost that contains massive ice up to tens of metres in thickness (Hegginbottom et al. 1995; Smith et al. 2005; Kokelj et al. 2017*c*). This ice-rich fluvially incised landscape is also highly susceptible to retrogressive thaw slumps that have proliferated in this region over the past two decades (Kokelj et al. 2017*a*, 2017*c*). Although site conditions drive fine-scale variation in permafrost conditions, thaw depth at the Peel Plateau is typically less than 100 cm at undisturbed locations, and most areas adjacent to the Dempster Highway are underlain by mineral soils (Hughes et al. 1981; Kokelj et al. 2017*c*; O'Neill et al. 2015*a*).

Vegetation

The Peel Plateau is within the taiga plain ecozone and is dominated by spruce forests that transition to tundra at higher elevations (Stanek 1982; Roots et al. 2006; Cameron and Lantz 2016). Tundra vegetation in our study area con-

Fig. 1. Map of the study area showing locations of experimental sites along the Dempster Highway at the Peel Plateau, NWT (NAD83). (A) The Dempster Highway with experimental sites. Contour interval is 40 m and the location of the meteorological station on the Peel Plateau is marked with a star. (B) The extent of the experimental site (A) within a regional context of the Peel Plateau and the Mackenzie Delta. (C) The extent of the regional location (B) of the Peel Plateau within Northwestern Canada. Both regional and national extents are bounded by the red box in the inset maps. This map contains information licensed under the Open Government License—Canada, including contour lines, Provincial and Territorial boundaries, and highways (Statistics Canada 2016, 2019*a*, 2019*b*).



sists of a patchy mosaic of tall shrub tundra dominated by *Alnus fruticosa* (Ruprecht) Nyman, *Betula glandulosa* (Michx.), and *Salix* spp. and dwarf shrub tundra characterized by *Rhododendron tomentosum* Harmaja, *Rubus chamaemorus* (L.), *Arctous alpina* ((L.) Nied), *Carex* spp. (L.), and *Vaccinium* spp. (L.).

Climate

The subarctic climate in our study area is characterized by short cool summers and long cold winters. At the meteorological station on the Peel Plateau (67.24622°N 135.22030°W, 455 m elevation, station 14HD51.1), the mean annual air temperature (MAAT) between 2011 and 2018 was −5.24 °C for years with fewer than 10 days of missing temperature data (Table S2; Kokelj et al. 2022). Mean annual precipitation in Fort McPherson was 310 mm during 2000–2006, approximately half of which occurred as snow (Burn and Kokelj 2009). Strong winter air temperature inversions and a relatively deep winter snowpack in the tundra portions of the study area result in elevated permafrost temperatures (O'Neill et al. 2015*b*) that make this terrain sensitive to disturbances that influence ground heat flux (Gill et al. 2014; Cameron and Lantz 2016; O'Neill and Burn 2017).

Patterns of tall shrub proliferation across the Dempster Highway

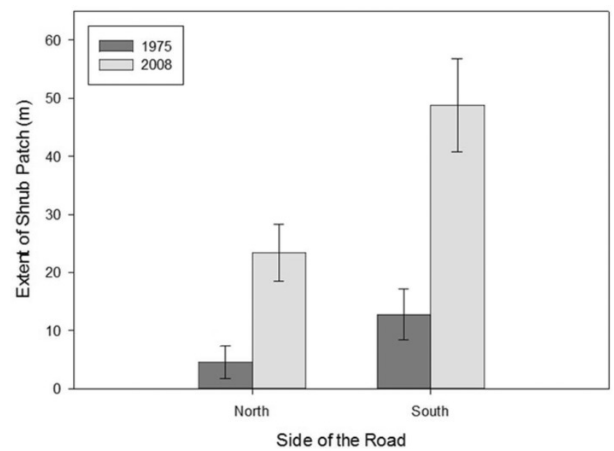
In this study, we define tall shrub tundra as areas where shrub patches, predominantly *A. fruticosa*, are greater than 40 cm (Lantz et al. 2010). Dwarf shrub patches are areas dominated by shrub species that are less than 40 cm tall and, depending on soil type, are typically associated with tussock-forming sedges or mosses. Although increases in tall shrub cover have been documented across the Peel Plateau, tall shrub proliferation has been especially pronounced next to the Dempster Highway (Cameron and Lantz 2016). During 2012–2013, patterns of tall shrub proliferation were observed in the field to be more extensive on the south rather than the north side of the road.

To select sites where the greatest amount of recent tall shrub proliferation occurred and to control for environmental factors that might influence tall shrub proliferation, we mapped tall shrub expansion on both sides of the Dempster. To test whether patterns of tall shrub patch expansion differed between the north and south sides of the Highway, pan-sharpened Quickbird imagery (0.6 m resolution) was compared with 1:15 000 greyscale air photos from 1975. Historical images were acquired from the National Air Photo Library (Table S1), scanned at 1200 dpi (effective pixel size 0.6 m), and used to create georeferenced stereomodels in Summit Evolution (version 6.4, DAT/EM Systems International, Alaska). Stereomodels (second-order polynomial transformation) were created using Quickbird imagery, a LiDAR digital elevation model (DEM), and 8–12 control points with a root mean square error (RMSE) $= 3.34 \pm 0.77$ m. Stereomodels were visualized and used to digitize historic shrub cover in Summit Evolution. Shrub cover in 2008 was digitized by visualizing Quickbird imagery in ArcMap (2D, versions 10.0 and 10.1). To determine whether shrub patches exceeded the >40 cm tall shrub threshold, informal field observations were undertaken during 2011 that showed even "short" *A. fruticosa* were typically >40 cm. Quickbird imagery acquired during fall 2008 allowed for shrub species identification based on fall colours and patches of tall shrubs were identified by tone and texture. Summit Evolution models were used to assess height of shrubs based on orthorectified aerial photos from 1975. The Quickbird imagery and greyscale air photos were used to map tall shrub patches in 2008 and 1975. In each time period, we measured the extent of the shrub patch beside the Highway along lines running perpendicular to the road. This mapping was completed every 25 m across the length of the road ($n = 448$). To test for significant differences in the extent of the tall shrub patches that extend on either side of the road between 2008 and 1975, we used the GLIMMIX procedure in SAS (version 9.3) to create a mixed-effects model (SAS Institute, Cary, NC, USA). This model included year (2008 and 1975) and side of the road (north and south) as fixed factors.

Site selection and biomass removal

To investigate feedbacks between vegetation structure, snow conditions, thaw depth, and ground temperature beside the Highway, a shrub removal experiment was conducted in partnership with the Tetlit Gwich'in Renewable Resources Council. Six tall shrub sites were located on the south side of the road, where observations and analysis showed significant tall shrub expansion from 1975 to 2008 (Fig. 2; Cameron and Lantz 2016). All six tall shrub encroachment sites were covered by green alders that were over 3 m tall, formed a dense consistent canopy cover exceeding 80%, and were situated in locations where prevailing winds were expected to cause snowdrift formation in shrub patches on the south side of the Highway. Tall shrubs typically grew within a metre of the toe of the embankment (Fig. 3). Of the six tall shrub encroachment sites, three sites were randomly selected for shrub removal in August 2014 and three sites were selected as controls. At shrub removal sites, an area of approximately 1300 m^2 was cleared of upright woody vegetation using brush saws (Figs. 3 and 4).

Fig. 2. Extent of shrub patches beside the Dempster Highway measured every 25 m from aerial photographs taken in 1975 and Quickbird imagery acquired in 2008. Extent was measured perpendicular to the direction of the highway on both the north and the south sides at the same location in both time periods. Bars represent 95% confidence intervals of the mean. All differences in tall shrub patch extent (m) between side of road and year are significant.



Since other work has shown that both proximity to the Dempster Highway and shrub encroachment impact ground thermal regimes (Gill et al. 2014; O'Neill et al. 2015*a*), two dwarf shrub sites were selected from the south side of the Highway where no tall shrub proliferation occurred between 1975 and 2008 (Cameron and Lantz 2016). These sites were selected to act as a reasonable analog for what ground thermal regimes may have looked like at tall shrub sites prior to tall shrub encroachment.

Three control tall shrub and two control dwarf shrub reference sites were underlain by mineral soil, two cut tall shrub sites were underlain by mineral soil, and one cut tall shrub site had an active layer largely consisted of peat and organic materials, for a total of eight sites (Table S2).

Topography adjacent to the embankment was similar between all experimental sites. A LiDAR DEM obtained in 2013 with methods described by Van der Sluijs et al. (2018) had a horizontal resolution of 1 m, a vertical resolution of <1 m,

Fig. 3. Photos showing the vegetation structure of site types, including (A) a control tall shrub site, (B) a cut tall shrub site, (C) a dwarf shrub site, (D) typical tall shrub growth was adjacent to the road embankment, (E) tall shrubs re-sprouting from the crown 2 years after cutting, and (F) the Dempster Highway in the winter when patterns of tall shrub encroachment on the south (left) side of the road are apparent. Note that the arrow shows the edge of an expanding shrub patch on the south side of the road. The photo of the cut tall shrub site was taken near edge of the cut area to emphasize the difference between cut and uncut sites. Maximum shrub height is approximately 3–4 m.

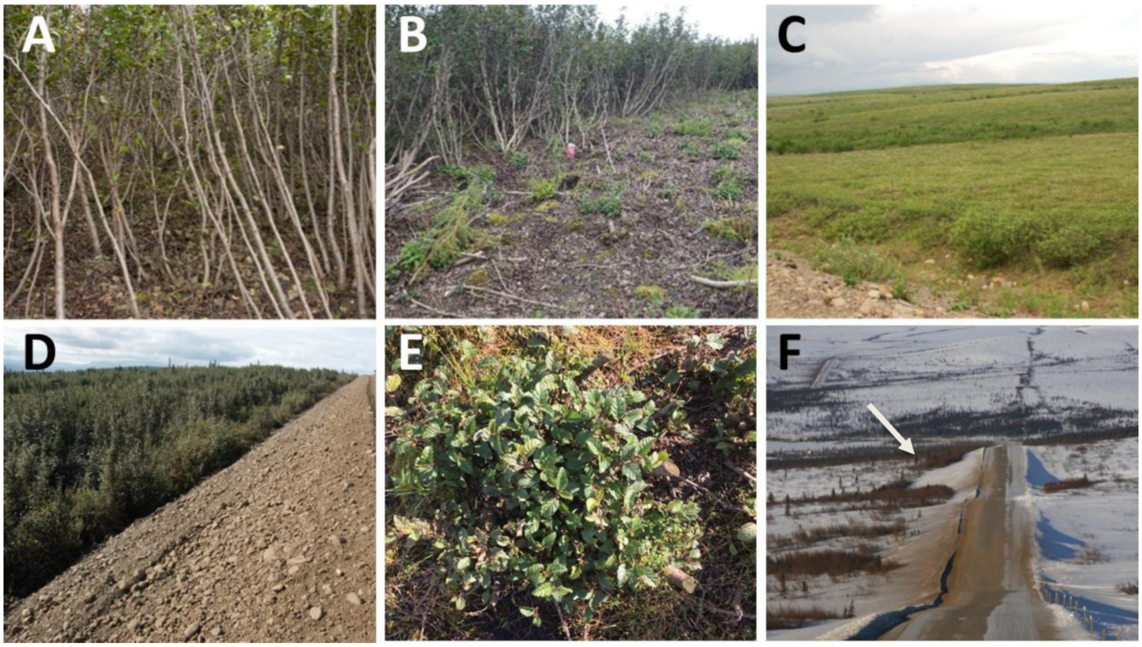
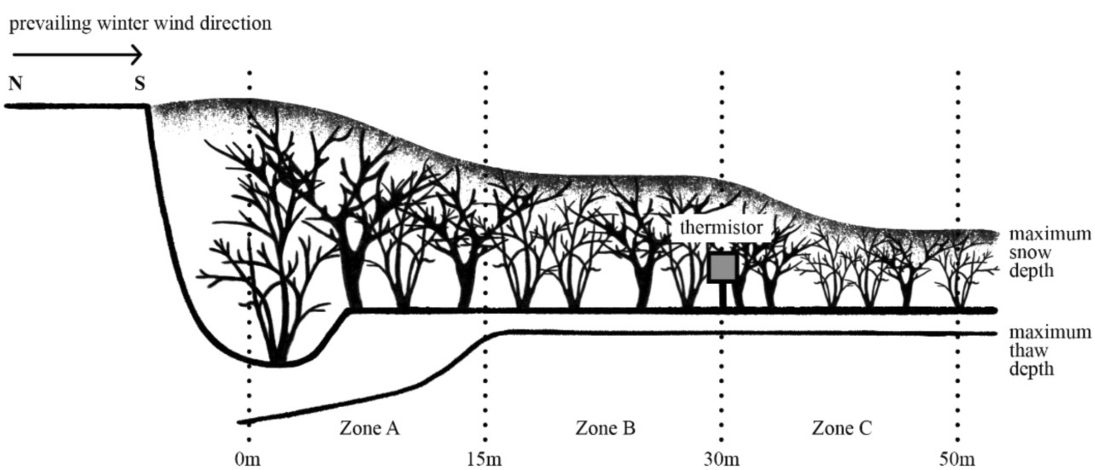


Fig. 4. Schema of the sampling design on the south side of the Dempster Highway at a tall shrub site. Response variables measured along 51 m transects include distance of tall shrub proliferation from the road, snow depth, thaw depth, and ground temperatures at 10 and 100 cm below the surface of the ground. Note that thaw depth and snow sampling is stratified by distance from the road into three zones. Zone A represents the section of the transect impacted by the road embankment and subsequent thaw consolidation. Zone B indicates the area where tall shrub canopy cover is greatest. Zone C indicates the extent of the maximum tall shrub expansion in 2008.



and showed small depressions immediately adjacent to the road, likely due to thaw consolidation. Cameron and Lantz (2016) also determined that average embankment height was not significantly different between tall shrub encroachment and dwarf shrub sites next to the Dempster Highway. Site specific conditions at the control tall, cut tall, and control dwarf shrub sites were representative of conditions at similar tall shrub encroachment and dwarf shrub sites along the Dempster, and experimental sites were level to gently sloping (<5% slope). A greater area of ponding water was typically found adjacent to the road, indicating that proximity to the road changed hydrology patterns (Cameron and Lantz 2016). In contrast to dwarf shrub sites, areas associated with tall shrubs were wetter, as evidenced by a topographic wetness index and gravimetric soil moisture measurements (Cameron and Lantz 2016), though it is unknown whether these tall shrub encroachment sites were predisposed to wetter conditions or whether subsidence and feedbacks from tall shrubs impacted site hydrology.

Thermistors attached to data loggers (HOBO U23-003 and TMC6-HD) were installed 30 m from the toe of the road embankment during the summer of 2011 so that three control tall shrub sites with mineral soil (ContTSm1, ContTSm2, and ContTSm3), two cut tall shrub sites with mineral soil (CutTSm1 and CutTSm2), and two control dwarf shrub sites with mineral soil (ContDSm1 and ContDSm2) were instrumented with thermistors and data loggers. The single cut tall shrub site with organic soil was instrumented with two thermistors (CutTSo1 and CutTSo2), but all other sites had one thermistor string for a total of nine thermistors at eight sites (Table S2). At cut tall shrub sites, thermistors located 30 m from the toe of the embankment were roughly in the centre of each cleared area. The depth of these thermistors was checked annually in late August 2012–2018 to record instances of frost heave and to re-adjust the thermistor string. Near-surface ground temperatures were recorded every 2 h at 10 (T_{10}) and 100 cm (T_{100}) below the ground surface. Thermistor and data logger failure was frequent at sites due to battery and (or) sensor connection failure due to extremely cold temperatures and moisture inside the casing. Two thermistors from a control tall shrub site with mineral soils (ContTSm3) and control dwarf shrub site with mineral soils (ContDSm2) site failed and were excluded from analysis (Table S2). Thermistor data were discarded when (1) readings were clearly the result of instrument malfunction and (2) the thermistors were observed to have heaved over the winter and thermistor and air temperature profiles were identical. Available data and gaps are shown in Table S2.

Mean seasonal ground temperatures and MAGT were calculated from daily temperature readings at 10 (T_{10}) and 100 cm (T_{100}) below the ground surface using observations from June–September for the summer season, December–March for the winter season, and from 1 September to 31 August for the annual period (2011–2018). April–May and October–November were excluded from seasonal temperature calculations because data gaps limited the number of sites with years of comparable data. Time periods were excluded when more than 10 days of temperature data were missing. To reduce air temperature gaps for the Peel Plateau, data from a nearby meteorological station (67.24622°N 135.22030°W, 400 m elevation, station 10PP01) were used to infill air temperature data from Peel Plateau meteorological station (station 14HD51.1) on the Dempster Highway (Kokelj et al. 2022). Mean seasonal and annual air temperatures were calculated following the same method as ground temperatures. Minimum and maximum T_{100} before and after tall shrub removal were determined within the annual period between 1 September to 31 August (2011–2018). Duration of freezeback was defined as the time period starting when ground surface temperatures were 0 °C or below for 3 days in a row until ground temperatures at 100 cm below the ground surface were colder than −0.5 °C.

To compare differences in the effects of soil conditions and vegetation manipulations on ground surface temperatures between sites, thermistor data and infilled air temperature data (T_A) (Fig. 1) were used to calculate thawing and freezing n-factors before and after tall shrub biomass removal. Thawing and freezing season n-factors were used to explore the influence of surface conditions on the relationship between air temperatures and ground surface temperatures, where relatively high n-factors indicate a strong coupling between air and ground surface temperatures, and relatively low n-factors indicate that the decoupling of air and ground surface temperatures is likely mediated by buffer layer conditions (snow cover and vegetation type) or latent heat effects (Karunaratne and Burn 2004). For example, the evolution of snow conditions through the winter can modify the n-factor at a given site and can be used to compare sites within a season and different years. Freezing (n_f) and thawing (n_t) n-factors were obtained by dividing cumulative near-surface freezing (FDD_s) or thawing (TDD_s) degree days by cumulative seasonal air freezing (FDD_a) or thawing (TDD_a) degree days as outlined by Karunaratne and Burn (2004):

$$(1) \qquad n_f = \frac{FDD_s}{FDD_a}$$

$$(2) \qquad n_t = \frac{TDD_s}{TDD_a}$$

Due to data gaps in both T_{10} and air temperature records, only sites with late winter n-factors are presented for 1 year prior to tall shrub removal (2011–2012) and 2 years after tall shrub removal (2014–2016).

At each site, thaw depth was measured by pushing a 120 cm steel probe to the depth of refusal along transects oriented perpendicular to the road and centered on each thermistor. Transects extended for 50 m from the toe of the embankment (0 m) through the interior of the shrub patch or cut area (Fig. 4). Zones at fixed distances from the road were established to capture embankment effects. Zone A (0–14 m) was typically occupied by the extremely dense tall shrub cover, zone B (15–30 m) was characterized by dense tall shrub cover, and zone C (31–50 m) included relatively open to sparse cover of tall shrubs (<25%) interspersed with vegetation characteristic of dwarf shrub tundra. To capture fine-scale variation in thaw depth beside the Highway, measurements were made every metre along the first part of the transect (0–14 m) and every 2 m along the remainder of each transect (15–50 m) (Fig. 4). Thaw depth at all sites was recorded immediately before shrub removal in late August 2014 and again 2 years after tall shrub removal in late August 2016. In 2014, our sampling effort was limited to one transect per site. Following shrub removal in 2014, we measured thaw depth in 2016 along four transects at each cut tall shrub site, and two transects at each control tall shrub site. Replicate transects were separated by 5 m. Snow depth was measured along transects with graduated avalanche probes in late March 2014 and 2016. Snow depth measurements followed the protocol described for thaw depth sampling. In 2014, snow depth was measured along a single transect at each site. Following shrub biomass removal, we intensified our sampling effort to 6–8 transects at cut tall shrub sites, eight transects at control tall shrub sites, and a single transect at each control dwarf shrub site. Within-site replicates were 5 m apart, and at least 5 m away from a cut–uncut transition line.

Environmental drivers of observed tall shrub patterns across the Dempster Highway

To explore landscape-level drivers of feedbacks between the road and tall shrub proliferation such as the potential for snow redistribution by wind, we evaluated the direction of winds between 4 and 11 m s^{-1} when the maximum daily temperature was below 0 °C (Li and Pomeroy 1997). Air temperature, wind speed, and wind direction from 2010–2015 were measured at a meteorological station located within 8 km of our sites.

To test whether winter winds capable of dry snow transport (≥4–11 m s^{-1}) occurred more frequently than expected from northern (270°–89°) or the southern (90°–269°) cardinal directions, we used a χ^2 test (R Core Team 2018).

Statistical analysis

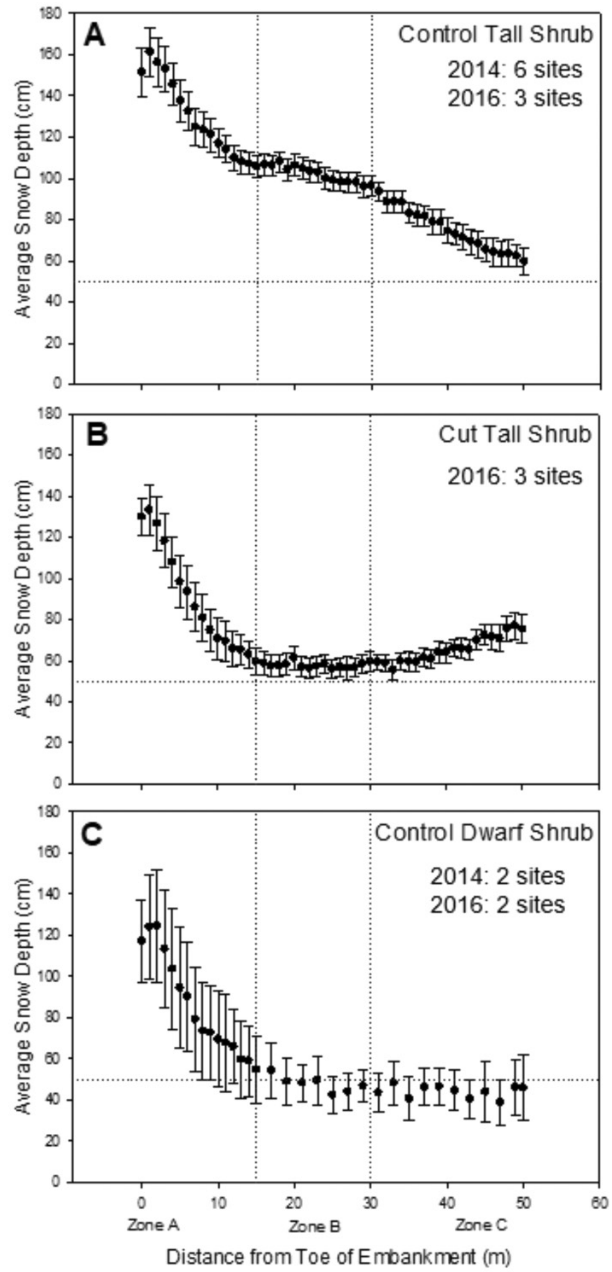
The GLIMMIX procedure in SAS (version 9.3) was used to create mixed-effects models to test for significant differences in snow depth and thaw depth among site types and embankment zones (SAS Institute, Cary, NC, USA). In models of snow depth and thaw depth, category of shrub cover (cut tall shrub, control tall shrub, and dwarf shrub) and embankment zones (zone A (0–15 m), zone B (17–31 m), and zone C (33–51 m)) were included as fixed factors. Transect replicates within site were grouped by including site as a random factor. We analysed cut tall shrub sites with mineral and organic soils separately because of the known effects of soil type on thermal properties and ground heat fluxes (Burn and Smith 1988; Romanovsky and Osterkamp 1995). In all models, we used the Kenward–Roger approximation to estimate the degrees of freedom (Kenward and Roger 1997).

Results

Patterns of tall shrub growth across the Dempster Highway

Although tall shrub proliferation occurred on both sides of the Dempster Highway between 1975 and 2008, tall shrub patch expansion extended twice as far from the toe of the embankment on the southern side of the road than the northern side (Fig. 2, $p < 0.001$, $F_{1,446} = 24.34$). More rapid shrub expansion on the south side of the road corresponded to a higher frequency of northerly winter winds capable of transporting snow. A χ^2 test shows that that winds capable of transporting snow (2011–2015) were more frequent from the north than the south, with 71% of winds between 4–11 m s^{-1} originating from the north ($\chi^2 = 350.9$, df = 1, $p < 2.2 \times 10^{-16}$) (Fig. S1).

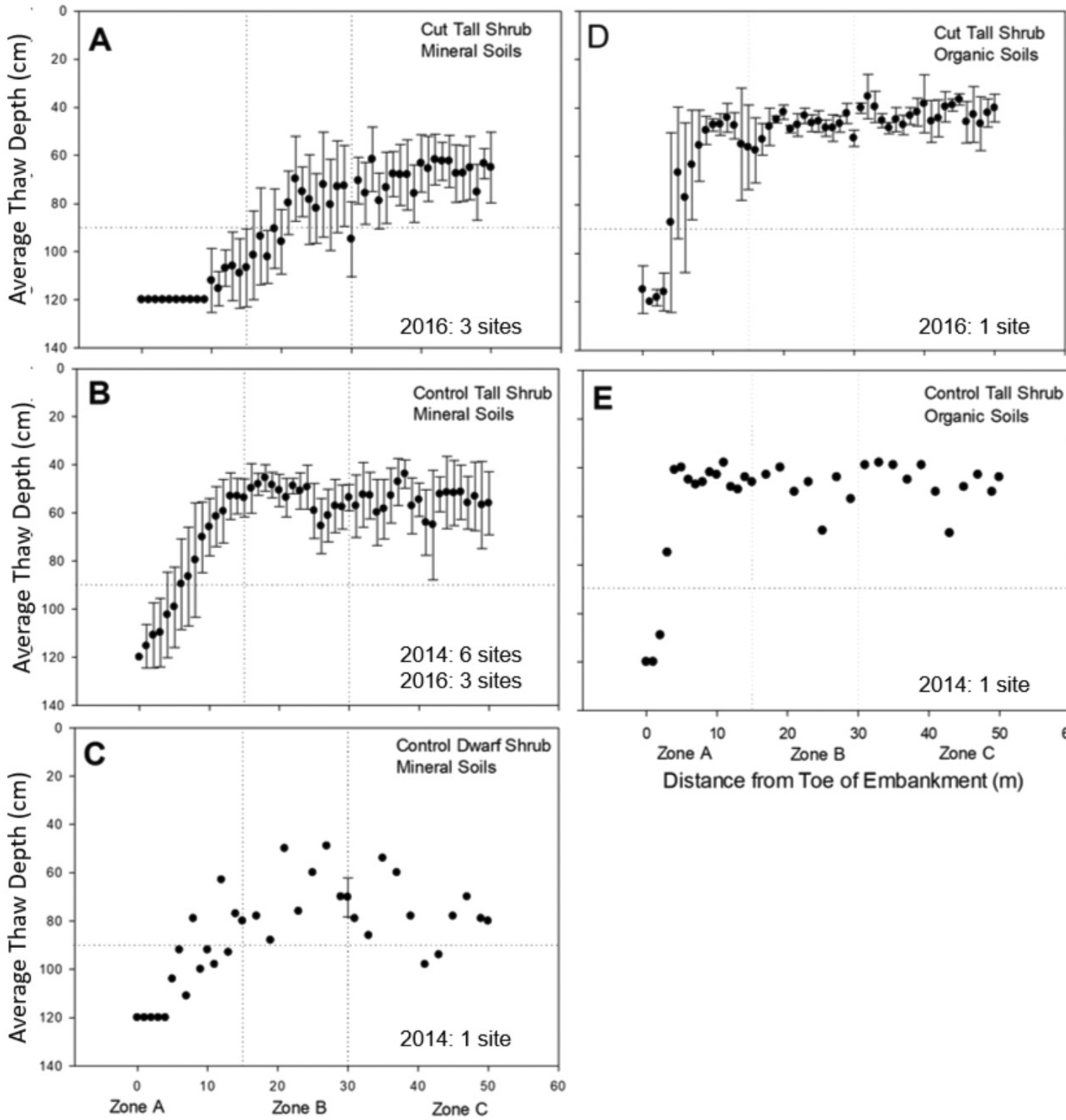
Fig. 5. (A) Average snow depth in late March 2014 and 2016 measured beside the Dempster Highway at control tall shrub sites, (B) cut tall shrub sites measured only in 2016, and (C) control dwarf shrub sites. Points show the mean and bars represent 95% confidence interval of the mean at each distance. The dotted vertical lines show the zones depicted in Fig. 3: A (0–15 m from toe of embankment), B (16–30 m from toe of embankment), and C (31–50 m from the toe of the embankment). Horizontal reference lines are set at 50 cm of snow depth.



Snow accumulation

Tall shrub removal significantly reduced late winter snow depth in 2016 beside the road relative to control tall shrub sites ($p < 0.0001$, $F_{2,48.89} = 63.93$, Table S3). On average, snow at control tall shrub sites was approximately 1.5 times greater

Fig. 6. (A) Average thaw depth 1 year after manipulation measured beside the Dempster Highway in late August (2016) at cut tall shrub sites in mineral soils, (B) control tall shrub sites in mineral soils, (C) control dwarf shrub sites with mineral soils, and (D) the cut tall shrub site in organic soils. (E) Measurements from the control tall shrub site in organic soils were measured in 2014 prior to tall shrub removal and are associated with a single transect through the site. Points show the mean, and bars represent the 95% confidence interval of the mean at each distance. Vertical dotted lines indicate zones: A (0–15 m from toe of embankment), B (16–30 m from toe of embankment, and C (31–50 m from the toe of the embankment). Thaw depth at the site with organic soils was measured along a single transect in 2014, prior to shrub cutting events. Horizontal reference lines are set at 50 cm.

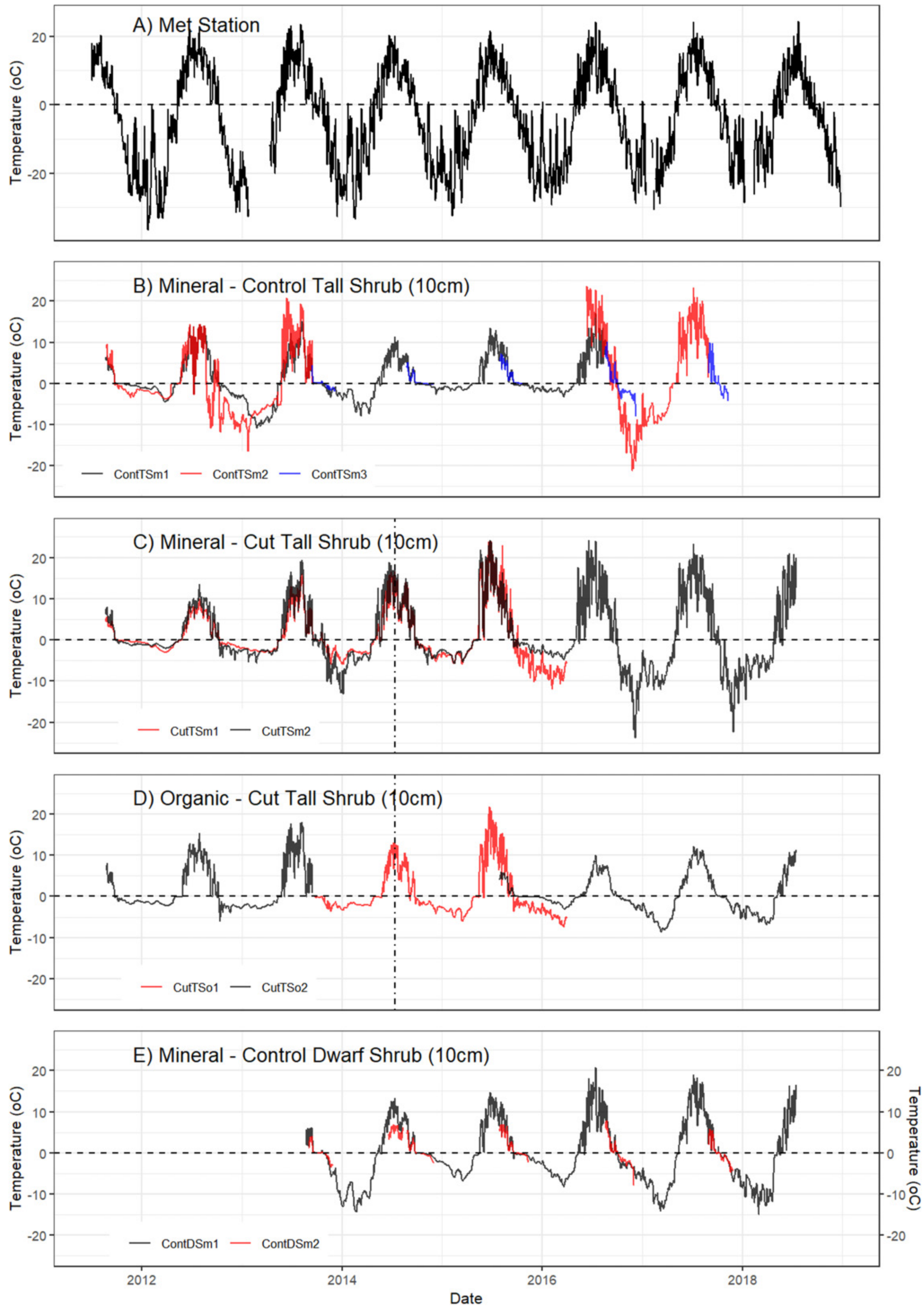


than at cut tall shrub sites (Figs. 5A–5C, Table S3) and 1.8 times deeper than at dwarf shrub sites. When measured in 2016, snow depth at cut tall shrub sites demonstrated similar trends to snow conditions at dwarf shrub sites, though snow depth at cut tall shrub sites remained above 50 cm thickness. At all site types, snow was deepest immediately adjacent to the embankment and decreased with increasing distance from the road (Fig. 5, Table S3, $p < 0.0001$, $F_{2,101.3} = 106.97$). On average, snow in zone A (0–15 m) was 1.5 times deeper than zone B (16–30 m) and 1.7 times deeper than zone C (31–50 m) regardless of category of shrub cover (Fig. 5, Table S3). A significant "zone by category of shrub cover" interaction showed that differences in snow depth between zones B and C only occurred at control tall shrub sites, and that snow conditions in zones B and C were similar between cut tall shrub and dwarf shrub sites (Fig. 5, Table S3). Standard error values for snow depth were approximately equivalent between both control and cut tall shrub sites but were 2.4 and 2.2 times greater at dwarf shrub sites than at cut tall shrub sites and control tall shrub sites, respectively (Fig. 5).

Thaw depth

The impacts of tall shrub removal on late-August thaw depth depended on soil type. Thaw depth in late August 2016

Fig. 7. (A) Air temperatures at the meteorological station on the Peel Plateau, and near-surface (10 cm) ground temperature at site types including (B) control tall shrub sites with mineral soils, (C) tall shrubs with mineral soils before and after shrub removal in 2014, (D) tall shrub sites with organic soils before and after shrub removal in 2014, and (E) uncut dwarf shrub sites. The dashed vertical line after 2014 indicates the date of tall shrub removal. Ground temperature data were collected 30 m away from the toe of the road embankment.



increased by approximately a third at cut tall shrub sites with mineral soils relative to control tall shrub sites and dwarf shrub sites ($p < 0.0001$, $F_{2,13.17} = 43.59$, Figs. 6A–6C, Table S4). At the cut tall shrub site with organic soils, thaw depth measured in late August 2016 was not significantly different from thaw depth prior to tall shrub removal in 2014 (($p = 0.3962$, $F_{1,244} = 0.72$) (Figs. 6D and 6E, Table S4). At all sites thaw depth decreased with distance from the embankment ($p < 0.0001$, $F_{2,452.4} = 90.37$) and was generally greater in mineral soils than in organic soils, irrespective of shrub cover category (Fig. 6). Within a given site type, thaw depth was approximately 1.5 times greater in zone A than in zones B and C,

Table 1. Mean annual T_{10} (°C) and mean annual air temperature (MAAT (°C)) at the Peel Plateau.

	Mean annual T_{10} (°C)							
Soil type	Mineral soils					Organic soils		
Category of shrub cover	Control dwarf shrub	Control tall shrub		Cut tall shrub		Cut tall shrub		
Site name	ContDSm1	ContTSm1	ContTSm2	CutTSm1	CutTSm2	CutTSo1	CutTSo2	MAAT (°C)
2011–2012	X	1.81^{H}	1.34^{H}	1.09^{L}	1.65	X	1.83^{H}	-6.36^{L}
2012–2013	X	-0.89^{L}	-1.84^{L}	1.14	1.41	X	1.54	X
2013–2014	-1.85^{L}	0.14	X	1.47	0.90	X	X	-4.38^{H}
2014–2015	0.99^{H}	1.70	X	2.46^{H}	2.38	1.71	X	−4.97
2015–2016	0.77	1.50	X	X	2.41^{H}	X	0.95	−5.26
2016–2017	−0.67	X	−0.63	X	-0.31^{L}	X	0.01^{L}	X

Note: Mean annual T_{10} calculated from temperatures at 10 cm below the ground surface with observations from 1 September to 31 August. Years were excluded when more than 10 days of temperature data were missing and are indicated by an X. Tall shrub removal occurred in late August 2014. At each thermistor, the highest temperature is indicated with a superscript H and the lowest temperature is indicated with a superscript L.

which did not differ significantly from each other (Fig. 6, Tables S3 and S4). Mean thaw depth immediately adjacent to the highway (zone A) at control tall shrub and dwarf shrub sites with mineral soils was not significantly different (Figs. 6B and 6C, Table S4), but further from the road (i.e., zones B and C) thaw depth at control tall shrub sites was approximately 20% lower than dwarf shrub sites in zone B and 35% lower in dwarf shrub sites in zone C (Figs. 6B and 6C, Tables S3 and S4). Since thaw depth was only measured during one summer after tall shrub removal, it is not possible to assess long-term changes in thaw depth.

Air temperatures

MAATs were relatively consistent through 2011–2016, where the greatest difference in MAAT within this time period was approximately 2 °C (Figs. 7 and S2). Mean seasonal air temperatures (MSATs) for the summer and winter varied at most by approximately 4 °C during 2011–2018 (Fig. S2, Tables 1–4 and 6). The highest mean summer air temperature (12.06 °C) occurred during 2012, and the lowest mean summer air temperature (8.23 °C) was in 2015. The lowest mean winter air temperatures were recorded in 2011–2012, and the highest in 2013–2014, which were both before tall shrub removal.

Ground temperatures

Seasonal and annual summaries of T_{10} (Fig. 7, Tables 1 and 2) and T_{100} (Fig. 8, Tables 3–5) are presented to explore the thermal effects of tall shrub removal on different site types and to display limitations of interpretation associated with data gaps due to instrument malfunction. Although annual and seasonal data gaps occurred in both T_{10} and T_{100} datasets, ground temperature data showed annual variation both between and within sites of the same treatment. Shrub removal reduced mean winter T_{10} at cut tall shrub sites with mineral and organic soils (Figs. 7C and 7D, Table 2), but changes to ground surface temperature in summer varied based on soil type (Figs. 7C and 7D, Table 2). Immediately after tall shrub biomass removal, both cut tall shrub sites with mineral soils (CutTSm1 and CutTSm2) demonstrated mean annual T_{10} increases between 0.99 and 1.51 °C when compared with temperatures prior to shrub removal (Tables 1 and 2). In the 2 years immediately after manipulation, significant increases in mean summer T_{10} by 3.57–4.95 °C at CutTSm1 and CutTSm2 offset progressively lower winter temperatures (Figs. 7B and 7C, Table 2). Mean winter T_{10} were between 4.43 and 6.35 °C lower at CutTSm1 and between 3.94 and 8.6 °C lower at CutTSm2 after tall shrub removal (Table 2). These lower winter temperatures did not offset summer warming in the first 2 years after manipulation but mean annual T_{10} at CutTSm2 in 2016–2017 was reduced from above 0 °C to −0.31 °C in 2016–2017 (Table 1). At CutTSm1, data gaps precluded mean annual estimates beyond 2014–2015 when the site experienced the highest mean annual T_{10} (Table 1). After tall shrub removal, the cut tall shrub site with organic soils CutTSo2 demonstrated mean seasonal T_{10} that were between 2.66 and 4.92 °C lower in the summer and up to 3.37 °C lower in the winter when compared with mean seasonal temperatures of all years prior to tall shrub removal (Fig. 7D, Table 2). At CutTSo2, the greatest difference in mean annual T_{10} of 1.82 °C was between the lowest mean annual T_{10} in 2016–2017 and the highest mean annual T_{10} at the site in 2011–2012 prior to tall shrub removal (Fig. 7D, Table 1). The second thermistor string (CutTSo1) at the organic soil site had a shorter pre- and post-disturbance time series for T_{10}, and so determining trends in mean annual T_{10} associated with tall shrub removal was not feasible, though it is worth noting that mean winter T_{10} decreased over the two winters following shrub removal (Fig. 7D, Table 2). Control tall shrub sites with mineral soils had mean summer T_{10} that were 1.05–1.63 °C less than control dwarf shrub sites with mineral soils and mean winter T_{10} that were between 2.53–6.43 °C higher than control dwarf shrub sites with mineral soils (2014–2016), with the lone exception of 2016–2017 when ContTSm2 mean winter T_{10} was 0.52 °C less than the control dwarf shrub site (ContDSm1, Table 2). Mean annual T_{10} were 0.73–1.99 °C higher at control tall shrub sites with mineral soils than control dwarf shrub sites with mineral soils when data overlapped (Table 1). Both control dwarf and tall shrub site types with mineral soils had mean summer T_{10} that were 2.25–4.54 °C lower than cut tall shrub sites with mineral soils for all years after tall shrub removal (Figs. 7B, 7C, and 7E; Table 2).

Table 2. Mean seasonal T_{10} (°C) calculated from temperatures at 10 cm below the ground surface with summer observations from 1 June to 31 September and winter observations from 1 December to 31 March.

	Mean seasonal T_{10} (°C)															
Soil type	Mineral soils										Organic soils					
Category of	Control dwarf shrub		Control tall shrub				Cut tall shrub				Cut tall shrub					
shrub cover	ContDSm1		ContTSm1		ContTSm2		CutTSm1		CutTSm2		CutTSo1		CutTSo2		MSAT (°C)	
Site name	Summer	**Winter**	Summer	**Winter**	Summer	**Winter**	Summer	**Winter**	Summer	**Winter**	Summer	**Winter**	Summer	**Winter**	Summer	**Winter**
2011–2012	X	**X**	X	**−1.54**	X	**−2.31^{H}**	X	**−1.41^{H}**	X	**−1.26 ^{H}**	X	**X**	X	**−1.49**	9.47	**−22.52^{L}**
2012–2013	X	**X**	7.67^{H}	**−6.50^{L}**	5.44^{L}	**−8.52**	5.45^{L}	**−2.28**	7.12^{L}	**−3.02**	X	**X**	8.00	**−2.47**	12.06^{H}	**X**
2013–2014	X	**−9.97^{L}**	6.25	**−3.54**	10.46^{H} (107 days)	**X**	6.72	**−3.33**	8.50	**−5.86**	X	**−2.16 ^{H}**	9.50^{H} (107 days)	**X**	10.18	**−18.42^{H}**
2014–2015	6.82^{L}	**−3.75^{H}**	5.19^{L}	**−1.22^{H}**	X	**X**	8.65	**−4.02**	9.56	**−3.51**	6.45^{L}	**−3.60**	X	**X**	9.39	**−18.50**
2015–2016	6.91	**−4.47**	5.86	**−1.67**	X	**X**	10.40^{H}	**−7.76^{L}**	9.79	**−3.15**	8.68 ^{H}	**−4.42^{L}**	X	**−1.16^{H}**	8.23^{L}	**−18.78**
2016–2017	8.12	**−8.46**	X	**X**	X	**−8.98^{L}**	X	**X**	10.37	**−9.80^{L}**	X	**X**	4.58^{L}	**−4.86^{L}**	9.33	**X**
2017–2018	9.49^{H}	**−8.28**	X	**X**	X	**X**	X	**X**	12.07 ^{H}	**−7.29**	X	**X**	6.84	**−4.10**	10.92	**X**

Note: Seasons were excluded when more than 10 days of temperature data were missing and are indicated by an X. Tall shrub removal occurred in late August 2014. At each thermistor, the highest temperature is indicated with a superscript H and the lowest temperature is indicated with a superscript L.

Tall shrub removal decreased winter ground T_{100}, but the magnitude and timing of this effect depended on soil type (Fig. 8, Table 4). T_{100} were lowest at the control dwarf shrub site with mineral soils (CutDSm1), where annual minimum temperatures ranged from −3.48 to −7.87 °C, and mean winter ground temperatures ranged between −1.06 and − 4.86 °C (Fig. 8E, Tables 4 and 5). The year prior to tall shrub removal (2013–2014) demonstrated the lowest mean winter T_{100} for all control sites (Fig. 8, Tables 3 and 4). The timing of the lowest mean winter T_{100} at control sites differed from the lowest mean winter T_{100} at cut tall shrub sites, which in all cases, occurred after tall shrub removal (Figs. 8B–8D, Table 4). At CutTSm1 and CutTSm2, mean winter T_{100} was 0.51 and 0.1 °C lower after tall shrub removal at sites with mineral soils than the lowest T_{100} prior to tall shrub removal (Figs. 8B–8D, Table 4). At both cut tall shrub sites with mineral soils, the lowest annual T_{100} decreased from −0.2 and −1.07 °C before shrub removal to −0.45 and −2.18 °C after tall shrub removal (Figs. 8B and 8C, Table 5). At the cut tall shrub site with organic soils, mean winter T_{100} was 1.09 °C lower at CutTSo1 and up to 0.97 °C lower at CutTSo2 after tall shrub removal when compared with pre-treatment mean winter T_{100} (Fig. 8D, Table 4). Winter minimum T_{100} at the cut tall shrub site with organic soils ranged from −0.67 °C (2015–2016) to −4.96 °C (2016–2017), but T_{100} at the site (CutTSo2) was isothermal throughout the period prior to shrub cutting (Fig. 8D, Table 5). Irrespective of soil type, sites where tall shrubs were removed showed the lowest T_{100} during 2016–2017, 2 years after tall shrub removal (Figs. 8B and 8C, Table 5). Following shrub removal at sites with mineral soil, maximum T_{100} temperatures increased above 0 °C at CutTSm2 and increased from 0.16 °C in 2011–2012 to a high of 2.37 °C in 2016–2017 at CutTSm1 (Table 5), indicating an increase in active layer thickness as a result of warming surface temperatures. Mean summer T_{100} increases of up to 0.93 °C occurred at CutTSm1 and increases of up to 0.39 °C occurred at CutTSm2 after tall shrub removal (Fig. 8C, Table 4).

Duration of freezeback

Duration of freezeback was modestly shortened after tall shrub removal at cut tall shrub sites with organic soils. At CutTSo1, the duration of freezeback decreased by 28–66 days after tall shrub removal (Table 6). At CutTSo2, the second thermistor at the site with organic soils, the ground froze 171–237 days sooner two winters after tall shrub removal where previously it did not freeze before tall shrub removal (Table 6). Duration of freezeback decreased modestly after tall shrub removal at cut tall shrub sites with mineral soils, where duration of freezeback was shortest 3 years after tall shrub removal at CutTSm1, decreasing by 21 days and at CutTSm2 by 1 day when compared with the shortest duration of freezeback prior to tall shrub removal (Table 6). The active layer at the control dwarf shrub site with mineral soils (ContDSm1) refroze sooner than control tall shrub sites with mineral soils (ContTSm1 and ContTSm2). For all control tall and dwarf shrub sites with mineral soils, the shortest and longest duration of freezeback did not occur on years with the lowest and highest MAATs, respectively (Table 6).

Table 3. Mean annual T_{100} (°C) calculated from temperatures at 100 cm below the ground surface with observations from 1 September to 31 August.

Soil type	Mean annual T_{100} (°C): Mineral soils					Organic soils		
Category of shrub cover	Control dwarf shrub	Control tall shrub		Cut tall shrub		Cut tall shrub		
Site Name	ContDSm1	ContTSm1	ContTSm2	CutTSm1	CutTSm2	CutTSo1	CutTSo2	MAAT (°C)
2011–2012	X	−0.56	-0.32^{L}	−0.16	−0.11	X	−0.26	-6.36^{L}
2012–2013	-2.62^{L}	X	−0.73	−0.21	−0.19	X	-0.22^{H}	X
2013–2014	-0.82^{H}	-1.10^{L}	-0.81^{H}	-0.26^{L}	−0.36	X	X	-4.38^{H}
2014–2015	−0.89	−0.35	X	−0.03	−0.14	-0.52^{H}	X	−4.97
2015–2016	−1.99	-0.30^{H}	X	0.11^{H}	-0.06^{H}	-1.28^{L}	−0.27	−5.26
2016–2017	X	X	−0.55	−0.24	-0.37^{L}	X	-0.90^{L}	X

Note: Years were excluded when more than 10 days of temperature data were missing and are indicated by an X. Tall shrub removal occurred in late August 2014. At each thermistor, the highest temperature is indicated with a superscript H and the lowest temperature is indicated with a superscript L.

Freezing n-factors

Due to data gaps in both T_{10} and air temperature records, only sites with late winter n-factors are presented for 1 year prior to tall shrub removal and 2 years after tall shrub removal. Tall shrub removal increased freezing n-factors (Figs. 9A, 9C, and 9E; Table 7). In 2011–2012, prior to tall shrub removal, all freezing n-factors were below 0.11, indicating that T_{10} was not strongly coupled with air temperature at tall shrub sites, irrespective of soil type (Fig. 9A, Table 7). At both cut tall shrub sites with mineral soils, freezing n-factors increased from 0.06 before tall shrub removal to 0.17–0.41 after tall removal (Fig. 9A, 9C, and 9E; Table 7). After tall shrub removal, all cut tall shrub sites had freezing n-factors that were approximately 3.5–5 times greater than control tall shrub sites with mineral soils, which had freezing n-factors less than 0.1 (Figs. 9A, 9C, and 9E; Table 7), and values for all tall shrub removal sites were comparable or almost two times higher than the control dwarf shrub site with mineral soils (Figs. 9A, 9C, and 9E; Table 7).

Thawing n-factors

Prior to tall shrub removal, thawing n-factors at sites with intact tall shrub canopies ranged from 0.42 to 0.60 (Fig. 9B, Table 7). After tall shrub removal, thawing n-factors increased two- to three-fold at mineral soil sites due to the loss of the shading effect of tall shrubs in summer (Figs. 9D and 9F, Table 7). At these sites, n-factors approaching or exceeding 1.0 indicate tight coupling between summer air and ground surface temperatures following shrub removal. Similar, but slightly dampened effects of shrub removal were observed for thawing n-factors at the cut tall shrub site with organic soils that showed an increase of approximately 0.3 in the summer after tall shrub removal (Figs. 9D and 9F, Table 7). The control tall shrub site with mineral soils (ContTSm1) had thawing n-factors that remained consistent through the duration of this experiment, ranging from 0.51 to 0.62 (Figs. 9B, 9D, and 9F; Table 7). The control dwarf shrub site had slightly higher thawing n-factors than the tall shrub mineral control, but they were significantly less than those at the cut tall shrub mineral soil site (Fig. 9, Table 7).

Observations of tall shrub regrowth

Two years after tall shrub removal, green alder stems showed vigorous re-sprouting, suggesting that the removal of above-ground tall shrub biomass is a short-term change (Fig. 3).

Discussion

Snow impacts on ground thermal regimes

Our observations build on previous research showing that snow trapped by tall shrubs beside the road insulates the ground surface in winter and results in higher MAGTs than sites without tall shrubs (Gill et al. 2014; O'Neill et al. 2015*a*). This is evidenced by mean annual T_{100} approximately 1.5 °C higher, mean annual T_{10} that were on average 1.13 °C warmer, and mean winter T_{10} that were 2.6–3 °C higher in tall shrub tundra compared to dwarf shrub tundra, (Fig. 8, Tables 1 and 2). The insulative effects of snow were also reflected in freezing n-factors, which were lowest at control tall shrub sites (Fig. 9, Table 3). Although snow depth was only measured for a single year after tall shrub removal, freezing n-factors at cut tall shrub sites that are 3–3.5 times greater than those at control tall shrub sites demonstrate reduced snow depth at cut tall shrub sites for at least two winters (2014–2016) after tall shrub removal (Figs. 9B and 9C, Table 7). Although not statistically significant, average snow depth in 2016 at cut tall shrubs sites was 10–20 cm greater than that at control dwarf shrub sites where winter T_{100} decreased rapidly to reach between −4 and −8 °C. Snow was potentially deeper at the cut tall shrub sites than the control dwarf shrub sites because the relatively small size of the cut area may have facilitated snow transport from nearby tall shrub patches along the edges of the cut area, including any remaining shrubs beyond the maximum distance of shrub removal from the road embankment.

Although snow density was not recorded at experimental sites, O'Neill and Burn (2017) measured snow density from 2013 to 2015 at tall and dwarf shrub sites along the Dempster Highway near to our research sites by excavating snow pits. The range of thermal resistance ($m^2\,K\,W^{-1}$)

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Table 4. Mean seasonal T_{100} (°C) calculated with summer observations from 1 June to 31 September and winter observations from 1 December to 31 March.

Soil type	Mineral soils										Organic soils					
	Mean seasonal T_{100} (°C)															
Category of shrub cover	Control dwarf shrub		Control tall shrub				Cut tall shrub				Cut tall shrub				MSAT (°C)	
Site name	ContDSm1		ContTSm1		ContTSm2		CutTSm1		CutTSm2		CutTSo1		CutTSo2			
	Summer	**Winter**	Summer	**Winter**	Summer	**Winter**	Summer	**Winter**	Summer	**Winter**	Summer	**Winter**	Summer	**Winter**	Summer	**Winter**
2011–2012	X	**X**	X	**−0.41**	X	**-0.28^{H}**	X	**−0.12**	X	**−0.09**	X	**X**	X	**−0.23**	9.47	**-22.52^{L}**
2012–2013	X	**X**	-0.34^{H}	**X**	-0.25^{H}	**−1.03**	−0.07	**−0.17**	−0.11	**−0.10**	X	**X**	−0.26	**−0.20**	12.06^{H}	**X**
2013–2014	X	**-4.86^{L}**	X	**-1.17^{L}**	−0.31	**-1.39^{L}**	-0.14^{L}	**−0.31**	−0.22	**−0.37**	X	**-0.20^{H}**	-0.22^{H} (107 days)	**X**	10.18	**-18.42^{H}**
2014–2015	-0.52^{L}	**-1.06^{H}**	-0.62^{L}	**−0.32**	−0.31	**−0.49**	−0.07	**−0.15**	-0.24^{L}	**−0.12**	-0.24^{L}	**-0.20^{H}**	X	**X**	9.39	**−18.50**
2015–2016	−0.19	**−1.14**	−0.35	**-0.26^{H}**	X	**X**	0.36	**-0.10^{H}**	−0.06	**-0.07^{H}**	−0.36	**−0.21**	X	**-0.17^{H}**	8.23^{L}	**−18.78**
2016–2017	-0.16^{H}	**−3.39**	X	**X**	X	**−0.94**	0.79	**-0.82^{L}**	0.17^{H}	**-0.47^{L}**	−0.47	**-1.29^{L}**	−0.28	**-1.20^{L}**	9.32	**X**
2017–2018	−0.27	**−3.26**	X	**X**	X	**X**	0.86^{H}	**−0.35**	0.06	**−0.08**	-0.68^{H}	**−0.30**	-0.39^{L}	**−0.86**	10.92	**X**

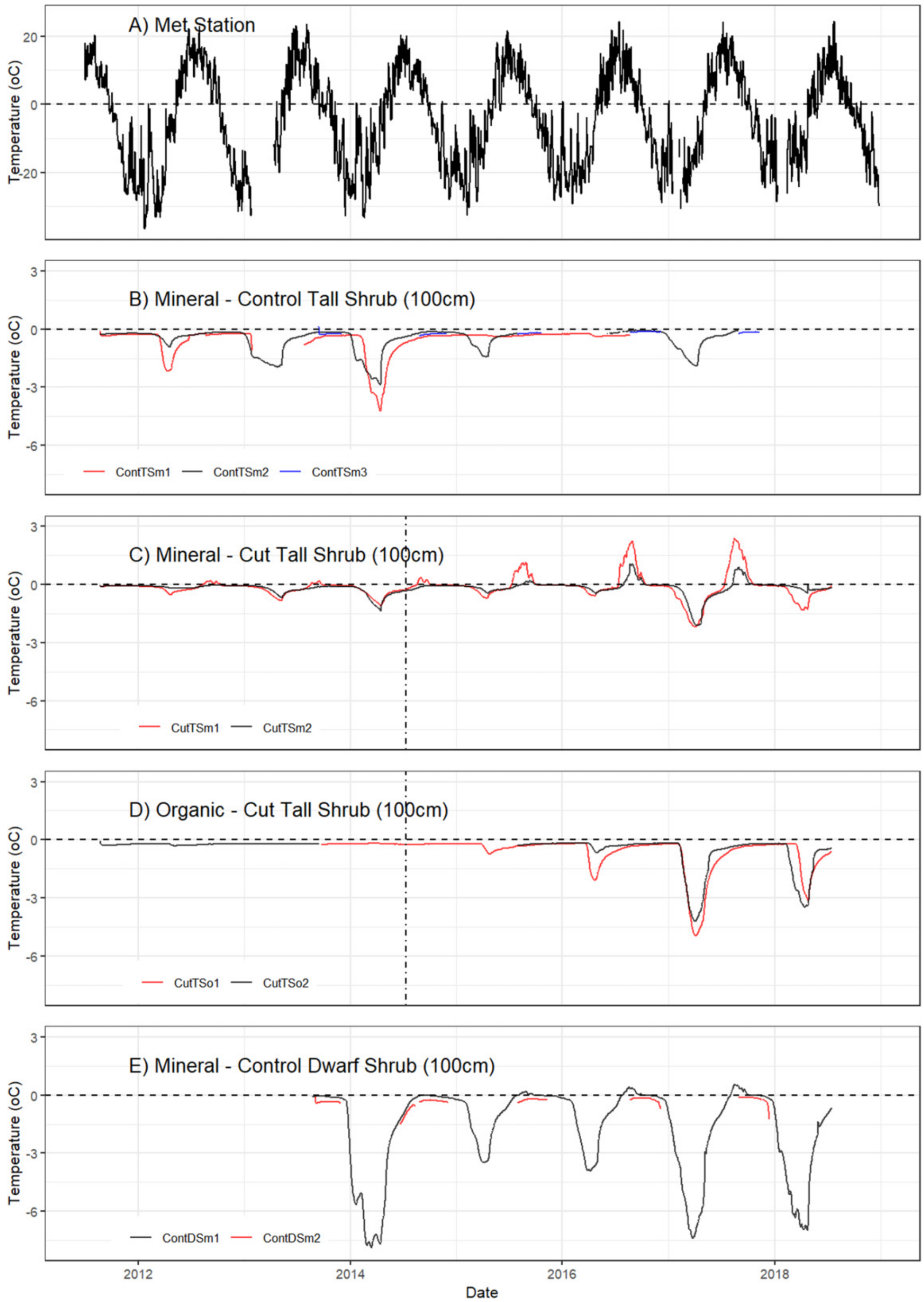
Note: Seasons were excluded when more than 10 days of temperature data were missing and are indicated by an X. Tall shrub removal occurred in late August 2014. At each thermistor, the highest temperature is indicated with a superscript H and the lowest temperature is indicated with a superscript L.

was smaller at dwarf shrub sites next to the road than that of tall shrub sites next to the road (O'Neill and Burn 2017). These results are consistent with Domine et al. (2016) who demonstrate that snow density and thermal conductivity are significantly lower in shrub areas than adjacent herb tundra in the high Arctic tundra, likely due to shrubs preventing compaction of snowpack (Domine et al. 2015). Busseau et al. (2017) also observed a decrease in snowpack density and increase in snow depth at tall shrub sites in the low Arctic–subarctic transition, and Ling and Zhang (2006) have shown that decreased snow density can increase tundra ground surface temperature. These studies suggest that shrub removal may have increased snow density. Given the influence of snow density on ground temperatures, the lack of snow density data after vegetation removal is a source of uncertainty that should be addressed in future studies.

Impacts of tall shrubs on ground thermal regimes

The experimental manipulations conducted in this study demonstrate that tall shrubs impact permafrost conditions by influencing snow pack in winter and ground shading in summer. Lower ground surface temperatures during winter at cut tall shrub and control dwarf shrub sites compared to tall shrub sites likely resulted from thinner snow and greater ground heat loss (Goodrich 1982; Stieglitz et al. 2003), reflected by lower winter mean and minimum ground temperatures and higher freezing n-factors at cut tall shrub sites irrespective of soil type compared to those with intact tall shrub canopies (Fig. 9, Table 7). Despite changes in near-surface conditions, tall shrub removal experiments did not significantly lower mean annual T_{100} at cut tall shrub sites with mineral soil for 2 years after tall shrub removal because reductions in snow cover and ground heat loss in winter were not great enough to counteract summer warming (Fig. 8C, Tables 1 and 2). It is likely that latent heat effects from freezing of soil pore water in warm permafrost at these sites also delayed the thermal response at depth. After the third year following tall shrub removal, mean winter T_{10} showed that a cut tall shrub site with mineral soils (CutTSm2) was 3.94 °C lower than the lowest mean winter T_{10} observed prior to tall shrub removal (Table 2). Although mean annual T_{100} for these same cut tall shrub sites with mineral soils were comparable to temperatures at those sites before tall shrub removal, the increased thaw depth at this site (Fig. 6) and latent heat from warm permafrost were not offset by colder ground surface temperatures in winter for the first 2 years following manipulation. However, complete freezeback of the active layer (Table 3) and the lowest winter and mean annual temperatures at T_{10} and T_{100} occurring in the later years of record suggest a potential long-term cooling effect at cut tall shrub sites with mineral soils (Fig. 8B, Tables 3–5). At control tall shrub sites with mineral soils, lower near-surface summer temperatures maintained T_{100} in permafrost, although low rates of ground heat loss in winter and a large latent heat component contributed to long durations of active layer freezeback (Tables 2 and 6), a short duration of winter conductive cooling (Fig. 8B),

Fig. 8. (A) Air temperatures at the meteorological station on the Peel Plateau and ground temperatures (100 cm) at site types, including (B) control tall shrub sites with mineral soils, (C) tall shrubs with mineral soils before and after shrub removal in 2014, (D) tall shrub sites with organic soils before and after shrub removal in 2014, and (E) uncut dwarf shrub sites. The dashed vertical line after 2014 indicates the date of tall shrub removal. Ground temperature data were collected 30 m away from the toe of the road embankment.



and winter minimum T_{100} that ranged from −0.4 to −2.16 °C (Table 5), and mean annual T_{100} that ranged from −0.30 to −1.10 °C (Fig. 8C, Tables 3 and 4). Prior to shrub cutting, T_{100} remained isothermal at the tall shrub site with organic soil (Fig. 8D, Table 4). After tall shrub removal at the site with organic soils, the active layer refroze (Table 2), leading to conductive heat loss, lower winter minimum T_{100} that ranged between −0.24 and −0.31 °C before tall shrub removal to −0.73 and −4.96 °C after tall shrub removal, and lower mean annual and seasonal T_{100} (Fig. 8D, Tables 3 and 4). This suggests that shrub cutting has had a gradual, long-term cooling effect on permafrost at the cut tall shrub site with organic soils (Fig. 8D, Table 4). However, 4 years after tall shrub removal, none of the cut tall shrub sites had T_{100} as low as the control

Table 5. Minimum and maximum annual T_{100} (°C) calculated from temperatures at 100 cm below the ground surface with observations from 1 September to 31 August.

Minimum and maximum annual T_{100} (°C)															
Soil type	Mineral soils									Organic soils				Minimum and maximum annual air temperatures (°C)	
Category of shrub cover	Control dwarf shrub		Control tall shrub				Cut tall shrub				Cut tall shrub				
	ContDSm1		ContTSm1		ContTSm2		CutTSm1		CutTSm2		CutTSo1		CutTSo2		
Site name	Max	**Min**	Max	**Min**	Max	**Min**	Max	**Min**	Max	**Min**	Max	**Min**	Max	**Min**	Max	**Min**
2011–2012	X	**X**	-0.20^{H}	**−2.16**	-0.19^{L}	**-0.90^{H}**	0.16^{L}	**-0.54^{H}**	−0.06	**-0.2^{H}**	X	**X**	-0.23^{L}	**-0.31^{H}**	23.01	**-36.55^{L}**
2012–2013	X	**X**	X	**X**	−0.15	**−1.95**	0.20	**−0.83**	−0.03	**−0.68**	X	**X**	−0.20	**−0.24**	23.50	**−32.64**
2013–2014	0.00^{L}	**-7.87^{L}**	−0.30	**-4.23^{L}**	−0.14	**-2.86^{L}**	0.38	**−1.07**	-0.09^{L}	**−1.36**	-0.17^{H}	**X**	X	**X**	20.44^{L}	**−33.40**
2014–2015	0.19	**-3.48^{H}**	-0.31^{L}	**−0.44**	X	**X**	1.13	**−0.70**	0.17	**−0.45**	−0.19	**-0.73^{H}**	X	**X**	31.54^{H}	**−32.46**
2015–2016	0.39	**−3.91**	−0.26	**-0.40^{H}**	X	**X**	2.25	**−0.59**	1.05^{H}	**−0.48**	-0.17^{H}	**−2.10**	-0.17^{H}	**−0.67**	24.26	**-29.22^{H}**
2016–2017	0.55^{H}	**−7.39**	X	**X**	-0.06^{H}	**−1.90**	2.37^{H}	**-2.18^{L}**	0.98	**-2.10^{L}**	−0.20	**-4.96^{L}**	-0.17^{H}	**-4.20^{L}**	24.21	**−30.77**
2017–2018	0.37	**X**	X	**X**	X	**X**	1.96	**−1.31**	0.78	**X**	-0.23^{L}	**−3.14**	−0.18	**−3.48**	24.50	**X**

Note: Years were excluded when temperature data were missing and are indicated by an X. Tall shrub removal occurred in late August 2014. At each thermistor, the highest minimum temperature is indicated with a superscript H and the lowest minimum temperature is indicated with a superscript L.

dwarf shrub site with mineral soils despite reduced snowpack at cut tall shrub sites in 2016, and likely other years, as indicated by freezing n-factors and winter ground temperatures (Table 5).

Ground temperature time series and thawing n-factors at cut tall shrub sites strongly suggest that removal of shading increased ground heat flux in the summer and counteracted the influence of reduced snow thicknesses on winter cooling (Figs. 8 and 9, Tables 1–5). At cut tall shrub sites with mineral soils, an increase in mean summer T_{10} (Table 2), maximum surface soil temperatures (Table 5), and increased thaw depth (Fig. 6) following canopy removal likely resulted from decreased shading. This conclusion is supported by thawing n-factors at tall shrub removal sites that are approximately twice as high as control tall shrub sites, and the n-factors at the cut tall shrub sites went from being the lowest thawing n-factors of all sites to the highest thawing n-factors after tall shrub removal (Fig. 9, Table 7). These observations are consistent with other research showing that dense shrub canopies intercept solar energy, reduce ground heat flux and thaw depth, and increase evapotranspiration (Walker et al. 2003; Blok et al. 2010; Marsh et al. 2010; Myers-Smith et al. 2011*b*; Fisher et al. 2016).

Interactions between seasonal processes and soil types after tall shrub removal

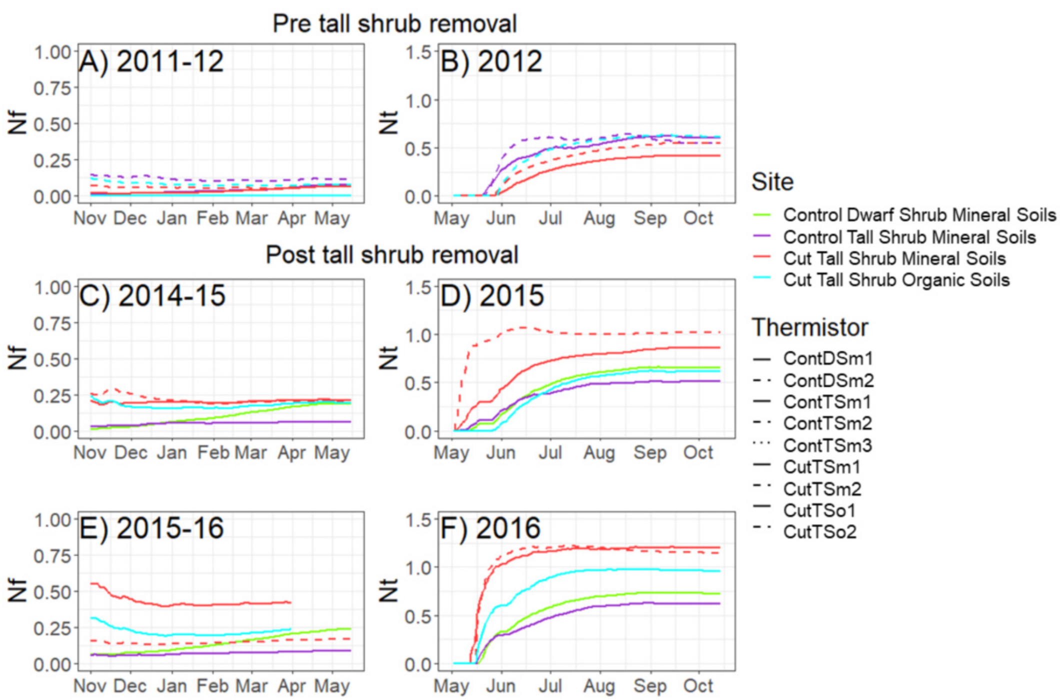
Diverging responses to shrub removal at sites with mineral and organic soils suggest that vegetation effects on ground temperatures depend on soil type. When tall shrubs were removed from cut tall shrub sites with mineral soils, ground surface temperatures became warmer and more variable in the summer because the higher conductivity of mineral soils coupled with increased solar radiation make these sites sensitive to alterations of summer energy input at the ground surface. Tall shrub removal at the cut tall shrub sites with mineral soil sites caused increases in thaw depth (Figs. 6A and 6B) and permafrost thaw at 100 cm below the surface of the ground (Fig. 8C, Table 4). When shrubs were removed from the cut tall shrub site with organic soils, summer permafrost surface temperatures remained unchanged at one of the thermistors, likely due to the low thermal conductivity of peat, which dampened the impact of increased solar radiation and surface warming (Walker et al. 2003; Johnson et al. 2013; Fisher et al. 2016). The other thermistor at the same cut tall shrub site with organic soils showed higher summer T_{10} than both control tall and dwarf shrub sites for the same time periods, but the temperatures at this thermistor were still lower than those at the cut tall shrub sites with mineral soils (Fig. 7). Tall shrub removal at sites with organic soils also accelerated freezeback, decreased minimum winter temperatures at 100 cm depth by approximately 4 °C, and decreased MAGTs at 10 cm depth (Fig. 8D, Tables 1 and 6). Reduced winter cooling at shrub removal sites with mineral soils compared with organic soils for the first 2 years after tall shrub removal was likely due to increased thaw depths in mineral soils, which resulted in longer ground freezeback and a shorter period of conductive cooling of the permafrost, in addition to latent heat effects due to the cooling of warm permafrost (Tables

Table 6. Duration of freezeback at experimental sites.

Soil type	Duration of freezeback							
	Mineral soils					Organic soils		
Category of shrub cover	Control dwarf shrub	Control tall shrub		Cut tall shrub		Cut tall shrub		
Site name	ContDSm1 DOF (days)	ContTSm1 DOF (days)	ContTSm2 DOF (days)	CutTSm1 DOF (days)	CutTSm2 DOF (days)	CutTSo1 DOF (days)	CutTSo2 DOF (days)	MAAT (°C)
2011–2012	X	165	182^{H}	198^{H}	DNF^{H}	X	DNF^{H}	−6.364^{L}
2012–2013	74^{L}	108^{L}	133	174	196	X	DNF^{H}	X
2013–2014	129	143	X	153	163	219^{H}	X	−4.375^{H}
2014–2015	142^{H}	DNF^{H}	X	181	DNF^{H}	191	X	−4.972
2015–2016	85	*DNF*^{H}	X	197	DNF^{H}	153^{L}	194	−5.261
2016–2017	91	X	113^{L}	132^{L}	162^{L}	166	128^{L}	X

Note: Duration of freezeback (DOF) was defined as the time period starting when ground surface temperatures were 0 °C or below for 3 days in a row until ground temperatures at 100 cm below the ground surface were colder than −0.5 °C.Tall shrub removal occurred in late August 2014. Italics for the control tall shrub site with mineral soil ContTSm1 2015–2016 indicate missing data; DOF should likely be 365 during this year, but 10 days of data was missing after 20 August, when temperature at 100 cm depth was −0.289 °C. At each thermistor, the longest DOF is indicated with a superscript H and the shortest DOF is indicated with a superscript L. DNF indicates sites where the thermistors indicate freezeback does not occur. Years with missing data are indicated by an X.

Fig. 9. (A, C, and E) Daily freezing and (B, D, and F) thawing n-factors at experimental sites on the Peel Plateau. Tall shrub removal had not yet occurred in 2011–2012. Plots C–F show n-factors following shrub removal, which occurred in late August 2014.



4 and 6; Kokelj et al. 2017*b*). Peat soils may also influence winter conductive cooling of the permafrost because their low heat capacity and relatively high frozen thermal conductivity promote rapid freezing and ground heat loss in winter (Burn and Smith 1988; Hinzman et al. 1991; Romanovsky and Osterkamp 2000 p. 2000; Yi et al. 2007; Kokelj et al. 2014; Atchley et al. 2016). Our observations of cooler summer and winter T_{100} and more rapid freezeback at the shrub removal site with organic soils compared to the mineral soil sites (Table 2) suggest that organic active layers can confer a degree of resilience to permafrost impacted by shrub encroachment and other ecological changes. This observation is consistent with other studies that document permafrost persistence under thick peat deposits, though soil moisture and snow depth have also been observed to have pronounced impacts on ground thermal regimes in these areas in both experimental and modelling approaches (Jorgenson and Osterkamp 2005; Quinton and Baltzer 2013; Kokelj et al. 2014; Cameron and Lantz 2017; O'Neill and Burn 2017; Holloway and Lewkowicz 2020; Way and Lapalme 2021).

Table 7. Freezing and thawing n-factors at experimental sites on the Peel Plateau in 2011–2016.

Soil type	Mineral soils										Organic soils			
Category of shrub cover	Control dwarf shrub		Control tall shrub				Cut tall shrub				Cut tall shrub			
Site name	ContDSm1		ContTSm1		ContTSm2		CutTSm1		CutTSm2		CutTSo1		CutTSo2	
Year	nf	nt	nf	nt	nf	nt	nf	nt	nf	nt	nf	nt	nf	nt
2011–2012	X	**X**	0.07	**0.60**	0.11^{L}	**0.55**	0.06^{L}	**0.42^{L}**	0.06^{L}	**0.55^{L}**	X	**X**	0.08^{L}	**0.61**
2014–2015	0.19^{L}	**0.66^{L}**	0.06^{L}	**0.51^{L}**	X	**X**	0.21	**0.86**	0.20	**1.02**	0.19^{L}	**0.62^{L}**	X	**X**
2015–2016	0.24	**0.73^{H}**	0.08	**0.62^{H}**	X	**X**	0.41^{H}	**1.20^{H}**	0.17	**1.15^{H}**	0.25^{H}	**0.96^{H}**	X	**X**

Note: Tall shrub removal occurred in late August 2014. At each thermistor, the highest n-factor is indicated with a superscript H and the lowest n-factor is indicated with a superscript L. Years with missing data are indicated by an X.

Tall shrub removal as a permafrost management strategy

Our results indicate that tall shrub removal is likely not a viable short-term strategy to mitigate permafrost thaw adjacent to the Dempster Highway. These results are specific to permafrost and climate conditions of the Peel Plateau, where extreme cold is dampened by inversions and warm permafrost temperatures are compounded by additional thermal disturbance from the Dempster Highway to make this area particularly sensitive to tall shrub proliferation and other disturbances (Gill et al. 2014; O'Neill et al. 2015*b*). Although tall shrub removal decreased snow depth in 2016 and likely additional winters, modest winter cooling of the ground surface was counteracted by increases in summer ground heat flux caused by the removal of a dense shrub canopy. Furthermore, latent heat effects from cooling of warm permafrost at our study sites may contribute to their slow thermal response to the decreased snow cover resulting from shrub removal. This suggests that a longer term reduction of snow cover would be required to reduce ground temperatures in our study area. While tall shrub removal did promote some cooling of surface temperatures at the site with organic soils since most areas adjacent to the Dempster on the Peel Plateau are underlain by mineral soil, cutting shrubs at sites underlain by organics would do little to promote rapid ground cooling next to the road. It is possible that repeated tall shrub removal may be a more effective strategy for cooling winter ground temperatures at other locations with colder MAAT and permafrost or at other locations with less snow accumulation as tall shrub growth, and snow accumulation have likely increased since the Dempster Highway was completed 45+ years ago.

Tall shrub removal along the Peel Plateau is also a challenging management strategy because this area is predisposed to snow accumulation irrespective of tall shrub presence. This section of the Dempster Highway is characterised by a thick road embankment that is oriented east to west, and winds capable of transporting dry snow (Li and Pomeroy 1997) blow primarily from the northwest (Fig. S1). These winds redistribute snow into large drifts on the leeward side of the road (Tabler 1980; Hinkel and Hurd 2006). Consistently deeper snowdrifts on the south side of the road create favourable conditions for tall shrub growth by elevating soil moisture and available nutrients (Hallinger et al. 2010; Brooks et al. 2011; Gill et al. 2014; Cameron and Lantz 2016), increasing winter ground temperatures and thaw depth (Hinkel and Hurd 2006; Fortier et al. 2011; Lafrenière et al. 2013), and degrading permafrost (O'Neill and Burn 2017). Since snow redistribution predisposes this portion of the highway to subsidence, moisture accumulation, and tall shrub proliferation, tall shrub removal would need to be repeated frequently as conditions next to the road are already favourable for tall shrub growth. Our observations of vigorous shrub re-sprouting and growth 2 years following removal indicate that shrub removal would need to be repeated every 3–4 years to maintain open conditions.

Conclusions

1) Reduced snow depth (measured in 2016 and inferred for other years) following tall shrub removal better coupled air and ground surface temperatures in winters, promoting winter cooling, particularly at sites with organic soils.
2) Increased winter ground heat loss at sites with mineral soils was not sufficient to significantly lower MAGT because shrub removal increased thaw depth and summer ground heat flux.
3) Sites with organic soils appeared to be more resilient to changes in summer heat flux following shrub canopy removal.
4) Shrub removal did not promote rapid recovery to conditions observed at dwarf shrub sites next to the Dempster Highway despite reduced snowpack following tall shrub removal.
5) Removal of tall shrubs may not to be a viable permafrost management strategy at the Dempster Highway because permafrost on the Peel Plateau is warm, the region is subject to winter thermal inversions, and the highway is predisposed to snow redistribution by winter winds and tall shrub proliferation.
6) Additional research is required to investigate the long-term implications of tall shrub removal on snow properties and thermal regimes of warm permafrost, as well as impacts of climate change on the resilience of continuous permafrost as impacted by the development of dense shrubs and deep snow pack.

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Competing interests

The authors declare there are no competing interests.

Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/AS-2022-0032.

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