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Ground ice, organic carbon and soluble cations in tundra permafrost and active-layer soils near a Laurentide ice divide in the Slave Geological Province, N.W.T., Canada

Rupesh Subedi[1], Steven V. Kokelj[1,2], and Stephan Gruber[1]

[1]Department of Geography and Environmental Studies, Carleton University, Ottawa, ON, K1S 5B6, Canada
[2]Northwest Territories Geological Survey, Yellowknife, NT, X1A 2L9, Canada

Correspondence: Stephan Gruber (stephan.gruber@carleton.ca)

Abstract. The central Slave Geological Province is situated near a divide of the Laurentide Ice Sheet and it differs from the western Canadian Arctic, where thaw-induced landscape changes in Laurentide ice-marginal environments are already abundant. Although much of the terrain in the central Slave Geological Province is mapped as predominantly bedrock and ice-poor, glacial deposits of varying thickness occupy significant portions of the landscape, creating a mosaic of conditions. Some evidence of ice-rich ground, a key determinant of thaw-induced landscape change, exists. Carbon and soluble cation content in permafrost are largely unknown in the area. Twenty-four boreholes with depths up to ten metres were drilled in tundra north of Lac de Gras to address these regional gaps in knowledge and to better inform projections and generalizations at coarser scale. Excess-ice contents of 20–60 %, likely remnant Laurentide basal ice, are common in till and thaw subsidence of metres to more than ten metres is possible. Beneath organic terrain and in fluvially-reworked sediment, aggradational ice is found. The abundant ground-ice poses long-term challenges for engineering, and it makes the area susceptible to thaw-induced landscape change and mobilization of sediment, solutes and carbon several metres deep. The characteristics of landscape changes, however, are expected to differ from ice-marginal landscapes of western Arctic Canada, for example, based on subsurface properties. Average soil organic-carbon storage is approximately 8 and 14 $kg\,C\,m^{-2}$ for the depth ranges 0–1 m and 0–3 m. The concentration of total soluble cations in mineral soils is much lower than at other previously studied locations in the western Canadian Arctic.

Permafrost in the study area contains much more ground ice than expected, and slightly less organic carbon and fewer soluble cations than well studied areas in the western Canadian Arctic. As these differences are strongly related to geology and glacial history, this study may inform investigations in other parts of the Slave Geological Province and its data can support scenario simulations of future trajectories of permafrost thaw at continental and circumpolar scales.

1 Introduction

A unique drilling program in the tundra north of Lac de Gras resulted in 24 boreholes with depths up to ten metres. It sampled permafrost and active-layer soils and allowed investigating their contents of ground ice, organic-carbon and soluble cations. These three interrelated topics (e.g., Littlefair et al., 2017; Lacelle et al., 2019) are relevant for understanding the nature of

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permafrost and for anticipating consequences of its thaw, which are expected to become increasingly persistent and widespread due to anthropogenic global climate change.

The Lac de Gras region, as part of the Slave Geological Province, is of interest because its geomorphic setting and Quaternary history differ from more intensively studied areas in the previously glaciated western Canadian Arctic and in unglaciated terrain in Yukon and Alaska (Dredge et al., 1999; Karunaratne, 2011). Its Holocene periglacial evolution spans only about 9,000 years, it is situated close to the Keewatin Ice divide of the Laurentide Ice Sheet, and mineral soils are coarse and locally sourced from igneous and metamorphic rocks. Several mines in the area as well as the planned Slave Geological Province Corridor (road, power transmission, communication) add applied relevance in the long term. This billion-dollar infrastructure project will connect Yellowknife with mines and future mineral resources in the study area and may eventually connect Canada's highway system to a deep-water port on the Arctic Ocean in Nunavut.

The ice content of permafrost strongly determines the consequences of thaw such as subsidence or thermokarst development. It thereby also controls potential damage to infrastructure as well as the amount and timing of carbon fluxes into the atmosphere (Turetsky et al., 2019) and nutrient release into terrestrial and aquatic ecosystems (Lantz et al., 2009; Kokelj et al., 2013). The surroundings of Lac de Gras are shown as continuous permafrost with low (0–10 %) visible ice content in the upper 10–20 m and sparse ice wedges in the Permafrost Map of Canada (Heginbottom et al., 1995) and are designated as having thin overburden cover (<5–10 m) and exposed bedrock in the Circum-Arctic Map of Permafrost and Ground-Ice Conditions (Brown et al., 1997). For both, it is the lowest class of ground-ice content in continuous permafrost. The new Ground Ice Maps for Canada (O'Neill et al., 2019) show the study area (50 km $\times$ 50 km) to contain no or negligible wedge ice, negligible to low segregated ice and no relict ice, which includes buried glacier ice. By contrast, the thick and hummocky tills that cover about a quarter of the study area have been hypothesized to contain large ice bodies, possibly of glacigenic origin (Dredge et al., 1999) as proposed also in other areas (e.g., Dyke and Savelle, 2000). The vertical distribution and characteristics of ground-ice are a key prerequisite for simulating and anticipating the consequences or permafrost thaw.

Large stocks of organic carbon that can be decomposed and transferred to the atmosphere upon thaw (Schuur et al., 2008) are held in permafrost (Hugelius et al., 2010). The integration of organic carbon into the near-surface permafrost is related to either periods of deeper thaw, which can redistribute carbon within the soil profile, or to a rising permafrost table due to colluviation or alluviation, ecological succession, or climate cooling. These processes affect both carbon and geochemical profiles (Lacelle et al., 2019). To support the generation of future climate scenarios, the quantification and characterization of permafrost organic carbon storage is important and little information on soil organic carbon exists within a large area surrounding Lac de Gras, especially at depths exceeding one metre (Hugelius et al., 2014; Tarnocai et al., 2009).

Nutrients, organic materials and contaminants (natural and anthropogenic) can be released from permafrost during thaw (Dyke, 2001; Leibman and Streletskaya, 1997; Mackay, 1995), translating geomorphic disturbance, forest or tundra fire, or atmospheric warming into impacts on the chemistry of soils and surface water, and provoking noticeable ecological and down-stream effects (e.g., Frey and McClelland, 2009; Kokelj and Burn, 2005; Kokelj et al., 2009; Littlefair et al., 2017; Malone et al., 2013; Tank et al., 2016). Studies from northwestern Canada report permafrost, the transient layer and the active layer to have distinct physical and geochemical characteristics (Kokelj et al., 2002; Kokelj and Burn, 2003, 2005; Lacelle et al., 2014)

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and sometimes distinguish relict/paleo-active layers (Burn, 1997; Lacelle et al., 2019). These vertical patterns are attributed to (a) past thawing causing loss of ground ice, leaching of solutes from thawed soils and redistribution of organic carbon by cryoturbation (Kokelj and Lewkowicz, 1999; Kokelj et al., 2002; Leibman and Streletskaya, 1997; Pewe and Sellmann, 1973), and (b) thermally-induced moisture migration during soil freezing redistributing water and soluble ions (Cary and Mayland, 1972; Qiu et al., 1988) contributing to solute enrichment in near-surface permafrost (Kokelj and Burn, 2005). These study areas, however, are different from the Slave Geological Province. For example, the alluvial materials derived from sedimentary and carbonate rock of the Taiga plain together with regular flooding produce solute rich active layer and permafrost deposits in the Mackenzie Delta. As another example, the sediments that comprise Herschel Island are silty-clay tills that include coastal and marine deposits excavated by the Laurentide Ice Sheet (Burn, 2017). In contrast to previous findings in these areas, we hypothesize that the tills in the Lac de Gras region are solute poor because they are locally sourced from granitic bedrock (Hu et al., 2003) and had limited potential for chemical weathering at depth.

This study aims to improve the understanding and quantitative characterization of permafrost and active layer materials in tundra environments near Lac de Gras and contribute to better understanding permafrost environments near Laurentide ice divides and in the Slave Geological Province more broadly. The objectives are to *(i)* quantify the amounts and vertical patterns of excess ice, organic carbon and soluble cations, *(ii)* explore factors contributing to the variation in physical and chemical characteristics between terrain types, and *(iii)* compare excess-ice content, organic-carbon density and soluble cation concentration with other permafrost environments and with compilations such as overview maps and databases. We interpret multiple boreholes grouped by terrain type and, with the data available, distinguish unfrozen (active layer) and frozen (predominantly permafrost) samples but do not additionally separate transient or relict active layers.

2 Study region

The study region (110.3° W, 64.7° N) is north of Lac de Gras, approximately 200 km south of the Arctic Circle and about 310 km northeast of Yellowknife. The regional climate is continental, with summers cool and short and winters cold and extremely long (Hu et al., 2003). Ekati, a diamond mine in the study region, has a mean annual and summer air temperature of -8.9 °C and 14 °C, and an annual precipitation sum of 275 mm during 1988–2008 (Environment Canada, 2019). Deglaciation occurred before 8,500 BP and between 6,000 and 3,000 BP, forest tundra extended to approximately the study area and then retreated again (Dyke, 2005; Dredge et al., 1999).

The region is in the zone of continuous permafrost (Figure 1) and mapped as having low (0–10 %) visible ice content in the upper 10–20 m (Heginbottom et al., 1995; Brown et al., 1997). One map indicates sparse ice wedges and the other thin overburden (<5–10 m) with exposed bedrock. A recent circumpolar compilation of permafrost carbon data (Hugelius et al., 2014) estimated soil organic-carbon storage (SOCs) to be 5–15 (0–1 m) and 15–30 $kg\ C\ m^{-2}$ (0–3 m). Recent work in the area has produced a wealth of permafrost stratigraphic (Gruber et al., 2018a) and thermal (Gruber et al., 2018b) data that enabled not only this contribution but also several simulation studies (Cao et al., 2019a; Melton et al., 2019; Cao et al., 2019b) predicting permafrost temperature driven by global atmospheric models.

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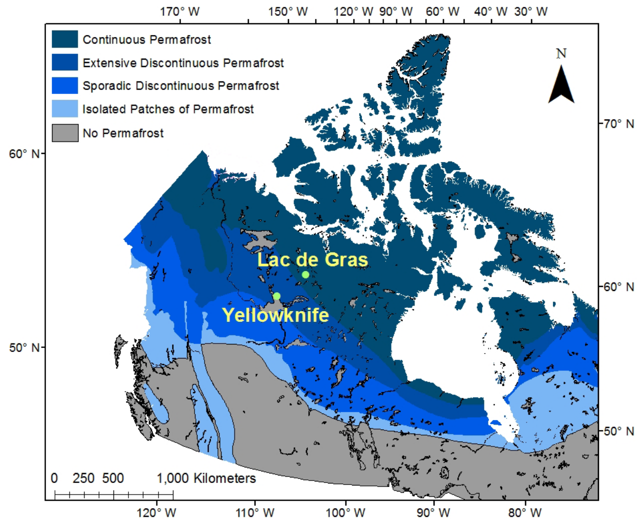

Figure 1. Location of the study area in the context of permafrost zones in Canada (modified from Heginbottom et al. 1995). Yellowknife is the closest city.

The area is characterized by low relief where irregular bedrock knobs and cuestas form hills up to 50 m high (Dredge et al., 1999). Located near the ice divide of the Keewatin sector of the Laurentide Ice Sheet, it generally is a source area for sediments, unlike ice marginal locations. The spatial abundance of surface materials is derived from the surficial geology map 1:125,000 (110–112° W, 64–65° N) for Lac de Gras (NTS 76-D, Geological Survey of Canada, 2014). The northern part is dominated by till deposits, whereas the southern half consists more prominently of bedrock (8 %) with patches of till (Hu et al., 2003). Numerous eskers and outwash complexes (1 %), mostly composed of sand and gravel, are found in the area (Dredge et al., 1994). Till deposits are differentiated by their estimated thickness into till veneer (<2 m thick, 21 %), till blanket (2–10 m thick, 24 %), and hummocky till (5–30 m thick, 3 %). These deposits typically have a silty sand to sand matrix with low percentages of clay and 5–40 % gravel (Wilkinson et al., 2001). Organic material covers 5 % and lakes 38 % of the area.

Soils consist of till, glacio-fluvial sediments, or peat. Upland till surfaces are characterized by earth hummocks and organic material, visible to depths of up to 80 cm, that has been redistributed within the active layer by cryoturbation (Dredge et al., 1994). The tills derived from granitic and gneissic terrain have a silty or sandy matrix, whereas those derived from metasedimentary rocks contain a higher silt-clay content (Dredge et al., 1999). Low-lying areas are mostly comprised of colluvium or alluvium rich in organics and wet areas often have peatlands (Karunaratne, 2011).

The area is in continuous shrub tundra (Wiken et al., 1996) and common shrubs include northern Labrador tea *(Rhododendron tomentosum)* and dwarf birch *(Betula glandulosa)*, while bog cranberry *(Vaccinium vitis-idaea)* and dwarf bog rosemary *(Andromeda polifolia)* often comprise the understory (Karunaratne, 2011). Well-drained upland areas are typically covered with a thin layer of lichens and mosses (Hu et al., 2003) (Figure 2A). Grasses and sedges with a ground cover of moss comprise the vegetation cover in valleys (Figure 2B) and some poorly-drained low-lying areas have thick peat associated with

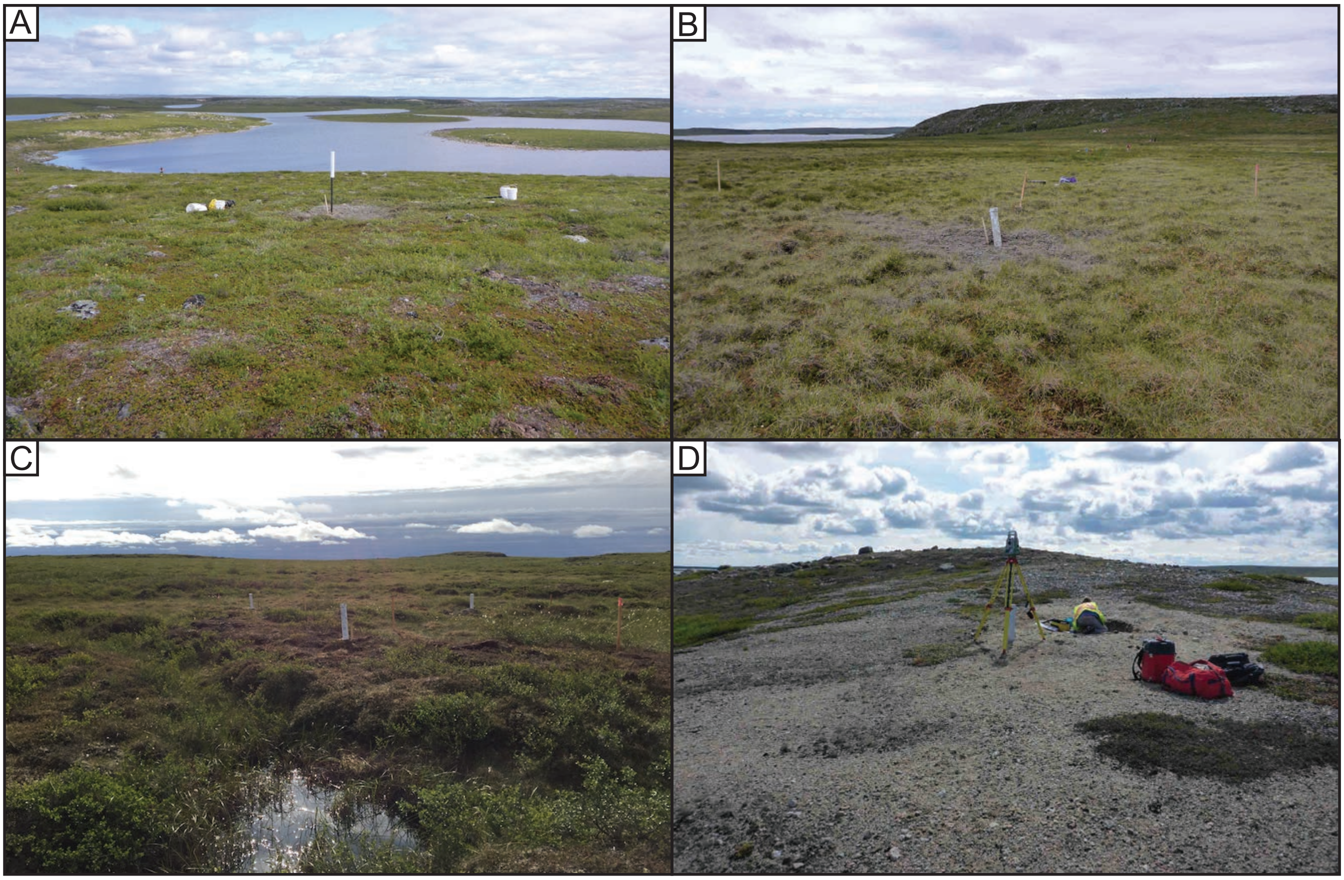

Figure 2. Examples of the four terrain types used: (A) upland tills, (B) the Valley, (C) organic deposits, and (D) eskers.

ice-wedge polygons and sedge meadows (Hu et al., 2003; Karunaratne, 2011) (Figure 2C). Frequently, low-lying areas have tall shrubs along small streams and at the rise of steeper slopes. Esker tops have little vegetation and are often comprised of exposed soil (Figure 2D).

3 Methods

3.1 Field

Soil cores with a diameter of 5 cm were obtained using a diamond drill (Kryotek Compact Diamond Sampler), sectioned into 20 cm intervals and logged (soil texture, colour, ice content and visible organic matter) in the field while still frozen (Subedi, 2016; Gruber et al., 2018a). Two soil pits were excavated within approximately 10 m of each borehole to describe and sample typical near-surface soil conditions. The depth of thaw at the time of sampling was estimated by probing. Drill core and pit samples were double-bagged for thawed shipment to the laboratory in Yellowknife.

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3.2 Laboratory

All samples were thawed and processed at ambient temperature. Samples were homogenized, poured into beakers, weighed, and allowed to settle for 12 h (cf. Kokelj and Burn, 2003). Volumes of sediment V_s and supernatant water V_w were recorded to estimate volumetric excess ice content (%) of the permafrost samples as

$$V_{ei} = \frac{1.09\,V_w}{V_s + 1.09\,V_w} \times 100, \tag{1}$$

where 1.09 approximates the density of water divided by that of ice. The volumetric percentages of coarse fragments (>5 mm), sand (0.074–5 mm) and fines (<0.074 mm) in the sediment was estimated visually to the nearest 5 %. The volumetric percentage of coarse fragments (V_c) relative to the total sample volume was obtained by multiplying the estimated coarse percentage with $1 - V_{ei}/100$.

Supernatant water was extracted directly from samples where sufficient volume was available and to all other samples, a known amount of deionized water was added (1:1 extraction ratio; Janzen, 1993). These samples were mixed thoroughly and then allowed to settle for 12 h. Water was collected with a syringe and filtered through 0.45 μm cellulose filter paper. The remainder of the sample was dried for 24 h at 105 °C to determine the gravimetric water content (%), expressed on a dry basis (GWC_d) and on a wet basis (GWC_w) (cf. Phillips et al., 2015).

The concentration (mg/l) of the soluble cations Ca^{++}, Mg^{++}, Na^{+} and K^{+} was determined by atomic adsorption spectrophotometer at the Taiga lab in Yellowknife. Measured soluble ion concentrations C^m (mg/l) were converted to an expression E using milli-equivalents per unit mass of soil (meq/ 100g of dry soil)

$$E = \frac{C^m}{M^e} \times M_w^{100g}, \tag{2}$$

where M^e is the equivalent mass of ions (g) and M_w^{100g} is the mass of water per 100 g of dry soil as present in the sample at the time of water extraction. Presentation of soluble cation concentrations per unit weight of dry soil facilitates comparison between samples of varying moisture contents.

Organic-matter content LOI (%) is expressed on a gravimetric dry basis and was determined using the sequential loss-on-ignition method (Sheldrick, 1984) at Carleton University. A small amount (2–3 g) of the homogenized and oven dried sample (< 0.5 mm soil fraction) was placed in a crucible and heated to 550 °C for 6 h to determine the organic-matter content as

$$LOI = \frac{M_S^{105} - M_S^{550}}{M_S^{105}} \times 100, \tag{3}$$

where M_S^{105} is the mass of sediment after oven drying at 105 °C, and M_S^{550} is the mass of sediment after ignition at 550 °C. To avoid combustion problems, reduced amounts (0.5–1 g) were processed when samples consisted of plant residue with very little visible mineral soil. When no mineral soil component was visible after coarse components were removed, samples were not processed and an LOI of 80 % was estimated. This occurred only in the top metre and almost exclusively in samples from soil pits. The gravimetric percentage ($P_{0.5}$) of the <0.5 mm soil fraction has been lost from the original analysis. Later, this was determined again based on dry sieving for 183 of 357 samples.

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Data quality was assessed in a second analysis on the samples using the same procedures and tools as during the original processing. Based on measured blanks, the accuracy is about 0.03 % LOI, the median accuracy based on doubles is 0.04 % LOI with the highest difference being 0.30 % LOI.

Soil organic-carbon storage (SOCs, $kg\,C\,m^{-2}$) was computed for comparison with soil carbon inventories (e.g., Hugelius et al., 2014). For this, soil organic-carbon concentration (SOCc, % mass) was computed as

$$SOCc = \frac{LOI}{2.13}, \tag{4}$$

following Dean (1974) and dry bulk density (DBD, $kg\,m^{-3}$), which is known to correlate with SOCc (e.g., Alexander, 1989; Bockheim et al., 2003), was approximated as

$$DBD = 71 + 1322 \times e^{(-0.071 \times SOCc)}, \tag{5}$$

following Hossain et al. (2015), who conducted their study in geologic settings similar to the project area. This resulted in an estimated DBD for the fine-grained soil, i.e. excluding the volumes V_{ei} and V_c. To account for this, soil organic-carbon density (SOCd, $kg\ C\ m^{-3}$) was derived as

$$SOCd = \frac{SOCc}{100} \times \frac{P_{0.5}}{100} \times DBD \times \left(1 - \frac{V_{ei} + V_c}{100}\right), \tag{6}$$

and finally applied as average values over depth intervals within each terrain type to obtain SOCs. For the samples without measured values, $P_{0.5}$ was estimated by beta regression (Cribari-Neto and Zeileis, 2010) with LOI, GWC_w as well as the visually-estimated proportions of sand and fines as independent variables. Predictors are significant at the 0.1 %-level and residuals have a standard deviation of 11 %.

The spatial average of soil organic-carbon storage is estimated by aggregating SOCd with the spatial abundance and estimated depths of surface materials (NTS 76-D, Geological Survey of Canada, 2014) for the study area. Depths are restricted to the available observations, and for the three till classes restricted or extrapolated to their mean depths.

Estimating $P_{0.5}$ for 176 of 357 samples statistically, parameterizing DBD and estimating V_c visually introduce uncertainty in the resulting values for $SOCd$ and $SOCs$. The potential magnitude of this effect on average values is estimated by computing a low-carbon scenario and a high-carbon scenario by varying V_c and $P_{0.5}$ by ± 10 percentage points each and DBD by $\pm 50\ kg\,m^{-3}$. The averages of the resulting scenario values are 37 % lower and 38 % higher than the best estimate for SOCd that is reported and interpreted in the following sections.

Detailed grain-size distribution was measured on selected samples using a Beckman Coulter LS 13320 laser-diffraction particle-size analyzer. Samples were first oven-dried at 105 °C and then crushed and homogenized with a mortar and pestle. Samples were then passed through a 2 mm sieve to remove the coarse fraction that was then weighed. Organic matter was removed from the fines using hydrogen peroxide. The samples were then mixed with Calgon to prevent flocculation and passed through the particle-size analyzer. Results were classified according to the USDA textural classification system (2 mm > sand > 53 μm > silt > 2 μm > clay).

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4 Field observation and sampling

4.1 Study sites

Four terrain types (Figure 2) comprised of upland tills, fluvially reworked till (the Valley), organic terrain and eskers were sampled with drill cores and soil pit at 24 locations (Table A1).

Upland tills: Ten boreholes were sampled to depths of 2.5–9.5 m in smoothly rounded hills comprised of thick till and in till veneer over bedrock. The dominant plant species were dwarf shrubs, Labrador tea and grasses. Thaw depths were about 2 m on hill tops and nearly a meter at the bottom of hills.

The Valley: Eight boreholes were drilled to depths of 1–6 m in a gently sloped valley that contrasts with other terrain types because its silts and sands are well sorted and likely derived from fluvial reworking of local tills. Boreholes located on the more elevated sides of the Valley typically had coarser sediments, whereas those near its axis had mostly fine sediments with high silt contents and organics with ice-wedge polygons. Few water logged sites contained tall shrubs with water channels. Sites were sparsely to moderately covered with plant species such as dwarf birch, Labrador tea and grasses. Thaw depths were 35–40 cm.

Organic terrain: Two boreholes to depths of about 4.5 m were drilled on the centres of ice-wedge polygons in peatlands with hummocks. The dominant plant species were dwarf birch and Labrador tea, with plenty of low-lying grasses. The depth of thaw was 35 cm and the permafrost table 50–70 cm deep.

Eskers: Four boreholes were drilled to depths of 1.5–12 m at hilltop locations with sparse vegetation or exposed soil.

5 Results

5.1 Soil texture

Most soils consisted of poorly to very poorly sorted silt and sand. The relative proportion of silt was high in samples from mineral soils beneath organic terrain and in valley bottom sites with average values exceeding 40 %. Clay content was low and always below 20 %.

5.2 Ground ice

Field logged visible-ice content is available for 113 core sections. The average, weighted by the length of core sections, is 24 %. Laboratory analyses show that water and excess-ice contents increase progressively with depth in till. Zones of high moisture content (Figures 3A and 4A) were often associated with ice lenses, several centimeters thick (e.g., Figures B1 and B3). Excess-ice content greater than 50 % in till became increasingly common below 4 m depth. In organic terrain, high moisture content (>80 %) but low excess-ice content in permafrost reflect saturated organic soils with low bulk density (Figure 3B). The sharp decline in water content below 2 m depth coincides with a decline in organic matter contents (Figure 4B). A notable increase in moisture and excess ice content from 2.5–4 m depth occurred in underlying mineral soils. Profiles from the Valley showed

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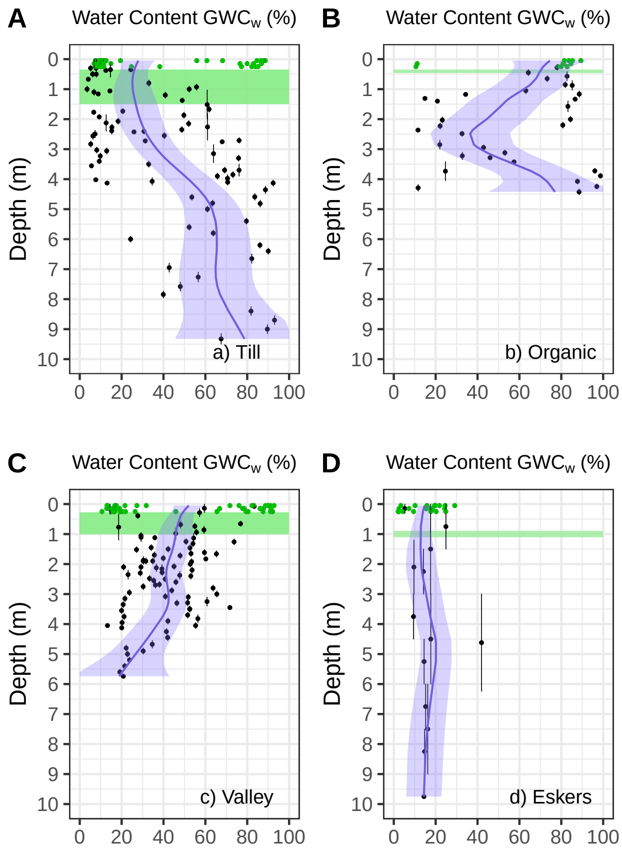

Figure 3. Gravimetric water content from four terrain types near Lac de Gras, N.W.T. Black points and their vertical lines represent borehole samples and their depth intervals. Green points show pit samples. Blue lines represent averaged values, taking into account sample depth intervals, with shaded blue areas indicating the standard error at 95% confidence. Green shaded areas indicate the range of thaw depths for the boreholes at the time of sampling.

high moisture content near the surface, where organics were present, and deeper down (Figure 3C) due to 20–50 % excess ice in mineral soil (Figure 4C). In eskers, water content was mostly below 20 % and pore ice the dominant ground-ice type (Figure 3D).

5.3 Organic carbon

Organic-carbon density in the active layer was typically greater than at depth in permafrost (Figure 5). Statistics of soil organic-carbon density and storage are given for consistent depth intervals and the four terrain types in Table 1. The spatial average of soil organic-carbon storage in the study area, accounting for the abundance of bedrock and lakes, is estimated as 8 and 14 $kg\,C\,m^{-2}$ for the depth ranges 0–1 m and 0–3 m, respectively.

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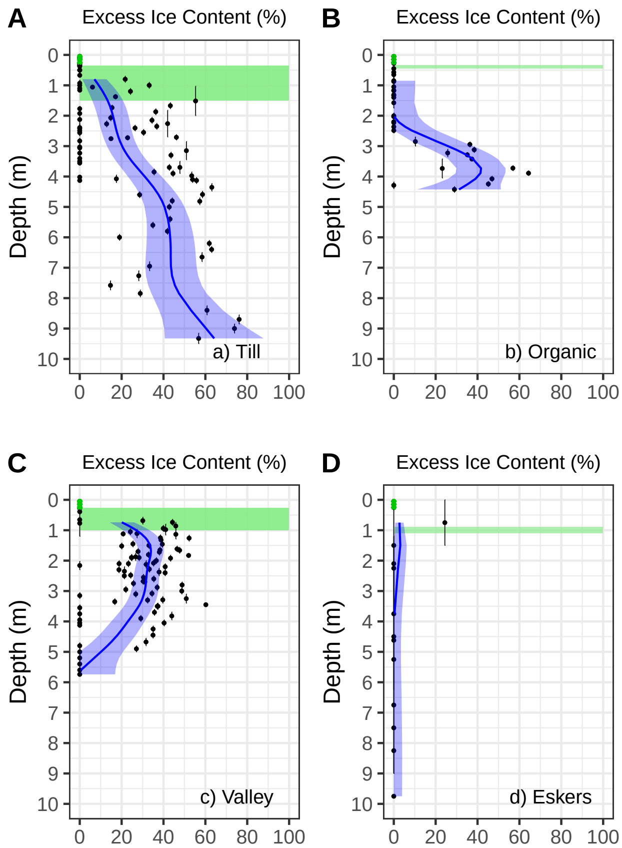

Figure 4. Excess-ice content from four terrain types near Lac de Gras, N.W.T. Black points and their vertical lines represent borehole samples and their depth intervals. Green points show pit samples. Blue lines represent averaged values, taking into account sample depth intervals, with shaded blue areas indicating the standard error at 95% confidence. Green shaded areas indicate the range of thaw depths for the boreholes at the time of sampling.

5.4 Total soluble cations

The concentration of soluble cations in organic-rich, shallow soils were mostly higher and more variable than those in mineral permafrost soils at depth (Figure 6). In organic materials, the concentration of soluble cations near the top of permafrost was relatively high (Figure 5B and 6B). In till, soluble cation concentrations, as with ice content, increased gradually with depth (Figure 4A and 6A). Differences between active layer and permafrost, as well as between organic and mineral soils are apparent from their median concentration of soluble cations; organic samples are distinguished using a threshold of 30 % LOI (cf. CSSC, 1998) and permafrost considered when logged as frozen. In organic samples the contrast (permafrost to active layer) was 2.02 to 0.34 meq/100 g dry soil and in mineral samples 0.26 to 0.09 meq/100 g dry soil. The four group medians are

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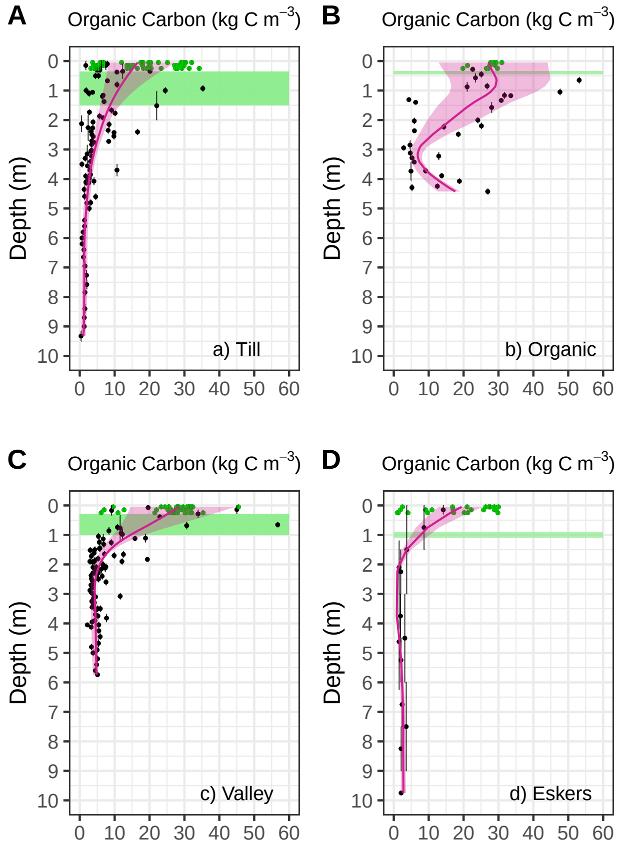

Figure 5. Soil organic-carbon density ($kg\,C\,m^{-3}$) from four terrain types near Lac de Gras, N.W.T. Black points and their vertical lines represent borehole samples and their depth intervals. Green points show pit samples with approximated values for the organic terrain. Magenta lines represent averaged values, taking into account sample depth intervals, with shaded magenta indicating the high/low-carbon scenarios used to estimate the uncertainty inherent in estimating and parameterizing some of the values used in calculations. Green shaded areas indicate the range of thaw depths for the boreholes at the time of sampling.

all significantly ($p < 0.01$) different from each other based on Kruskal-Wallis tests. Although the dry bulk density of organic soil is lower than that of mineral soil, these patterns persist even when expressed relative to wet soil mass.

6 Interpretation and discussion

6.1 Ground ice

The results presented are subject to a number of biases compared to a perfectly randomized sampling within each terrain type and perfect recovery of samples during drilling: Drilling induced errors in the recovery of ground ice where excessive heating

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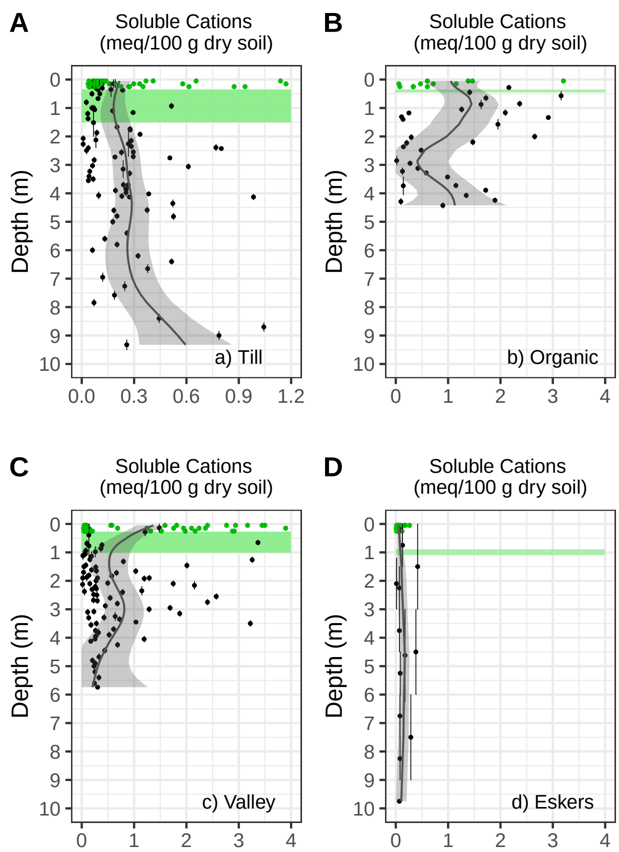

Figure 6. Total soluble cation concentration (meq/100 g dry soil) from four terrain types near Lac de Gras, N.W.T. Black points and their vertical lines represent borehole samples and their depth intervals. Green points show pit samples. Smooth black lines represent averaged values, taking into account sample depth intervals, shaded grey areas indicate the standard error at 95% confidence. Green shaded areas indicate the range of thaw depths for the boreholes at the time of sampling. Note differences in horizontal scales.

of the drill barrel caused partial or complete thaw of the core. Depending on the degree of thaw and core composition, this resulted in intervals erroneously shown with reduced or no excess ice content (Figure 4C). The results are, therefore, likely to be conservative (low biased) estimates of excess ice and gravimetric water content at the locations sampled. The difficulty of drilling though large clasts, on the other hand, may have caused bias towards sampling locations with higher contents of excess ice and of fines. When drilling organics within polygon networks, the drill rig was placed on polygon centres. As a consequence, wedge ice, which is known to be present in the area based on the surface expression of polygon networks, is systematically avoided in sampling and, therefore, largely excluded from the present quantitative data and interpretation.

While this study was not designed to elucidate the origin of ground ice, a number of observations merit discussion. In organic terrain, the excess ice recovered resembles pool ice (clear with small bubbles and embedded peat filaments) and wedge

Table 1. Soil organic-carbon density (SOCd, $kg\ C\ m^{-3}$) per depth interval and soil organic-carbon storage (SOCs, $kg\ C\ m^{-2}$) for the four terrain types investigated. SOCs is based on average SOCd accumulated from the surface down to the specified maximum depth. Ranges in parentheses indicate minimum and maximum values rounded to the nearest integer, the number of samples is indicated in square brackets.

	Organics		Valley		Till		Eskers	
Depth	SOCd	SOCs	SOCd	SOCs	SOCd	SOCs	SOCd	SOCs
0–0.3 m	26.7 (20–31) [13]	8	27 (6–46) [52]	8	16.2 (2–34) [59]	5	17.8 (1–30) [25]	5
0.3–1 m	29.9 (21–53) [5]	29	20.6 (8–57) [8]	23	11.8 (5–35) [10]	13	8.7 (9–9) [1]	11
1–2 m	25.6 (4–48) [9]	54	7.6 (3–19) [23]	30	8.4 (2–25) [13]	22	3.7 (4–4) [1]	15
2–3 m	12.7 (3–25) [8]	67	4.8 (3–8) [22]	35	5.8 (1–17) [16]	27	1.8 (2–2) [2]	17
3–5 m	10.9 (5–27) [11]	89	4.8 (2–12) [25]	45	2.9 (1–11) [23]	33	2.2 (2–3) [3]	21
5–10 m					1.3 (0–3) [16]	40	2.4 (2–4) [5]	34

ice (foliated with bubbles and some sediment, Figure B2 panels B and C) as previously reported for polygonal ground in organics (Mackay, 2000; Morse and Burn, 2013). In the Valley and in organic terrain, the increase in water and excess-ice content with depth (Figures 3 and 4) is likely due to ice segregation in frost susceptible and relatively well graded mineral soil (Figures B1 and B2 panel D) with frequent reticulate cryostructure. Both the Valley site, with materials that are likely to be fluvially-reworked tills, and organic terrain represent aggradational environments in low lying areas where water tends to accumulate and the terrain surface gained material either through the growth of peat or fluvial deposition. Shallow permafrost aggraded in these settings, as such, does not contain relict or preserved ice. Similarly, permafrost has aggraded in the sediment of eskers, where less fine material together with convex topography explains the absence of aggradational ice. Eskers in the study area occasionally contain relict ice, partially interpreted as derived from of glacial meltwater and deposited together with the esker sediments (Dredge et al., 1999; Hu et al., 2003) and show geomorphic evidence of melt-out (Prowse, 2017).

Cores from upland hummocky till, analyzed to 9 m depth (Figure B3), were often associated with high amounts of excess ice. Ice occurred in wavy layers and sometimes as massive ice several centimetres thick. In contrast to the Valley site and organic terrain, no reticulate structure and no apparent separation of consolidated fines and clear ice were visible in most till cores. Sediment was coarser and more poorly sorted in upland till than at the Valley site or beneath organics. Particles appeared to be suspended in the ice matrix, giving it a visual appearance of much lower ice content than it actually has, as reported previously for basal glacier ice facies (Knight, 1997; Murton et al., 2005). Soluble cation contents are lower in mineral soil active layers and near-surface permafrost than at depth, consistent with near-surface leaching and preservation of underlying materials in the frozen state since deglaciation. Finally, the convex topography of upland till sites makes them well drained and differentiates them from the Valley and from organic sites. These differences in cryostructure, cation content and sedimentological properties point to ice of differing origin. The presence of hummocky topography, thermokarst lakes and thaw-slump like features (Fig. **??**) indicating melt-out of ice-rich till, and involuted nature of hilltop surfaces resemble other permafrost preserved glaciated landscapes in northwestern Canada, which are known to host relict Pleistocene ground ice (Dyke and Savelle, 2000; Rampton,

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1988; St-Onge and McMartin, 1999). Both, ground ice characteristics and geomorphic features suggests that a large proportion of the excess ice in this hummocky till is Laurentide basal ice preserved beneath ablation till.

The volumetric contents of excess ice encountered in mineral soil were often 20–60%. As a first-order estimate, this implies that complete thaw of permafrost can cause about 0.2–0.6 m of subsidence for each vertical meter of permafrost in till. The boreholes in hummocky till, which is estimated to be 10–30 m thick in the area (Haiblen et al., 2018) show an increasing trend of excess ice content with depth, based on our limited sampling to 9 m, alone. A potential surface lowering of many meters, up to more than ten meters, is thus to be expected from areas of thick till if this permafrost was to thaw completely. This includes the potential for thermokarst processes to mobilize sediments, solutes and organic carbon at depth more quickly than expected in strictly conductive one-dimensional thaw. A number of geomorphic features reminiscent of retrogressive thaw slumps (Fig. **??**) and the presence of kettle lakes (Prowse, 2017) in the area both exhibit local relief that suggest meltout of massive ice several metres in thickness.

6.2 Organic carbon

Terrain variation in organic-carbon density and in organic matter content in fine material occur in association with surficial material and topographic setting. Organic terrain is frequently characterized by peat deposits up to 2.5 m thick and associated with low lying poorly drained portions of the landscape. In other terrain types, organic materials may have become vertically redistributed in the top few metres of soil profiles by cryoturbation (Dredge et al., 1994; Haiblen et al., 2018) and by burial during permafrost aggradation due to colluviation/alluviation (Kokelj et al., 2007). The low organic-carbon density at depth likely indicates the absence of sediment reworking and permafrost preservation in tills during the Holocene.

Mean organic-carbon density in the top 3 m of soil profiles near Lac de Gras is about half that reported in recent circumpolar statistics (Table D1). This is similar to the mean of about 12 ($kg\,C\,m^{-3}$) for the top 1 m in the northern Canadian Arctic and its difference to about 30 ($kg\,C\,m^{-3}$) in the southern Canadian Arctic reported by Hossain et al. (2015, Fig. 5D). A recent circumpolar compilation of permafrost carbon data (Hugelius et al., 2014) estimated SOCs for the study area to be 5–15 (0–1 m) and 15–30 (0–3 m) $kg\,C\,m^{-2}$. These values are similar (0–1 m) and slightly higher (0–3 m) than the spatially-averaged results of this study, that include zero SOCs in bedrock and in lakes. The low organic-carbon density in the study area, especially at depth, is interpreted to derive from the short duration of Holocene carbon accumulation following at least partial evacuation of older soil carbon by the Keewatin sector of the Laurentide Ice Sheet during Marine Isotope Stage 2. While deep carbon pools are important (Koven et al., 2015), corresponding data (Hugelius et al., 2014; Tarnocai et al., 2009) is rare.

6.3 Total soluble cations

In mineral soil, the lower concentration of total soluble cations in the active layer compared with permafrost is interpreted to be caused by leaching of ions from unfrozen soil, and is similar to observations in other regions (Table D2). Additionally, the redistribution of ions along thermal gradients during freezing may have caused solute enrichment during the development of segregated ice (Figure B1 and B2) in aggrading permafrost (cf. Cary and Mayland, 1972; Qiu et al., 1988) in mineral soils of the Valley and beneath peat in organic terrain. There, zones of increased cation concentrations at depth corresponded with

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ice-rich intervals in permafrost, especially at sites in till and in organic terrain (Figure 4 and 6). Where high amounts of organic matter are present, also the concentration of total soluble cations is high. As a consequence, mineral-soil permafrost has lower concentrations of soluble cations than organic active-layer soils but higher concentrations than mineral active-layer soils.

The absolute concentrations of soluble cations obtained in the study area near Lac de Gras are low compared to previous studies from northwestern Canada that report higher concentrations in active layer and permafrost across diverse terrain types (Table D2). In the Mackenzie Delta, alluvial materials derived from sedimentary and carbonate rock of the Taiga plain and regular flooding produce solute rich active layer and permafrost deposits. A range of forest-terrain types contained more soluble cations, often several times higher, in the active layer and permafrost than the mineral soils in this study. Also in comparison with undisturbed terrain on Herschel Island, the absolute concentrations of soluble cations in our study are low. Sediments on Herschel Island are silty-clay tills that include coastal and marine deposits excavated by the Laurentide Ice Sheet (Burn, 2017). These materials are frequently saline below the thaw unconformity indicating permafrost preservation of soluble materials below the maximum depth of early Holocene thaw (Kokelj et al., 2002) or their concentration in colluviated materials (Lacelle et al., 2019). The low concentrations in our study area are associated with the contrasting nature and origins of surficial materials. Tills in our study region are generally coarser grained than many glacial deposits studied in the western Arctic, are regionally sourced from mostly granitic rocks and have been exposed only to minor postglacial landscape modification (Haiblen et al., 2018; Rampton and Sharpe, 2014).

7 Conclusions

The research area near Lac de Gras is characterized by a mosaic of terrain types (48 % till, 38 % lakes, 8 % bedrock, 5 % organic material and 1 % eskers and outwash complexes) with a high degree of fine-scale spatial variability in subsurface conditions. Permafrost there contains much more ground ice, slightly less organic carbon and fewer soluble cations compared with global compilation products or published research from sites in the western Canadian Arctic. This study provides quantitative data in a region with few previous studies and it supports six specific conclusions:

1. Excess-ice contents of 20–60 % are common, especially in till and till-derived sediments, and the average field logged visible-ice content is 24 %. This new regional insight improves upon coarse-scale compilations that rate the area north of Lac de Gras as ice poor (O'Neill et al., 2019; Brown et al., 1997; Heginbottom et al., 1995).

2. Thick occurrences of excess ice found in upland tills are likely remnant Laurentide basal ice, and aggradational ice is found beneath organic terrain and in fluvially-reworked till.

3. Thaw-induced terrain subsidence on order of metres to tens of metres is possible in ice-rich till. Organic terrain hosts wedge ice and is typically underlain by ice-rich mineral deposits. Future thermokarst processes may therefore result in significant landscape change and fast mobilization of sediment, solutes and carbon several metres deep. Geomorphic evidence of past ground-ice melt, including retrogressive thaw slumping exists.

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4. Peatlands are up to 2.5 m thick and in till, cryoturbation and colluviation/alluviation have redistributed modest amounts of organic carbon locally to depths of 2–4 m. The mean organic-carbon density in the top 3 m of soil profiles near Lac de Gras is about half that reported in recent circumpolar statistics (Hugelius et al., 2014). Estimated areal means, accounting for the abundance of bedrock and lakes, of soil organic-carbon storage are 8 and 14 $kg\,C\,m^{-2}$ for the depth ranges 0–1 m and 0–3 m, respectively, similar to or slightly lower than in a global estimate (Hugelius et al., 2014).

5. The concentration of total soluble cations in active layer and permafrost mineral soils is markedly, often by one order of magnitude, lower in the Lac de Gras area than at other previously studied locations in the western Canadian Arctic. Mineral-soil active layers have a lower concentration of total soluble cations than permafrost. Total soluble cation concentrations are higher were soils are rich in organic matter.

6. Abundant relict ground ice and glacigenic sediments exist at locations in the interior of the Laurentide Ice Sheet and are poised for climate-driven thaw and landscape transformation, similar to permafrost-preserved ice-marginal glaciated landscapes where dramatic transformations are already observed (e.g., Kokelj et al., 2017; Rudy et al., 2017). The characteristics of thaw-driven landscape change, however, are expected to differ from observations in ice-marginal positions due to differences in topography and climate affecting location and timing, geotechnical properties affecting stability and mobility of sediments, and geochemistry affecting solute and carbon release to surface water, ecosystems and the atmosphere.

These findings highlight the importance of geological legacy in determining the characteristics of permafrost and the potential responses of permafrost systems to disturbance and climate change. Continued research on permafrost and landscape response to warming at locations in the interior of the Laurentide Ice Sheet will help to understand and predict changes specific to these landscapes and how they affect ecology, climate, land use and infrastructure.

Code and data availability. Drill logs, visible ice content and core photos from the 2015 campaign are published (Gruber et al., 2018a). Data and code for reproducing the main figures, constructed using GG-plot in R, are available at https://doi.org/10.5281/zenodo.3628070

Author contributions. SG and RS wrote the manuscript together with SVK. RS conducted the initial study, performed or oversaw the laboratory analyses, and produced the scripts for plotting. SG produced the sections on ground ice, soil organic-carbon as well as framing and conclusions.

Competing interests. No competing interests are present.

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Appendix A: Sample locations

Table A1 details on borehole locations and sampling dates.

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Table A1. Sample location and timing details. Full ID codes have the prefix 'NGO-DD15-'.

ID	Terrain Type	Longitude WGS84	Latitude WGS84	Elev. m	Date 2015
2008	Eskers	-110.1851	64.6003	458	12 Jul
2028	Eskers	-110.1851	64.6003	458	19 Jul
2029	Eskers	-110.1846	64.6002	458	20 Jul
2026	Eskers	-110.3451	64.7246	437	19 Jul
1006	Organic	-110.2333	64.6037	443	12 Jul
1005	Organic	-110.2356	64.5999	440	10 Jul
2009	Till	-110.2169	64.6041	446	12 Jul
2033	Till	-110.2152	64.6055	458	22 Jul
1004	Till	-110.2381	64.5951	471	9 Jul
1007	Till	-110.2328	64.6037	442	12 Jul
2004	Till	-110.2363	64.5963	480	10 Jul
2005	Till	-110.2332	64.5966	472	11 Jul
2006	Till	-110.2307	64.5968	453	11 Jul
2007	Till	-110.2354	64.5985	459	11 Jul
1014	Till	-110.7354	64.6254	489	21 Jul
2018	Till	-110.4360	64.7136	461	16 Jul
1009	Valley	-110.4430	64.7015	432	14 Jul
1010	Valley	-110.4398	64.7027	426	14 Jul
2011	Valley	-110.4479	64.7023	432	13 Jul
2012	Valley	-110.4459	64.7021	433	13 Jul
2013	Valley	-110.4501	64.7028	440	14 Jul
2015	Valley	-110.4421	64.7035	425	14 Jul
2016	Valley	-110.4441	64.7045	431	14 Jul
2019	Valley	-110.4357	64.7021	428	16 Jul

Appendix B: Typical core

Figures B1, B2, and B3 show typical core.

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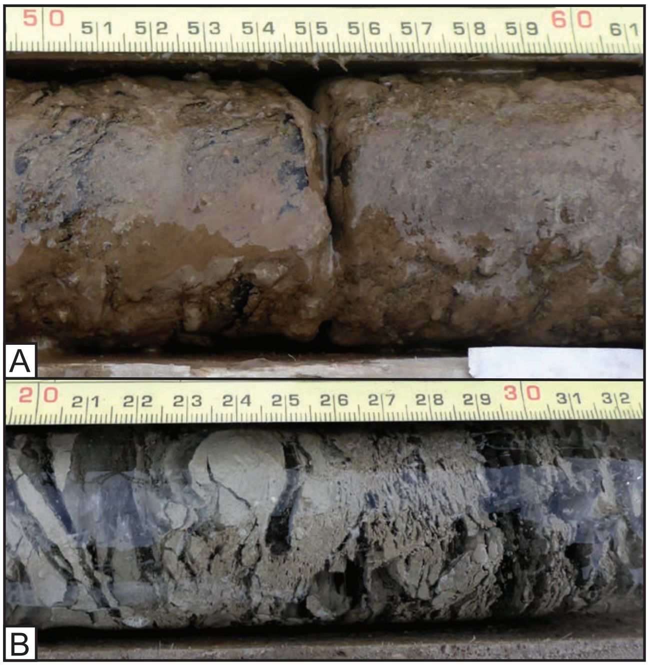

Figure B1. Drill core recovered from borehole NGO-DD15-1010 in the Valley. (A) shows core from 1.6 m depth with 71% excess ice and 1.3% organic matter. (B) is about 3.5 m depth with 77% excess ice and 1.5% organic matter. Scale bars are in cm.

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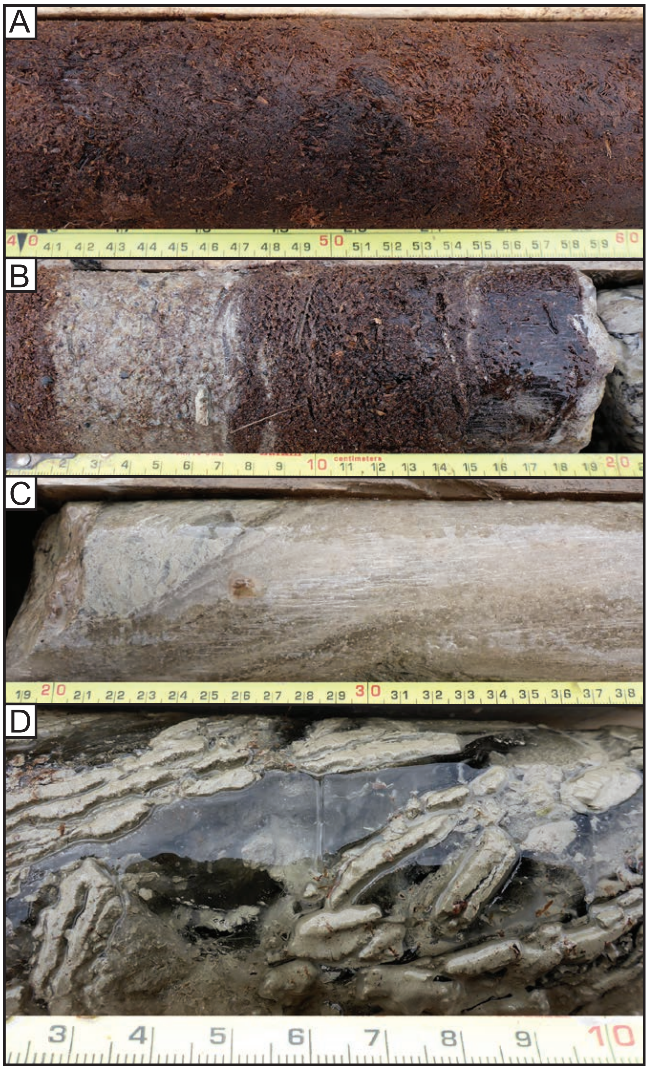

Figure B2. Drill core recovered from borehole NGO-DD15-1005 in organic terrain. (A) Compact frozen organics near 0.85 m without excess ice and 80% organic matter. (B) Alternating layers of organics and mineral soil near 1.6 m with 19% excess ice and 9.2% organic matter. (C) Nearly pure ice around 2.7 m, no analyses available. (D) Ice in mineral soil, 3.5 m deep with 57% excess ice and 1.6% organic matter. Scale bars are in cm.

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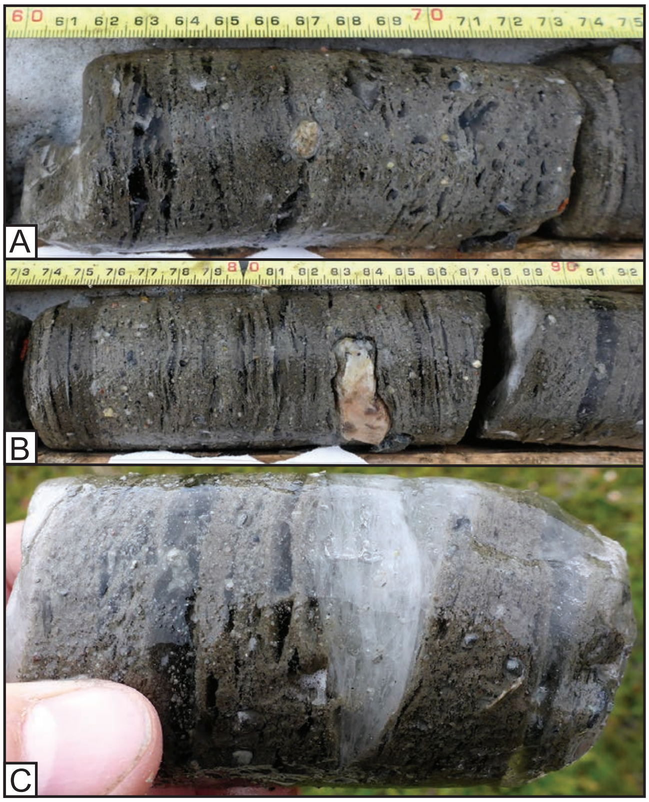

Figure B3. Drill core recovered from borehole NGO-DD15-2005 in hummocky till, near a hilltop. (A) Core near 3.8 m depth with 84% excess ice and 1% organic matter. (B) Core near 4.0 m depth with 71% excess ice and 0.6% organic matter. (C) Closeup of the right side of the core shown in (B). Scale bars are in cm.

Appendix C: Geomorphic evidence of post-glacial melt of ground ice

370 Figure C1 shows evidence of post-glacial ground-ice melt.

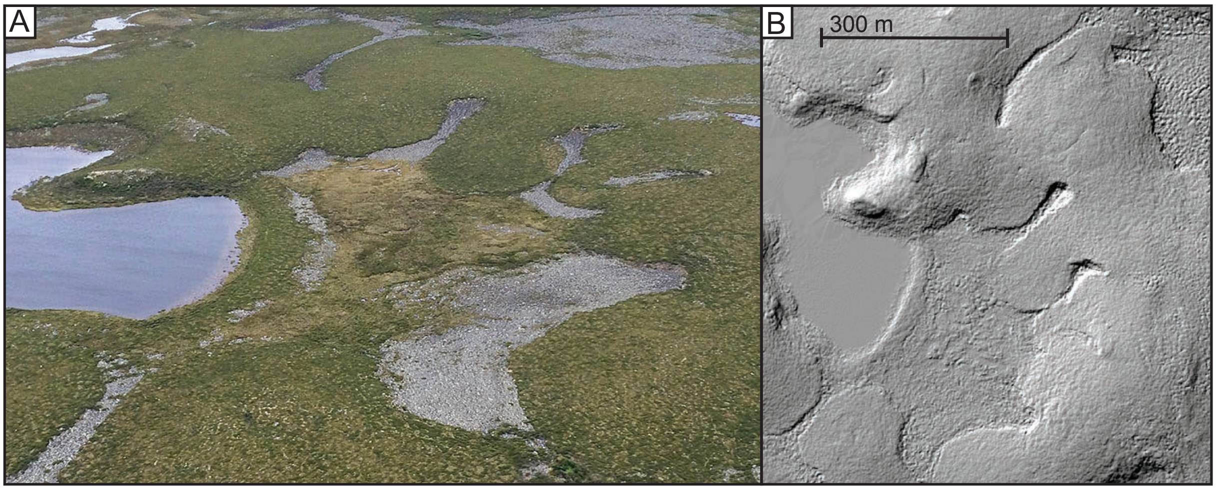

Figure C1. Terrain features indicative of post-glacial ground-ice melt (see also McWade et al., 2017) shown in oblique aerial photograph from July 13, 2015 (A) and hillshade image with 1 m resolution (B). Lower elevation areas expose many large boulders. The elevation difference between the concave features and the smooth upland tills is 5–10 m and hypothesized to derive largely from loss of ice in the ground. The centre of the area shown is 109.944° W, 64.615° N. The hillshade is based on a digital elevation model kindly provided by Dominion Diamond Mines.

Appendix D: Tabulated comparison with previous studies

Table D1 compares soil organic-carbon densities and Table D2 soluble cation concentrations between this and previous studies.

Table D1. Soil organic-carbon density (SOCd, $kg\,C\,m^{-3}$) per depth interval for three terrain types from the Lac de Gras study area compared with similar soils reported in a circumpolar compilation (Hugelius et al., 2014, Table 2). Tills are compared to Turbels (cryoturbated permafrost soils), Eskers with Orthels (mineral permafrost soils unaffected by cryoturbation) and Organics with Histels (organic permafrost soils). Circumpolar values below 1 m are for "Thin sediment". For Orthels, values in "Thick sediment" are more than ten times larger.

Depth	Histels	Organics	Turbels	Till	Orthels	Eskers
0–0.3 m	60.3±10.0	26.7	49.0±5.0	16.2	52.7±8.7	17.8
0–1 m	49.3±8.4	28.9	33.0±3.5	13.1	25.3±4.1	11.4
1–2 m	49.0±9.2	25.6	31.6±33.1	8.4	2.6±2.0	3.7
2–3 m	30.5±8.8	12.7	19.5±17.5	5.8	1.3±16.9	1.8

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Table D2. Concentration of soluble cations in active layer and permafrost in mineral soils compared with previous studies in northwestern Canada.

	Total soluble cations (meq/100 g dry soil)	
Terrain type	Active layer	Permafrost
Mackenzie Delta (Kokelj and Burn, 2005)		
Point-bar willow	2.06	3.83
Point-bar alder	1.54	2.15
Spruce-alder-bearberry	0.64	2.09
Spruce-feathermoss	0.49	1.24
Spruce-crowberry-lichen	0.38	1.62
Herschel Island (Kokelj et al., 2002)		
Undisturbed plateau	0.25–1.5	12–14
Undisturbed plateau	0.25–6	8–14
Undisturbed stable slope	<0.25	5
Disturbed AL detachment	2–10	12
Disturbed AL detachment	2–12	12
Lac de Gras area (this study), median (mean) values		
Till	0.09 (0.09)	0.20 (0.24)
Valley	0.14 (0.30)	0.29 (0.61)
Eskers	0.04 (0.06)	0.09 (0.15)

References

Alexander, E. B.: Bulk density equations for southern Alaska soils, Canadian Journal of Soil Science, 69, 177–180, https://doi.org/10.4141/cjss89-017, 1989.

Bockheim, J. G., Hinkel, K. M., and Nelson, F. E.: Predicting carbon storage in tundra soils of Arctic Alaska, Soil Science Society of America Journal, 67, 948, https://doi.org/10.2136/sssaj2003.0948, 2003.

Brown, J., Ferrians, O., Heginbottom, J., and Melnikov, E.: Circum-Arctic map of permafrost and ground-ice conditions, Tech. rep., Washington, D.C., https://doi.org/10.3133/cp45, 1997.

Burn, C. R.: Cryostratigraphy, paleogeography, and climate change during the early Holocene warm interval, western Arctic coast, Canada, Canadian Journal of Earth Sciences, 34, 912–925, https://doi.org/10.1139/e17-076, 1997.

Burn, C. R.: Herschel Island (Qikiqtaryuk), Yukon's Arctic Island, in: Landscapes and Landforms of Western Canada, edited by Slaymaker O., pp. 335–348, Springer, Cham, https://doi.org/10.1007/978-3-319-44595-3_24, 2017.

Cao, B., Brown, N., Quan, X., Stewart-Jones, E., and Gruber, S.: Site-level permafrost simulation in remote areas driven by atmospheric re-analyses: a case study from the Northwest Territories, in: Cold Regions Engineering 2019, vol. 5, pp. 534–543, American Society of Civil Engineers, Reston, VA, https://doi.org/10.1061/9780784482599.062, 2019a.

Cao, B., Quan, X., Brown, N., Stewart-Jones, E., and Gruber, S.: GlobSim (v1.0): Deriving meteorological time series for point locations from multiple global reanalyses, Geoscientific Model Development, https://doi.org/10.5194/gmd-2019-157, 2019b.

Cary, J. and Mayland, H.: Salt and water movement in unsaturated frozen soil, Soil Science Society of America Journal, 36, 549–555, 1972.

Cribari-Neto, F. and Zeileis, A.: Beta Regression in R, Journal of Statistical Software, 34, 1–24, https://doi.org/10.18637/jss.v034.i02, 2010.

CSSC: The Canadian System of Soil Classification, Research Branch, Agriculture Canada: Ottawa, Canada, 1998.

Dean, W. E.: Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods, SEPM Journal of Sedimentary Research, Vol. 44, 3247–3255, https://doi.org/10.1306/74D729D2-2B21-11D7-8648000102C1865D, 1974.

Dredge, L., Ward, B., and Kerr, D.: Glacial geology and implications for drift prospecting in the Lac de Gras, Winter Lake, and Aylmer Lake map areas, central Slave Province, in: Current Research 1994-C; Geological Survey of Canada., pp. 33–38, 1994.

Dredge, L. A., Kerr, D. E., and Wolfe, S. A.: Surficial materials and related ground ice conditions, Slave Province, N. W.T., Canada, Canadian Journal of Earth Sciences, 36, 1227–1238, 1999.

Dyke, A. S.: Late Quaternary vegetation history of northern North America based on pollen, macrofossil, and faunal remains, Géographie physique et Quaternaire, 59, 211–262, https://doi.org/10.7202/014755ar, 2005.

Dyke, A. S. and Savelle, J. M.: Major end moraines of Younger Dryas age on Wollaston Peninsula, Victoria Island, Canadian Arctic: implications for paleoclimate and for formation of hummocky moraine, Canadian Journal of Earth Sciences, 37, 601–619, https://doi.org/10.1139/e99-118, 2000.

Dyke, L. D.: Contaminant migration through the permafrost active layer, Mackenzie Delta area, Northwest Territories, Canada, Polar Record, 37, 215–228, https://doi.org/10.1017/S0032247400027248, https://www.cambridge.org/core/product/identifier/S0032247400027248/type/journal_article, 2001.

Environment Canada: National climate data and information archive, climate normals and averages, 2019.

Frey, K. E. and McClelland, J. W.: Impacts of permafrost degradation on arctic river biogeochemistry, Hydrological Processes, 23, 169–182, https://doi.org/10.1002/hyp.7196, 2009.

Geological Survey of Canada: Surficial geology, Lac de Gras, Northwest Territories, NTS 76-D, Tech. rep., Geological Survey of Canada, Ottawa, Ontario, Canada, https://doi.org/10.4095/295497, 2014.

Gruber, S., Brown, N., Stewart-Jones, E., Karunaratne, K., Riddick, J., Peart, C., Subedi, R., and Kokelj, S.: Drill logs, visible ice content and core photos from 2015 surficial drilling in the Canadian Shield tundra near Lac de Gras, Northwest Territories, Canada, v. 1.0 (2015-2015), Nordicana, D, https://doi.org/10.5885/45558XD-EBDE74B80CE146C6, 2018a.

Gruber, S., Brown, N., Stewart-Jones, E., Karunaratne, K., Riddick, J., Peart, C., Subedi, R., and Kokelj, S.: Air and ground temperature, air humidity and site characterization data from the Canadian Shield tundra near Lac de Gras, Northwest Territories, Canada, v. 1.0 (2015-2017), Nordicana, D, https://doi.org/10.5885/45561XD-2C7AB3DCF3D24AD8, 2018b.

Haiblen, A., Ward, B., Normandeau, P., Elliott, B., and Pierce, K.: Detailed field and LiDAR based surficial geology and geomorphology in the Lac de Gras area, Northwest Territories (parts of NTS 76C and 76D), Tech. rep., Northwest Territories Geological Survey, NWT Open Report 2017-016, 2018.

Heginbottom, J., Dubreuil, M., and Harker, P.: Permafrost - Canada, Tech. rep., Department of Energy, Mines and Resources Canada, Ottawa, 1995.

Hossain, M., Chen, W., and Zhang, Y.: Bulk density of mineral and organic soils in the Canada's arctic and sub-arctic, Information Processing in Agriculture, 2, 183–190, https://doi.org/10.1016/j.inpa.2015.09.001, 2015.

Hu, X., Holubec, I., Wonnacott, J., Lock, R., and Olive, R.: Geomorphological, geotechnical and geothermal conditions at Diavik Mines, in: 8th International Conference on Permafrost. Zurich, Switzerland., p. 18, 2003.

Hugelius, G., Kuhry, P., Tarnocai, C., and Virtanen, T.: Soil organic carbon pools in a periglacial landscape: a case study from the central Canadian Arctic, Permafrost and Periglacial Processes, 21, 16–29, https://doi.org/10.1002/ppp.677, 2010.

Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J. W., Schuur, E. A. G., Ping, C. L., Schirrmeister, L., Grosse, G., Michaelson, G. J., Koven, C. D., O'Donnell, J. A., Elberling, B., Mishra, U., Camill, P., Yu, Z., Palmtag, J., and Kuhry, P.: Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps, Biogeosciences, 11, 6573–6593, https://doi.org/10.5194/bg-11-6573-2014, 2014.

Janzen, H.: Soluble salts, Soil sampling and methods of analysis. Lewis Publishers, Boca Raton, FL, pp. 161–166, 1993.

Karunaratne, K. C.: A field examination of climate-permafrost relations in continuous and discontinuous permafrost of the Slave Geological Province, Ph.D. thesis, Carleton University, Ottawa, Canada, 2011.

Knight, P. G.: The basal ice layer of glaciers and ice sheets, Quaternary Science Reviews, 16, 975–993, https://doi.org/10.1016/S0277-3791(97)00033-4, 1997.

Kokelj, S. V. and Burn, C. R.: Ground ice and soluble cations in near-surface permafrost, Inuvik, Northwest Territories, Canada, Permafrost and Periglacial Processes, 14, 275–289, https://doi.org/10.1002/ppp.458, 2003.

Kokelj, S. V. and Burn, C. R.: Geochemistry of the active layer and near-surface permafrost, Mackenzie delta region, Northwest Territories, Canada, Canadian Journal of Earth Sciences, 42, 37–48, https://doi.org/10.1139/e04-089, 2005.

Kokelj, S. V. and Lewkowicz, A. G.: Salinization of permafrost terrain due to natural geomorphic disturbance, Fosheim Peninsula, Ellesmere Island, Arctic, 52, 372–385, https://doi.org/10.14430/arctic942, 1999.

Kokelj, S. V., Smith, C. A. S., and Burn, C. R.: Physical and chemical characteristics of the active layer and permafrost, Herschel Island, western Arctic Coast, Canada, Permafrost and Periglacial Processes, 13, 171–185, https://doi.org/10.1002/ppp.417, 2002.

Kokelj, S. V., Burn, C. R., and Tarnocai, C.: The structure and dynamics of earth hummocks in the subarctic forest near Inuvik, Northwest Territories, Canada, Arctic, Antarctic, and Alpine Research, 39, 99–109, https://doi.org/10.1657/1523-0430(2007)39[99:TSADOE]2.0.CO;2, 2007.

Kokelj, S. V., Lantz, T. C., Kanigan, J., Smith, S., and Coutts, R.: Origin and polycyclic behaviour of tundra thaw slumps, Mackenzie Delta region, Northwest Territories, Canada, Permafrost and Periglacial Processes, 20, 173–184, https://doi.org/10.1002/ppp, 2009.

Kokelj, S. V., Lacelle, D., Lantz, T. C., Tunnicliffe, J., Malone, L., Clark, I. D., and Chin, K. S.: Thawing of massive ground ice in mega slumps drives increases in stream sediment and solute flux across a range of watershed scales, Journal of Geophysical Research: Earth Surface, 118, 681–692, https://doi.org/10.1002/jgrf.20063, 2013.

Kokelj, S. V., Lantz, T. C., Tunnicliffe, J., Segal, R., and Lacelle, D.: Climate-driven thaw of permafrost preserved glacial landscapes, northwestern Canada, Geology, 45, 371–374, https://doi.org/10.1130/G38626.1, https://pubs.geoscienceworld.org/geology/article/45/4/371-374/195473, 2017.

Koven, C. D., Lawrence, D. M., and Riley, W. J.: Permafrost carbon-climate feedback is sensitive to deep soil carbon decomposability but not deep soil nitrogen dynamics, Proceedings of the National Academy of Sciences, 112, 3752–3757, https://doi.org/10.1073/pnas.1415123112, 2015.

Lacelle, D., Fontaine, M., Forest, A. P., and Kokelj, S.: High-resolution stable water isotopes as tracers of thaw unconformities in permafrost: A case study from western Arctic Canada, Chemical Geology, 368, 85–96, https://doi.org/10.1016/j.chemgeo.2014.01.005, 2014.

Lacelle, D., Fontaine, M., Pellerin, A., Kokelj, S. V., and Clark, I. D.: Legacy of Holocene landscape changes on soil biogeochemistry: a perspective from paleo-active layers in Northwestern Canada, Journal of Geophysical Research: Biogeosciences, 124, 2662–2679, https://doi.org/10.1029/2018JG004916, 2019.

Lantz, T. C., Kokelj, S. V., Gergel, S. E., and Henry, G. H. R.: Relative impacts of disturbance and temperature: persistent changes in microenvironment and vegetation in retrogressive thaw slumps, Global Change Biology, 15, 1664–1675, https://doi.org/10.1111/j.1365-2486.2009.01917.x, 2009.

Leibman, M. O. and Streletskaya, I. D.: Land-slide induced changes in the chemical composition of active layer soils and surface-water run-off, Yamal Peninsula, Russia., in: Proceedings of the International symposium on physics, chemistry, and ecology of seasonally frozen soils, Fairbanks, Alaska., edited by Iskandar, I., Wright, E., Radke, J., Sharratt, B., Groenevelt, P., and Hinzman., L., p. 120–126, CRREL Special Report 97-10, Co, 1997.

Littlefair, C. A., Tank, S. E., and Kokelj, S. V.: Retrogressive thaw slumps temper dissolved organic carbon delivery to streams of the Peel Plateau, NWT, Canada, Biogeosciences, 14, 5487–5505, https://doi.org/10.5194/bg-14-5487-2017, 2017.

Mackay, J. R.: Active layer changes (1968 to 1993) following the forest-tundra fire near Inuvik, N.W.T., Canada., Arctic and Alpine Research, 27, 323, 1995.

Mackay, J. R.: Thermally induced movements in ice-wedge polygons, western arctic coast: a long-term study, Géographie physique et Quaternaire, 54, 41, https://doi.org/10.7202/004846ar, 2000.

Malone, L., Lacelle, D., Kokelj, S., and Clark, I. D.: Impacts of hillslope thaw slumps on the geochemistry of permafrost catchments (Stony Creek watershed, NWT, Canada), Chemical Geology, 356, 38–49, https://doi.org/10.1016/j.chemgeo.2013.07.010, 2013.

McWade, T. L., Morse, P. D., Gruber, S., and Wolfe, S. A.: Identification, classification, and distribution of retrogressive creeping slumps, Lac de Gras region, Northwest Territories, Tech. rep., Geological Survey of Canada, Ottawa, https://doi.org/10.4095/304245, 2017.

https://doi.org/10.5194/tc-2020-33
Preprint. Discussion started: 10 February 2020

The Cryosphere Discussions

Melton, J. R., Verseghy, D. L., Sospedra-Alfonso, R., and Gruber, S.: Improving permafrost physics in the coupled Canadian Land Surface Scheme (v.3.6.2) and Canadian Terrestrial Ecosystem Model (v.2.1) (CLASS-CTEM), Geoscientific Model Development, 12, 4443–4467, https://doi.org/10.5194/gmd-12-4443-2019, 2019.

Morse, P. D. and Burn, C. R.: Field observations of syngenetic ice wedge polygons, outer Mackenzie Delta, western Arctic coast, Canada, Journal of Geophysical Research: Earth Surface, 118, 1320–1332, https://doi.org/10.1002/jgrf.20086, 2013.

Murton, J., Whiteman, C., Waller, R., Pollard, W., Clark, I., and Dallimore, S.: Basal ice facies and supraglacial melt-out till of the Laurentide Ice Sheet, Tuktoyaktuk Coastlands, western Arctic Canada, Quaternary Science Reviews, 24, 681–708, https://doi.org/10.1016/j.quascirev.2004.06.008, 2005.

O'Neill, H. B., Wolfe, S. A., and Duchesne, C.: New ground ice maps for Canada using a paleogeographic modelling approach, The Cryosphere, 13, 753–773, https://doi.org/10.5194/tc-13-753-2019, 2019.

Pewe, T. L. and Sellmann, P. V.: Geochemistry of permafrost and Quaternary stratigraphy, in: Permafrost: North American Contribution to the Second International Conference, Yakutsk, U.S.S.R. National Academy of Science Press, Washington, DC, p. 166–170, 1973.

Phillips, M. R., Burn, C. R., Wolfe, S. A., Morse, P. D., Gaanderse, A. J., O'Neill, H. B., Shugar, D., and Gruber, S.: Improving water content description of ice-rich permafrost soils, in: Proceedings of the GeoQuebec 2015 Conference, September 20-23, Quebec, Canada, 2015.

Prowse, N. D.: Morphology and Sedimentology of Eskers in the Lac de Gras Area, Northwest Territories, Canada, Ph.D. thesis, Carleton University, 2017.

Qiu, G., Wenkun, S., Cuilan, H., and Kaiwen, Z.: Direction of ion migration during cooling and freeing processes, in: Proceedings, Fifth International Conference on Permafrost, 2-5 August, Trondheim, Norway., pp. 442–447, Tapir Publishers, Trondheim, Norway:, 1988.

Rampton, V. N.: Quaternary geology of the Tuktoyaktuk Coastlands, Northwest Territories, Tech. rep., Geological Survey of Canada, Ottawa, https://doi.org/10.4095/126937, 1988.

Rampton, V. N. and Sharpe, D. R.: Detailed surficial mapping in selected areas of the southern Slave Province , Northwest Territories (Open File 7562), Tech. rep., Geological Survey of Canada, https://doi.org/10.4095/293879, 2014.

Rudy, A. C. A., Lamoureux, S. F., Kokelj, S. V., Smith, I. R., and England, J. H.: Accelerating thermokarst transforms ice-cored terrain triggering a downstream cascade to the ocean, Geophysical Research Letters, 44, 11–80, 2017.

Schuur, E. A. G., Bockheim, J., Canadell, J. G., Euskirchen, E., Field, C. B., Goryachkin, S. V., Hagemann, S., Kuhry, P., Lafleur, P. M., Lee, H., Mazhitova, G., Nelson, F. E., Rinke, A., Romanovsky, V. E., Shiklomanov, N., Tarnocai, C., Venevsky, S., Vogel, J. G., and Zimov, S. a.: Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle, BioScience, 58, 701, https://doi.org/10.1641/B580807, 2008.

Sheldrick, B. H.: Analytical methods manual 1984., Land Resource Research Institute, Agriculture Canada, Ottawa, Canada. LRRI Contribution No. 84–30., 1984.

St-Onge, D. A. and McMartin, I.: La Moraine du Lac Bluenose (Territoires du Nord-Ouest), une moraine à noyau de glace de glacier, Géographie physique et Quaternaire, 53, 287, https://doi.org/10.7202/005696ar, 1999.

Subedi, R.: Depth profiles of geochemistry and organic carbon from permafrost and active layer soils in tundra landscapes near Lac de Gras, Northwest Territories, Canada. Master's thesis, Carleton University, 2016.

Tank, S. E., Striegl, R. G., McClelland, J. W., and Kokelj, S. V.: Multi-decadal increases in dissolved organic carbon and alkalinity flux from the Mackenzie drainage basin to the Arctic Ocean, Environmental Research Letters, 11, 054 015, https://doi.org/10.1088/1748-9326/11/5/054015, 2016.

https://doi.org/10.5194/tc-2020-33
Preprint. Discussion started: 10 February 2020

The Cryosphere Discussions

Tarnocai, C., Canadell, J. G., Schuur, E. a. G., Kuhry, P., Mazhitova, G., and Zimov, S.: Soil organic carbon pools in the northern circumpolar permafrost region, Global Biogeochemical Cycles, 23, n/a–n/a, https://doi.org/10.1029/2008GB003327, 2009.

Turetsky, M. R., Abbott, B. W., Jones, M. C., Walter Anthony, K., Olefeldt, D., Schuur, E. A. G., Koven, C., McGuire, A. D., Grosse, G., Kuhry, P., Hugelius, G., Lawrence, D. M., Gibson, C., and Sannel, A. B. K.: Permafrost collapse is accelerating carbon release, Nature, 569, 32–34, https://doi.org/10.1038/d41586-019-01313-4, http://www.nature.com/articles/d41586-019-01313-4, 2019.

Wiken, E., Gauthier, D., Marshall, I., Lawton, K., and Hirvonen, H.: A perspective on Canada's ecosystems:, Canadian Council on Ecological Areas, Occasional Paper, 14, 1996.

Wilkinson, L., Harris, J., Kjarsgaard, B., Mcclenaghan, B., and Kerr, D.: Influence of till thickness and texture on till geochemistry in the Lac de Gras area, Northwest Territories, with applications for regional kimberlite exploration., Current Research. Geological Survey of Canada. C9, 2001.