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Permafrost occurrence in subarctic forests of the Great Slave region, Northwest Territories, Canada

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ABSTRACT
Permafrost in the Great Slave region, Northwest Territories is absent beneath bedrock outcrops, but occurs beneath peatlands. A three-year (2010 to 2013) investigation determined that permafrost also occurs in unconsolidated fine-grained sediments beneath forested sites. Annual mean shallow permafrost temperatures range from -1.4 to 0°C, with spatial variation primarily reflecting organic-layer and soil moisture conditions. Discontinuous permafrost is extensive within Great Slave Lowland, in direct relation to the distribution of forested areas in unconsolidated fine-grained sediments, but is sporadic northward within Great Slave Upland where bedrock outcrops are more extensive.

RÉSUMÉ
Dans la région du Grand lac des Esclaves, Territoires du Nord-Ouest, le pergélisol est absent sous les affleurements rocheux mais se retrouve sous les tourbières. Une étude de trois ans (2010 à 2013) a établi que le pergélisol se retrouve aussi dans les sédiments fins non-consolidés des sites forestiers. Les températures moyennes annuelles du pergélisol près de la surface varient de -1,4°C à 0°C, la variation spatiale étant principalement due à la présence de matière organique et à l'humidité du sol. Les basses terres du Grand lac des Esclaves se retrouvent dans la zone de pergélisol discontinue étendue, directement reliée aux régions forestières se situant sur des sédiments fins non-consolidés. Toutefois, plus au nord, dans la région des hautes terres du Grand lac des Esclaves, là où les affleurements rocheux sont plus fréquents, le pergélisol est de type discontinu et sporadique.

1 INTRODUCTION

The Great Slave region around Yellowknife, NT (Fig. 1) is within the extensive discontinuous permafrost zone (Heginbottom et al. 1995). Permafrost occurs beneath open black spruce peatlands but not beneath bedrock outcrops or within unconsolidated sediments (Brown 1973; Karunaratne et al. 2008). However, peatlands account for a small area (<3%) (Olthof et al. 2013), implying that permafrost occurs in isolated patches. A mosaic of other forest types exists (Olthof et al. 2013), including black spruce (Picea mariana) dominated, mixed deciduous and coniferous forests, with scattered stands of white birch (Betula papyrifera) above ice-rich ground (Wolfe et al. 2011; Wolfe et al. 2014). Consequently, Zhang et al. (2014) modelled permafrost in these forest settings, but permafrost has not been confirmed.

The purpose of this paper is to characterize the terrain conditions and thermal characteristics of permafrost below treeline in unconsolidated sediments in order to delineate the extent of permafrost within the Great Slave region around Yellowknife. The area is distinguished by two prominent ecoregions, the Great Slave Lowland (GSL) where fine-grained sediments are widespread, and the bedrock-dominated Great Slave Upland (GSU) (ECG 2008) (Fig. 1). We hypothesize that permafrost occurs in peatlands and fine-grained unconsolidated sediments in association with coniferous and deciduous forests, due to buffer layer conditions that promote permafrost. Moreover, discontinuous permafrost is extensive at GSL, in relation to the distribution of peatlands and fine-grained sediments, but is sporadic at GSU where bedrock outcrops extensively. To test these hypotheses, and describe buffer-layer conditions controlling spatial variation of ground, we analyzed air, near-surface, and shallow ground temperatures, late-winter snow depths, and ecological site descriptions gathered at a variety of sites (Fig. 1) through an extensive three-year field investigation (2010-2013). The thermal investigations on permafrost in conjunction with terrain mapping allows us to estimate regional permafrost distribution.

2 STUDY AREA

2.1 Regional Settting

The study area (Fig. 1), located in the southern portion of the Slave Geological Province of the Canadian Shield, is bordered to the south by the North Arm of Great Slave Lake and to the north by the Taiga Shield Low Subarctic ecoregion (ECG 2008). Following deglaciation, Glacial Lake McConnell inundated the GSL from about 13 000 until about 9 500 cal BP, with Great Slave Lake forming subsequently as water levels declined (Lemmen et al. 1994; Smith 1994; Dyke et al. 2003). Consequently, the

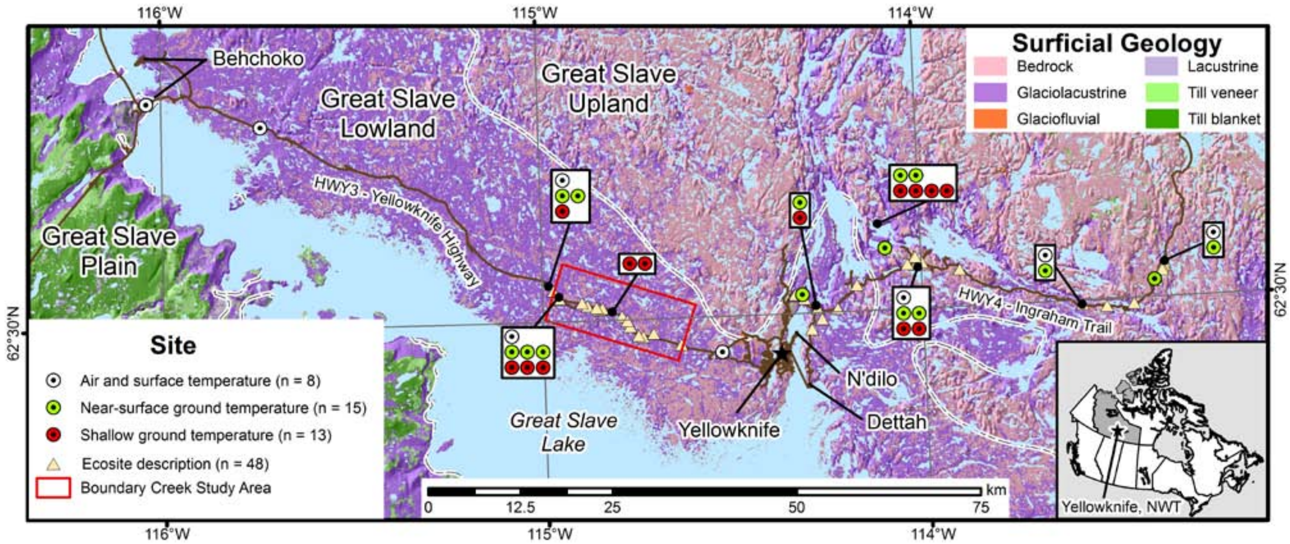

Figure 1. Study sites along a 170 m east-west transect of Great Slave Lowland and Upland High Boreal ecoregions (ECG 2008), along the north shore of Great Slave Lake, on predominantly fine-grained sediments or bedrock (surficial geology data are from Stevens et al. 2012a, 2012b), with the location Boundary Creek Study Area indicated.

majority of unconsolidated sediments across the GSL are clays and silts deposited into these former water bodies, with infilling of valleys as bedrock outcrops were washed by the receeding lake level (Fig. 1) (Stevens et al. 2012a). Permafrost aggradation followed terrestrial emergence, and continues today as GSL recedes. Numerous water bodies occupy bedrock depressions and faults within this low relief, poorly-drained landscape. The distribution of bedrock, unconsolidated sediments and variation in drainage produce a mosaic of vegetated environments in GSL in which forest fires are rare. Vegetation is mainly black-spruce forest with a heath understory on hummocky ground, barren bedrock outcrop with sparse jackpine (Pinus banksiana), and mixed black spruce-deciduous forest (Wolfe et al. 2011), which constitute, respectively, about 37%, 25%, and 25% of the land area. In contrast, white birch forest with herbaceous understory and open forest peatland comprise only about 1% and 2% of land cover, respectively. The remaining land area consists of fens.

In contrast to the GSL, the GSU has higher bedrock occurrence (Fig. 1), relief, drainage, fire frequency, and burn extent (Stevens et al. 2012a). Less extensive overburden consists mainly of thin discontinuous till veneers and scattered outwash deposits, with thin, discontinuous deposits of wave-washed tills, glaciolacustrine sediments, and glaciofluvial materials occurring in rock fractures and between outcrops as a consequence of lake inundation (Kerr and Wilson 2000).

Permafrost occurs at peatlands beneath a 0.30 to 0.70 m active layer with annual mean ground temperatures of -2°C or higher (Brown 1973; Karunaratne et al. 2008), and a thickness of up to 50 m (Brown 1973). Medium to low visible near-surface ground ice content (<10 to 20%) has been attributed to wedge ice (Heginbottom et al. 1995), but visible polygonal terrain is rare. However, ice-rich lithalsas, formed by ice segregation in fine-grained sediments during the late Holocene, are numerous (>1700) within the GSL, represent thaw-sensitive terrain, and are identified by white birch forest and mixed forest vegetation (Wolfe et al. 2014).

Yellowknife experiences a continental subarctic climate (1981-2010), characterized by cold winters (-25.6°C January mean), warm summers (17.0°C July mean), and a mean annual air temperature of -4.1°C (Environment Canada http://climate.weather.gc.ca). With an annual mean air temperature trend of 0.6°C a^{-1} (1981-2010), a 0.5°C increase in mean annual air temperature over the 1971-2000 climate normal is consistent with a pan-Arctic warming trend beginning AD 1966 (IPCC 2013). About 40% of the annual 291 mm precipitation is snowfall, and the maximum mean monthly snow depth (0.39 m) is reached in February. Regional air temperatures are consistent in space and time; variation of daily mean temperature at field sites and at YZF were not significantly different (α=0.05; p=0.99), and all cross-correlations between temperature time series were greatest with zero lag ($\geq$0.954; p$\leq$0.001). Thus, air temperature data from field sites with a three year record were pooled to represent field conditions, as YZF suffers from numerous short-term data gaps after 17 January 2013 when the meteorological station was relocated.

2.2 Study Sites

In summer, 2010, Wolfe et al. (2011) described ecological conditions at 48 ecosites throughout the study region (Fig. 1), and four forest types represent the main elements of the spectrum of forest vegetation: (i) black spruce forest (BS); (ii) white birch forest (WB); (iii) open black spruce peatland (PL); and (iv) bedrock outcrop with jackpine scrub (BR). In order to investigate differences in the ground thermal regimes amongst BS, WB, PL, and BR (air temperature only) ecotopes, air, near-surface, and shallow ground temperatures were monitored at 8, 15, and 13 sites, respectively, over three years along a 170 km transect of the GSL and the GSU (Fig. 1). These data enable characterization of the influences of ecotope biophysical characteristics on relations between air temperature and near-surface ground temperatures. Most sites are visibly undisturbed, but several show signs of thermokarst with ponded water accompanied by trees that are either leaning in at the margin or submerged and dead (Near-surface: WB2, WB4, PL7; Shallow: WB_GT2, WB_GT3, WB_GT5). Visibly disturbed sites include those that have burned (Near-surface: BS4, PL6; Shallow: BS_GT4), and others that have burned and been cut for wood (PL5; Shallow: PL_GT2, PL_GT3). Three shallow temperature sites near lakeshores are likely influenced thermally by the adjacent water body (BS_GT4, WB_GT5, PL_GT3).

3 METHODS

3.1 Biophysical Characteristics of Ecotopes

Ecosite data reported by Wolfe et al. (2011) were used to define the variation of vegetation cover, late summer thaw depth, soil moisture, and organic-layer thickness within the dominant BS, WB, and PL ecotopes (Fig. 1). Detailed methods for ecosite descriptions given in Wolfe et al. (2011) are summarized herein. A LAI-2000 Plant Canopy Analyzer (LI-COR) was used to determine leaf-area-index (LAI) at a standard 1-m elevation to assess the structural density of the vegetation canopy in summer. Early September thaw depth was measured by probing with a graduated steel rod to the depth of refusal. Soil gravimetric moisture content (mass of the water per total sample mass) was determined from a bulk sample extracted from a depth of 0.30 m in a soil pit at each ecosite. Organic-layer thickness was measured down to the mineral soil horizon. End-of-winter snow depth (average of five measurements) was measured with a graduated probe at ecological description and temperature monitoring sites in March 2013, and snow density was measured (average of 3 measurements) at 18 selected sites in March 2010. Differences in ecological conditions between BS, WB, and PL groups were assessed with a Kruskal-Wallis ANOVA, followed by post-hoc comparisons of all pairs of groups ($\alpha=0.05$) (Siegel and Castellan 1988).

3.2 Thermal Characteristics of Ecotopes

Using Onset Computing data loggers (HOBO U23-04 and U12-008-04), thermistors (TMC6-HA) and radiation shields (RS3), temperatures were recorded every 2 h in the air (1 m height), at the ground surface (0.02 m), and 0.50 and 1.00 m below the ground surface. With this equipment, true annual mean values, calculated for the hydrologic year, are known within 0.21°C±0.015°C. Local characteristics at each site were assessed by comparing annual mean temperatures calculated for the air (T_a), ground surface (T_s) and 1-m depth (T_g). T_g was compared between sites, though thermistors were sometimes at the base of the active layer rather than the top of permafrost.

Shallow ground temperature measurements were made in water-jet-drilled boreholes preserved with 0.025-m diameter PVC casing filled with silicone oil. Factory calibrated thermistor (Type 4403, Yellow Springs Inc.) strings, installed to depths of up to 11.5 m, were connected to eight channel data loggers (XR-420-T8, RBR Ltd.; <0.001°C resolution) programmed to record temperatures hourly. With such apparatus, true temperatures at each thermistor are known to ±0.1°C, but actual temperature change with time is resolved at 0.001°C increments. Temperatures at four of the sites were determined manually during visits at approximately 4-month intervals with a digital multimeter (Model 77-IV, Fluke Corporation), which yields measurements within 0.01°C agreement with data loggers (Burgess and Allen 1991). Thermal effects from drilling dissipated after 6 months, and data recorded during that initial period were ignored. Shallow ground temperature characteristics were assessed by comparing temperature envelopes, annual mean temperature at the top of permafrost (TTOP), and annual mean ground temperature (AMGT) calculated at the depth of zero annual amplitude (DZAA) following Williams and Smith (1989).

4 RESULTS

4.1 Buffer-layer Characteristics

LAI values (Fig. 2a), which relate to the amount of summer shading by the canopy, were high in WB, lower in BS, and lowest in the PL. LAI median values ranged from 2.18 in WB to 0.09 in PL. LAI of WB was significantly different than BS and PL ($p<=0.015$), but BS and PL were statistically similar ($p=0.490$), likely due, in part, to the low number of PL samples ($n=2$).

Median snow cover values (Fig. 2b) were significantly different between ecotopes ($p<0.001$), increasing from 0.39 m in WB, to 0.43 m in BS, up to 0.47 m in PL. However, the snow cover ranges were similar. Snow densities determined at 10 sites (3 BS, 3 WB, 4 PL) in late March, 2010 (Wolfe et al. 2011), ranged from 106 to 225 kg m^{-3} about a median 143 kg m^{-3}. Within-site variation of snow density was about 30 kg m^{-3}, but variation between ecotopes was not significant ($p=0.176$) as all of the sites are forested and relatively sheltered from the wind and air temperatures are regionally similar.

Surface organic-layer thicknesses (Fig. 2c), which ranged from 0.04 m in WB to 3.00 m in PL, were similar between WB and BS (0.20 m medians; $p=0.688$). Peatland (PL), by the very nature of being defined by an organic layer thickness of 0.40 m or more, was significantly different than WB and BS (0.51 m median; $p<0.001$).

Variation of gravimetric moisture content within the active-layer (0.30 m depth) was substantial among the ecotopes (Fig. 2d), but was significantly different only between WB and PL ($p=0.002$) where medians were 15% and 85%, respectively. WB forests are commonly found on elevated mineral-soil terrain formed by lithalsa growth (Wolfe et al. 2014), and consequently have much improved drainage and lower saturation potential compared to peatlands. Moisture content in BS was homogeneous with the other ecotopes ($p \geq 0.144$) due to high variation (113 S.D.), compared to WB and PL sites

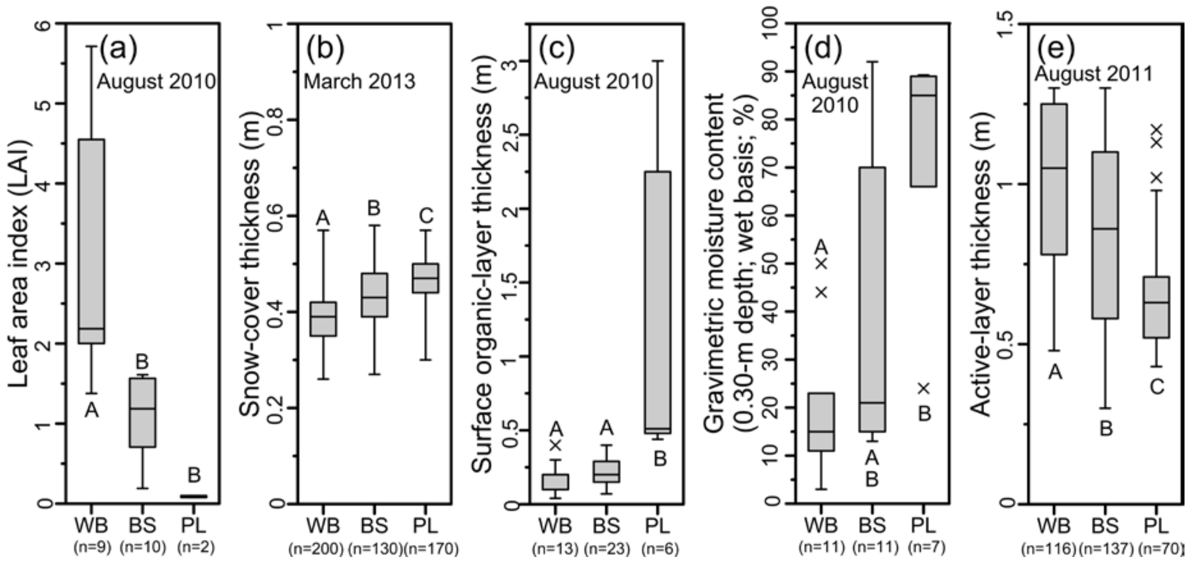

Figure 2. Box-and-whisker plots of each ecotope for distribution of: (a) leaf area index (LAI); (b) snow-cover thickness; (c) surface organic-layer thickness; (d) wet-basis gravimetric moisture content of the active layer (0.30-m depth); and (e) active-layer thickness determined in birch forest (WB), spruce forest (BS), and peatland (PL) ecotopes. Uppercase letters indicate whether the ecotopes are significantly different as determined by Kruskal-Wallis ANOVA, followed by post-hoc comparisons of all pairs of ecotopes, where similar letters indicate no significant difference (α=0.05). Data for (a) and (c) to (e) are from Wolfe et al. (2011).

(10 and 9 S.D., respectively). The high variation at BS is likely due to hummocky microtopography, where organic rich inter-hummock troughs typically have high soil moisture contents in contrast with hummock tops comprised of well-drained mineral soils (Kokelj et al. 2007).

Active-layer thickness (Fig. 2e) varied between ecotopes ($p<0.001$). Thicknesses were greatest at WB (1.05 m median), least at PL (0.63 m median), and intermediate at BS (0.86 m median). The highly variable thicknesses at BS are related to bowl-shaped permafrost table associated with the hummocky microtopography. The magnitude of summer thawing was also inversely related to moisture contents and surface organic-layer thickness, but proportional to shading (LAI), indicating the relative importance of soil versus canopy conditions on the ground thermal regime.

4.2 Near-surface Temperatures

The near-surface ground thermal regime varied substantially among ecotopes (Fig. 3). At sites with shallow thaw depths (Fig. 3a), summer surface (0.05 m) temperatures were relatively similar, but varied between sites in winter. Ground temperatures at 0.5 and 1.0 m depths contrasted substantially, but exhibited greater variation in winter than in summer. Generally, the xeric peatland, PL2, had higher surface temperatures throughout both the thawing and freezing seasons compared to birch forest, WB1, and the spruce forest, BS4, but maximum and minimum 0.5- and 1.0-m ground temperatures were lower at the peatland than at the other ecotopes. The active-layer freeze-back duration at PL2 was 61 days in 2011-2012 and 52 days the following year. Surface temperatures were lowest at WB1 in winter, but temperatures at 0.5- and 1.0-m depths were up to about 8.5°C higher than PL2, despite a freeze-back duration about half of that at PL2. In comparison with PL2 and BS4 sites, the relatively strong amplitude dampening of the surface temperature wave at the 1-m depth beneath WB1 indicates a low thermal diffusivity typical of a dry clay soil (Fig. 3a) (Williams and Smith 1989, Table 4.1).

At sites where the active layer was greater than 1.0 m (Fig. 3b), summer surface temperatures at the white birch,

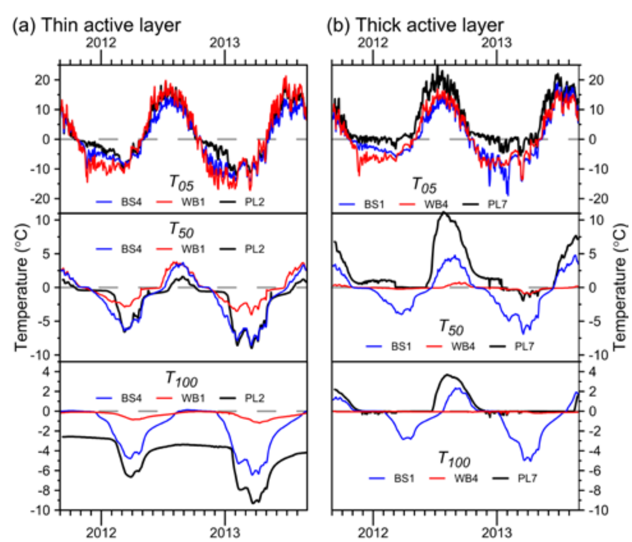

Figure 3. Variation of surface (T_{05}), 0.5-m (T_{50}), and 1-m (T_{100}) ground temperatures at representative black spruce

forest (BS), white birch forest (WB), and peatland (PL) sites (2011-2013) where (a) depth to permafrost is ≤1 m, and (b) depth to permafrost is >1 m.

WB4, and black spruce, BS1, forest sites were similar to their counterpart ecotope sites with shallow active layers (Fig. 3a). In winter the temperatures were on average higher, likely due to a larger latent heat component associated with freezeback of a thicker active layer. At the degrading peatland, PL7 (Fig. 3b), surface temperature at peak summer season was about 5°C higher than at PL2 (Fig. 3a). PL7 was also notable for having the highest 0.5- and 1.0-m ground temperatures, and the 100 cm depth temperatures do not indicate active-layer freezeback (Fig. 3b).

Summary indices of air (T_a), surface (T_s), and 1-m ground (T_g) temperatures presented in Figure 4, characterize the influence of buffer-layer conditions on air-to-ground temperature relations among ecotopes. T_s, which ranged above and below 0°C among sites and between years, varied with T_a. The 2011-2012 values were higher than in 2010-2011 and 2012-2013. T_g followed a similar, but muted pattern, with interannual variation generally decreasing with T_g nearer to 0°C. Overall, the maximum ranges of T_s and T_g at all field sites were -2.3 to 6.4°C and -5.3 to 0.7°C, respectively. However, much of this variation is attributed to the thermal contrast between a degrading, warm, hydric peatland (PL7) and an undisturbed, cold, xeric peatland (PL2). T_g were below 0°C at all sites, except at PL7, and maximum 1-m ground temperatures indicated permafrost at that depth at over 50% of the sites and in all ecotopes. At sites with permafrost at 1-m depth, the ranges of T_s and T_g reduce to -1.6 to 2.4°C and -5.3 to 0.1°C, respectively.

4.3 Shallow Permafrost Conditions

Shallow ground temperature envelopes are shown in Figure 5, and ground temperature indices are summarized in Table 1. Permafrost was present at all sites examined, with AMGT ranging from -1.43°C at an undisturbed old growth spruce forest site (BS_GT1) to -0.02°C at a burned and cut peatland (PL_GT2). Ground temperatures were likely also influenced by the proximity of the boreholes to lakes (BS_GT3, WB_GT5, PL_GT3). The shallow DZAA (≤7 m) and small amplitude of thermal variations in permafrost indicate considerable damping of the annual surface temperature wave. This can be attributed to low thermal diffusivities resulting from latent heat effects in the active layer and in warm permafrost comprised of fine-grained, ice-rich soils with high unfrozen moisture contents. The DZAA is generally deeper at the coldest sites with thinner active layers and shallower at the warmest sites with thick active layers. The DZAA is just below the permafrost table at some WB and PL sites where a talik zone may be developing.

5 DISCUSSION

5.1 Ecotope Iinfluences on the Ground Thermal Regime

Variation in ground temperatures for sites from a range of ecotopes is due primarily to soil type and moisture conditions in the active-layer and permafrost. Canopy conditions (LAI) do not appear to have a strong influence on the ground thermal regime: there is a positive relation between LAI and active-layer thickness (Fig. 3). Although snow depth is significantly different among the ecotopes, the median and climate-normal month-end snow values are close to 0.40 m. Since this is the optimal insulating thickness of snow (Zhang 2005), variation between ecotopes does not likely contribute significantly to thermal differences between sites. Whereas snow depth and air temperature are regionally consistent (Fig. 2), mean ground temperatures are dominantly related to soil conditions that influence latent-heat effects during freezing. These factors include soil material, soil porosity, active-layer thickness, and soil moisture in the active layer and top of permafrost. In the subarctic forest environment, high latent-heat content of soils can prolong freezeback duration, significantly dampening surface temperature waves (Fig. 3), resulting in high AMGT (Fig. 5, Table 1) (Kokelj et al. 2014). These results contrast with continuous permafrost regions where ground temperature is dominantly driven by snow depth that varies according to vegetation and topography, with soil moisture conditions being of secondary importance (Morse et al. 2012; Palmer et al. 2012; Kokelj et al. 2014).

5.2 Distribution of Discontinuous Permafrost

Results presented here indicate that permafrost is associated with all forest types found on fine-grained sediments in the Great Slave region. Thus, to a large extent, the distribution of fine-grained sediment in this region may be considered to locally define the distribution

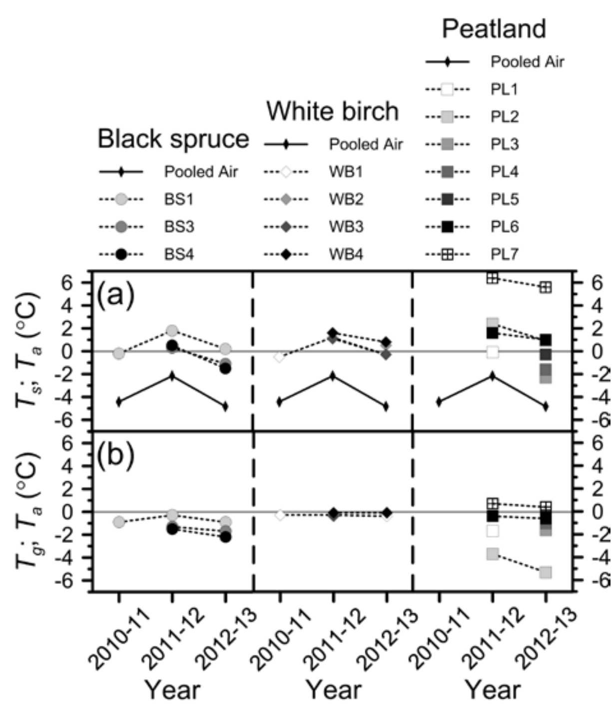

Figure 4. Summary of temperature indices at sites in black spruce (BS) and white birch (WB) forests and in peatlands (PL): (a) pooled air temperature (T_a), annual mean surface temperature (T_s), and (b) annual mean 1-m ground temperature (T_g).

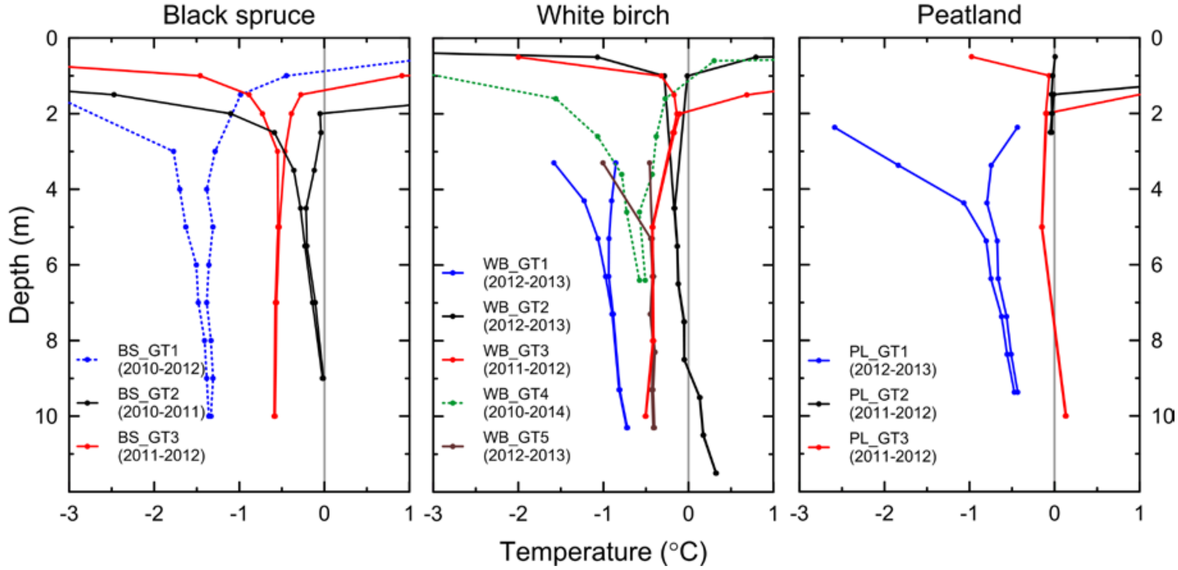

Figure 5. Ground temperature envelopes for black spruce forest, white birch forest, and peatland sites with permafrost, at undisturbed, visibly degrading, and lakeshore locations. Annual mean values derived from continuous data are indicated by solid lines and intermittent manual readings are indicated by dashed lines. Data were plotted subject to their availability, hence the range of years shown. Note that data for BS_GT2 are excluded until March 2011 when thermal equilibrium was re-established following installation.

of permafrost. This is supported by modelling results (Riseborough et al. 2013; Zhang et al. 2014) that indicate nearly all undisturbed terrain underlain by silt or clay contains frozen sediment throughout the profiles.

Fine-grained sediments are the dominant material type within the GSL, suggesting that approximately two-thirds of the land area is underlain by permafrost. The land cover map in Figure 1 shows the Boundary Creek Study area (BCSA) (Fig. 1), which is representative of terrain conditions in the GSL. The terrain cover suggests 65% of the area is underlain by permafrost in association with black-spruce forest (37%), black-spruce-dominated mixed forest (25%), white birch forest (1%), and open black spruce peatland (2%) ecotopes. Consequently, if only peatlands were considered, permafrost extent at GSL would classify as isolated patches (0–10%), but extensive discontinuous permafrost (50 – 90%) is more likely, in agreement with Heginbottom et al. (1995) and as modeled by Zhang et al. (2014). Conversely, GSU located to the north and east, has much lower unconsolidated sediment distribution, and greater bedrock outcropping than GSL (Fig. 1) raising the possibility that permafrost is sporadic discontinuous (10–50%). That extent would be similar to the permafrost extent south of Great Slave Lake in the Taiga Plains Mid-boreal ecoregion, where the sporadic permafrost distribution is associated solely with peatlands (40%) (ECG 2009).

The distribution of permafrost within GSL will ultimately decrease with continued climate warming. It is likely that patches of ecosystem-driven permafrost at undisturbed peatlands will persist simply because of a thick organic layer (Shur and Jorgensen 2007, Jorgenson et al. 2010) (Fig. 4b). However, an increase in moisture content of organic soils is sufficient to inhibit active layer freezeback and initiation thermal degradation (Kokelj et al 2014). The majority of permafrost occurs in fine-grained ice-rich sedi-

Table 1. Depth to permafrost, annual mean temperature at the top of permafrost (TTOP), depth of zero annual amplitude (DZAA), and the annual mean ground temperature (AMGT) at the DZAA for shallow ground temperature sites in black spruce forest (BS), white birch forest (WB), and peatland (PL) ecotopes.

Site ID	TTOP (°C)	DZAA (m)	AMGT (°C)	Year
Black spruce forest				
BS_GT1	-2.91	7.0	-1.43	2011[a]
BS_GT2	-0.62	4.3	-0.24	2010-2011[b]
BS_GT3	-0.44	2.9	-0.51	2011-2012
BS_GT4	~-2.71	> 4.0	-	2011[a]
White birch forest				
WB_GT1	-0.43[c]	5.6	-0.97	2012-2013
WB_GT2		3.3	-0.14	2012-2013
WB_GT3	-0.11	2.0	-0.12	2011-2012
WB_GT4		-	-	2011[a]
WB_GT5		4.6	-0.52	2012-2013
WB_GT6	-	-	-	2011[d]
Open black spruce peatland				
PL_GT1	-	6.0	-0.71	2012-2013
PL_GT2	-0.02	1.5	-0.02	2011-2012
PL_GT3	-0.09	2.0	-0.09	2011-2012

[a]Determined from intermittent manual readings made in spring and fall from September 2010 to September 2012.
[b]Incomplete year: 1 March 2011 to 29 August 2011.
[c]From adjacent near-surface ground temperature site WB4.
[d]One manual reading from September 2011.

ments beneath forests, where high latent-heat effects ameliorate active-layer thickening (Shur et al. 2005). Permafrost of this nature may be considered to posses considerable "thermal inertia" that prevents rapid thermal degradation (James et al. 2013), but does not eliminate it. Ecosystem protection is enhanced by greater organic layer thickness, thus permafrost beneath white birch forest may be ultimately more susceptible to climate warming than black spruce forest. However, mature forests with thick organic mats and ice-rich permafrost are particularly susceptible to mechanical disturbance or fire.

Our observations and interpretations are consistent with predicted reduction rates of permafrost occurrence in this region by Zhang et al. (2014), who attribute a slowed reduction of permafrost to protection by organic-layer thickness. However, we suggest that a thermal buffer at forest sites may be due more to protection by latent-heat effects. Zhang et al. (2014) indicate that predicted permafrost extent in the Great Slave region (Great Slave Lowlands and Uplands combined) would reduce from 52% in the 2000s to 2.5% by the 2090s, with permafrost occurring only within peatlands. Whereas this future extent is likely, the inclusion of latent-heat effects related to ice-rich, fine-grained unconsolidated sediments may lower predicted rates of permafrost degradation beneath forested sites.

6 CONCLUSIONS

The following conclusions are drawn from this investigation:

1. The overall variations of T_s and T_g (-2.3 to 6.4°C and -5.3 to 0.7°C, respectively) range across 0°C, and demonstrate substantial temperature variation under a common climate. AMGT beneath peatlands and forested sites are all below 0°C, ranging from -1.4°C at a black spruce forest site, to near 0°C at a disturbed peatland.
2. Snow conditions are generally similar between different ecosites. Spatial variation of ground temperatures primarily reflects organic-layer and active-layer moisture conditions.
3. Latent-heat effects in the active layer and near-surface permafrost significantly dampen the surface temperature wave, as indicated by long freezeback, narrow ground temperatures envelopes, shallow DZAAs (7 m or less), and warm AMGTs. Saturation of organic soils is sufficient to inhibit freezeback and initiate permafrost degradation.
4. Extensive discontinuous permafrost in the GSL occurs in direct relation to the distribution of forested ecotopes that develop on unconsolidated fine-grained sediments, and sporadic discontinuous permafrost may occur northward within the GSU due to significantly greater surfical exposure of bedrock.
5. Predicted rates of permafrost degradation beneath forested sites may lower with inclusion of latent heat effects originating within shallow, ice-rich permafrost in fine-grained unconsolidated sediments.

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