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Evaluation of threshold freezing conditions for winter road construction over discontinuous permafrost peatlands, subarctic Canada

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ABSTRACT

Winter roads provide an important transportation service in northern regions. The Tibbitt to Contwoyto Winter Road (TCWR), traversing subarctic Canada, is the busiest heavy-haul road in the world with as many as 10,900 truckloads per season. In addition to lake-ice thickness, trafficability on the TCWR depends upon adequate freezeback of overland portages, which are primarily peatlands underlain by discontinuous permafrost. We investigate threshold requirements for the initiation of winter road operations in this region and assess the use of a recommended 305 °C-day air-freezing index (FDD_{305a}) value as an operational predictor of ground freezing at 30 cm depth, the desired depth to allow winter road construction to commence. Snow compaction and flooding were found to enhance freezeback of portages with early winter overland flow having a similar effect. The majority of winter road portages were not adequately frozen to a depth of 30 cm by FDD_{305a}. Our results indicate that for drained and wet peatlands in this discontinuous permafrost environment, an FDD_a threshold of 1100 °C-days is more appropriate than the 305 °C-day threshold. However, TCWR winter road operators presently plan the construction of the winter road by a calendar date rather than by evaluation of the air-freezing index. This practice results in a conservative approach to the start of the construction season, close to 1100 °C-days with a higher percentage of sites frozen to 30 cm depth than would be if the 305 °C-day air-freezing index was used as a guideline. In addition, the use of low-pressure vehicles for snow compaction during the start of the construction season is an effective adaptation practice to accelerate freezing penetration.

1. Introduction

Winter roads service remote communities, mines, and resource development sites in northern North America and Eurasia. In Canada, the public road system in the Northwest Territories nearly doubles in winter to 1400 km (Prowse et al., 2009). Winter road traffic is supported by a frozen surface constructed using a combination of snow compaction and flooding on lake-ice sections, or compacted and flooded snow on overland "portage" sections. The frozen surface provides a stable base for portage sections in areas with soft or wet soils, such as peat, allowing transport over terrain that is otherwise unsuitable when thawed (MacFarlane, 1969; Shoop, 1995). In addition, the snow or snow-ice cover at portages protects the underlying vegetation and soil. This helps to reduce the environmental impacts of winter roads such as active-layer deepening and soil moisture increase (Adam and Hernandez, 1977; Bader and Guimond, 2004), and to preserve the surface-organic layer protecting permafrost (Morse and Wolfe, 2016). This is especially relevant to the circumpolar permafrost region where almost 20% of the terrain is peatland (Tarnocai et al., 2009).

Winter roads are an inexpensive approach to transport goods and services to northern communities and industry and have been constructed in Canada since the 1940s (Proskin et al., 2011). Though typically more cost-effective to build and maintain than all-season roads, they have a short operational duration. The duration depends mainly on regional climate (air temperatures and snowfall), natural surface conditions, and road use requirements (Proskin et al., 2011). With predicted climate change, operational duration is expected to decrease with increasing seasonal air temperatures and precipitation, causing socio-economic impacts to industry and remote communities through curtailed winter-road access and increased air transport (Prowse et al., 2009).

Portage construction is initiated when there is sufficient snow cover to minimize environmental impact and ground freezing to support heavy equipment. Until the 1970s, these minimal requirements for construction in North America were mainly based on experience rather than defined standards. More recent studies consider 15 cm of snow and 30 cm of frozen soil to be acceptable criteria (Schindler, 1988; Bradwell et al., 2004). Whereas snow depth is relatively easily determined, the

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depth of soil freezing is commonly estimated, rather than directly measured, from air temperatures according to a threshold value of the air-freezing degree-day (FDD_a) index, which is the cumulative sum of mean daily air temperatures below 0 °C during the freezing season (Smith et al., 2016). Ground freezing will be insufficient if the FDD_a threshold value is too low, whereas winter road construction is delayed if the value is too high. The optimal FDD_a ensures adequate freezing while maximizing winter road operation.

The start of winter road construction in Canada is often based on Adam's (1978) recommendation that 305[1] FDD_a provides the necessary thickness of frozen ground to yield a firm base in most soils. However, this recommendation does not explain this threshold with respect to variation of soil type, water content, or snow cover. Subsequently, Proskin et al. (2011) tested the 305 FDD_a threshold against a range of soil conditions, although the material properties are not detailed. They estimated that, by 305 FDD_a, the freezing penetration depths vary from 30 cm in dry peat to 100 cm in moist sand. In addition to the 305 FDD_a, Proskin et al. (2011) recommend snow depths of 5 cm to initiate pre-packing and 10 cm for preparation of the road surface, based on empirical evidence. To determine conditions that would minimize environmental impacts of winter road construction and optimize operational duration over tundra, the U.S. Department of Natural Resources (DNR) conducted a field experiment on the continuous permafrost terrain of North Slope, Alaska (Bader and Guimond, 2004; Bader, 2005). Based on the results, DNR recommends construction initiate once the soil temperature at 30 cm depth reaches −5 °C and the snow depth reaches 15 cm in wet sedge terrain and 23 cm in tussock terrain. Requiring measured ground temperatures, which are operationally more difficult to obtain than air temperatures, the DNR guidelines are the most stringent in North America. However, the DNR does not link ground and air temperature conditions, which makes it uncertain how to apply these criteria. Even greater uncertainty exists for peatlands in discontinuous permafrost where ground thermal conditions in relation to winter road construction have never been examined.

This study evaluates the freezing conditions at a range of peatland settings on the Tibbitt to Contwoyto Winter Road (TCWR) in subarctic Canada north of Yellowknife, Northwest Territories, and compares them to the existing standards for timing to initiate winter road construction (Fig. 1). We measured air, surface, and near-surface ground temperatures at drained, wet, and periodically flooded peatlands from 2012 to 2017 to determine the ground thermal regime from the beginning of the winter through to the end of winter road construction, both on and off the right-of-way (ROW). This paper focuses on the timing of freezing front penetration at 30 cm depth in relation to the cumulative air-freezing index threshold of 305 FDD_a, snow compaction, and artificial and natural (overflow) flooding.

2. Study area

The study area is within the Slave Geological Province of the Canadian Precambrian Shield, which hosts numerous gold and diamond deposits (Kerr et al., 1997; Norwicki et al., 2004). The region was last glaciated by the Laurentide Ice Sheet about 10,000 years ago (Dyke et al., 2003) and the ice-scoured, southwest-sloping landscape is dominated by gently undulating to moderately rugged exposed bedrock. Surficial sediments, comprised of bouldery till veneers and blankets, occur mainly in topographic depressions. Organic deposits (up to at least 130 cm) are common but individually limited in extent, with fens and bogs occurring in low-lying areas (Ecosystem Classification Group, 2008). The landscape, dotted by thousands of lakes, is traversed by two main rivers, the Yellowknife and the Cameron, that drain into Great Slave Lake. The dominant forest vegetation is black spruce (Picea mariana) on poorly drained terrain, paper birch (*Betula papyrifera*) on better drained ground, and sparsely distributed jack pine (*Pinus banksiana*) on bedrock outcrops (Ecosystem Classification Group, 2008). Ground cover is commonly dwarf birch (*Betula pumila*) and various heath species, and most wetlands are composed of *Sphagnum* spp. and sedges (*Carex* spp.). Permafrost in the region is extensive but discontinuous (Heginbottom et al., 1995), occurring beneath peatlands and black spruce forest (Morse and Wolfe, 2016).

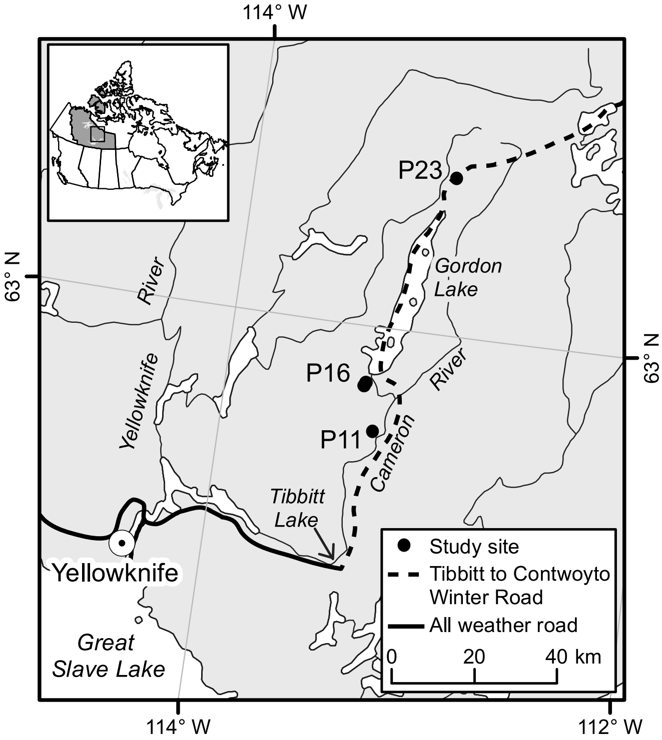

Fig. 1. Map showing the location of the study portages on the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

The subarctic continental climate of the region is characterized by conditions at Yellowknife airport (the closest weather station), where the climate normal mean annual air temperature is −4.3 °C (1981–2010, Environment Canada, 2018). The freezing season typically lasts from mid-October to mid-May, and the lowest mean monthly temperature is in January (−25.6 °C). Mean total annual precipitation is 289 mm, with 41% falling as snow. Although the study locations are situated within the same climatic system as Yellowknife, annual air temperatures decrease slightly with latitude (Sladen, 2017).

The TCWR is the longest perennial winter road in Canada (Prowse et al., 2009), and is the primary access to this resource-rich region. Built mainly on lake ice (87%), and with 64 portages, the current 400 km road serves the region's diamond mines at Lac de Gras (Ekati and Diavik), Snap Lake (closed in 2015), and Gahcho Kué. The TCWR is the busiest heavy-haul winter road in the world (Mullan et al., 2016), with the number of northbound truckloads per year ranging from 3500 to 10,900 for a total weight hauled ranging from 120,000 to 330,000 short tons ("short ton" ≈ 907 kg) (Joint Venture, 2016). The variation in loads is a function of either meeting targeted numbers, or the duration of the operating season, which ranged from 33 to 80 days between 2000 and 2014 (Joint Venture, 2016). In addition to mine-related traffic, the road is used by exploration and outfitting companies to supply camps, by responsible authorities to access contaminated sites for remediation, and by residents and tourists to access the land.

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[1] Adam (1978) recommends an air-freezing index of 306 °C-days. An FDD_a of 305 °C-days is used in this paper for consistency with Proskin et al. (2011).

Table 1

Coordinates, stratigraphy, peat moisture content, active-layer depth, and water table depth based on 2012 probing transects and drilling on and off ROW at the study portages.

ROW location	Lat (°)	Long (°)	Depth (cm)	Material	Peat moisture content (%)	Active-layer depth (cm)	Water table depth (cm)
P11 On	62.77	−113.27	0–20 20–88 88–110	Road aggregate Peat Mineral soil	218[a]	66–102	18
P11 Off			0–75 75–130	Peat Mineral soil	NA	90– > 125[b]	8
P16S On	62.87	−113.34	0–20 20–140	Road aggregate Peat	698	64–88	NA
P16S Off			0–130	Peat	544	43–63	NA
P16N On	62.88	−113.33	0–80 80–120	Peat Mineral soil	682	67–91	0
P16N Off			0–120	Peat	477	76–122	NA
P23 On	63.34	−113.03	0–112	Peat	400	57–63	20
P23 Off			0–130	Peat	610	46–61	90

NA = not observed.

[a] Moisture value is for peat with trace mineral soil (< 10%).

[b] Active-layer depth is greater than the maximum thaw probe length (125 cm).

2.1. Study sites

In autumn 2012, we established several peatland study sites at four locations on three TCWR portages to determine the ground thermal regime on and off ROW (Fig. 1, Table 1). Together, the sites on these portages create a 120-km north-south transect along the observed climatic gradient (Sladen, 2017). The sites, located in fens or raised bogs that are common wetland types found in the subarctic Canadian Shield (Ecosystem Classification Group, 2008), represent environments with different moisture conditions and thermal regimes.

The southernmost sites are on Portage 11 (P11) at kilometre 32 of the TCWR. The portage follows a soil-filled, fen-dominated valley constrained by bedrock uplands. Off ROW, water up to 95 cm deep flows over an underlying soil stratigraphy comprised of approximately 75 cm of sphagnum-covered peat above fine sand. On ROW, sandy gravel road aggregate overlies peat, which in turn overlies silty sand with ice lenses up to 2-mm thick below the permafrost table. The water table was encountered at 18 cm depth. The on-ROW surface is hummocky with water ponded in shallow depressions. The active-layer thickness, as determined from probing the frost table in September 2012, ranged from 66 to 102 cm on ROW, and from 90 cm to > 125 cm in the fen off ROW. This site has a troublesome history of water overflowing onto the ROW during the operating season, which negatively affects road safety. Consequently, the TCWR operators constructed a 1-m thick blast rock embankment over this section of the road in March 2013. The site was also affected by a wildfire in July 2014.

The second group of sites is located at kilometre 46 on the southern portion of Portage 16 (P16S) on a well-drained bog that is recovering from a 1998 wildfire. The stratigraphy consists of peat to at least 140 cm depth, on and off ROW, with ice crystals visible below the frost table. On ROW, the peat is capped by a 20 cm thick layer of sand and gravel aggregate. The active-layer thickness ranges from 64 to 88 cm on ROW, and 43–63 cm off ROW. The water table was not encountered during drilling.

The third group of sites is one kilometre north of P16S on Portage 16 (P16N). This location is downstream of two watercourses that converge at the ROW where water flowing in the channel is up to 15 cm deep. Off ROW, the ground is slightly raised and better drained. The stratigraphy at the ROW consists of 80 cm of peat overlying 20 cm of silty sand, overlying clayey silt, with 10% visible ice below the frost table to 120 cm depth. Off ROW, the stratigraphy consists of peat to 120 cm depth. On ROW, the water table is at or above the surface; the frost table is shallowest (67–71 cm) at the drier edges and deepest (91 cm) where the water depth is at its maximum. Off ROW, the active-layer thickness ranges from 76 to 122 cm.

The northernmost sites are north of Gordon Lake on Portage 23 (P23) at kilometre 58. Here, the soil stratigraphy consists of peat over bedrock. On ROW, the peat thickness ranges from 110 to 120 cm. Off ROW, the peat is 105 cm thick in a local depression with flowing water and > 130 cm thick beneath a drained, raised bog. The active-layer thickness ranges from 57 to 63 cm on ROW, and 46–61 cm off ROW. This portage has a history of water overflowing onto and along the road during winter road construction and operation.

P16S represents the drained study location where the peat on and off ROW is well-drained compared to the three other study locations. P16N is the wet study location, where the ROW has flowing water on it. P11 and P23 were selected based on their history of water flowing onto the ROW during the operating season. Flowing water is present at P11, P16N, and P23.

3. Methods

3.1. Instrumentation

We measured air, surface, and near-surface ground temperatures at each location to determine the thermal regimes. Dual channel data loggers with internal and external temperature sensors (Onset HOBO U23-004) recorded air temperature inside a radiation shield at approximately 1.5 m above the ground surface, and ground surface temperatures at a nominal depth of 2–5 cm. Temperature accuracy ranged from ± 0.38 °C at −20 °C to ± 0.2 °C at 0 °C, and resolution ranged from 0.05 °C to 0.02 °C, respectively. Single channel data loggers with an internal sensor (Onset HOBO U22–001) recorded additional surface temperatures. Temperature accuracy for these loggers was ± 0.21 °C over 0°–50 °C and the resolution was 0.02 °C at 25 °C. We placed sensors at 15, 30, 60, and 120 cm (or 100 cm if 120 cm depth could not be achieved) and recorded active-layer and top-of-permafrost temperatures on and off the ROW with four-channel loggers (Onset HOBO U12–008). The temperature accuracy for this system ranged from ± 0.59 °C at −20 °C to ± 0.25 °C at 0 °C and the resolution was 0.03 °C at 20 °C. All loggers recorded temperatures during the study period at intervals ranging from 1 to 6 h, from which daily mean values were calculated.

We used time-lapse photography to record the winter road construction activities, overflow events, and snowfall events and thickness. Reconyx PC800 Hyperfire Professional cameras were programmed to record an image every hour during daylight periods. We applied the time-lapse imagery in combination with the ground temperatures to identify the influence of the winter road construction and overflow on the ground thermal regime.

Table 2
Variation in annual (Sep.–Aug.), early freezing season (Oct.–Dec.), and total freezing season (Oct.–Apr.) air temperatures during the 1981–2010 climate normal period and the 2012–2017 study period at Yellowknife airport meteorological station (Environment Canada, 2018).

Statistic	Mean air temperature (°C)					
	1981–2010			2012–2017		
	Sep.–Apr.	Oct.–Dec.	Oct.–Apr.	Sep.–Apr.	Oct.–Dec.	Oct.–Apr.
Mean	−4.2	−12.3	−15.4	−3.8	−12.4	−15.1
SD	1.4	2.7	2.1	1.3	2.3	2.0
Minimum	−6.4	−17.6	−18.4	−5.0	−15.1	−17.5
Maximum	−0.9	−7.3	−10.5	−2.2	−9.6	−13.2

SD = standard deviation.

3.2. Analysis

We used daily mean air temperatures to determine the first day with sub-zero conditions (FS_{a0}), the start of the freezing season (FS_a), FDD_a, and annual, monthly, and seasonal mean temperatures and indices. FS_{a0} denotes the first day that daily mean air temperature fell below 0 °C in the autumn, whereas the start of the air-freezing season (FS_a) was determined as the first day in autumn when daily mean air temperature fell below 0 °C and remained so until the end of the freezing season. We defined the start of the ground freezing season (FS_s) similarly using the daily mean surface temperature. FDD_a for one winter according to air temperature, T_a, in °C is (Lunardini, 1981; Klene et al., 2001):

$$FDD_a = \int_0^{\theta_a} (T_F - T_a)dt \approx \sum_0^{\theta_a} \overline{T}_a \tag{1}$$

where T_F is the temperature of the freezing point (0 °C); θ_a is the duration of the freezing season in days, and $\overline{T}_a$ is the mean daily air temperature. By convention, FDD_a is positive. In order to evaluate threshold values for winter road construction, we compare the date on which FDD_a reaches 305 °C-days (FDD_{305a}) (see Adam, 1978; Proskin et al., 2011) to the thermal state of the ground at 30 cm depth (T_{30}) where frozen conditions are desirable (Proskin et al., 2011). We assessed differences in FDD_a timing for freezing front penetration to 30 cm depth between sites with one-way ANOVA and Tukey-Kramer post-hoc comparison of all pairs of groups ($\alpha = 0.5$) (McDonald, 2019).

Annual mean values are based on the hydrological year starting September 1st. As early winter air temperatures are important for ground freezing and the timing of winter road construction, we calculated mean temperatures for early winter (October to December) as well as the entire freezing season (October to April). The ground temperatures at 15, 30, 60, and 100 or 120 cm depths are used to evaluate thermal conditions during active-layer freezeback as well as the influence of winter road construction on the ground thermal regime. Thermistors at 120 cm depth represent the temperature at the top of permafrost (TTOP). We used temperature data from the 30 cm depth to evaluate the thermal state of the ground at the start-of-construction guideline of 305 °C-days.

Due to the high latent heat capacity of water, soils may remain near 0 °C for a prolonged period while freezing; this effect is called the zero curtain and its length is related to moisture content (Outcalt et al., 1990). This is important for winter road construction on peatlands with high moisture contents because it delays freezing front penetration. In these soils, ground temperatures remain near 0 °C until all the water has frozen and then the temperature starts to decrease rapidly. We consider the freezing front to pass a particular depth when daily mean ground temperature at that depth falls below −0.5 °C and remains so for the freezing season. The duration of active-layer freezeback is the time between the start of FS_s and when the temperatures at 120 cm, which fluctuate minimally over the season, start to decrease. Winter road construction includes snow compaction to eliminate the insulating properties of the snow layer and enhance ground freezing. Water added to the compacted snow layer during flooding freezes at the inter-grain contacts, increasing the overall strength and hardness of the snow-ice road surface (Proskin et al., 2011). This allows for heavier vehicles and higher traffic volumes, and likely increases the thermal conductivity of the snow-ice layer. To assess the effect of snow compaction and both natural and artificial flooding on the ground thermal regime, we calculated the temperature difference between readings at 30 cm depth taken at 6-h intervals (dT_{30}). A positive dT_{30} represents an increase in temperature, whereas a negative dT_{30} represents a decrease. We compared temperature differences from November to January at the drained location (P16S) and the wet location (P16N) to examine the effects of drainage on the thermal regimes in relation to snow compaction and flooding. We examined temperature differences observed at P23 for the thermal effects of natural overflow.

4. Results

4.1. Freezing season air temperatures

Freezing season air temperatures drive ground freezing. At Yellowknife airport, variation in annual and freezing season mean temperatures over the study period is similar to variation over the 1981–2010 normal period (Table 2), indicating that air temperatures observed during the study period are typical of longer-term values. All locations demonstrate similar air temperature patterns. Freezing season mean air temperatures are similar in 2012–13 and 2013–14, and are the lowest of the study period (−18.7 and −19.1 °C, respectively), though the early winter (October to December) mean temperature is slightly lower in 2012–13 (Table 3). The highest freezing season mean temperature (−14.7 °C) is in 2015–16, 4.4 °C higher than in 2013–14. These differences in winter air temperatures are well-reflected in the variations in FDD_a, which averaged 3607 °C-days during the study period. Monthly mean air temperatures (MMAT) show the greatest interannual variability in November (SD = 4.9 °C), December (SD = 5.0 °C), and January (SD = 4.0), which are critical months for winter road freezeback conditions, whereas MMATs for other months are more consistent. Air temperature variation over the 1981–2010 normal period exhibits a similar pattern (Environment Canada, 2018).

4.2. The timing of FS_a, FS_s, and FDD_{305a}

Although 0 °C air temperatures occasionally occur between the end of September and mid-October, the onset of the air and ground freezing seasons is between mid-October and mid-November (Fig. 2). In any given year, the difference between the onset of freezing at Yellowknife and the most northerly portage (P23) varies from 1 to 10 days, with the exception of 36 days in 2016–17. Annual freezing at the ground surface varies among sites at each study location by up to 23 days. Typically, the ground surface freezes before the onset of the air-freezing season (FS_a) by up to 22 days, or shortly thereafter by 1–5 days.

On average, FDD_{305a} is reached by mid- to late-November and, as expected, FDD_{305a} is reached later further south although the difference is typically only a few days (Fig. 2). In general, FDD_{305a} at Yellowknife occurs 1–3 days after P11 and 3–7 days after P23. The exception is in 2016–17 when a short episode of above freezing air temperatures in early November delays the start of the FS_a and FDD_{305a} at Yellowknife and P11 to early-December. Despite inter-annual differences in early freezing season (Oct.-Dec.) air temperatures between 2013–14 and 2015–16 (Table 3), FDD_{305a} for those years are reached within two calendar days. In contrast, the extreme mean November air temperatures correspond to a FDD_{305a} that is a week earlier in 2012–13, and two weeks later in 2016–17 at Yellowknife and P11.

Table 3

Summary of freezing season air temperatures at P11 for the study period.

Period	FS_a start[a]	Mean air temperature (°C)[b]										FDD_a[f]
		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Oct.–Dec.[c]	Oct.–Apr.[d]	Year[e]	(°C-day)
2012–13	21-Oct	−2.7	−19.3	−28.1	−30.4	−20.5	−19.8	−10.3	−16.7	−18.7	−6.3	4000
2013–14	31-Oct	0.1	−15.5	−32.1	−26.3	−28.0	−22.5	−9.5	−15.8	−19.1	NA	4110
2014–15	01-Nov	−0.8	−18.0	−23.1	−27.4	−28.2	−18.0	−5.3	−13.9	−17.1	−5.1	3657
2015–16	18-Oct	−2.4	−11.0	−18.9	−20.9	−24.6	−16.5	−8.7	−10.7	−14.7	−3.2	3156
2016–17	12-Nov	−2.6	−7.7	−24.8	−21.9	−22.2	−20.2	−7.2	−11.7	−15.2	−3.4	3113
Mean[g]	29-Oct	−1.7	−14.3	−25.4	−25.4	−24.7	−19.4	−8.2	−13.8	−17.0	−4.5	3607
± 1 SD[g]		1.2	4.9	5.0	4.0	3.4	2.3	2.0	2.6	2.0	1.5	463

Note: All study locations showed similar air temperature patterns. NA = incomplete year of data.

[a] FS_a start is the start of the freezing season based on the first day that daily mean air temperatures were ≤0 °C and remained so until the spring.

[b] Monthly, seasonal, and annual mean air temperatures were calculated using daily mean air temperatures for the period indicated.

[c] Early freezing season (October – December).

[d] Entire freezing season (October – April).

[e] Annual mean air temperature for year starting September 1st.

[f] FDD_a = air-freezing degree-days.

[g] Study period means and standard deviations (SD) were determined from monthly, seasonal, and annual averages.

4.3. Ground thermal regime

All of the portage sites investigated are underlain by permafrost, except for the off ROW fens at P11 and P23, as determined from active-layer probing, drilling, and ground temperatures at 120 cm depth (Fig. 3). Due to emplacement of the embankment at P11 in March 2013, only minimum ground temperatures are available there for the on ROW site. In general, ground temperatures are colder on ROW, with annual minimum temperatures throughout the ground profile 8–21 °C lower than for sites off ROW. The exception is the "on ROW" site at P23 (which is located on the edge of the ROW) where ground temperatures are only 2–12 °C lower than off ROW ground temperatures. The lower temperatures on ROW are reflected in the lower annual mean temperature at the top of permafrost. The three-year average TTOP is consistently lower on the ROW compared with off ROW by 0.9–2.5 °C. The temperature envelopes and TTOPs indicate that winter road activities are effective at lowering active-layer temperatures and at maintaining permafrost (Fig. 3).

4.3.1. Thermal state at 30 cm depth and FDD_{305a}

Frozen ground at 30 cm depth is a common criterion for winter road construction (Proskin et al., 2011). At all of the study sites, the ground starts to freeze in October (Fig. 2). By the FDD_{305a} date, the ground at 30 cm depth is typically either within the zero curtain or is frozen (< −0.5 °C) (Table 4). Every year at the drained location (P16S), the on and off ROW sites both froze to 30 cm depth within a few days of the FDD_{305a} threshold. Drained sites on ROW at P11 also froze to 30 cm by FDD_{305a} in 2012–13, as did drained sites off ROW at P23 in 2012–13 and 2014–13. However, the majority of sites (on and off ROW) are still within the zero curtain at FDD_{305a}. The exception is the wet site off ROW at P23, which remained unfrozen in 2012–13. In 2012–13, the average FDD_a when the freezing front penetrates to 30 cm at all sites is 1164 °C-days (SD = 599 °C-days), with all sites frozen to ≥30 cm by 2168 °C-days. Over the study period, the median FDD_a required for the freezing front to penetrate 30 cm at all sites is higher than FDD_{305a} (Fig. 4). Drained peat sites on and off ROW are the first to freeze at 30 cm (average FDD_a 670 °C-days). Wet peat sites freeze later on ROW (median FDD_a 820 °C-days) and latest off ROW (1400 °C-days). Compared to drained sites, the variability in FDD_a is greater for wet peat sites especially off ROW. Median FDD_a values to reach 30 cm of frozen ground are statistically similar between the drained peat sites on and off ROW and the on ROW wet peat sites ($p \geq 0.913$), but are significantly different from off ROW wet peat sites ($p \leq 0.022$). The earlier FDD_a observed at wet peat sites on ROW compared to off ROW is likely associated with snow clearing and greater peat compaction due to a history of winter road construction.

4.4. Thermal influence of winter road construction

To prepare the TCWR for the transport season, snow is initially

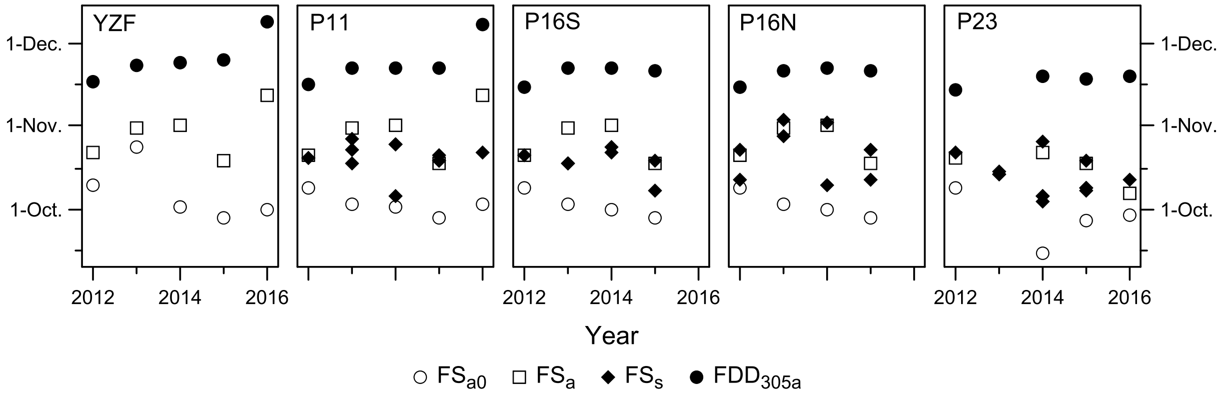

Fig. 2. Annual variability in freezing season indices for Yellowknife (YZF) and study site portages (P11, P16S, P16N, and P23). FS_{a0} is the first day that daily mean air temperatures drop below 0 °C in the autumn. FS_a is the date that daily mean air temperatures remain below 0 °C until spring. FS_s is the date that daily mean surface temperatures remain below 0 °C. FDD_{305a} is the date when 305 cumulative freezing degree-days is reached. FS_{a0}, FS_a, and FDD_{305a} are based on air temperature recorded at each study location; FS_s is shown for all ground surface measurements available at each study location.

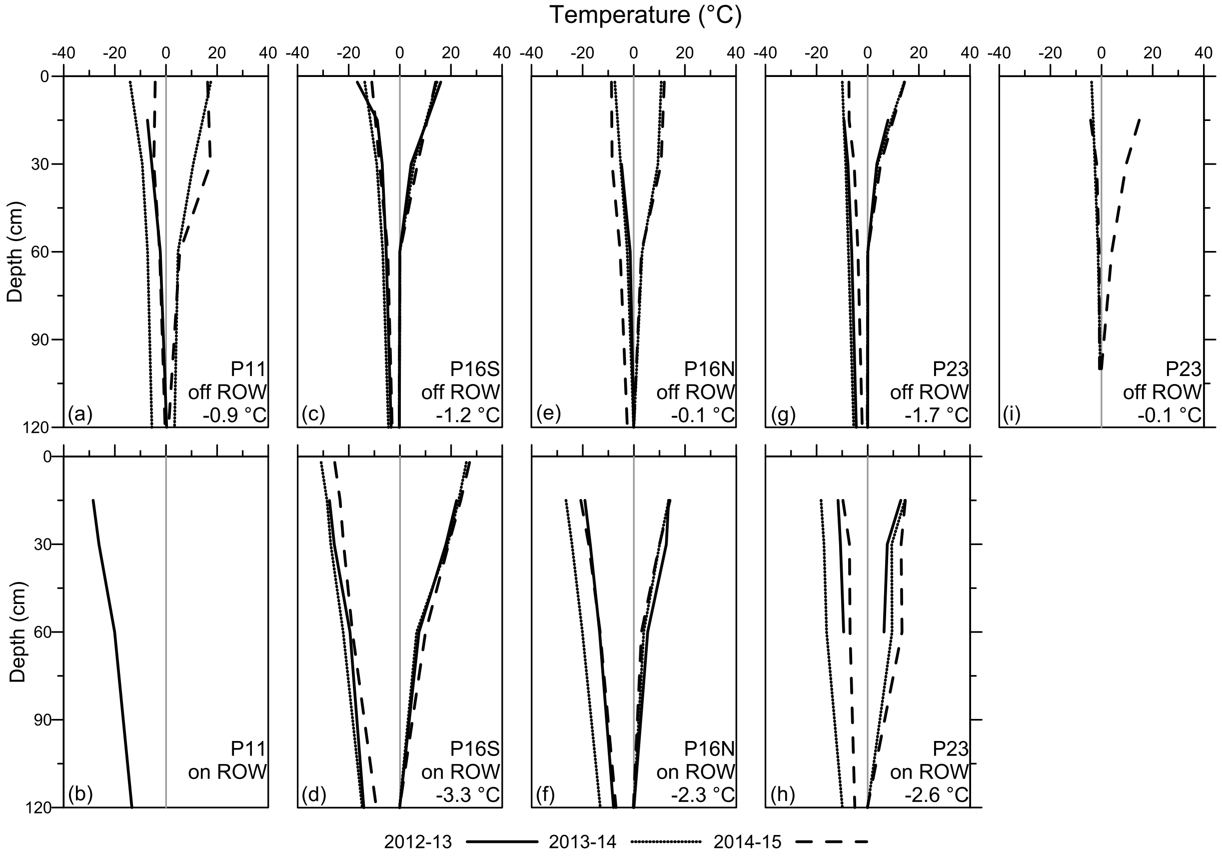

Fig. 3. Ground temperature envelopes showing the minimum and maximum temperatures recorded off and on ROW for all sites for 2012–13, 2013–14, and 2014–15. The 3-year mean temperature at the top of permafrost (120 cm) is indicated, except in (a) where TTOP is the mean for 2013–14 and 2014–15, (b), and (i) where TTOP is for 2013–14 only.

Table 4
Summary of ground thermal state at 30 cm depth by the date FDD_{305a} is reached for all sites (n = number of sites measured).

Period	n	Thermal state of sites (%)			
		Frozen	Freezing	Zero curtain	Unfrozen
		(< −0.5 °C)	(≈ −0.5 °C)	(0 to −0.5 °C)	(> 0 °C)
2012–13	23	2 (9%)	3 (13%)	17 (74%)	1 (4%)
2013–14	20	4 (20%)	0	16 (80%)	0
2014–15	17	7 (41%)	0	10 (59%)	0
2015–16	14	1 (7%)	2 (14%)	11 (79%)	0
2016–17	8	1 (12.5%)	1 (12.5%)	6 (75%)	0

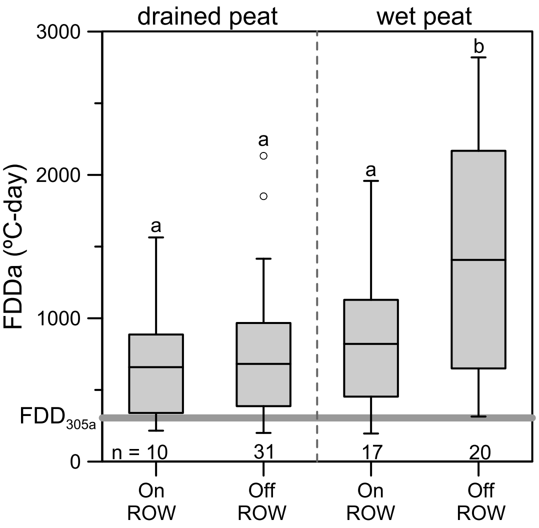

Fig. 4. Box-and-whisker plots (outliers indicated by point symbols) of FDD_a when the freezing front penetrated to 30 cm depth for drained and wet peat sites on and off ROW for the 2012–2017 study period. Sample numbers are indicated below each plot. For each parameter, one-way ANOVA and Tukey-Kramer post-hoc comparisons of all pairs of sites are indicated by lowercase letters, where matching letters indicate no significant difference between sites (α = 0.05).

compacted in late December to accelerate ground freezing on the portages and ice growth on the lakes. In early January, snow on the ROW is again compacted and flooded on the portages to create a hard-packed surface to handle the heavy vehicular traffic loads. Fig. 5 shows the daily mean air and 30 cm (T_{30}) ground temperatures, and 6 h temperature change (dT_{30}) on and off ROW at the drained location (P16S) and wet location (P16N) for 2012–13. The timing of snow compaction and flooding is also indicated. The influence of snow compaction and of flooding on the ROW is highlighted by episodes of rapid heat flow not observed at off ROW sites. At the drained location (P16S), where the ground typically freezes to ≥30 cm depth early in the season, the T_{30} and dT_{30} show the effectiveness of initial snow compaction, which lowered daily mean ground temperatures by 2–3 °C. This increased rate of cooling causes the freezing front to progress from 30 cm to beyond 60 cm depth in 5 days at the centre of the ROW. Subsequent snow compaction events have similar effects on the ground temperatures. In contrast, the combined snow compaction and flooding on January 11 causes a short-term (24 h) 3–5 °C rise in sub-zero ground temperatures before cooling continues again. At the edge of the ROW, the ground at

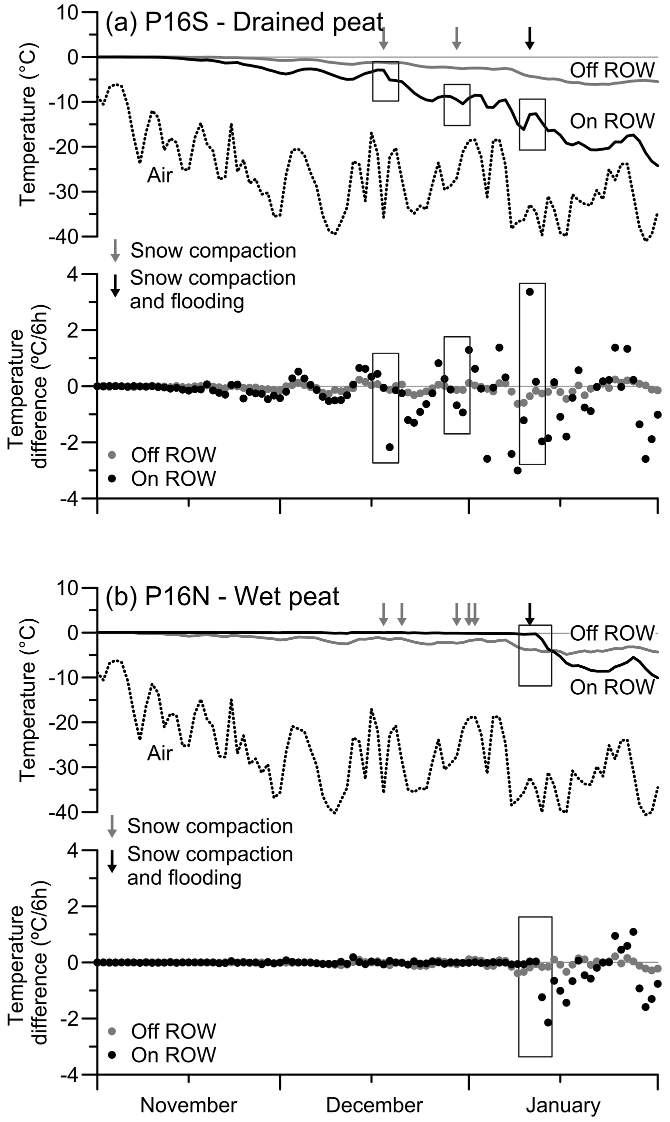

Fig. 5. Daily mean air and 30 cm depth temperature, and 6 h temperature difference on and off ROW in (a) drained peat (P16S) and (b) wet peat (P16N) for 2012–13. The grey boxes highlight rapid temperature change episodes. Vertical arrows indicate the timing of snow compaction and artificial flooding.

30 cm depth is still freezing as of January 11 (not shown). At this site, the snow compaction and flooding also produces a short-term increase in sub-zero ground temperature of about 3 °C, followed by freezing beyond 30 cm (not shown). In summary, both snow compaction alone and combined compaction and flooding are effective at increasing the rate of freezing at the drained peat location.

At the wet peat location (P16N), where water flows at the surface, the on-ROW T_{30} is still in the zero curtain at the time of initial snow compaction. Initial snow compaction does not appear to affect ground temperatures. However, after the combination of snow compaction and flooding on January 11, ground temperatures decrease rapidly and the freezing front passes 30 cm depth. At both locations, the effectiveness of flooding and snow compaction at increasing the rate and depth of freezing on ROW is clear.

4.5. *Thermal influence of natural overflow*

Location P23 has a history of water overflowing onto and along the road during winter road construction and operation. The natural events are a problem in the early winter because the addition of heat slows freezeback, and during the operating season the water can cause local thawing that weakens the integrity of the road surface. This water reduces traction and layers of ice can also build up, making driving conditions hazardous. In 2012–13, periods of natural overflow onto the snow surface are evident in time-lapse images at P23 during the freezeback season before winter road construction began. A short-term rise in sub-zero ground temperatures occurs during these events, followed by a rapid decline once the surface water has frozen (Fig. 6). Following a second overflow event, the freezing front quickly progresses below 30 cm depth. These natural overflow events have a similar effect on the ground thermal regime as snow compaction and artificial flooding, whereby surface conditions change from an insulating snow cover to a conductive ice cover. Although overflow may be hazardous to traffic when it occurs during the operating season, the overflows observed during the study period occurred early in the winter season and enhanced freezeback, and were therefore beneficial to winter road construction.

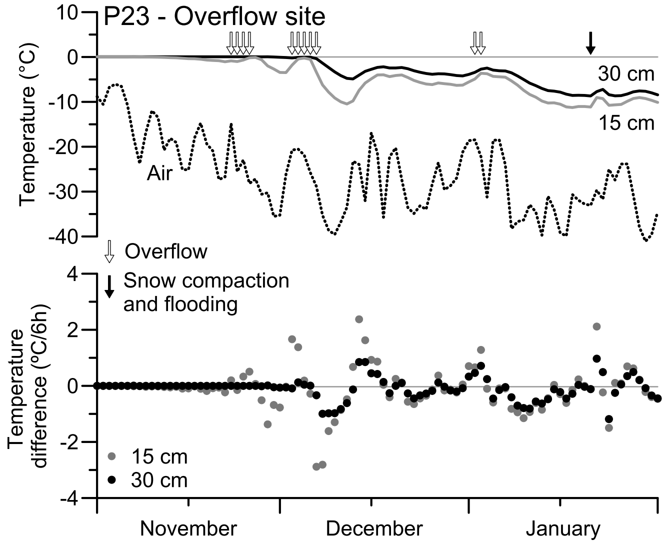

Fig. 6. Daily mean temperature and 6 h temperature difference at 15 cm and 30 cm depths on the edge of ROW at P23 for 2012–13. Vertical arrows indicate the timing of snow compaction and artificial and natural flooding (overflowing).

5. Discussion

5.1. *FDD_{305a} threshold*

Portages of the TCWR frequently traverse peatland-dominated valleys with variable organic-layer thickness. The load-bearing capacity of peat can increase by 350–400 times when it freezes, making terrain passable that would not be otherwise (MacFarlane, 1968). Winter road guidelines require the ground to have “adequate frost” (frozen ground) in order for construction to start. MacFarlane (1969) suggests that 30 cm of frozen peat will support most heavy equipment. This thickness is in line with the general guidelines recommended by others (i.e. Adam, 1978; Schindler, 1988; Bader and Guimond, 2004; Proskin et al., 2011). Proskin et al. (2011) consider Adam's (1978) climate index (FDD_{305a}) to reasonably predict the timing of freezing front penetration to 30 cm depth in most soils including drained peat.

In this study, we recorded air and ground temperatures at four locations on TCWR portages to determine the timing of freezing front penetration to 30 cm depth in relation to FDD_{305a}. The study sites were peatlands, typical of this region, with varying degrees of moisture (undrained fens and drained bogs). Despite interannual variability in freezing season air temperatures, the date which FDD_{305a} is reached at any site is within eight calendar days of all the other sites, except between Yellowknife and P11 in 2016–17 due to a November air temperature anomaly (Fig. 2). The FDD_{305a} date each year is similar among the locations and Yellowknife, illustrative of the regional climate. For most years, T_{30} at the majority of sites is still in the zero curtain at the time FDD_{305a} is reached (Table 4). The drained peat location, P16S, is the only location where the freezing front passes the 30 cm depth before FDD_{305a}. Freezing front penetration is typically slowed by latent heat generated during freezing of high water-content ground (Outcalt et al., 1990), as well as by heat advected by unfrozen water at depth (Carey and Woo, 2005). Therefore, in wet subarctic peatlands, the FDD_{305a} threshold does not provide adequate time for freezing to penetrate to 30 cm depth.

In addition to freezing front penetration, the more stringent DNR regulations (Department of Natural Resources, 2015) require a 30 cm ground temperature of −5 °C, because of the ground hardness reached under these conditions (Bader and Guimond, 2004). However, Bader and Guimond (2004) made no hardness measurements for ground temperatures between −5 and −0.7 °C. It may be possible that sufficiently hard ground occurs at ground temperatures above −5 °C, depending on the unfrozen water content, and indeed, observations by Lilly et al. (2008) of saturated, organic-rich soil (also on the North Slope) showed little change in unfrozen soil water content at temperatures less than −2 °C. Consequently, the authors suggested that the DNR temperature requirements be increased to −2 °C. Yet none of the TCWR sites reached either of these temperature thresholds by the FDD_{305a} date, suggesting that the FDD_{305a} threshold does not appear to provide adequate time to reach a suitable ground hardness in either wet or drained peat locations.

Frozen soils with high ice contents behave similarly to polycrystalline ice (Ladanyi, 1981). Therefore, depending on water content, the compressive strength of frozen peat can be five times stronger than unfrozen peat (Proskin et al., 2011). Shoop (1995, Fig. 3, p. 555) reported the strength of frozen peat to be similar to that of frozen inorganic soils, falling within the range of low water content silt and nearly saturated clay soils, and increasing with decreasing temperature. Therefore, peat strength is inversely related to unfrozen water content. Measurements of thermal conductivity and unfrozen water content in frozen peat indicate that most water freezes between 0 and −0.8 °C (Kujala et al., 2008). In wet environments where peat thicknesses exceed 30 cm, $T_{30} \leq -0.8$ °C may be sufficient for achieving adequate bearing capacity, well above Lilly et al.'s (2008) -2 °C threshold. In our study, freeze-up was considered complete when ground temperatures at 30 cm depth began to decrease below −0.5 °C and it may be presumed that −0.8 °C was reached shortly after the freeze-up date. Evidence by Kujala et al. (2008) and Lilly et al. (2008) supports the theory that when T_{30} is in the zero curtain, the sites do not have adequate bearing capacity. Consequently, the FDD_{305a} threshold is not adequate to achieve sufficient bearing capacity in wet subarctic peatlands. Over the study period, the majority of sites on ROW froze to 30 cm depth by 1100 °C-days (Fig. 4). Therefore, an FDD_a threshold of 1100 °C-days may be more appropriate for perennial winter roads in subarctic peatlands underlain by discontinuous permafrost.

5.2. Allowable loads and freezing depth

The DNR requirements may be stringent, in part, because any vehicle type may be allowed to operate on the road once they are met (Department of Natural Resources, 2015). In contrast, at the start of winter road construction in Canada, only low-pressure vehicles that compact the snow cover to promote further cooling of the ground are used. Shoop (1995) developed the guide commonly used for estimating frozen subgrade bearing capacity (Proskin et al., 2011). She proposed two equations based on empirical data to determine the allowable bearing capacity of dry [2] and wet [3] peat for frozen ground depths up to 50 cm, where the allowable load P (kg) for a given frozen ground depth z (m) is:

Table 5
Depth of freezing in drained and wet soils required to support gross vehicle weights (GVW) of different vehicles used in TCWR construction, calculated according to Shoop (1995).

Vehicle type	GVW (kg)	Depth of freezing (cm)	
		Drained peat	Wet peat
Prinoth Trooper	5670	40	25
Hagglund Bv 206	6580	43	27
Prinoth Husky	7500	46	29
Bombardier Snowcat BR275	7800	47	30
Water truck	11,230	56	36

$$P = 3.6\ z^2 \text{ (dry conditions)} \tag{2}$$

$$P = 8.8\ z^2 \text{ (wet conditions)} \tag{3}$$

The wet condition represents peat with moisture contents on the order of 500–800% by dry weight. The dry peat represents typically drained conditions (moisture contents less that 500% by dry weight). The constants (load parameters; kg/cm^2) are a function of the material strength, and were determined from fitting an empirical equation to published guidelines for peatland operations. The constants differ for "wet" and "dry" conditions. The frozen ground depths based on these equations for the vehicle types typically used in constructing the TCWR are listed in Table 5. The frozen ground depth (25–29 cm) required for the Prinoth Trooper and Husky snow grooming vehicles on wet peat are consistent with MacFarlane (1969) and general winter road construction guidelines. Slightly deeper freezing front penetration (36 cm) is required for water trucks. However, drained peat requires 14–20 cm greater frozen ground depth than wet peat. In our study, none of these frozen ground depths were met by the time the FDD_{305a} threshold was reached, except at P16S, the drained site. By using the gross vehicle weight instead of a distributed load, Shoop's (1995) approach is conservative. For example, guidelines in Finland suggest a frozen ground depth of ≥20 cm for operation of medium-sized forwarders, vehicles which have a gross vehicle weight similar to a water truck (9000–13,000 kg), and a ground pressure for loaded medium forwarders with and without tracks of 50 and 90 kPa, respectively (Eeronheimo, 1991). This is an order of magnitude greater than the ground pressure of the Prinoth Trooper (5.7 kPa) and the Bombardier Snowcat BR275 (8.0 kPa). Observations at the wet location (P16N) in 2012–13 indicate the ground on ROW was frozen to at least 15 cm depth by the end of November, but still in the zero curtain at 30 cm depth by the time the water trucks were operating on January 11. During this time interval, low-pressure vehicles operated without evident adverse effects on the ROW. Therefore, bearing capacity for low-pressure vehicles, as well as water trucks, may be achieved at frozen ground depths < 30 cm.

5.3. Bearing capacity of lake ice versus portages

More winter road construction occurs over lake ice than land, thus it is important to consider when the load bearing capacity at each setting is reached as this may affect construction timing and techniques. The majority of the TCWR traverses lakes, where 41 cm of ice is required to operate snow grooming machines that compress or clear snow, and 56 cm of ice is required for water trucks that flood the surface (C. Ambrose, pers. comm.). The estimated freezing degree-days to reach 41 cm lake ice thickness range from 220 to 570 °C-days, depending on snow and wind conditions, and from 420 to 1080 °C-days to reach 56 cm (Lunardini, 1981; U.S. Army Corps of Engineers, 2002, Table 2.2, p. 2–13) (Fig. 7).

Ground temperatures measured in this study indicate that in the coldest year (2012−13), the freezing front passes the 30 cm depth at 339 °C-days on ROW and 682 °C-days off ROW in drained peat; at the

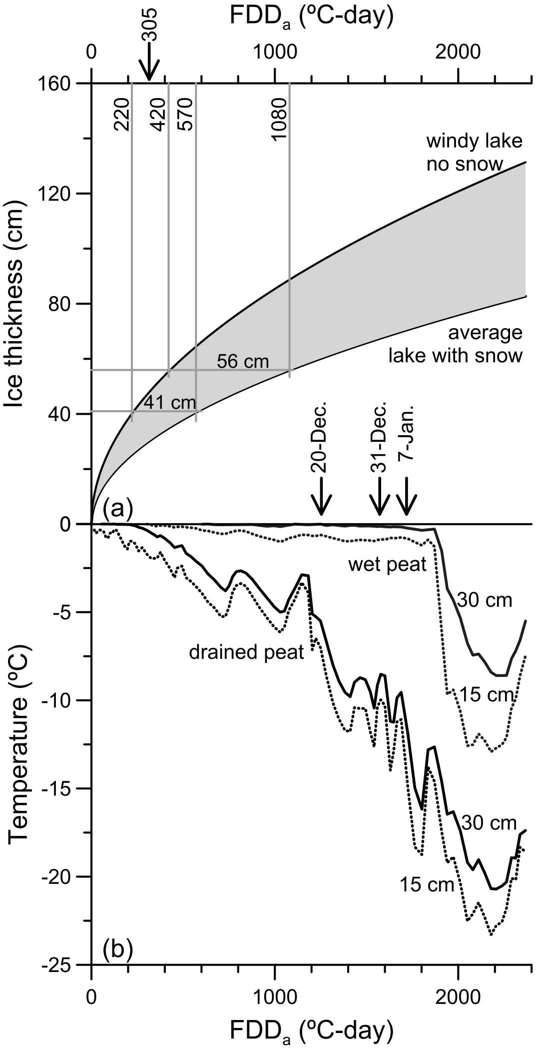

Fig. 7. Thresholds of FDD$_a$ for travel on lake ice and frozen ground. (a) Plot showing ice thickness as a function of air-freezing degree-days (FDD$_a$) for lakes with and without snow (Michel, 1971). The ranges in cumulative FDD$_a$ to achieve 41–56 cm of lake ice thickness are highlighted. (b) Ground temperature on ROW as a function of air-freezing degree-days (FDD$_a$) in drained peat (P16S) and wet peat (P16N) for 2012–13. FDD$_{305a}$, operational calendar dates for TCWR winter road construction, and other FDD$_a$ thresholds discussed in the text are indicated.

wet peat location this increases to 1958 and 1355 °C-days, on and off ROW, respectively (Figs. 5 and 7). A comparison of T$_{30}$ freezeback at all sites over the study period shows that typically 70% of the sites have not frozen by 570 °C-days and that on average 30% are still not frozen by 1080 °C-days (Table 6). These numbers suggest that by the time the lakes adequately freeze for construction vehicle traffic (56 cm), drained peat portages reach an adequate bearing capacity, but wet peat portages do not.

Table 7

Air-freezing degree-days (FDD$_a$) at P11 for operational calendar dates used to initiate TCWR construction.

Date	Vehicle type	FDD$_a$ (°C-day) at P11				
		2012–13	2013–14	2014–15	2015–16	2016–17
20-Dec.	Small snow groomer	1250	1105	1021	712	800
31-Dec.	Big snow groomer	1569	1498	1301	1014	1083
07-Jan.	Water truck	1716	1723	1494	1120	1243

5.4. Calendar date

In reality, for many operators, construction of winter roads is planned by the calendar date, rather than by thresholds for ground thermal conditions. In the case of the TCWR, ‘small’ snow grooming vehicles (Husky and Trooper) start near P11 on December 20, ‘big’ snow grooming vehicles (Bombardier) start on December 31, and water trucks start on January 7. North of Gordon Lake, near P23, construction starts later with water trucks passing on January 15 (Fig. 1) (C. Ambrose, pers. comm.). Using 2012–13 as an example, which is the coldest year in the study period, Fig. 7 shows that the FDD$_a$ on those calendar dates exceeds both the FDD$_{305a}$ threshold and the air-freezing degree-days typically accumulated by the time the various desired lake-ice thicknesses for winter road construction are reached. In addition, Table 7 shows that for each year of the study period, the FDD$_a$ associated with the calendar dates are routinely greater than both the FDD$_{305a}$ and FDD$_a$ needed to reach ice-thickness thresholds, as well as the FDD$_a$ when most sites are frozen to 30 cm depth (Fig. 4).

Comparison of the three thresholds shows that more sites are frozen to 30 cm depth by the calendar date, than by the FDD$_a$ thresholds (Table 6). Therefore, the calendar date threshold presently offers the most conservative approach for winter road construction in these subarctic peatlands. The start date to initiate work at P23 is additionally conservative, because at this northern location, the FDD$_a$ on the calendar date exceed 1100 °C-days. Furthermore, this conservative calendar approach allows winter road operators to plan annual construction and operations around dates, rather than dealing with the added logistical complication of installing, maintaining, and accessing the apparatus required to calculate freezing indices or measure frozen ground depths and ground temperatures, and then mobilizing equipment and personnel on short notice. However, when an earlier start is warranted, an FDD$_a$ threshold of 1100 °C-days is more appropriate than 305 °C-days for drained and wet peatlands on ROW in this discontinuous permafrost environment.

At present, the calendar date threshold offers a conservative and

Table 6

Number (n) and percentage of sites frozen to 30 cm depth on air-freezing degree-day thresholds (FDD$_a$) that yield lake ice thickness required for various construction activities and on calendar date thresholds used to initiate TCWR construction (see Sections 5.3 and 5.4 for details), for the 2012–2017 study period.

Period	n	Number (percentage) of sites where freezing front has passed 30 cm depth															
		FDD$_a$ Threshold (°C-days)										Calendar date threshold					
		220		305		420		570		1080		20-Dec.		31-Dec.		07-Jan.	
2012–13	23	1	(4%)	1	(4%)	3	(13%)	5	(22%)	11	(48%)	11	(48%)	17	(74%)	18	(78%)
2013–14	20	2	(10%)	4	(20%)	4	(20%)	5	(25%)	15	(75%)	15	(75%)	15	(75%)	17	(85%)
2014–15	17	2	(12%)	3	(18%)	7	(41%)	10	(59%)	17	(100%)	17	(100%)	17	(100%)	17	(100%)
2015–16	14	1	(7%)	2	(14%)	2	(14%)	3	(21%)	7	(50%)	5	(36%)	7	(50%)	8	(57%)
2016–17	8	0	(0%)	2	(25%)	2	(25%)	2	(25%)	6	(75%)	5	(63%)	7	(88%)	8	(100%)

practical approach to TCWR planning and construction, however, climate warming is likely to have an impact in the future. For instance, early winter mean monthly temperatures and autumn rainfall for Yellowknife are projected to increase throughout this century (Scenarios Network for Alaska and Arctic Planning, 2018). These trends will likely delay ground freezing in the discontinuous permafrost peatlands through a combination of warmer air temperatures, increased water content, and subsurface heat advection, and the current calendar date thresholds for road construction will need to be reassessed.

5.5. Snow compaction and flooding

Observations in this study clearly show that snow compaction and flooding accelerate freezing front penetration in drained and wet peat environments (Fig. 5). In drained peat, when the freezing front has already passed 30 cm depth, snow compaction alone effectively lowers T_{30} and allows the ground to freeze past 60 cm depth. However, at the wet peat location, a combination of snow compaction and flooding is necessary to freeze the ground to 30 cm depth. In 2012–13, the wet peat location (P16N) took an especially long time to freeze back (132 days) despite being the coldest year in the study period (Fig. 5 and Table 3). This may relate to greater than normal heat advection through the saturated ground over the freezing season, as rainfall the preceding autumn was 45% higher than the 1981–2010 normal (Environment Canada, 2018). Heat advection at this site may also explain the extended zero-curtain period at 30 cm depth, despite the ground having frozen six weeks earlier to at least 15 cm depth (Carey and Woo, 2005). Nevertheless, natural overflow (similar to artificial flooding) was effective at decreasing ground temperatures by changing thermal conditions at the surface from insulating snow to conductive ice (Fig. 6).

6. Conclusions

In this study we investigated the air-freezing degree-day (FDD_a) threshold of 305 °C-days (FDD_{305a}) commonly applied by winter road operators to determine whether or not the ground is sufficiently frozen to enable construction to commence. Typically, 30 cm of ground freezing is required, and we found FDD_{305a} does not enable sufficient freezing front penetration especially in wet peatlands typical of discontinuous permafrost in subarctic Canadian Shield. Therefore, the FDD_{305a} should be avoided in similar terrain and climatic conditions. Our observations show that an FDD_a threshold of 1100 °C-days is more appropriate for drained and wet peatlands on ROW. The TCWR presently uses calendar date thresholds to guide the initiation of winter road construction. The dates provide sufficient time for adequate freezing front penetration in all peatland types and are later in the freezing season than the date the FDD_{305a} threshold is met. The calendar dates are also later than the dates when sufficient FDD_a have accumulated to achieve the minimum ice thicknesses required to bear the loads of early winter road construction vehicles. The calculated freezing-penetration depths for bearing capacity based on gross vehicle weight was found to be similar to established guidelines, but are probably conservative for low-pressure vehicles. Snow compaction and flooding are effective at accelerating freezing penetration, especially in wet peatlands that take longer to freeze due to latent heat effects and probable heat advection at depth. To properly assess the thresholds for the start of winter road construction further research is required on the strength behaviour of peat at negative temperatures close to 0 °C.

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