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Report on 2012–2017 shallow ground thermal investigations on the Tibbitt to Contwoyto Winter Road portages, Northwest Territories

W.E. Sladen, P.D. Morse, and S.A. Wolfe

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Permanent link: https://doi.org/10.4095/306454

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Recommended citation
Sladen, W.E., Morse, P.D., and Wolfe, S.A., 2014. Report on 2012–2017 shallow ground thermal investigations on the Tibbitt to Contwoyto Winter Road portages, Northwest Territories; Geological Survey of Canada, Open File 8274, 1 .zip file. https://doi.org/10.4095/306454

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ABSTRACT

A field campaign was conducted in 2012-2017 to collect baseline geoscience data to determine air, surface, and near-surface ground temperature conditions along the Tibbitt to Contwoyto Winter Road (TCWR), Great Slave region, Northwest Territories. This field initiative was conducted in support of Natural Resources Canada's Climate Change Geoscience Program project entitled Transportation Risk in the Arctic to Climatic Sensitivity. Thermal data are presented in a digital format that can be utilized for assessments of permafrost sensitivity to climate change and for infrastructure planning.

DISCLAIMER

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1 INTRODUCTION

Permafrost is an important component of the landscape in the south-central Northwest Territories (NT), which is within the extensive discontinuous permafrost zone (Figure 1.1). Thaw of permafrost and its associated ground ice results in modification of drainage patterns and reduction of ground stability, which can affect entire ecosystems and presents challenges to northern society. In particular, permafrost change can have a significant influence on the integrity of ground-based transportation infrastructure, which is critical to northern communities and economic wellbeing, the latter being largely related to mineral resource development in the Slave Geological Province. Presently, access to many communities and mines in the region relies on winter roads (Figure 1.1), which cross numerous frozen lakes that are connected by comparatively short overland sections called portages. Climate warming in the region poses risks to existing transportation infrastructure, and development of winter road infrastructure also affects the thermal regime of underlying permafrost. Therefore, knowledge of thermal conditions at portages is required to understand the potential for permafrost change in this region and to inform adaptation measures to deal with increasingly unreliable ice roads.

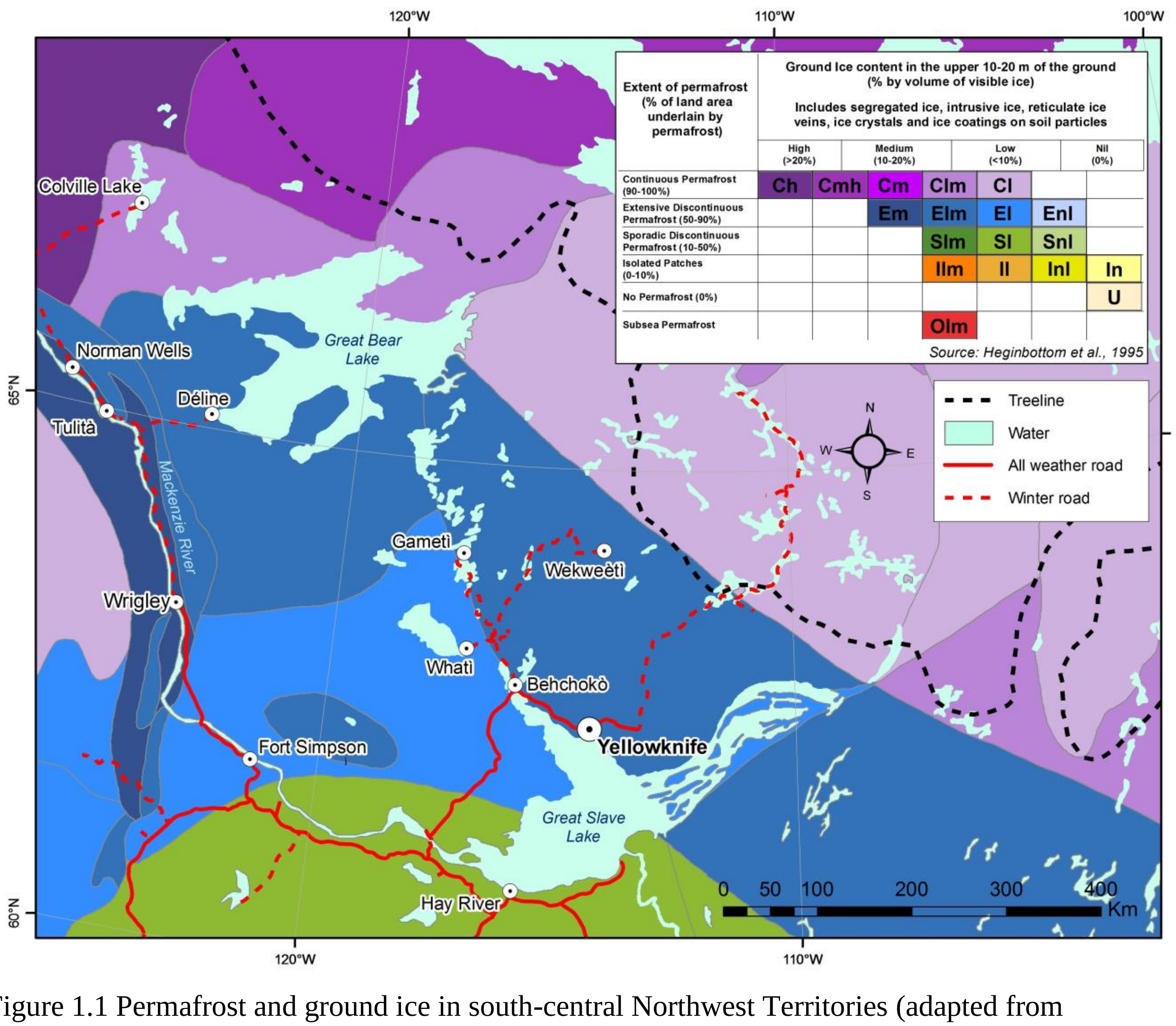

Figure 1.1 Permafrost and ground ice in south-central Northwest Territories (adapted from Heginbottom *et al.*, 1995).

The Geological Survey of Canada (GSC), Natural Resources Canada, conducted a field campaign to collect baseline geoscience data on winter road portages in support of an initiative focused on addressing Transportation Risk in the Arctic to Climatic Sensitivity in the Great Slave region. A key aspect of this project was to assess the shallow ground thermal conditions along the Tibbitt to Contwoyto Winter Road (TCWR), both on the right-of-way (ROW) and in the adjacent undisturbed terrain. This Open File report presents air, surface, and near-surface ground temperature data measured from 2012 to 2017 at three portages along the TCWR (Figure 1.2). These data are essential to understanding the influence of the winter roads on the near-surface ground thermal regime and freezeback of the active layer above permafrost, and are critical to understanding the influences of winter road construction and changing climate.

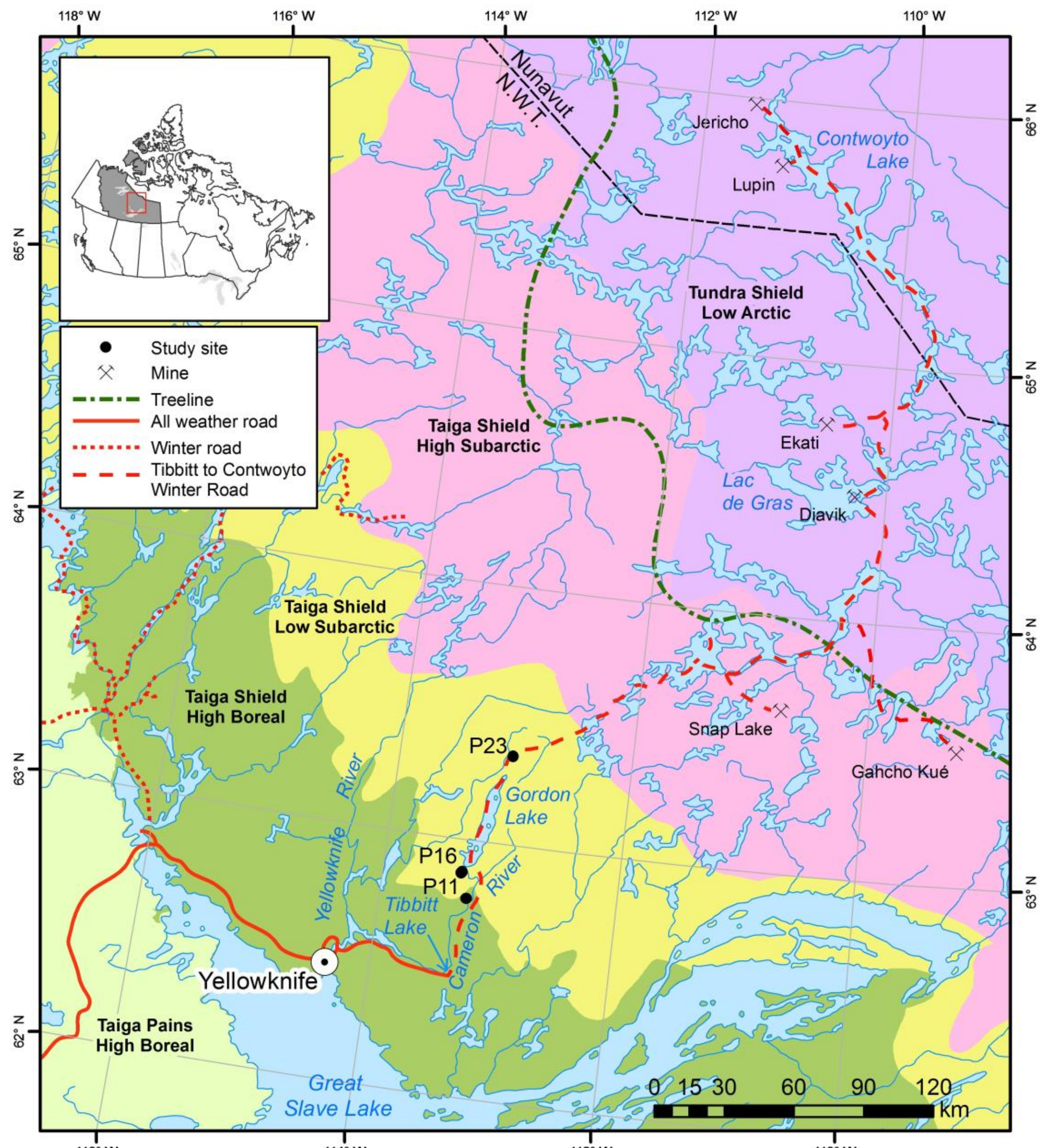

Figure 1.2 Ecoregions of the Great Slave Uplands and the Tibbitt to Contwoyto Winter Road (adapted from Ecosystem Classification Group, 2008; 2012). The study portages are indicated.

2 GEOMORPHIC CONTEXT

The study sites reside within the Great Slave Upland High Boreal and Low Subarctic ecoregions of the Taiga Shield (Figure 1.2; Ecosystem Classification Group, 2008). The Great Slave Upland is underlain by the Slave Geological Province, an Archean craton of the Precambrian Canadian Shield, trending southwest – northeast from Great Slave Lake to Coronation Gulf. The craton, composed of granitoid, metasedimentary, and metavolcanic rocks, covers an area of approximately 213,000 km^2 (Padgham and Fyson, 1992).

The area was last glaciated about 9000 years ago by the Late Wisconsinan Laurentide Ice Sheet (Dyke *et al.*, 2003). The resultant ice-scoured terrain ranges from gently undulating to moderately rugged exposed bedrock, and slopes overall to the southwest with elevation that ranges from 450 to 275 m a.s.l. Bouldery till covers portions of the region as veneers and blankets (Stevens *et al*., 2013; Olthof *et al*., 2014), with sandy to gravelly outwash deposits in the north and east. Organic deposits are numerous but are limited to fens and bogs in low-lying areas (Stevens *et al*., 2013). The region contains myriad lakes of varying sizes connected by streams and channels that range from ephemeral to perennial, and the main rivers, the Yellowknife and the Cameron, drain into Great Slave Lake (Kokelj, 2003; Ecosystem Classification Group, 2008).

The Great Slave Upland is located south of the treeline with forest vegetation dominated by black spruce (*Picea mariana*) in relatively poorly drained areas and dwarf birch (*Betula pumila*), paper birch (*Betula papyrifera*) on better drained areas, and jack pine (*Pinus banksiana*) on bedrock dominated terrain (Ecosystem Classification Group, 2008). Mosses (*Sphagnum* spp.) and sedges (*Carex* spp.) dominate the wetlands. Extensive areas have been burned over the last several decades (GNWT, 2017), with the most recent fires occurring in 2014.

Permafrost in the Yellowknife area is widespread but discontinuous (Figure 1.1) (Heginbottom *et al.*, 1995), occurring beneath forests on fine-grained deposits and peatlands where it is up to 50 m thick, but it is absent beneath exposed bedrock or coarse-grained surficial deposits (Brown, 1973; Karunaratne *et al*., 2008; Morse *et al*., 2016). Active-layer thicknesses range from 0.4 to 1.1 m (Karunaratne *et al*., 2008; Morse *et al*., 2016). Permafrost temperatures range from -0.02 to -1.9 ºC and are largely influenced by soil moisture content and organic layer thickness (Karunaratne *et al*., 2008; Morse *et al*., 2016). Permafrost, where present, is in disequilibrium with present climatic conditions (Morse *et al*., 2016) and its distribution is expected to be considerably less in the future as a result of climate warming (Zhang *et al*., 2015).

3 TIBBITT TO CONTWOYTO WINTER ROAD

The TCWR, used to transport goods to support year-round mining operations, begins on Tibbitt Lake 73 km east of Yellowknife at the end of Highway 4 (a.k.a. the Ingraham Trail). Depending on mining activities it extends 400 to 600 km north (Figure 1.2). It evolved from an earlier winter road built in the 1960s to access the now closed Tundra Mine near Courageous Lake, NU (EBA, 2002), and was extended in the 1970s to service the now closed Lupin Gold Mine on Contwoyto Lake, NU. More recently, the road has been servicing diamond mines at Lac de Gras (Ekati and Diavik), Snap Lake (closed in 2015), and Gahcho Kué (Figure 1.2). The majority of the road traverses frozen lakes, while the remaining 13% (~ 78 km) consists of 64 overland portages. It is the only surface-based transportation route in and out of this portion of the resource-rich Slave Geological Province, and the key vulnerability of the TCWR with respect to climate change is the length of the operating season (Perrin *et al*., 2015). On several portages, however, the main problem faced by the TCWR operators is water flowing onto the road surface (overflow) during winter construction and operation (T. Tattrie, Nuna Logistics Ltd., pers. comm., 2012).

4 FIELD DESIGN

The GSC established and instrumented four study sites in 2012 and 2013 to capture air and near-surface ground temperature variation in natural terrain off the ROW and in terrain modified by winter road construction. The sites were selected based on accessibility and history of water flow onto the portages during winter road construction. The sites were located on portages 11 (km 32), 16 (km 46 and 47), and 23 (km 58) of the TCWR (Figure 1.2). All the sites are in soil-filled valleys, constrained by bedrock uplands. The valleys consist mainly of peatlands with peat thicknesses ranging from 48 to >120 cm. Sites P11, P16N, and P23 were chosen based on their water flow history and P16S (no overflow history) was established as a control site.

The instrumentation at each site consisted of air and ground surface (WAG), and near-surface temperature sensors on (WR) and off (WO) the ROW, as well as a set of thermistors at 30 cm depth that transected the transition from natural to modified terrain (WT). Water temperature sensors (WL) were also placed at P16S and P23. Figure 4.1 shows a general schematic of the instrumentation layout. Details on instrumentation follow in Section 6. All sites were visited three times a year (September, February, and June) and have continuous data records except for gaps due to logger malfunctions related to human error or wildlife damage.

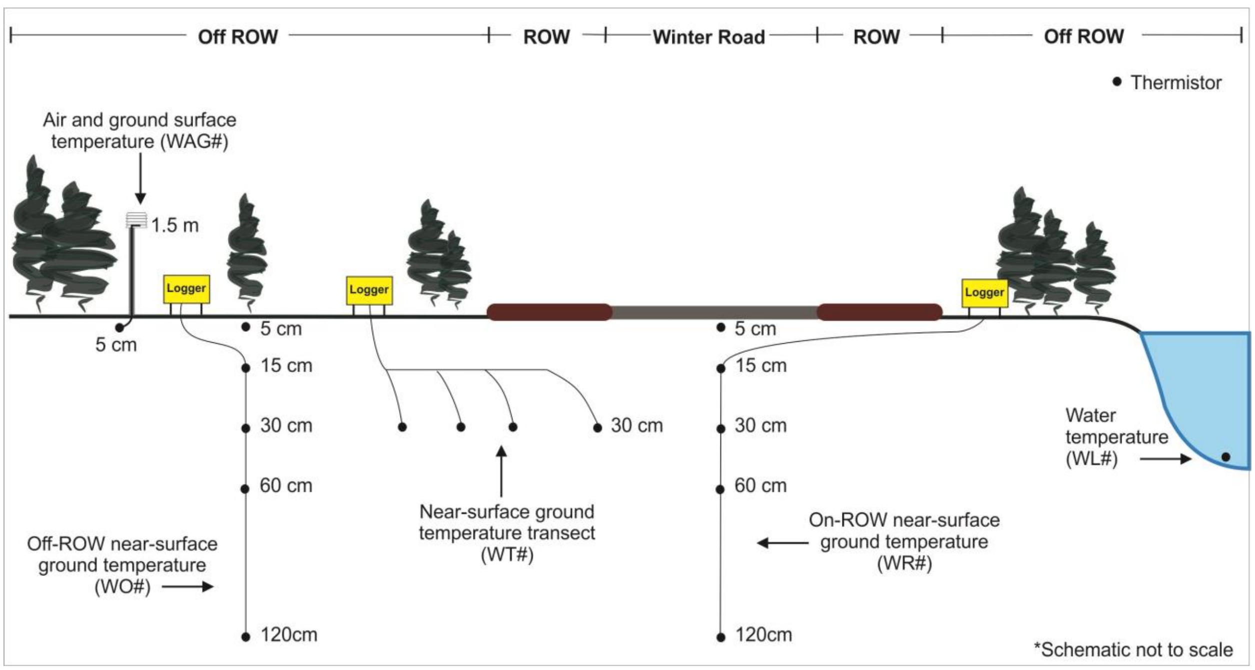

Figure 4.1 Schematic of instrumentation layout at each portage study site.

5 STUDY SITE CONDITIONS

5.1 Portage 11

The P11 site is located approximately 360 m north of Dome Lake on the southern portion of Portage 11. The portage route is oriented east – west at the site (Figure 5.1), the general site conditions are a wetland with diffuse water flow, and a confluence of two valleys is upstream. The valley to the west contains the current TCWR route and has an average gradient of approximately 1°. The valley to the northwest, which contains a previous alignment, runs from Lake P11 (elevation 272 m a.s.l.) at an average gradient of approximately 0.7°. The elevation at the monitoring site is 261 m a.s.l. The valley, about 40 to 45 m wide at the instrumentation site, is immediately constrained by bedrock uplands that create a local relief of up to 19 m.

The ROW in the vicinity of WR1 and WT1, is mainly vegetated with graminoids up to 60 cm tall in 2012 (Figure 5.2 (b) and (d)). The stratigraphy at WR1 consists of 40 cm of sandy gravel road aggregate overlying 48 cm of saturated peat, overlying silty sand. The water table was at 18 cm depth and the frost table was at 78 cm depth at the time of drilling in September 2012. Three thermistors (T_1, T_2, T_3) along the horizontal transect, WT1, were located on ROW, where water was 10 – 15 cm above the surface and the thaw depth ranged from 90 to 102 cm in September 2012. The fourth sensor of WT1, T_4, was located off ROW in thick willow (*Salix spp.*) and birch (*Betula glandulosa*) shrub to 2.5 m in height and sedges. Between March 18th and April 1st, 2013, about 100 cm of crushed rock and sand was placed on the ROW by the TCWR operators in an attempt to mitigate the winter water flow problems (Figure 5.1 (b) and Figure 5.2 (f)). As a result, the crushed rock was placed over the sensors at WR1 and WT1 (T_1, T_2, T_3).

The air and ground temperature sensors were located in undisturbed terrain to the south of the ROW (Figure 5.1 and Figure 5.2 (a)). The terrain is hummocky with water ponded at the surface in depressions. Vegetation is dominated by willow and birch shrubs, sedges, horsetail (*Equisetum spp.*), and mosses. The north side of the ROW, in the vicinity of WO1 and WO1-2, is vegetated mainly with willow shrubs up to 80 cm tall and sphagnum, but about 40% of the surface cover was water. The stratigraphy consists of 75 cm of saturated peat over sand and silt (Figure 5.2 (c) and (e)). The water was 30 cm deep at WO1 when it was installed in September 2012. The water table was at 8 cm depth at WO1-2 when it was installed in September 2013. Both locations were unfrozen to 120 cm depth (end of borehole). In July 2014, a wildland fire swept through the area, burned the bog and upland vegetation, and damaged WAG1 (Figure 5.1 (c)).

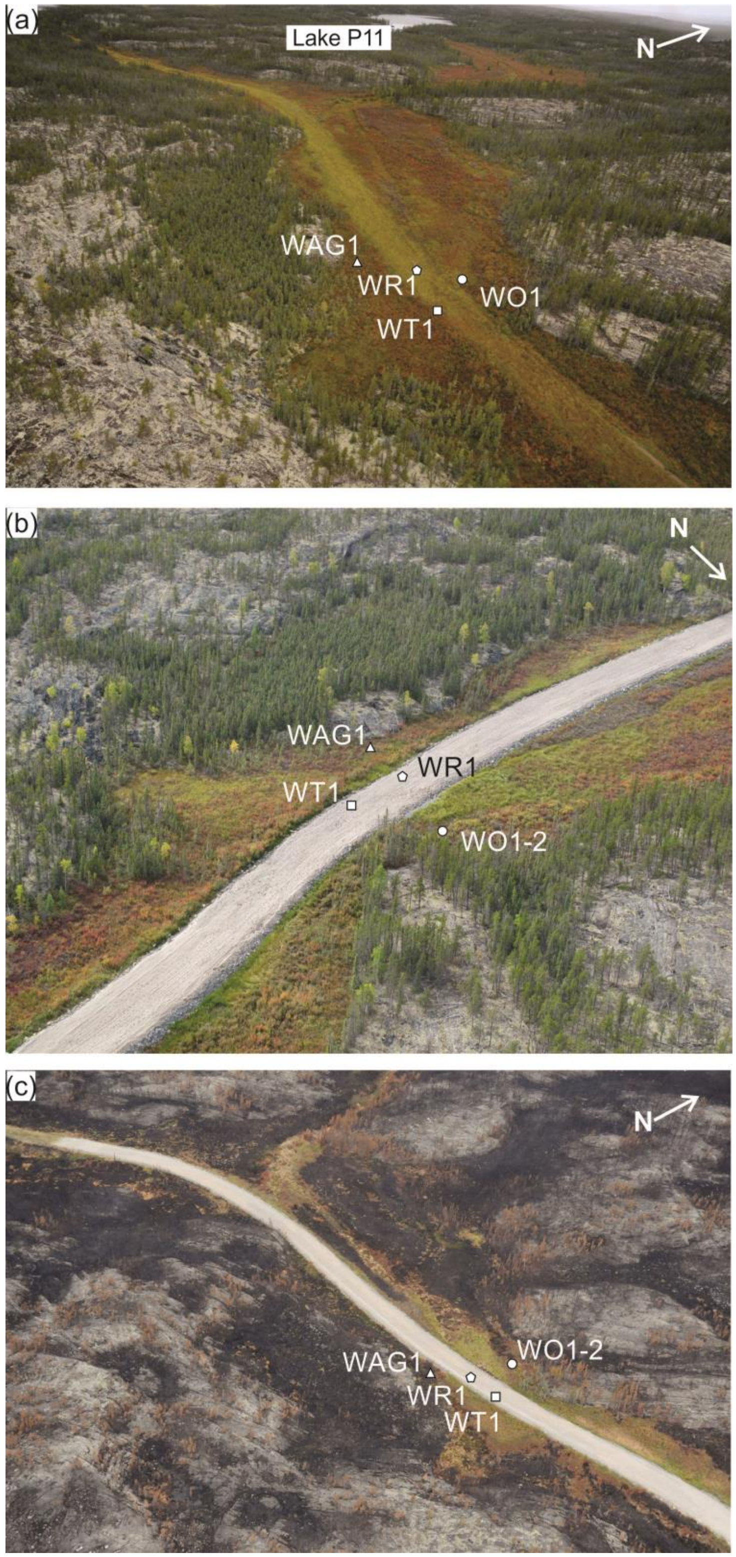

Figure 5.1. Aerial view of P11 showing the instrument locations (a) prior to placement of the aggregate, (b) after placement, and (c) post wildland fire. Photos taken in (a) September 2012, (b) September 2013, and (c) September 2014.

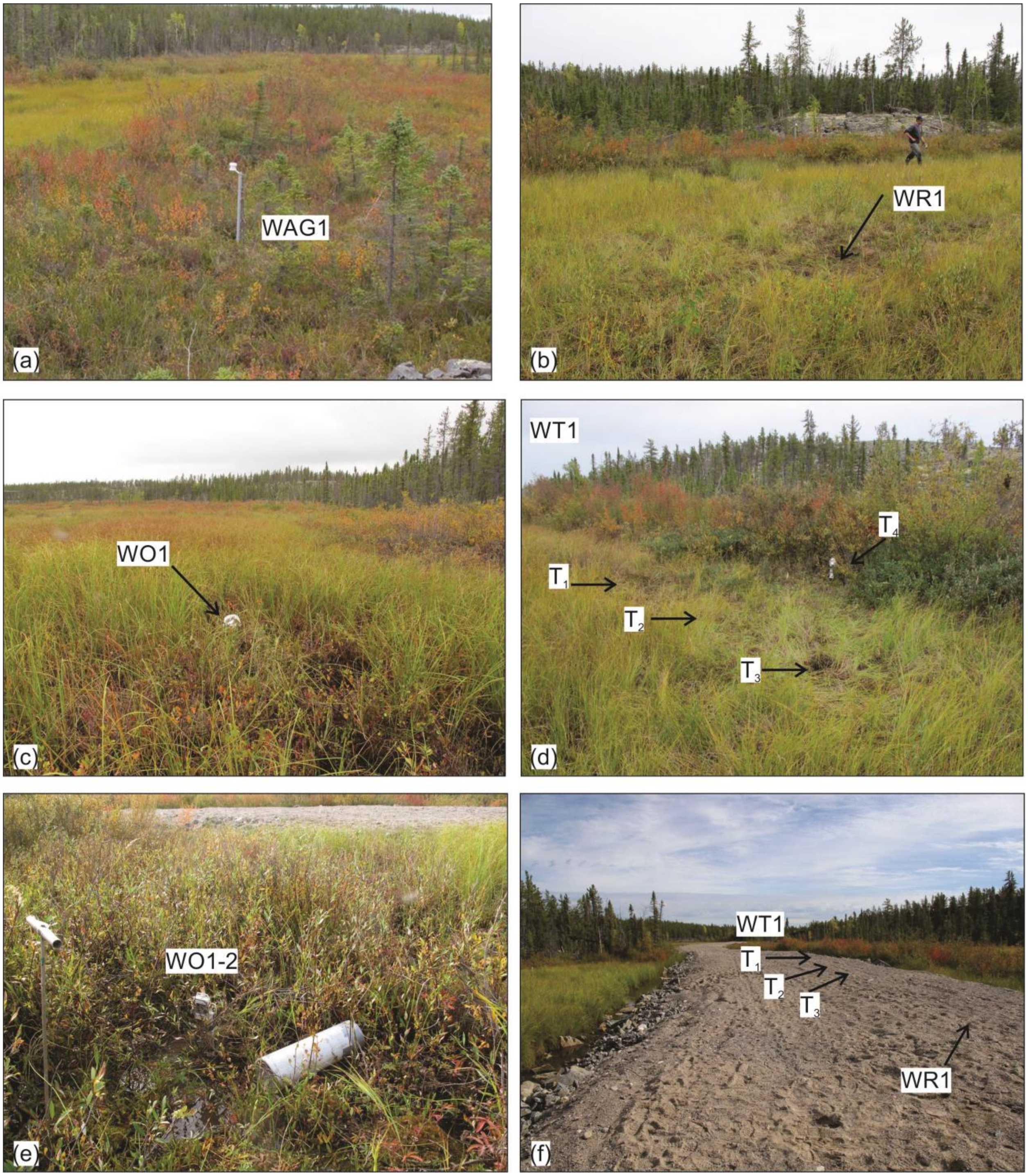

Figure 5.2 Instrumentation sites at P11: (a) air and ground surface temperature (WAG1); (b) on ROW vertical thermistor string (WR1); (c) off ROW vertical thermistor string (WO1); (d) horizontal transect sensor locations (WT1); and (e) off ROW vertical thermistor string (WO1-2). (f) Shows the surface conditions at WR1 and WT1 ($T_1 – T_3$) after aggregate was placed on ROW. Photos (a – d) were taken in September 2012 and photos (e – f) were taken in September 2013. Road aggregate was added to the ROW in March 2013.

5.2 Portage 16 south

The P16S site is located on the southern portion of Portage 16 (Figure 5.3 and Figure 5.4). The portage route, oriented east – west at the instrumentation site, traverses a well-drained bog. The area was burned in 1998 by wildland fire (GNWT, 2017). The site is at 296 m a.s.l. with a very gentle slope to the southwest.

The surface cover of the ROW in the vicinity of WR2 and WT2 (T_1), consists mainly of sandy gravel aggregate with exposed peat and sparse grass (Figure 5.4). The air and surface temperature sensors, WAG2, as well as sensors WT2 (T_2-T_4) and WO2 were located off the ROW in the bog to the north. The bog is hummocky and well drained, and the vegetation that has recovered from the fire consists mainly of Labrador tea (*Rhododendron groelandicum*) that ranges in height from 25 to 60 cm, lichen (*Cladina*), mosses, and the occasional black spruce tree.

P16S is the driest study site. The stratigraphy consists of damp (not saturated), fibrous peat to a minimum depth of 140 cm (end of borehole). On ROW, there is a 20-cm-thick layer of sand and gravel road aggregate at the surface. The thaw depth ranged from 65 to 88 cm on ROW and from 43 to 63 cm off ROW in September 2012. Below the frost table, the peat contains visible ice. Bedrock was not encountered during drilling.

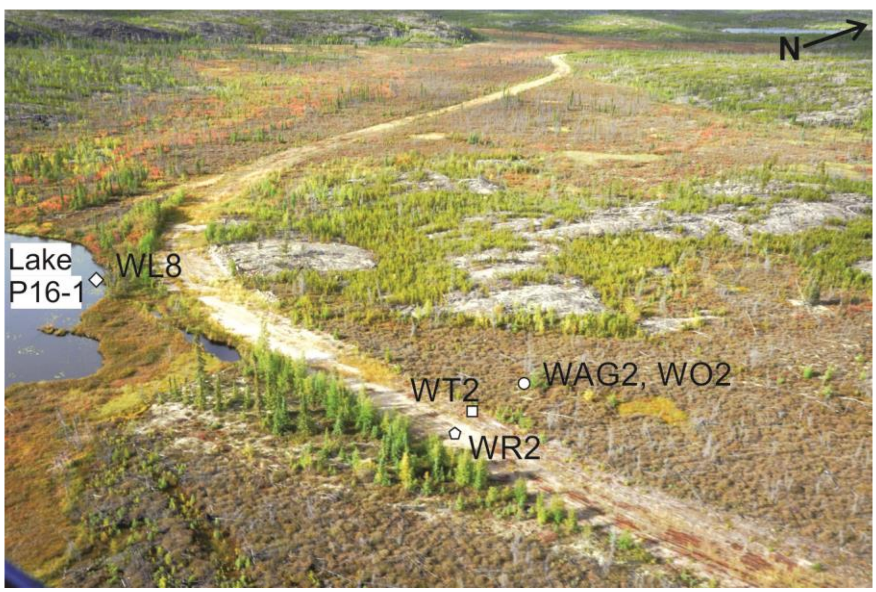

Figure 5.3. Aerial view of the instrument locations at P16S. Photo taken in September 2012.

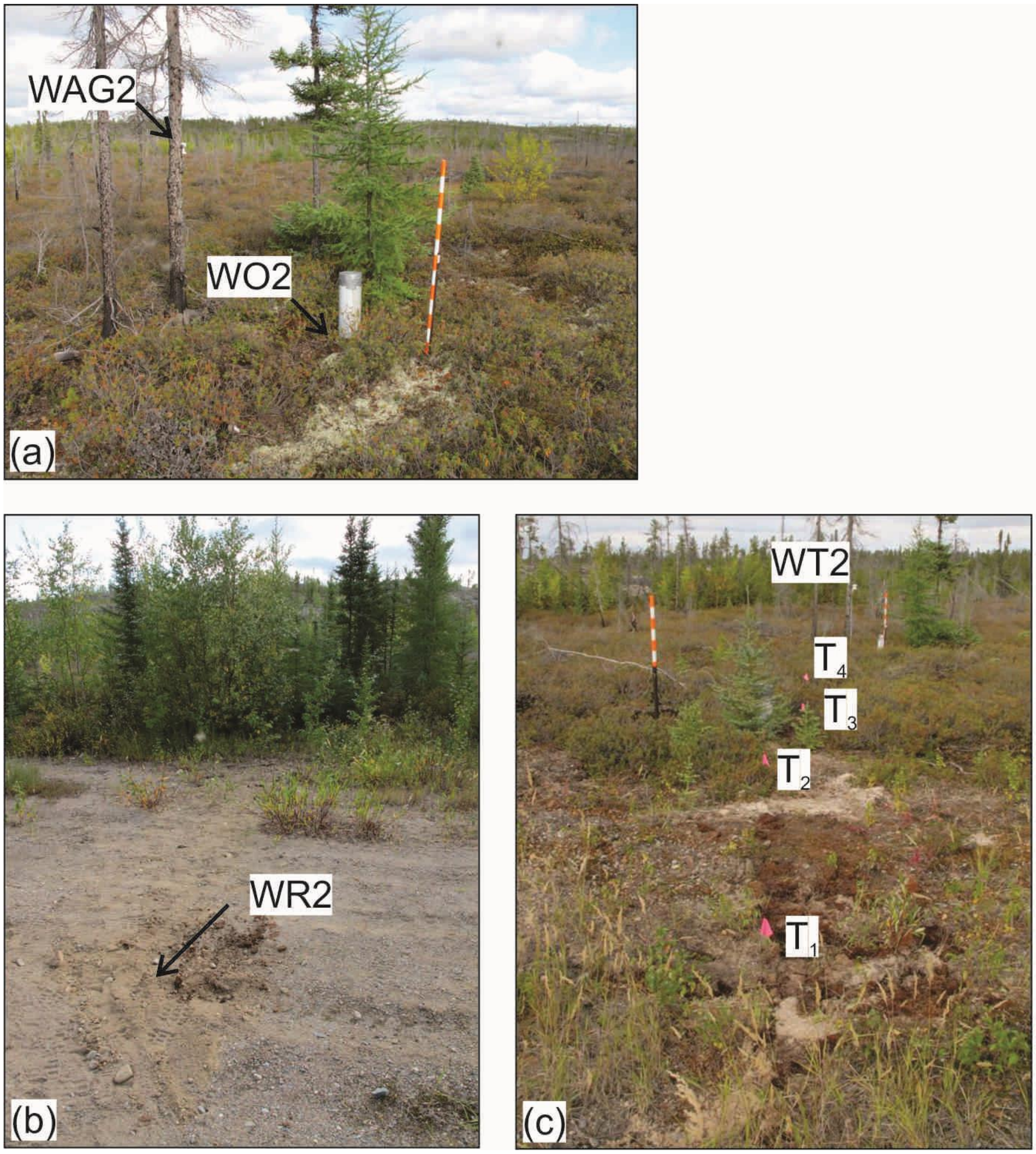

Figure 5.4 Instrumentation sites at P16S: (a) air and ground surface temperature (WAG2) and off ROW vertical thermistor string (WO2); (b) on ROW vertical thermistor string (WR2); and (c) horizontal transect (WT2) sensor locations (T_1 – T_4, denoted by pink flags), WO2 and WAG2 can be seen in the background. Photos taken in September 2012.

5.3 Portage 16 north

P16N is located mid-way along Portage 16 (Figure 5.5 and Figure 5.6) that is oriented east – west at the study site. Similar to P16S, the elevation of P16N is 296 m a.s.l. The site is located downslope of two watercourses that drain southeast towards Lake P16-2, and the ROW had flowing water up to 15 cm deep in September 2012. Overall gradients for both watercourses are approximately 0.6º. Vegetation on the ROW is dominated by graminoids up to 130 cm tall, but off the ROW the ground is drier. Vegetation south of the ROW consists mainly of mosses, grasses up to 70 cm tall, and birch and willow shrubs up to 180 cm in height. North of the ROW, the vegetation is mostly moss, 40 – 60 cm tall graminoids, and black spruce up to 110 cm in height. There are some birch and willow shrubs, and jack pine up to 160 cm in height where bedrock outcrops. The temperature sensors WR3 and WT3 (T_2 – T_4) were located within the ROW. The sensors WO3 and WT3 (T_1) were installed in undisturbed terrain on the south side of the ROW, while the air and surface sensors (WAG3) were located to the north of the ROW.

The stratigraphy beneath the ROW at WO3 consists of 80 cm of saturated peat overlying 20 cm of saturated silty sand, overlying clayey silt containing 10% visible ice to 120 cm depth. Off ROW at WO3, the stratigraphy consists of damp, unsaturated peat to 120 cm depth. In September 2012, the thaw depth ranged from 67 to 107 cm. The thaw depth was the shallowest (67 – 71 cm) at the drier edges of the ROW and greatest (91 cm) on ROW where the surface water was at its deepest and off ROW near WAG3 (107 cm).

Figure 5.5. Aerial view of the instrumentation at P16N. Photo taken in September 2012.

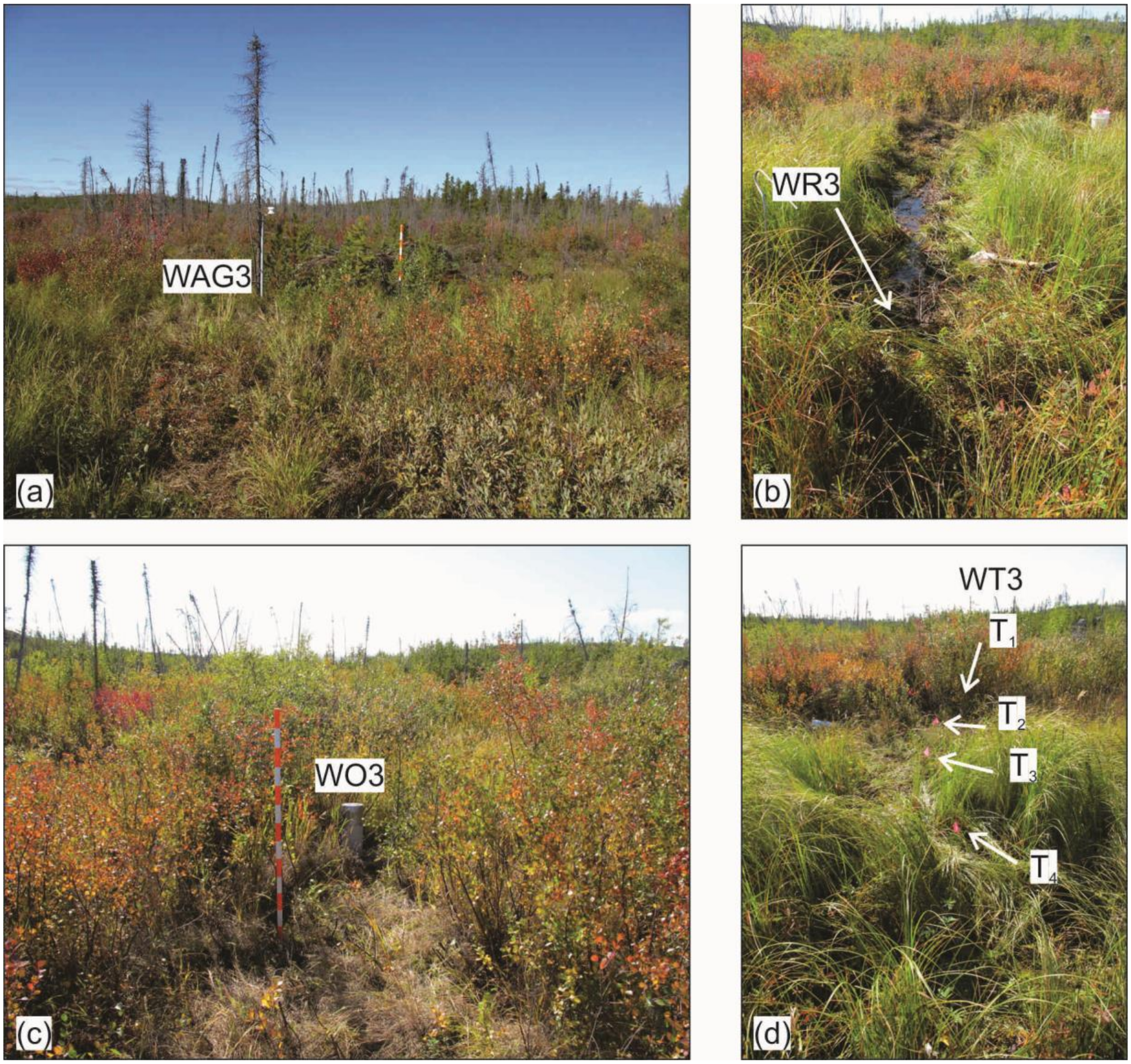

Figure 5.6 Instrumentation sites at P16N: (a) air and ground surface temperature (WAG3); (b) on ROW vertical thermistor string (WR3); (c) off ROW vertical thermistor string (WO3); and (d) horizontal transect (WT3) sensor locations (T_1 – T_4; denoted by pink flags). Photos taken in September 2012.

5.4 Portage 23

The P23 site is at the northern end of the Portage 23 at 369 m a.s.l (Figure 5.7 and Figure 5.8). The portage route at this location is oriented north – south. The site is 225 m downstream from Lake P23 (371 m a.s.l.) at an overall gradient of 0.5º. This portion of the portage is characterized by fen, bog, and a defined watercourse. The width of the fen at the instrumentation site, about 40 m, is constrained to the east by bedrock outcrop and to the west by raised bog that extends about 70 m westward to another bedrock outcrop (Figure 5.7).

The soil stratigraphy at the site consists of peat over bedrock. On the ROW at WR4, there is 112 cm of peat, and the water table was at 20 cm depth in September 2012. Off ROW to the east at WO4-2, the peat layer is 105 cm thick and the frost table was at 51 cm in September 2013. The peat was saturated above and below the frost table. To the west of the ROW, beneath the raised bog at

WO4, 50 cm of unfrozen peat was encountered in September 2012 above peat that was frozen to 130 cm (end of borehole).

The east side of the ROW is vegetated with mosses, graminoids up to 25 cm tall, blueberry (*Vaccinium myrtilloides*) and willow shrubs. The surface of the ROW consists of a scattering of aggregate and exposed peat and is mainly vegetated with graminoids up to 40 cm in height. The bog, which burned in the past (date unknown), is hummocky with mosses, lichen, sedges, blueberry, and willow and birch shrubs that range in height from 10 to 40 cm and constitute the dominant vegetation. A few black spruce trees, 40 to 200 cm in height, are also present. The bedrock outcrop is densely vegetated with black spruce, birch, and lichen.

The thaw depth beneath the road ranged from 47 to 74 cm in September 2012. On the raised bog the thaw depth was 50 cm. East of the ROW, the thaw depth was at 54 to 61 cm depth and bedrock was encountered at depths of 48 to 77 cm.

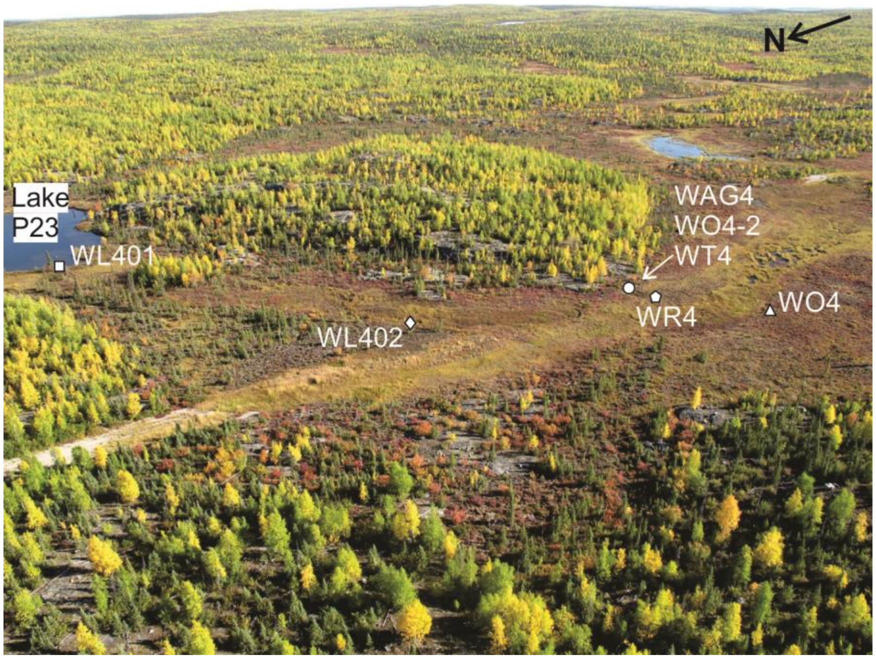

Figure 5.7. Aerial view of instrumentation at P23. Photo taken in September 2012.

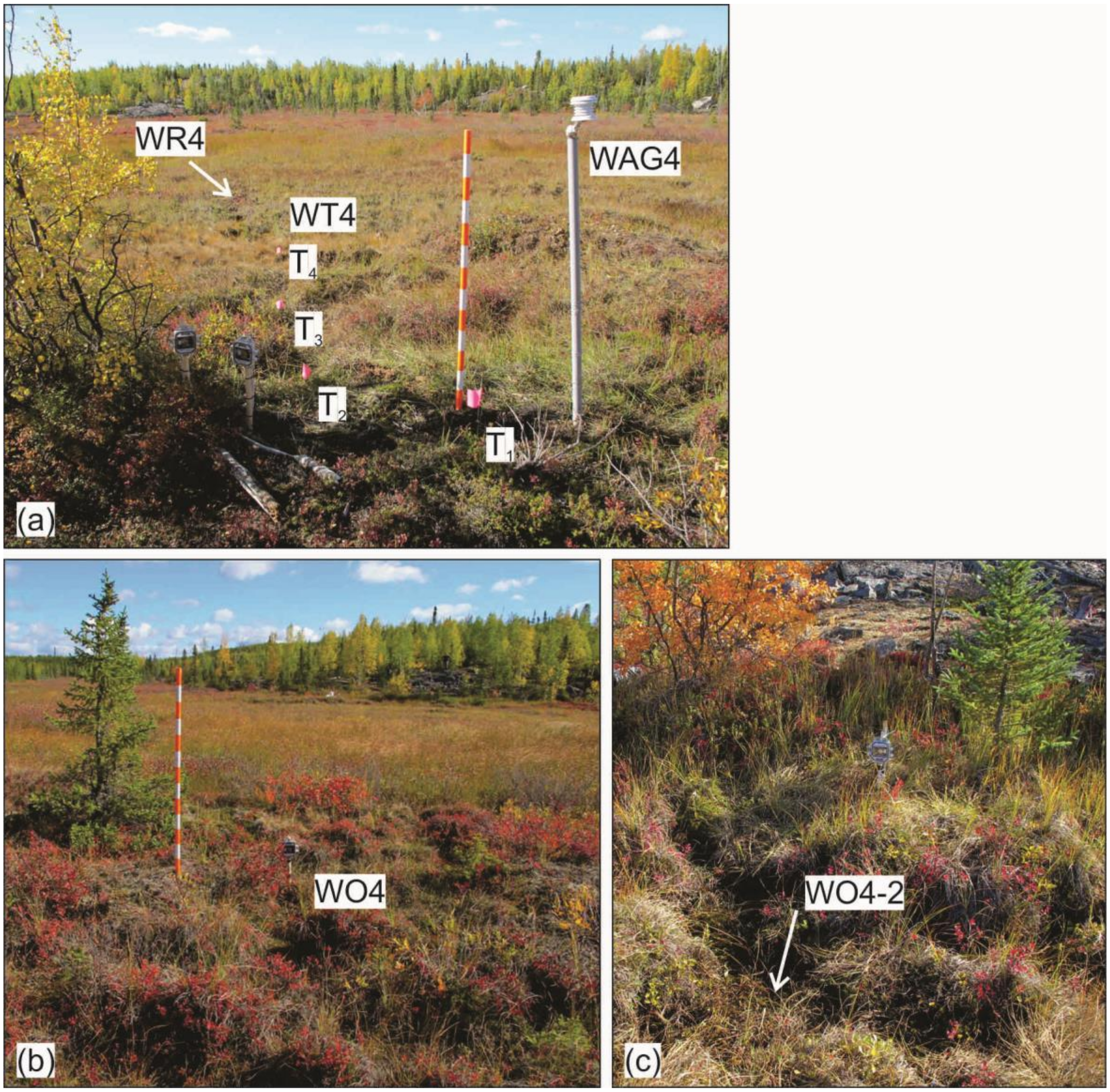

Figure 5.8 Instrumentation sites at P23: (a) air and ground surface temperature (WAG4), on ROW vertical thermistor string (WR4), and horizontal thermistor string (WT4) sensor locations (T_1 – T_4, denoted by pink flags); (b) off ROW vertical thermistor string (WO4); and (c) off ROW vertical thermistor string (WO4-2). Photos (a, b) taken in September 2012 and photo (c) was taken in September 2013.

6 INSTRUMENTATION

6.1 Air and ground surface temperature sites

Air and ground surface temperatures were measured at each site with a dual-channel data logger (HOBO® Pro v2 (U23-004), Onset Computer Corporation) (Table 6.1) installed in September 2012. The external thermistor was mounted within a radiation shield 1.5 m above the ground surface to measure air tempearture and the logger, with its internal sensor, was buried at a nominal depth of 2 – 5 cm below the ground surface. Operational ranges are -40 °C to 70 °C for internal temperature sensors and -40 °C to 100 °C for external sensors. Sensor accuracy is ±0.21 °C from 0 ºC to 50 °C, and sensor resolution is 0.02 °C at 25 °C. Temperatures were recorded continuously at 6-hour intervals (September 2012 to June 2013) and at 1-hour intervals (June 2013 to September 2017).

Table 6.1 Summary of the air and ground surface temperature sites.

Site code	Latitude (°N)	Longitude (°W)	Site description	Available data	Vegetation and organic[1]
WAG1	62.7727	113.2667	Portage 11 – south of ROW	2012-2017[2]	Shrub bog, thick organic
WAG2	62.8690	113.3357	Portage 16 south – north of ROW	2012-2016	Labrador tea and lichen bog, thick organic
WAG3	62.8754	113.3311	Portage 16 north – north of ROW	2012-2016[3]	Graminoid and spruce bog, thick organic
WAG4	63.3441	113.0258	Portage 23 – east side of ROW	2012-2017[4]	Crowberry and lichen bog, thick organic

[1] Organics: Thin (0-10 cm), moderate (11-40 cm), thick (41-100 cm), very thick (>100 cm).
[2] Missing data: 23/07/2014 – 04/09/2014.
[3] Missing data: 11/01/2015 – 12/06/2015 (T air).
[4] Missing data: 20/06/2013 – 05/09/2014.

Dedicated ground surface temperature loggers were installed in September 2013 to capture surface temperature variation on (WR#s) and off ROW (WO#s) (Table 6.2). HOBO Water Temp Pro v2 loggers (U22-001), which contain one internal sensor were placed 2 – 5 cm below the ground surface at the vertical ground temperature sensor locations. The resolution and accuracy of the sensors is similar to the dual-channel logger described above. Temperatures were recorded continuously at 1-hour intervals (September 2013 to June/September 2016).

Table 6.2 Summary of ground surface temperature sites.

Site code	Latitude (°N)	Longitude (°W)	Portage number	Site description	Vegetation and organic[1]
WO1-2s	62.7730	113.2662	11	Undisturbed	Shrub, sphagnum bog, thick organic
WR1s	62.7729	113.2665	11	Disturbed ROW	Bare aggregate, thick organic at depth
WR2s	62.8688	113.3359	16S	Disturbed ROW	Bare aggregate bog, very thick organic
WO3s	62.8752	113.3311	16N	Undisturbed	Shrub, graminoid bog, thick organic
WO4s	63.3440	113.0268	23	Undisturbed	Blueberry, graminoid bog, very thick organic
WO4-2s	63.3440	113.0260	23	Undisturbed	Graminoid, moss fen, very thick organic
WR4s	63.3440	113.0261	23	Disturbed ROW	Graminoid bog, very thick organic

[1] Organics: Thin (0-10 cm), moderate (11-40 cm), thick (41-100 cm), very thick (>100 cm).

6.2 Near-surface ground temperature sites

Near-surface ground temperature measuring equipment was installed in September 2012 and 2013. At each portage a minimum of two vertical thermistor strings up 120 cm depth were installed, one on or near the winter road (WR#) and one off ROW (WO#) (Table 6.3). At each installation, sensors were placed at a depth of 15, 30, 60, and between 100 to 120 cm below the ground surface. Thermistors were installed into vertical holes drilled with a peat auger, except at sites WR1 and WR2 where they were placed directly in the wall of a soil pit that was dug to the frost table and then backfilled. In addition, a horizontal transect (WT#) of four sensors (30 cm depth) was installed spanning the on-to-off ROW transition. These sensors were placed directly into a slit made in the ground with a shovel.

Table 6.3 Summary of near-surface ground temperature sites.

Site code	Latitude (°N)	Longitude (°W)	Portage no.	Sensor depths (cm)	Site description	Vegetation and organic[1]	Frost jacked (mm/yy)[2]
WO1	62.7730	113.2667	11	15, 30, 60, 120	Undisturbed	Graminoid fen, thick organic	N/A
WO1-2	62.7730	113.2662	11	15, 30, 60, 120	Undisturbed	Shrub, sphagnum fen, thick organic	06/16: 47 cm
WR1	62.7729	113.2665	11	15, 30, 60, 120	Disturbed ROW	Graminoid bog, thick organic, covered with ~1 m coarse aggregate in March 2013	N/A
WT1	62.7728	113.2662	11	30, 30, 30, 30	On and off ROW	Graminoid fen (T_1-T_3), covered with ~1 m coarse aggregate in March 2013, shrub, sedge bog (T_4), thick organic	N/A
WO2	62.8690	113.3357	16S	15, 30, 60, 120	Undisturbed	Labrador tea, lichen bog, very thick organic	09/13: 10 cm 06/16: 14 cm
WR2	62.8688	113.3358	16S	15, 30, 60, 120	Disturbed ROW	Bare aggregate bog, very thick organic	N/A
WT2	62.8689	113.3358	16S	30, 30, 30, 30	On and off ROW	Bare aggregate bog (T_1-T_2), Labrador tea bog (T_3-T_4), thick organic	N/A
WO3	62.8752	113.3311	16N	15, 30, 60, 120	Undisturbed	Shrub, graminoid bog, thick organic	09/13: 8 cm 06/16: 22 cm
WR3	62.8752	113.3310	16N	15, 30, 60, 120	Disturbed ROW	Graminoid fen, thick organic	N/A
WT3	62.8753	113.3311	16N	30, 30, 30, 30	On and off ROW	Shrub bog (T_1), graminoid fen (T_2-T_4), thick organic	N/A
WO4	63.3440	113.0268	23	15, 30, 60, 120	Undisturbed	Blueberry, graminoid bog, very thick organic	06/16: 5 cm 09/17: 8 cm
WO4-2	63.3440	113.0260	23	15, 30, 60, 100	Undisturbed	Graminoid, moss fen, very thick organic	09/14: 9 cm 06/16: 19 cm
WR4	63.3440	113.0261	23	15, 30, 60, 120	Disturbed ROW	Graminoid bog, very thick organic	06/16: 19 cm 09/17: 49 cm
WT4	63.3441	113.0259	23	30, 30, 30, 30	Undisturbed	Crowberry bog (T_1), moss bog (T_2-T_3), grass bog (T_4), thick organic	N/A

[1] Organics: thin (0-10 cm), moderate (11-40 cm), thick (41-100 cm), very thick (>100 cm).
[2] Time of reading.
N/A = not observed.

Measurements were made using HOBO® thermistors (HOBO® TMC20-HD and TMC50-HD) that have a range of -40 °C to 50 °C in water; -40 °C to 100 °C in air. Measurements were recorded with HOBO® 4-external channel data loggers (U12-008). The accuracy of the system is ±0.25 °C from 0 °C to 50 °C, the resolution is ±0.03 °C at 20 °C, and the operating temperature range is -20 °C to 70

°C. Measurements were recorded at 6-hour intervals (September 2012 to June 2013), 1-hour intervals (June 2013 to June 2016), and 2-hour intervals (June 2016 to September 2017).

It is important to note that several installations were subject to frost jacking and therefore the sensor depths following the first freezing season do not always represent original installation depths. Installations where frost jacking was observed are noted in Table 6.3.

6.3 Water temperature sites

Water temperatures (WL#) were measured adjacent to P16S and P23, at the bottom of shallow water bodies (Table 6.4). Measurements were made with HOBO® Water Temp Pro v2 (U22-001) loggers with accuracy and resolution as described in Section 6.1.

Table 6.4 Summary of water temperature sites.

Site code	Latitude (°N)	Longitude (°W)	Portage number	Site description
WL8	62.8690	113.3373	16S	Edge of Lake P16-1, ~ 100 cm depth
WL401	63.3453	113.0227	23	Near Lake P23 outlet, ~60 cm depth
WL402	63.3447	113.0254	23	In P23 watercourse, ~60 cm depth

7 DATA SUMMARY

7.1 Air and ground surface temperatures

Table 7.1 summarizes the air and ground surface temperatures at the sites for the study period. The annual mean air temperature (AMAT) ranged from -6.3 °C in 2012-13 to -3.2 °C in 2015-16 at Portage 11 with similar trends observed at the other study sites, which together exhibited slight cooling with latitude. The annual mean ground surface temperatures among the sites were 5.4 to 8.4 °C higher than AMAT over the study period.

7.2 Near-surface ground thermal regime

The temperature envelopes for the sites are shown in Figure 7.1 to Figure 7.4 for the first year after installation, prior to any frost jacking. Table 7.2 summarizes the annual mean temperatures at the top of permafrost (TTOP). As the lowermost thermistor was not always at the top of permafrost per se, the temperature at 120 cm depth was used to calculate TTOP. In general, the minimum temperatures recorded at depth were lower on ROW than off ROW due to snow clearing. Similarly, TTOP was 1.4 to 2.9 °C lower on ROW than off ROW at the same portages.

Table 7.1 Annual (Sept-Aug) mean, minimum, maximum, and freezing season (Oct-Apr) air and ground surface temperatures.

		WAG1		**WAG2**		**WAG3**		**WAG4**	
Annual temperature index	**Year**	**Air (°C)**	**Surface (°C)**	**Air (°C)**	**Surface (°C)**	**Air (°C)**	**Surface (°C)**	**Air (°C)**	**Surface (°C)**
Mean									
	2012-13	-6.3	-0.9	-6.4	-0.5	-6.8	1.6	-	-
	2013-14	-	-	-6.2	-0.4	-6.6	1.3	-	-
	2014-15	-5.1	2.0	-5.1	-0.4	-	0.6	-6.5	-1.0
	2015-16	-3.2	3.6	-	-	-	-	-4.9	1.4
	2016-17	-3.4	3.0	-	-	-	-	-5.1	0.5
Minimum									
	2012-13	-40.8	-15.0	-41.1	-16.6	-40.6	-7.7	-41.8	-12.1
	2013-14	-43.2	-12.9	-42.6	-13.7	-43.2	-8.6	-	-
	2014-15	-42.9	-9.1	-39.6	-14.0	-	-8.2	-39.7	-13.8
	2015-16	-42.4	-4.4	-39.9	-10.9	-40.2	-4.2	-41.8	-6.7
	2016-17	-38.5	-6.9	-	-	-	-	-39.7	-10.0
Maximum									
	2012-13	23.7	14.8	23.2	16.0	22.5	14.4	16.9	12.6
	2013-14	-	14.6	22.5	14.5	22.2	14.4	-	-
	2014-15	22.3	17.9	21.8	14.0	20.9	10.9	19.1	11.9
	2015-16	25.1	18.9	-	-	-	-	24.0	12.5
	2016-17	23.8	17.5	-	-	-	-	22.7	12.5
Freezing season mean									
	2012-13	-18.7	-6.9	-19.1	-6.5	-19.4	-2.6	-20.0	-4.1
	2013-14	-19.1	-5.9	-19.1	-5.9	-19.4	-3.2	-	-
	2014-15	-17.1	-3.2	-17.1	-5.6	-	-3.2	-18.2	-6.1
	2015-16	-14.7	-1.5	-15.0	-3.8	-15.1	-1.5	-16.1	-2.5
	2016-17	-15.2	-6.9	-	-	-	-	-16.7	-10.0

"-" indicates insufficient data.

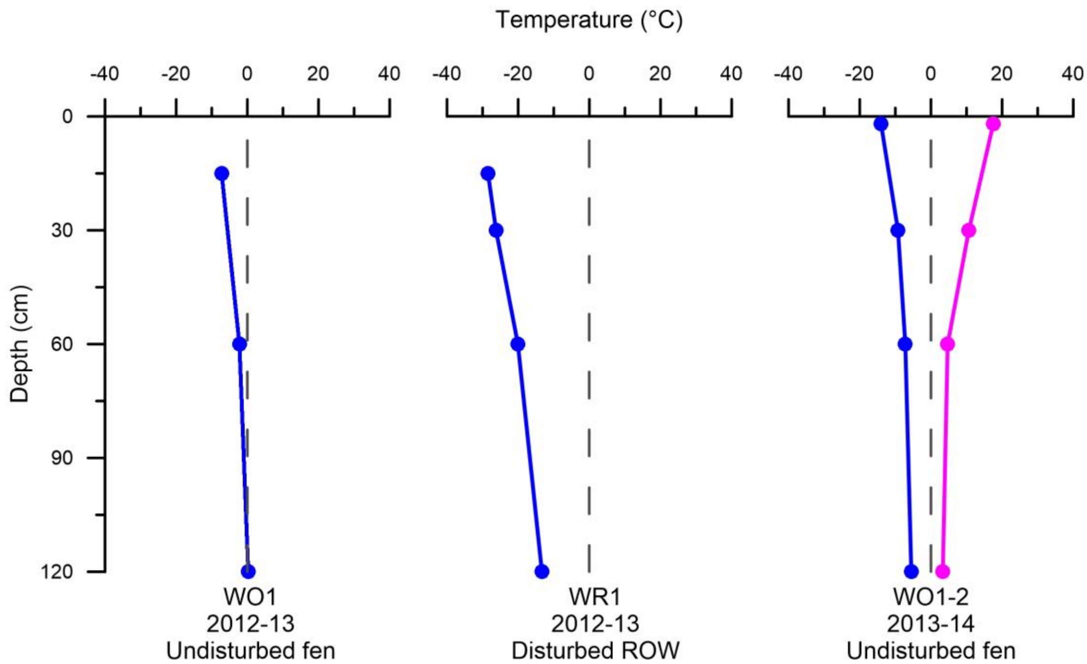

Figure 7.1 Temperature envelopes for the sites at P11.

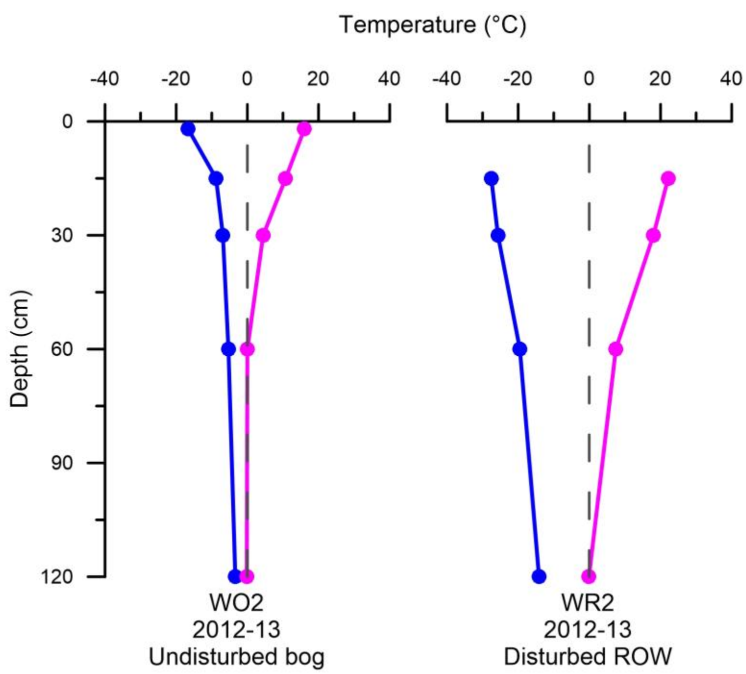

Figure 7.2 Temperature envelopes for the sites at P16S.

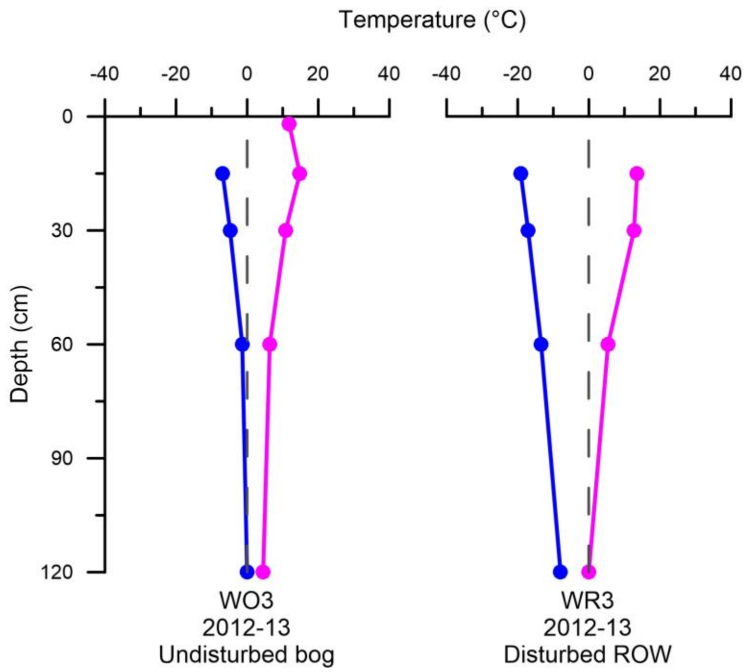

Figure 7.3 Temperature envelopes for the sites at P16N.

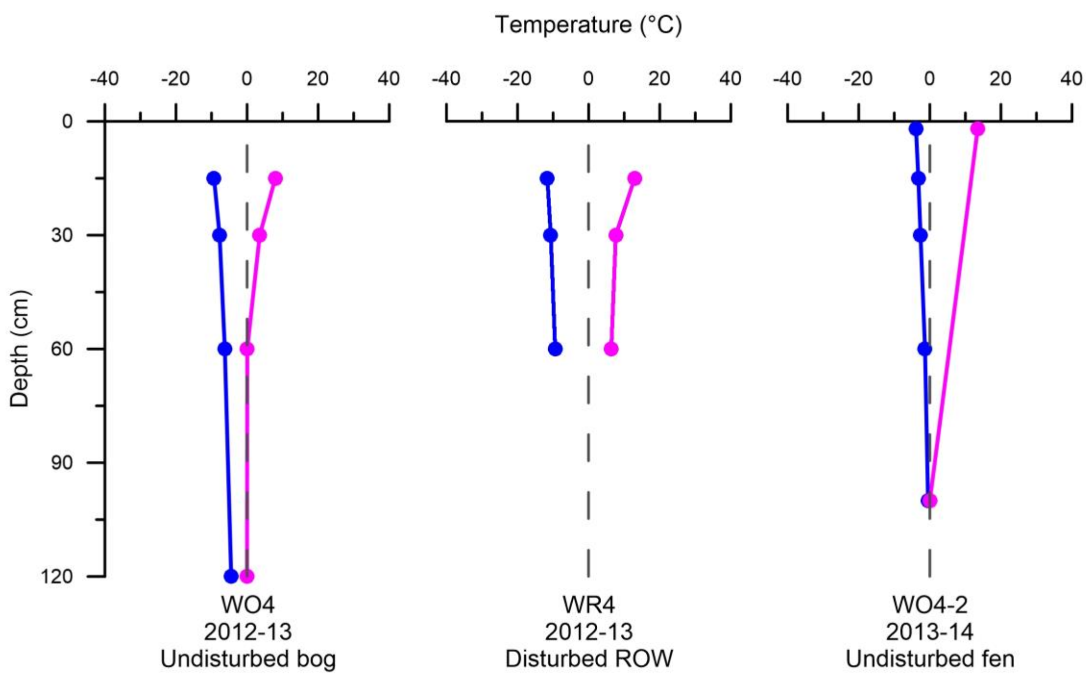

Figure 7.4 Temperature envelopes for the sites at P23.

Table 7.2 Temperatures at the top of permafrost (TTOP) for the study period.

	TTOP (°C)									
Year	**WO1**	**WO1-2**	**WR1**	**WO2**	**WR2**	**WO3**	**WR3**	**WO4**	**WO4-2**	**WR4**
2012-13	-	-	-	-1	-3.4	0.0	-1.4	-1.4	-	-
2013-14	-	-0.5	-	-1.2	-3.5	0.0	-2.9	-1.5	-0.1	-2.7
2014-15	-	-1.3	-	-1.3	-3	-0.3	-2.8	-2.3	-1.0	-2.6
2015-16	-	1.2	-	-	-	-	-	-0.5	-0.1	-
2016-17	-	0.6	-	-	-	-	-	-0.8	-0.2	-

"-" indicates insufficient data.

7.3 Active-layer freezeback

The initiation and completion of active-layer freezeback were determined when the daily mean ground surface temperature dropped below 0 ºC, and when TTOP dropped below -0.5 ºC, respectively (Table 7.3). Ground surface temperatures at WAG sites were used to determine the start of freezeback in 2012-13 and 2016-17. During the study period, the duration of active-layer freezeback varied from 70 to 187 days.

Table 7.3 Active-layer freezeback timing and duration.

Index	**Year**	**WO1**	**WO1-2**	**WR1**	**WO2**	**WR2**	**WO3**	**WR3**	**WO4**	**WO4-2**	**WR4**
Freezeback start											
	2012-13	10-Oct	-	10-Oct	09-Oct	09-Oct	13-Oct	13-Oct	12-Oct	-	12-Oct
	2013-14	-	20-Oct	23-Oct	18-Oct	18-Oct	15-Oct	03-Nov	14-Oct	15-Oct	14-Oct
	2014-15	-	03-Oct	25-Oct	03-Oct	13-Oct	07-Oct	02-Nov	04-Oct	04-Oct	06-Oct
	2015-16	-	11-Oct	08-Oct	08-Oct	08-Oct	09-Oct	23-Oct	09-Oct	08-Oct	09-Oct
	2016-17	-	22-Oct	-	-	-	-		12-Oct	12-Oct	12-Oct
Freezing front passes 120 cm depth											
	2012-13	-	-	09-Jan	13-Jan	19-Jan	#	22-Feb	24-Jan	-	-
	2013-14	-	13-Feb	-	14-Jan	21-Jan	#	04-Feb	27-Jan	20-Apr	17-Jan
	2014-15	-	15-Jan	-	05-Jan	16-Jan	21-Feb	18-Jan	22-Dec	28-Jan	04-Feb
	2015-16	-	DNF	-	17-Dec	07-Feb	11-Mar	28-Feb	29-Mar	#	18-Mar
	2016-17	-	-	-	-	-	-	-	23-Feb	13-Apr	26-Jan
Freezeback duration (d)											
	2012-13	-	-	91	96	102	-	132	104	-	-
	2013-14	-	116	-	88	95	-	93	105	187	95
	2014-15	-	104	-	94	95	137	77	79	116	121
	2015-16	-	-	-	70	122	154	128	172	-	161
	2016-17	-	-	-	-	-	-	-	134	183	106

DNF = did not freezeback; "#" = temperature was <0 °C but >-0.5 °C; "-" = insufficient data.

8 DATA PRESENTATION AND DATABASE STRUCTURE

An accompanying database presents all temperature data collected between 2012 and 2017, in comma delimited format. The data have been visually inspected and where obvious, erroneous data values have been removed. Each parameter measured is located in a separate directory. The file name convention refers to the site code (Table 6.1 to Table 6.4). The following section provides a description of the fields in the data files.

Directories:

\Data\Air_ground	Air and ground surface temperature
\Data\Ground_surface	Ground surface temperature
\Data\Near_surface	Near-surface ground temperature
\Data\Water	Water temperature

Filename convention: SiteCode.csv

Heading	Description
Site Code:	Unique site identifier
Date Time:	Date and time field (yyyy-mm-dd hh:mm)
T air (Celsius):	Air temperature (°C)[1]
T surface (Celsius):	Ground surface temperature (°C)[1]
T at D X m (Celsius):	Temperature (°C) at specified Depth X in metres[1]
TY at D X m (Celsius):	Temperature (°C) for sensor Y at specified Depth X in metres[1]

[1] N/A indicates that no values were available for that reading.

9 SUMMARY

A field campaign was conducted in 2012-2017 to collect baseline thermal data at three portages along the Tibbitt to Contwoyto Winter Road, Great Slave region, Northwest Territories. A digital database of air, ground surface, near-surface ground, and water temperature data collected is provided, herein. The public availability these data facilitates improved characterization of near-surface ground conditions and assessments of climate change impacts on operation of transportation infrastructure in the Great Slave region. The sites at Portage 16 (P16S and P16N) were decommissioned in June 2016 and the site at Portage 11 (P11) was decommissioned in September 2017. Data will continue to be collected at Portage 23 (P23) to support continued investigations on temporal changes in near-surface ground thermal conditions.

10 ACKNOWLEDGEMENTS

This work was supported by Natural Resources Canada Climate Change Geoscience and the Polar Continental Shelf programs. In kind support was provided by a number of personnel including Clint Ambrose and Nahum Lee of Indigenous and Northern Affairs Canada; Ron Near of Diavik Diamond Mines Inc.; Tim Tattrie of Nuna Logistics Ltd.; Art Blum and Kirk Keller of Dome Lake Camp; Shawne Kokelj of Northwest Territories Water Resources; Steve Kokelj of Northwest Territories Geological Survey; and Rick Hoos of EBA Engineering Consultants Ltd. Review comments by Sharon Smith at the GSC improved this open file.

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