Multi-decadal degradation and persistence of permafrost in the Alaska Highway corridor, northwest Canada (Supplementary materials)

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1. Methods used to re-locate Brown’s (1967) sites

Roger Brown’s unpublished daily journal, to which his family gave access, shows that he drove from Whitehorse to Fort St. John and back from September 4-20, 1964, making observations in both directions. Site locations in Brown (1967) were recorded using milepost (MP) numbers along the Alaska Highway to a precision of 0.1 miles (0.16 km) and these are presumed to have been derived from the vehicle odometer in combination with highway markers. Maps (scale 1:50,000 to 1:250,000) showing the highway in 1965, the year after Brown’s survey, as well as planned re-alignments (Department of Public Works, 1966) were used to convert Brown’s MP numbers into UTM co-ordinates which were stored on a hand-held GPS (Garmin Etrex Summit). Site photographs taken by Brown and archived at the National Research Council of Canada in Ottawa were also utilized for site location (Figure S1).

Areas on either side of the highway for a distance of 1 km, centred on the preliminary co-ordinates, were inspected to locate a site that appeared similar to that shown in a photograph (if available) and/or to the description of terrain, vegetation and drainage given in Brown (1967). Brown’s sampling was not random, as almost 60% of his sites exhibited permafrost while the regional average is much less than 50% (see Bonnaventure et al., 2012). Consequently, we focused on sites that appeared visually to be the most likely to be underlain by permafrost. The sites themselves were all located in terrain that was far enough from the road not to have been disturbed by highway construction, maintenance or dust. It is possible that the highway has altered drainage in its immediate vicinity but culverts are numerous and obvious impacts of this type were not observed at the field sites.

In a small number of cases, we were not confident in the relocation of a site due to an insufficiently detailed description in Brown (1967) or a major change in land cover, such as conversion of spruce forest to arable land. Results from those sites were not
included in our dataset. Some sites, mostly in the southern part of the transect, were inaccessible due to changes in the highway alignment.

2. Methods to detect frozen ground and other site observations

At each site, the presence or absence of frozen ground was determined manually to a depth of 2 m or to the frost table (whichever was shallower), using a shovel to excavate pits in combination with a 1.2 m long, 1 cm diameter frost probe. Two instantaneous ground temperature profiles were measured at each site, approximately 5 m apart, to a depth of 1.5 m or to the frost table if shallower. Measurements of organic mat thickness and active layer thickness (where permafrost was present) were made along at roughly 1 m intervals along a transect about 10 m long. Vegetation type and species, organic mat thickness, relief and substrate were recorded, and soil samples collected.

The full thickness of the organic layer was not ascertained at permafrost sites where the frost table was reached first, nor at non-permafrost sites where the organic layer was thicker than 1.2 m (the probe length).

Where permafrost was not found in a first attempt at a given site, two other likely locations were inspected and sampled in the same 1 km stretch of highway before concluding that it was absent.

3. Measurement of air and ground surface temperatures at monitoring sites

Hourly shielded air temperatures (at 1.5 m above the ground surface) and ground surface temperatures were recorded using Hobo data loggers equipped with an external thermistor (either model H08-03-08 or U23-003, both with accuracy ±0.2°C) (Onset Computer Corporation, 2013a, b). Active layer temperatures were recorded using H-08 four-channel data loggers (accuracy ±0.5°C; Onset Computer Corporation, 2013c). All of the stations nominally have records extending up to August 2012 but there are a number of breaks due to logger malfunction or damage caused by animals. Average values for a “blended” year were calculated to maximize the use of the records available: the average of each complete month was used to establish the average for each month of the year, and the MAAT was obtained by averaging all of the monthly means.
4. Measurement of borehole temperatures

Between 2008 and 2010, shallow boreholes were drilled at three of the monitoring sites using the water-jet method, and were cased with 25 mm diameter iron pipes and instrumented. At MP825.2, a multi-thermistor cable connected to an eight channel logger (RBR Ltd., Canada; measurement system accuracy ±0.1°C) was installed to a depth of 4 m in September 2008. Hobo U23-003 loggers with external thermistors were installed in boreholes at MP 286.0 (to 2.4 m in August 2009) and at MP 788.5 (to 3.75 m in August 2010). The casing and loggers were housed inside a 100 mm diameter PVC pipe painted white which shields the casing from direct insolation.

5. Geophysical methods

Electromagnetic (EM) induction surveys were used to infer permafrost presence or absence and to estimate its thickness at selected sites (see Hauck and Vonder Mühll, 1999; Kneisel et al., 2008; Sartorelli and French, 1982). An EM31 instrument (Geonics Limited, Canada), which generates secondary electromagnetic fields in regions of elevated electrical conductivity (McNeill, 1980), was used at 11 sites in August 2008, some with frost tables identified by probing and some without. Measurements were made along a 10 point transect, with 4 m between transect points. The EM31 was operated in both horizontal and vertical dipole configurations at two different operating heights (Geonics 2005; Sartorelli and French 1982). Using this method, evidence of terrain layering (unfrozen, unfrozen/frozen, unfrozen/frozen/unfrozen) can be inferred to a depth of approximately 6 m.

Electrical resistivity tomography (ERT) was carried out at two of the climate monitoring sites in September 2008 (Lewkowicz et al., 2011) and at these and eight other sites in August 2010 and 2012 to complement the EM31 surveys. ERT surveys utilized an ABEM Lund multi-electrode system in 2008 and an ABEM Terrameter LS system in 2010/2012, with a 1 m electrode spacing (40 m or 80 m profile length) or a 2 m electrode spacing (160 m profile), in each case deployed in a Wenner array. Maximum investigation depths were about 6 m, 13 m and 25 m, respectively. Profiles were topographically corrected and data were processed with RES2DINV software (Loke and Barker, 1996; Loke et al., 2003) using a robust inversion that attempts to respond to the
rapid transitions and high contrasts in resistivity that exist between frozen and unfrozen ground.

6. Association between organic layer thickness and permafrost

Organic layer thickness was measured at all of the study sites. However, these data could not be analysed for statistical differences between permafrost and non-permafrost sites because the true thickness could not be determined at many of the former due to a shallow frost table. Nevertheless, some differences were evident. The organic layer was generally thinner (median thickness 30 cm) at sites that did not exhibit permafrost in both 1964 and 2007-2008 compared to sites where permafrost was present in at least one of the surveys (Figure S4).

The median value for sites where permafrost thawed between surveys (median thickness of 55 cm) was actually greater than where it persisted (median thickness of 49 cm). This may be because the latter value was influenced by the position of the frost table: median depth to frost table was 51 cm where the frost table was within the organic layer, whereas the median organic layer thickness was 40 cm where the frost table was below the base of the organic layer.

Organic layer thickness, therefore provides a partial explanation for why some sites did not have permafrost in either survey: permafrost was usually absent in both surveys where the organic layer was thin. A thick organic layer was typically needed for permafrost to be present in 1964, but meeting this condition did not guarantee permafrost presence nor that it would persist to 2007-2008.

7. Influence of forest fire

Forest fire may be a confounding variable when trying to determine whether permafrost has degraded due to climate warming. Forest fire data from British Columbia (1940-2008) (Wildfire Management Branch, Government of British Columbia, 2009) and the Yukon (1946-2008) (Wildlands and Fire Management Branch, Government of Yukon, 2008) were compiled. The quality of these data varies due to differing collection methods and older data (1940s to 1960s) is considered incomplete with fires being poorly
mapped. In addition, areas could have remained unburned within the exterior burned perimeter.

Sites influenced by fire fell into four of the six potential categories based on the initial and final frozen ground state and whether the fire preceded the 1964 survey or occurred afterwards (Table S1). Fire can cause an increase in soil temperature and active layer thickness, and subsequent permafrost degradation (Burn, 1998; Burn, 2004; Mackay, 1995; Yoshikawa et al., 2002) but its effect varies according to fire type (crown, surface, or ground) and severity (Stocks et al., 2002). Fires that cause loss of vegetation reduce shade and evaporation, raising the ground surface temperature and destruction of canopy cover can result in increased snow cover (Burn, 2004; Mackay, 1995). Burning of the organic cover can result in up to 50% reduction in surface albedo (Yoshikawa et al., 2002). The dependence of the warm permafrost in the study transect on favourable surface conditions, such as a thick organic layer, makes it vulnerable to thaw after forest fire (Burn, 2004; Yoshikawa et al., 2002).

Brown (1967) described three sites as being ‘burned over’, presumably meaning that the impacts of fire were obvious at the time of his investigation. Based on the locations of these sites in relation to the fire boundaries, they had been burned respectively in 1944, 1950 and 1958. Signs of fire, such as burn scars on tree trunks and charred material in the organic layer, were observed at 17 of the 55 study sites during 2007-2008, including the three listed by Brown (Table S1). At least seven of the non-permafrost sites had been affected by fire, with a further three sites that are close to boundaries of fires. Vegetation succession and the regeneration of the organic layer could potentially lead to permafrost re-forming after it has been degraded by fire (Yoshikawa et al., 2002), but this did not happen at any of the sites. No site that had permafrost in 1964 was affected by fire after Brown’s survey. However at sites burned prior to 1964, at least three sites maintained permafrost between the two surveys while at least seven sites lost permafrost.

The pre-1964 fires could have had a lagged effect at the permafrost sites (see Burn, 1998) resulting in degradation by 2007-2008 (category 5 in Table S1). However, active layer thickness in 1964 was 41-61 cm, organic layers ranged in thickness from 30-162 cm at these sites (Brown, 1967), and the vegetation canopy included spruce trees 6 to
20 m high. Given the uncertainty in the fire maps, it is possible that the sites themselves had not been affected significantly. The relatively thin active layers observed 14 to 20 or more years after potential burning indicates that it is unlikely that permafrost loss after 1964 was directly caused by fire. The exception is site MP 219.6 where the fire occurred in 1958, leading to the ‘burned over’ description by Brown (1967). That site had very thin permafrost with a 53 cm active layer and a 100 cm organic layer and it may have been degrading at the time of his survey. This site subsequently lost near-surface frozen ground affecting the statistics in Table 2.

In summary, no sites lost permafrost due to fires between the two surveys. At least one may have experienced permafrost degradation as a result of fires prior to 1964 but some sites apparently subjected to fire pre-1964 maintained permafrost. Given descriptions of the sites in 1964, it is concluded that the impact of fire on permafrost change through to 2007-2008 has been slight.

8. References

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Table S1. Fire disturbance to sites along the study transect based on field evidence and compiled GIS.

| Category                        | 1                          | 2                          | 3                          | 4                          | 5                          | 6                          |
|---------------------------------|----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Frozen ground condition         | Permafrost absent in both surveys | Permafrost present in both surveys | Permafrost present in 1964 and absent in 2007-2008 |
| Timing of fire                  | Prior to 1964              | 1964 to 2007-2008          | Prior to 1964              | 1964 to 2007-2008          | Prior to 1964              | 1964 to 2007-2008          |
| Number of sites in 2007-2008 survey b | 5 + 1                      | 2 + 2                      | 3 + 2                      | 0                          | 7 + 2                      | 0                          |
| Total sites (burned and unburned) in frozen ground condition | 24                          | 16                          | 15                          |                            |                            |                            |

a Two other possible categories, representing fire effects on sites with permafrost absent in 1964 and present in 2007-2008, were not observed in the field.

b Number of sites before the plus sign are those where signs of fire were observed in the field. Those after the plus sign had no signs of fire observed in the field but are inside or very close to fire polygons in the compiled GIS.
Figure S1: Digital Elevation Model (DEM) of the study transect and adjacent areas along the Alaska Highway extending approximately 1330 km from Fort St. John, BC to Whitehorse, YT. (Source: Geomatics Yukon DEM, 2006; Geobase, 2010). Monitoring stations set up in 2007 are numbered from south to north (see Table 4).
Figure S2. Example of a study site (MP 394.5) relocated using archival photos: (left) from Roger Brown’s photo in 1964 and (right) photographed in 2007.
Figure S3. Vegetation and terrain at selected study sites: (A) MP 286.0: open black spruce forest over thin permafrost where disturbance associated with water-jet drilling caused local thaw through the frozen layer; (B) MP 400.5: stunted black spruce cover is a good indicator of the presence of permafrost and the ERT results show it to be >25 m thick at this site; (C) MP 788.5: sedge vegetation in the foreground is over seasonally frozen, poorly drained soils while people are standing on a low peat plateau underlain by up to 15 m of permafrost; (D) MP 844.1: tall spruce forest overlies 4 m of permafrost in gravelly materials beneath a thick organic mat.
Figure S4. Box-plots of organic layer thickness at sites along the transect. Black square - minimum thickness; diamond - first quartile; horizontal line in the middle of the box – median; black circle - third quartile; x - known maximum values. At sites with permafrost, the frost table was frequently encountered within the organic layer, so its full thickness could not be measured. At non-permafrost sites, some organic layers extended beyond the maximum probe length, resulting in only minimum values for organic layer thickness. Where maximum values are unavailable for these reasons, known thicknesses are shown by the upper end of the vertical line and question marks are used.
Figure S5. ERT surveys and frost probing on August 13-14, 2012: (A) site MP 286.0 showing patchy permafrost 1-5 m thick, typical of conditions along the transect. The ground temperature monitoring borehole at MP 286.0 (see Table 5) where thaw occurred following drilling is located at 20 m along the survey but 5 m away from the actual line; (B) site MP 400.5 which has the thickest permafrost observed, exceeding 25 m in the first half of the profile. The same colour scale is used on both parts of the figure. The horizontal scales are in metres and there is no vertical exaggeration on the ERT profiles, but the vertical and horizontal scales are not the same for both parts of the figure. The apparent resistivity value representing the boundary between frozen and unfrozen conditions is at about 300-400 ohm m (between yellow and olive green) and the interpreted base of permafrost is shown by a dashed line. The vertical scale for frost table depths is in cm. Maximum measurable frost-table depth is 120 cm (the length of the probe). In some places, the frost table could not be identified because of clasts in the soil or a very hard substrate (areas without a line).