Effects of 45 years of heavy road traffic and climate change on the thermal regime of permafrost and tundra at Prudhoe Bay, Alaska

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I INTRODUCTION

Following the discovery of oil at Prudhoe Bay in 1968, a series of environmental changes occurred that were the result of natural long-term processes and changes caused directly and indirectly by infrastructure. Here we examine changes associated with a road at Colleen Site A, Deadhorse, Alaska (**Fig. 1**).

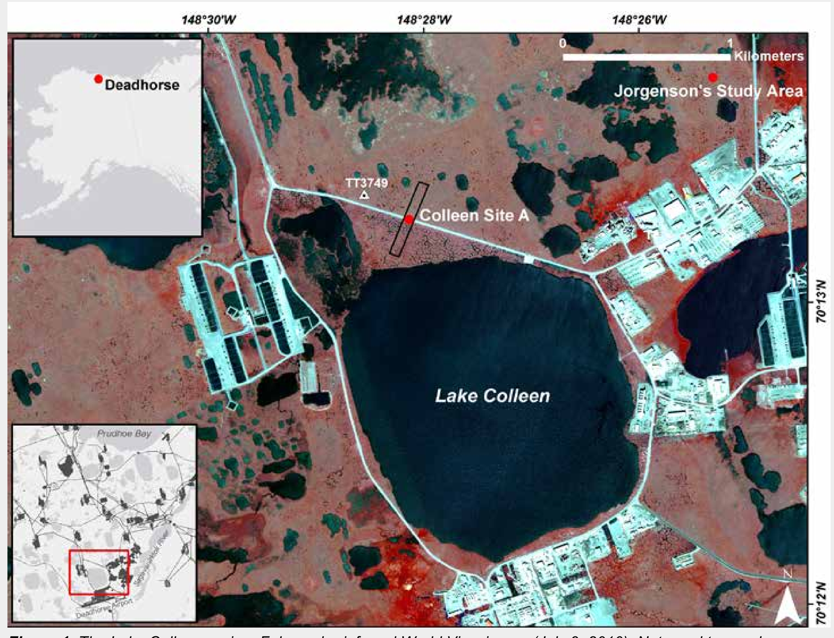

Figure 1. The Lake Colleen region. False-color-infrared World View image (July 9, 2010). Note: red tones show areas of highly productive vegetation.

Most changes in landscapes along roads are caused by a combination of (a) **flooding** due to the elevated road beds that interrupt natural drainage flow patterns; (b) heavy **road dust**, which smothers the vegetation and changes the albedo of the tundra surface; and (c) **snow banks** that form along the edges of the elevated roads. All of these factors tend to raise soil temperatures, which in turn increase the active layer thickness near roads, leading to roadside thermokarst (**Fig. 2**).

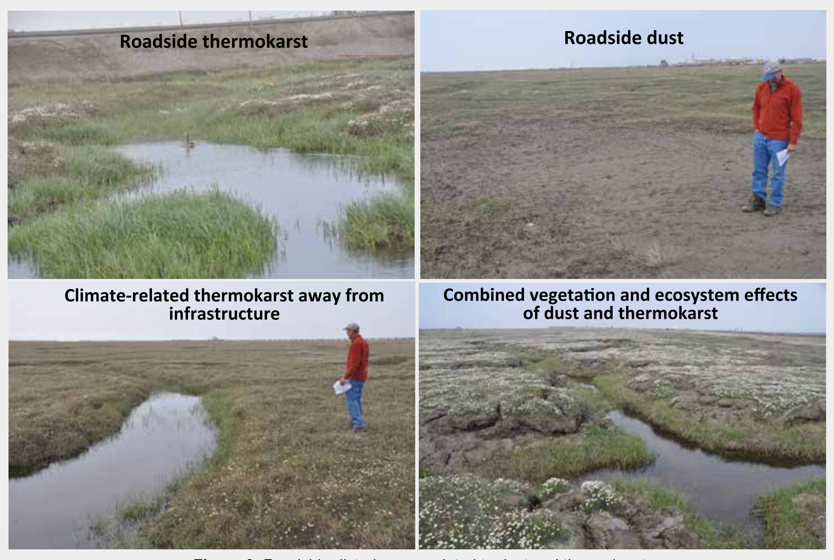

Figure 2. Roadside disturbances related to dust and thermokarst.

II METHODS

This study, initiated in 2014, builds on baseline data collected in the same area by Walker *et al.* 1980. A time series of aerial photographs of Colleen Site A was used to show the transition of the landscape between 1968 and 2013 (**Fig. 4**). Aerial photographs of 1972 and 2013 were used to produce a vegetation change map (**Fig. 7, 8**) (aerial photograph of 1968 was not available to the time of the analysis).

Vegetation plots along two transects were set up in polygon centers and troughs at 5, 10, 25, 50, 100 and 200 m from both sides of the heavily-traveled Spine Road at Colleen Site A to analyze road effects. Differential GPS and a robotic TotalStation were used to survey the transects (**Fig. 9**). Soil and vegetation data were collected at 1 m intervals within 100 m of the road and at 5 m intervals from 100 to 200 m from the road (**Fig. 9, 11, 12**). Fifty-seven boreholes were drilled in ice-wedge polygon centers and troughs (**Fig. 10**). One hundred and thirty Thermochron® Temperature Data Loggers (iButtons) were installed to monitor air and ground temperatures and determine ice-wedge stability (**Fig. 13**).

Figure 3. Drilling of cores in ice-wedge polgon center and troughs.

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Acknowledgements

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III TIME SERIES OF THE LAKE COLLEEN SITE A FROM 1968 TO 2013

An abrupt increase in the abundance of thermokarst features is evident in the time series analysis of aerial photos from 1968 to 2013 of the Lake Colleen Site A (**Fig. 4**). This effect has also been noted in three studies in the Prudhoe Bay area. (Jorgenson *et al.* 2006; Raynolds *et al.* 2014, Jogenson *et al.* 2015).

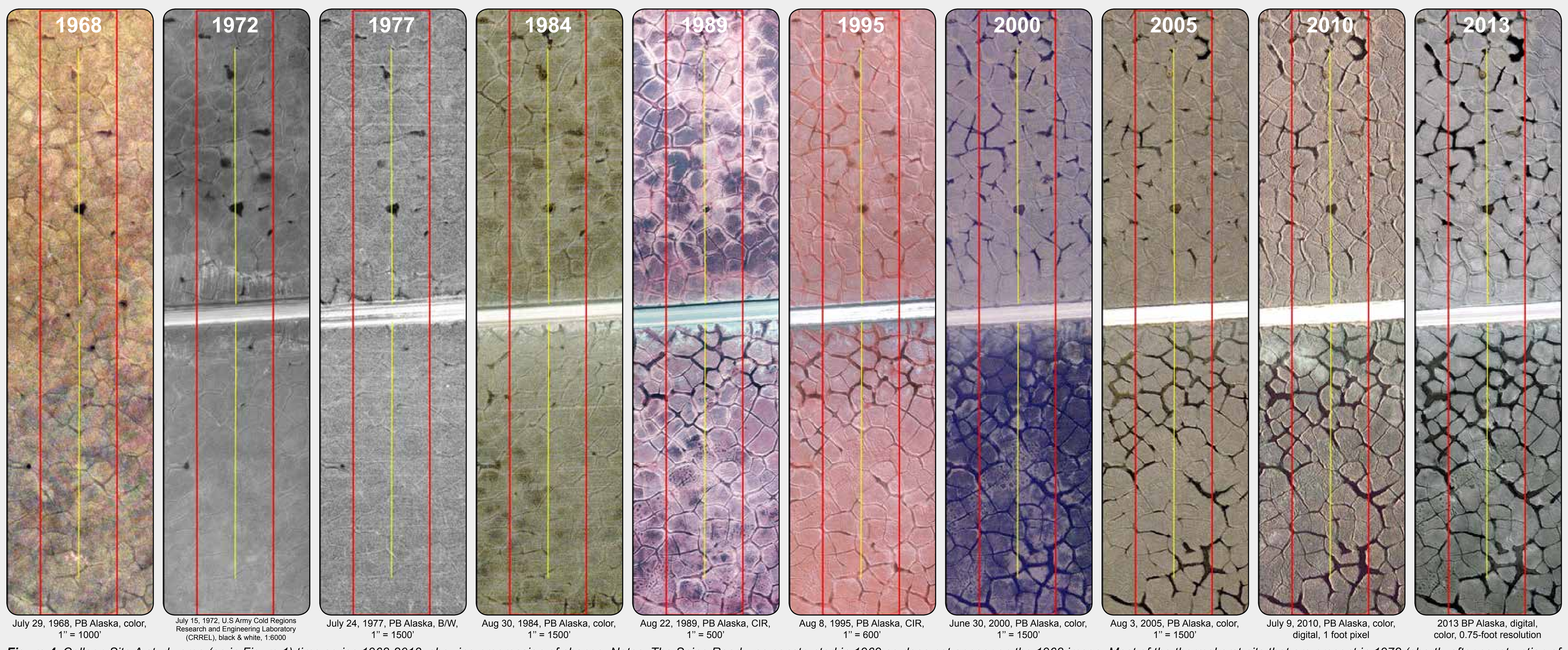


Figure 4. Colleen Site A study area (as in Figure 1) time series 1968-2013, showing progression of change. Notes: The Spine Road was constructed in 1969 so does not appear on the 1968 image. Most of the thermokarst pits that are present in 1972 (shortly after construction of the road) are also visible on the 1968 image. Greatly expanded thermokarst is seen beginning in 1989.

The changes in non-infrastructure-related thermokarst are thought to be due to a combination of a long-term upward trend in summer warmth and exceptionally warm summers in 1989, 1998, and 2012 when the active layer (layer of soil that thaws in summer) increased in thickness and melted the tops of ice wedges (**Fig. 5, 6**).

Prior to road construction in 1969, the north side of the road had more wet tundra and thermokarst pits than the south side of the road (**Fig. 7**). After the road was built, extensive deep thermokarst developed along polygon troughs on the south side of the road and aquatic vegetation increased. Other more subtle changes occurred to the species composition of the major vegetation types (**Fig. 8**).

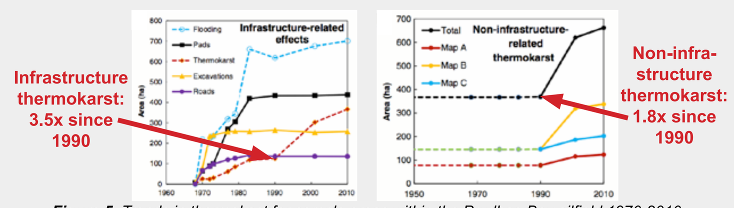


Figure 5. Trends in thermokarst for sample areas within the Prudhoe Bay oilfield 1970-2010.

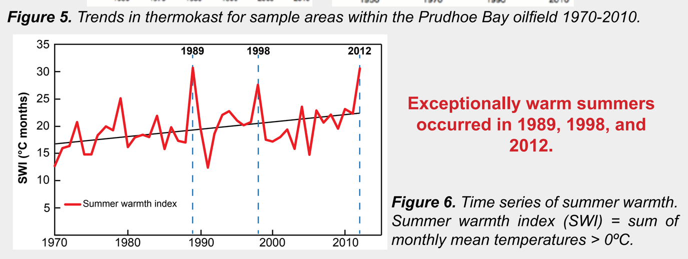
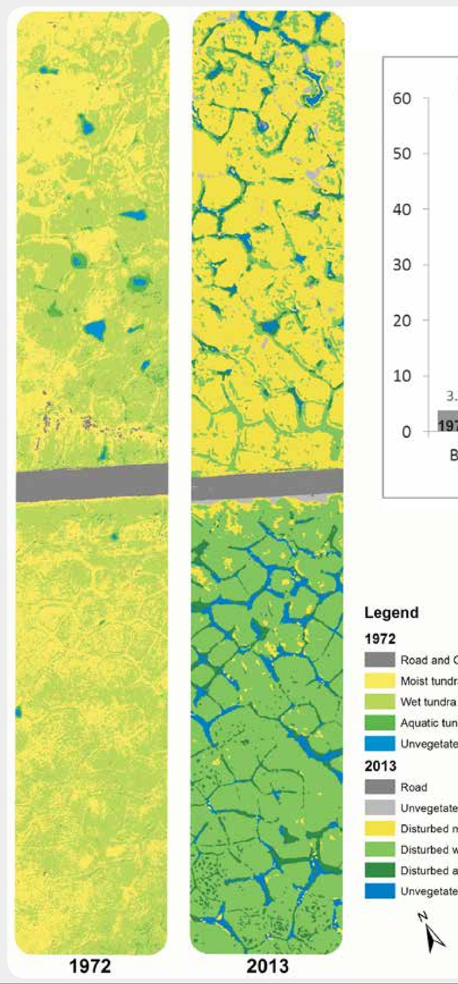


Figure 6. Time series of summer warmth. Summer warmth index (SWI) = sum of monthly mean temperatures > 0°C.



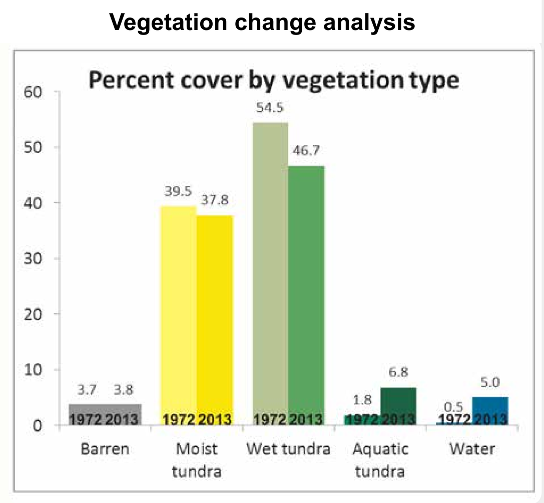


Figure 8. Comparison of the main vegetation types between 1972 and 2013.

Figure 7. Classification of the main vegetation types of the aerial photos from 1972 and 2013.

IV TRANSECT ANALYSIS

A visualisation of all collected geo-ecological parameters along the transects T1 (north) and T2 (south) at 1 m intervals within 100 m of the road and at 5 m intervals from 100 to 200 m from the road can been seen in **Figure 9**. In detail, aerial photography from 2014 is shown at the top of **Fig. 9**, with cross-sectional transect of surface elevation, vegetation height, thaw and water depth (b); surface geomorphology and vegetation type (c); probed thaw depth, LAI, and depth of surface dust layer (d); and comparison of the field survey to LiDAR data (e). The interpretations of ice-wedge cross-sections based on borehole profiles is seen in **Figure 10**.

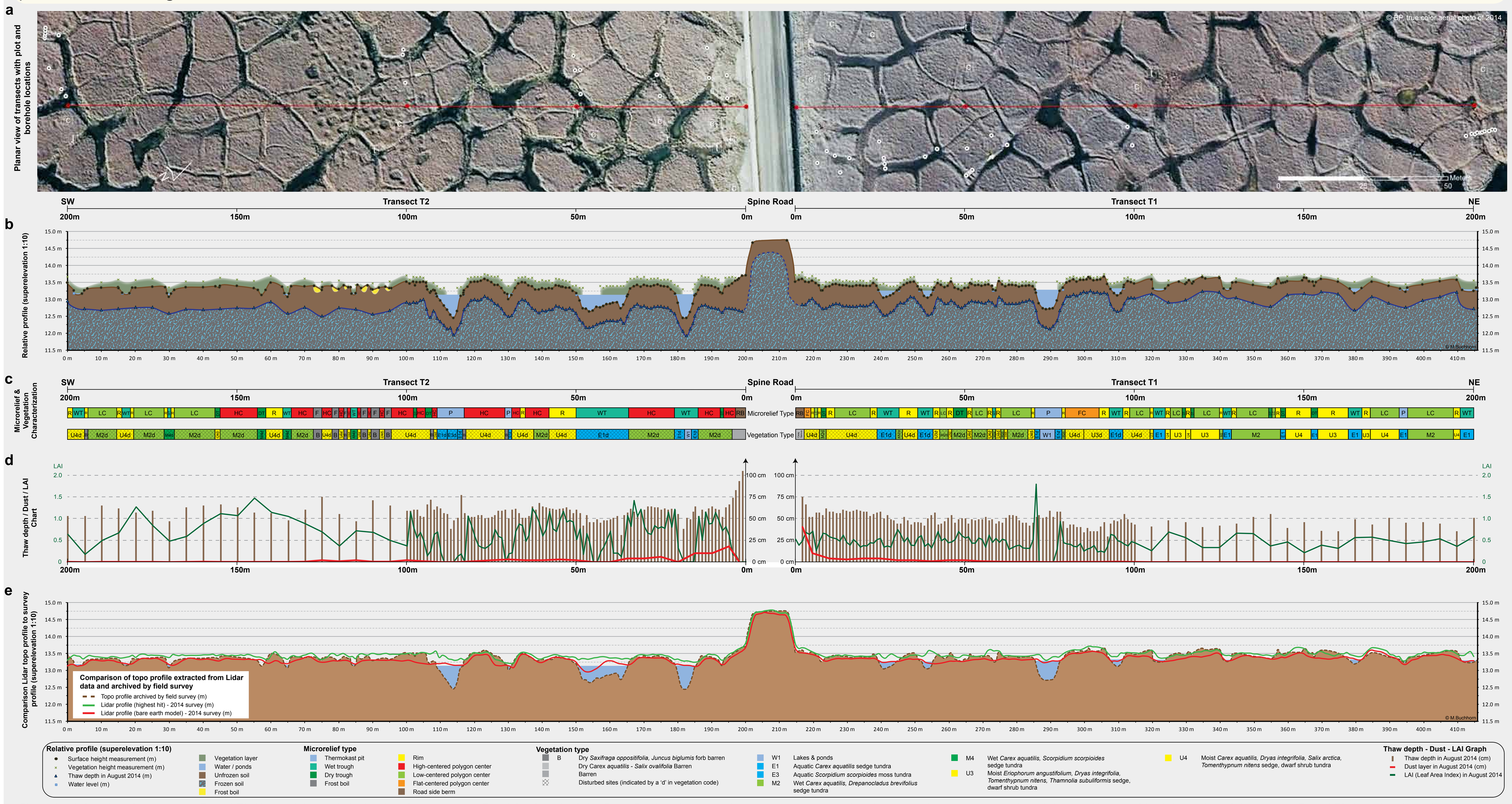


Figure 9. (*a*) Overview of the transects T1 and T2. Note: red line mark the location of the transects NE and SW from the Spine Road. Position of center and trough permanent vegetation plots are marked as squares, and boreholes as white dots. (**b**) relative profiles of the transects T1 and T2. Note the 10x vertical exaggeration (**c**) Microrelief and vegetation along the transects. (**d**) Graph showing the thaw depths, dust depths, and LAI measurements along the transects. (**e**) Comparison of the topo profile extracted from the LiDAR dataset (highest hit and bare earth model) and field survey.

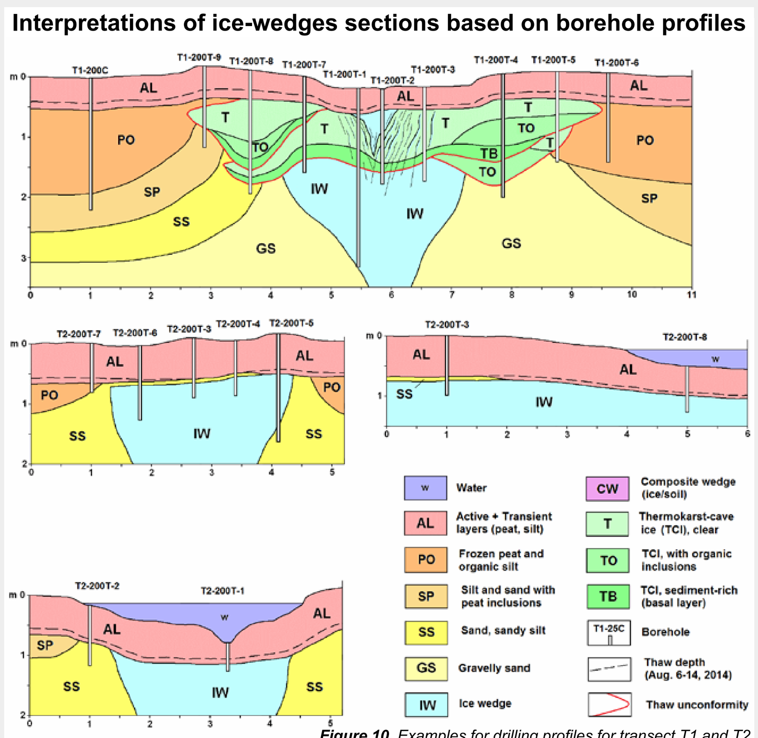


Figure 10. Examples for drilling profiles for transect T1 and T2.

Borehole drilling encountered massive ground ice, including wedge ice (WI), thermokarst cave ice (TCI) and composite (ice/soil) wedges (CW) (**Fig. 10**). Compared to polygon centers, troughs had almost no shrub cover, high graminoid cover and higher moss cover (often below water). Moss cover increased with distance from road, and total plant cover increased with distance from road on north side (transect T1), but not on south side (Transect T2) (**Fig. 11**). Soils within about 50 m on both sides of the road now have mineral surface horizons composed largely of road dust and gravel that overlie the original organic soil horizons (**Fig. 12**).
Surface and soil temperatures were warmer on the south side (transect T2) than the north side (transect T1), particularly in winter. (**Fig. 13**).

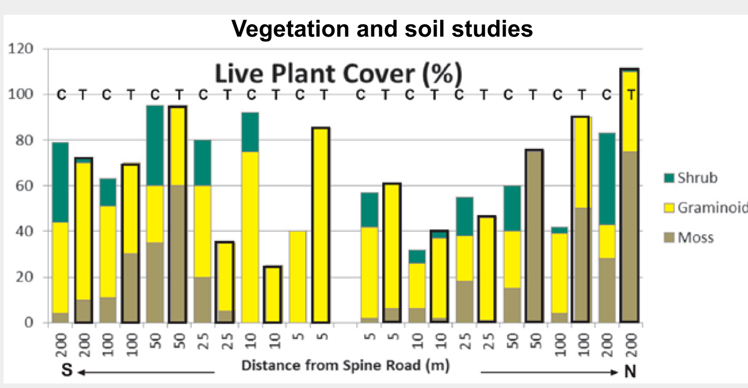


Figure 12. Soil plug from center of an ice-wedge polygon. Note the 13-cm thick mineral surface horizon, which is the dust layer above the original organic surface horizon.

Figure 11. Estimates of percent live plant cover for different life-forms on 1-m2 plots. Dark outline - polygon troughs (T); North side on right.

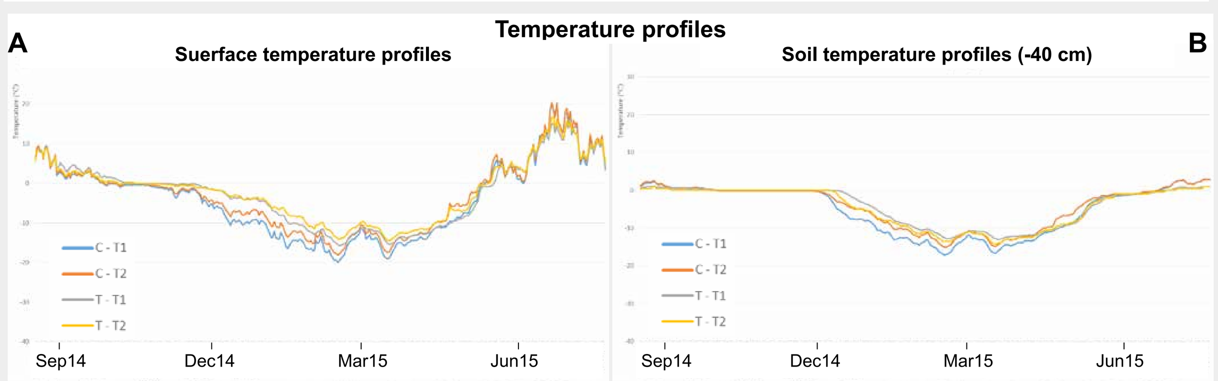


Figure 13. (a) Comparison of the average daily surface temperature at polygon centers (C) and troughs (T) at Colleen Site A for the time August 2014 to August 2015. (b) Comparison of the average daily soil temperature at -40 cm at polygon centers (C) and troughs (T) at Colleen Site A for the time August 2014 to August 2015.

V SUMMARY OF FINDINGS

TIME SERIES ANALYSIS

- Prior to construction of the Spine Road in 1969, the Colleen site A study area had numerous scattered thermokarst pits indicating that there was some thawing ice wedges at the intersections of polygon troughs. The pattern of thermokarst changed very little between 1949 and 1972.
- The Spine Road was constructed in 1969, altering drainage patterns and introduced gravel and large quantities of dust to the tundra adjacent to the road, such that over the past 45 years the pattern of thermokarst has changed dramatically.
- Thermokarst is now deepest and most extensive on the southwest side of the road, which is periodically flooded. Historical climate data and photos indicate that between 1989 and 2012 a regional thawing of the ice-wedges occurred, increasing the extent of thermokarst on the both sides of the road.

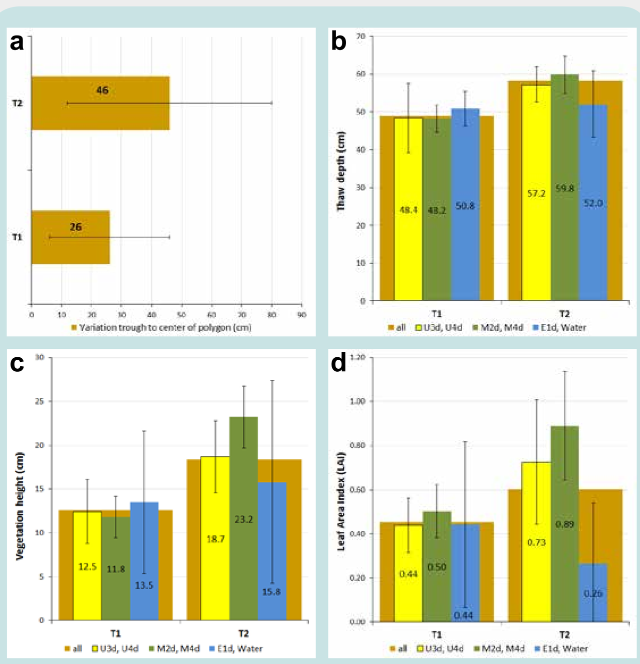


Figure 14. Differences in (*a*) trough-polygon center contrast, (*b*) thaw depth, (*c*) vegetation height, and (*d*) Leaf Area Index (LAI) between the transects T1 and T2.

TRANSECTS ANALYSIS

- Trough-to-polygon topographic contrast of Transect T2 is nearly double that of T1 (**Fig. 14a**).
- Thaw depths are greater for all plant communities on the south (wetter) side of the road (**Fig. 14b**).
- Vegetation heights are taller (**Fig. 14c**) and leaf-area-index is greater (**Fig. 14d**) on the south (wetter) side of the road.

- Most (35 of 43) boreholes drilled in ice-wedge troughs and surrounding rims encountered massive-ice bodies (mostly ice wedges at various stages of degradation and recovery).
- Despite the effects of road construction and heavy traffic on the stability of upper permafrost, ice-wedge degradation has halted on some degraded wedges.
- Initial degradation of ice wedges along T2 was probably related to the flooding of the south side of the Spine Road due to road construction, but at present even the wedges under deep, water-filled troughs are more stable than the wedges along T1, which have not been affected by flooding.

- Major vegetation changes occurred over 45 years: aquatic vegetation and water increased on both sides of the road, but most dramatically on the south side which is regularly flooded during spring snow melt.
- Species composition of the dominant moist and wet vegetation changed due to dust deposition.
- Moss cover decreased and bare soil cover increased with road proximity.
- The effect of the road embankment is visible in the soil temperature regime, showing warmer soils on the south-side transect.
- LiDAR data with >8 points per m² can be used for the production of high resolution relative profiles (SD was ±16 cm compared to our survey with a TotalStation).

VI CONCLUSIONS

1
Information from the Colleen Site A studies, combined with the rich record of historical aerial photographs provide an excellent basis for examining the changes to this region.

2
There have been substantial changes to the vegetation, soils, microtopography, permafrost and ice wedges due to both climate change and infrastructure effects.

3
Vegetation composition studies on these transects documented major reductions in lichen cover over 24 years, reduction in mosses, increase in shrub cover adjacent to the road & overall decrease in diversity.

4
Ice-wedge degradation has halted on some of the polygons on the south side of the road. Enhanced productivity due to wetter, more nutrient-rich conditions has produced insulating vegetation and litter.

5
There is a need to examine the consequences of these changes to other components of the ecosystem, including fish, birds and insects.

6
Many of the recorded impacts are recent and rapid. Continued monitoring will help industry and regulators apply these findings to management and development issues.