Impact of land cover disturbance on permafrost landscapes: Case Studies from Yukon communities

GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
Using examples from three case studies in Yukon communities, we investigate the role of anthropogenic disturbance on permafrost landscapes. Landscape modifications investigated include alternations to surface vegetation for fire protection adjacent to communities, and land clearing to support economic activities like surface mining and agriculture. In most cases, the removal of protective vegetative cover resulted in permafrost degradation, leading to the development of near-surface taliks over decadal-scale time periods. Conversely, light alteration to vegetative cover (e.g., stand thinning for fire protection) does not appear to have altered permafrost presence or distribution. Results have implications for community-scale land use planning in the context of a changing climate.

RÉSUMÉ
Trois études de cas ont été sélectionnées dans les communautés du Yukon afin d'illustrer les impacts des perturbations anthropiques sur les environnements à pergélisol. Les modifications des paysages étudiés incluent la coupe sélective des zones boisées pour la prévention de feu de forêts dans les communautés avoisinantes ainsi que le défrichage des terres pour soutenir certaines activités économiques telles que l'industrie minière et l'agriculture. Dans la plupart des cas l'élimination du couvert végétal a entrainé la dégradation du pergélisol, ce qui aurait contribué à la création de taliks à l'échelle décennale. Cependant, l'altération de la couverture végétale pour la prévention de feux de forêt ne semble pas avoir modifié l'état du pergélisol. Les résultats de cette étude serviront aux communautés, afin de mieux planifier l'utilisation du territoire dans le contexte des changements climatiques.

1 INTRODUCTION

The mounting effects of climate change on northern communities have been widely recognized in both the scientific (e.g., ACIA 2005; Lemmen et al. 2008; Derksen et al. 2012; IPCC 2014) and traditional knowledge (e.g., Riedlinger and Berkes 2001; Krupnik and Jolly 2002; Ford et al. 2008) communities. Of particular concern for northern communities is the occurrence and acceleration of permafrost thaw and related landscape disturbances. The Intergovernmental Panel on Climate Change has high confidence that the warming and thawing of permafrost will have detrimental effects on infrastructure (Larsen et al. 2014), which is of particular concern in the Yukon, where there is a high prevalence of warm permafrost (Smith et al. 2010) and permafrost degradation has already been widely documented (Government of Canada 2011). The largest percentage and total increases in active layer depth in Canada are also expected in this region (Furgal and Prowse 2008). In order for Yukon's communities to develop strategies to respond and adapt to the impacts of climate warming on permafrost, it is important to identify and characterize permafrost vulnerability and sensitivity to environmental change (Huntington et al 2005; Ford et al. 2010; Stephani et al. 2014).

To assist Yukon communities in planning adaptation and mitigation strategies in response to permafrost degradation, the Northern Climate ExChange (NCE, Yukon Research Centre, Yukon College) and its partners have been developing hazard risk maps for many communities (e.g. Benkert et al. 2015). Hazard risk maps, which create simplified representations of biophysical vulnerability (Cutter 1996), have emerged as useful tools in the assessment of landscape-scale vulnerability to climate change. These maps integrate science into decision-making by amalgamating and classifying geoscience data to create an easily-interpretable ranked representation of current and future hazard potential (Allard et al. 2007; Grandmont et al. 2012a,b; Lemieux et al. 2013; L'Hérault et al. 2013; Benkert et al. 2015).

Through the development of hazard maps for Yukon communities, the research team has noted distinctive permafrost conditions in response to a suite of surface disturbance types. Here, we present three case studies illustrating the impacts of land cover changes on permafrost landscapes, and discuss the key importance of vegetation removal on permafrost dynamics at decadal timescales.

2 IMPACT OF SURFACE DISTURBANCES ON PERMAFROST

Although climate is the dominant factor contributing to the existence of permafrost, several other biophysical factors also determine its presence, stability and resilience to change (Shur et al. 2007). In addition, permafrost distribution and characteristics are largely related to topography (slope and aspect), hydrology, soil properties, vegetation and snow cover conditions, all of which complicate the prediction of future trajectories of change and potential recovery rates following disturbance (Jorgenson et al. 2010). Assessing permafrost response to disturbance is further complicated by the suite of positive and negative feedbacks that occur in environmental systems in response to natural and anthropogenic stressors, which in turn result in impacts that can be indirect, difficult to predict, and variable on local and regional scales. However, the effect of disturbance on permafrost largely depends on the volume of ground ice and its proximity to the surface, the type of material present, and local topography, as well as the time since disturbance (Brown and Grave 1979; Walker and Walker 1991; Kokelj and Jorgenson 2013).

Natural and anthropogenic stressors in permafrost environments can induce changes over relatively short periods of time. Common types of stressors include fire and the removal or disturbance of vegetation cover for development purposes, including buildings, linear infrastructure, and resource extraction. Impacts from these disturbances can generate uprooting, soil surface removal and compaction (Williams et al. 2013), which can lead to a deepening of the active layer and permafrost degradation. Smith et al (2008) demonstrated that pipeline installation on permafrost can lead to several metres of permafrost thaw, the loss of thin permafrost, ponding, and notable ground subsidence. Small-scale anthropogenic surface disturbances can also have a long-term impacts on permafrost soils – for example, even trampling can trigger thermokarst processes (Mackay 1970).

Deep organic soil layers and thick moss cover are effective insulators that protect permafrost and play an important role in maintaining ground thermal equilibrium and the stability of permafrost (Linell 1973; Calmels et al. 2012; Jafarov et al. 2013). In flat areas, vegetation intercepts solar radiation and supports the growth and accumulation of organic matter, preventing an increase in active layer thickness (Jorgenson et al. 2010). In our case studies we show the impacts of vegetation disturbance on permafrost on a decadal scale.

3 PERMAFROST DISTURBANCE CASE STUDIES

3.1 Approach and methods

As part of NCE's hazard mapping projects in Yukon communities, we investigated permafrost characteristics at many case study sites throughout the territory. Here, we present results from three case study sites each exhibiting different surface disturbance types, to examine permafrost responses to change. One case study is from Burwash Landing and two are from the Dawson City region (Figure 1).

Historical airphotos and satellite images were used to characterize land cover changes. In the field, vegetation was described *in situ* and thaw depths were measured at several locations at each site using a graduated metal rod. Geophysics profiles (electrical resistivity tomography (ERT) and ground penetrating radar (GPR)) were used to characterize subsurface conditions. ERT and GPR methods used in Burwash Landing and Dawson City were described in NCE (2013) and Benkert et al. (2015), respectively. Geophysics surveys were complemented by hand augering, and by permafrost cores that were extracted using a portable earth-drill system with 4" core barrels. Cryostratigraphy of permafrost materials was described *in situ* (Murton and French 1994; French and Shur 2010), and laboratory analyses of permafrost properties (including grain size analysis, volumetric ice content and thaw settlement potential) were conducted (see NCE (2013) and Benkert et al. (2015) for details).

Figure 1. Location of Burwash Landing and Dawson City, Yukon, Canada.

3.2 Burwash Landing

Burwash Landing is located in the discontinuous permafrost zone (Brown 1970). It has a mean annual air temperature of -3.2°C and ~275 mm total precipitation annually, of which ~38% falls as snow (1981-2010 climate normal data; Environment Canada 2015). The community is located in the boreal cordillera ecozone where vegetation is dominated by northern boreal forest consisting of black and white spruce (*Picea glauca, Picea mariana*), birch (*Betula papyrifera*), lodgepole pine (*Picea contorta*) and heath shrubs (Smith et al. 2004). Firebreaks 40-50 m wide and FireSmart zones (areas where the most flammable material in a forest stand are removed and stands are thinned) have been established around Burwash Landing to reduce the risk of wildfire propagation locally (Figure 2). In this area, vegetation in the FireSmart zones is typically composed of a mossy groundcover, and scattered shrubs and spruce at different growth stages. In firebreaks, a thin organic layer with tall (1-2 m) grasses and scattered shrubs is typically present.

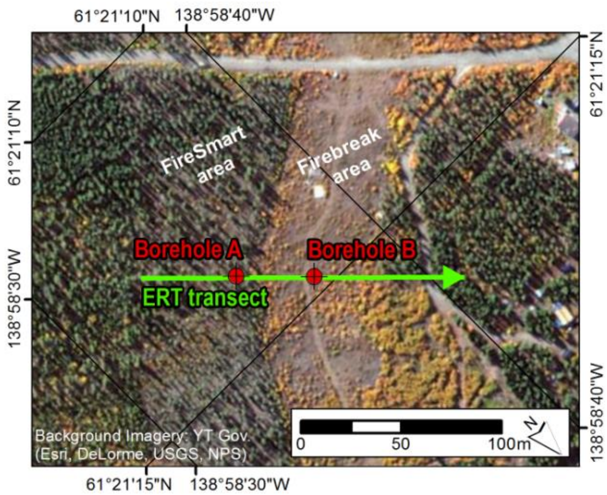

Figure 2. View of the FireSmart zone and firebreak in Burwash Landing. Green line represents ERT transect; red dots represent borehole locations.

To investigate the impacts of fire protection activities on permafrost around Burwash Landing, geophysics and borehole drilling were conducted (Figure 2). A 160 m-long ERT survey was run through a FireSmart area and a firebreak, across a gravel road and into relatively undisturbed forest. Two boreholes were also drilled. Borehole A (4.12 m deep) was drilled in the FireSmart zone, while Borehole B (2.4 m deep) was drilled in the firebreak.

The ERT profile (Figure 3) shows a shallow (<1 m) layer of low resistivity material, interpreted as thawed ground, overlying a higher resistivity frozen layer present in the FireSmart zone and in the forest. Under the firebreak and the gravel road, the low resistivity surface layer extends to depths of about 8 and 6 m, respectively. The boundary between frozen and unfrozen materials in this profile is interpreted to be at about 300 Ohm m. The high resistivity layer, associated with frozen ground conditions, extends at least to the base of the profile (25 m) for the entire length of the survey.

Near-surface stratigraphy at Borehole A, which was drilled in the FireSmart zone, was made up of a mix of organic matter and sandy silt (0-20 cm), covering a silty sand layer 65 cm thick, over a diamicton deposit (sand with gravel) extending to the base of the borehole. The water and permafrost tables were reached at depths of 55 and 65 cm, respectively. Materials at the top of permafrost were composed mainly of silt with a microlenticular structure and high volumetric ice content (VIC) of 78% by volume. Settlement potential (SP) in the upper 20 cm of permafrost was significant (52%). Below 90 cm, deposits were more sandy and gravelly, with a crustal cryostructure around gravels and a microlenticular cryostructure in finer sediments. VIC decreased to ~30%. SP in this portion of the core was very low (~4%). Between 147 and 412 cm, no frozen core was extracted due to thawing of ice-poor gravelly sand by heat generated during drilling. Borehole B, which was drilled in the firebreak, consisted of silt and sand mixed with organic matter (0-40 cm), overlying silty sand (41-90 cm), and a diamicton layer (sand and silt with gravel; 91 cm to the base of the core). The water table was encountered at a depth of 76 cm, but no permafrost was encountered.

Results of the ERT profile indicate that this site is underlain by permafrost that is at least 25 m thick, even below disturbed zones. In the FireSmart zone, the selective removal of highly flammable material and stand thinning has had little impact on the permafrost state, demonstrated by the presence of a thin active layer (~65 cm deep), comparable to that of the forested zone. Under the firebreak, where vegetation clearing was more extensive, a supra-permafrost talik (i.e., an area of year-round unfrozen ground overlying permafrost) has developed. The ERT survey also suggests the development of a talik under the road in the centre of the firebreak. Results of this case study highlight the importance of preserving the insulating vegetative cover to sustain permafrost conditions. Climate-related permafrost degradation is also likely taking place in this area, albeit at a slower rate than human-induced degradation. Given the thickness of the permafrost (>25 m), degradation and thawing will likely continue for decades.

3.3 Dawson City Region – Placer Mining Claim

Dawson City is located in the extensive discontinuous permafrost zone (Brown 1970). It has a mean air annual temperature of -4.1°C and ~325 mm precipitation annually, of which ~51% falls as snow (1981-2010 climate normal data; Environment Canada 2015).

A semi-cleared placer mining claim was investigated as part of broader permafrost studies in the Dawson region (Benkert et al. 2015). Located on the southern edge of the Klondike River floodplain, the stratigraphy of this site is comprised of glaciofluvial sand and gravel overlain by silty sand. The site lies on an alluvial fan that has been built onto the floodplain from drainage off an adjacent valley slope. A section of the case study site was cleared of surface vegetation and soil for placer mining operations in the early 2000s, approximately 10 years before site investigations took place (Figure 4). At the time this site was investigated, vegetation cover in cleared areas was composed of shrubs and tall grass up to 50 cm high, while in forested areas, spruce trees ~15 m high and 2-3 m-high shrubs were present.

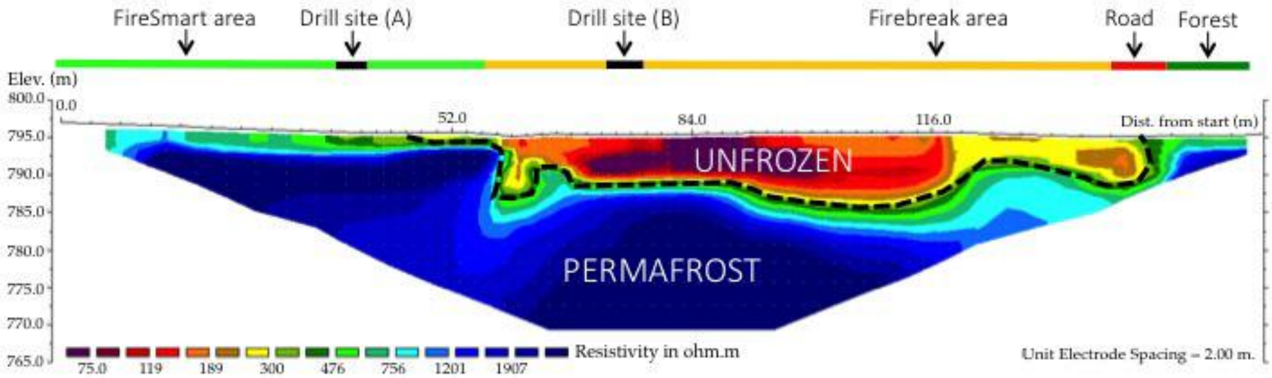

Figure 3. 160 m-long resistivity profile covering the FireSmart zone, the firebreak, a gravel road, and a portion of relatively undisturbed forest in Burwash Landing, YT. The boundary between frozen and unfrozen materials (dashed line) is interpreted to be at about 300 Ohm m (between the yellow and green shades).

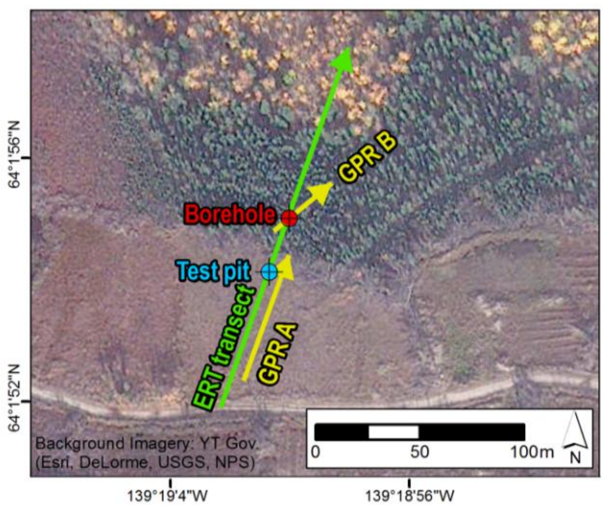

Figure 4. Semi-cleared placer-mining claim (image date: 2012) showing locations of geophysics profiles and boreholes in cleared field and forested area.

At this case study site, one ERT survey and two GPR surveys were completed, one test pit was excavated, and one borehole was drilled (Figure 4). Survey and borehole locations were selected to cover both cleared and forested areas, to compared permafrost conditions before and after disturbance.

In the cleared field, a 155 cm-deep test pit showed thin moss (0-10 cm), underlain by sandy silt layers (11-92 cm) and interlaced layers of iron oxide-stained silty sand and dark organic deposits (93 cm to base). The water table was reached at 111 cm but no permafrost was found. GPR survey A (Figure 5), which was 59 m long, reached a penetration depth of 7 m (penetration speed of 0.1 m/ns). Three distinctive contacts are visible on the profile. The first one, located at a depth of approximately 2 m, may correspond to a gravelly layer observed at 123-308 cm in the forest borehole (described below). The second and third contacts appear at depths of 4 m and 5-7 m respectively, but the nature of the deposits at these depths is unknown. The lowermost contact likely corresponds to the transition between a talik and permafrost. The portion of the ERT survey underlying the cleared field shows a continuous low resistivity layer (3-6 m thick) in the near-surface, which overlaps a much higher resistivity layer that extends to the base of the profile at 25 m (Figure 6).

In the adjacent spruce forest, a 308 cm-deep borehole was drilled (Figure 4). The stratigraphy was composed of a moss and lichen layer (0-21 cm) covering a tephra layer (22-53 cm). The permafrost table was found at a depth of 52 cm and was underlain by an ice-rich lenticular sandy organic silt layer (52-88 cm) over a 35 cm-thick microlenticular sandy organic silt layer, and a porous invisible silty sand with gravel layer from 123 cm to the base of the borehole. Ice lenses up to 3 cm thick were observed at the active layer-permafrost boundary, where thaw settlement was high (48 and 50% under a stress load of 25 and 150 kPa, respectively). GPR survey B (40 m long; Figure 7) reached a penetration depth of 6 m (penetration speed of 0.1 m/ns). This profile also exhibits 3 contacts, with the shallowest located at 0.5-1 m depth, likely corresponding to the permafrost table. The second contact, at 2-3 m depth, most likely corresponds to the gravel observed in the forest borehole while the third contact (unknown material) was detected between 4 and 6 m. The ERT profile in this portion of the site indicates a near-surface high resistivity layer associated to a shallow active layer (<1.2 m thick), and undisturbed permafrost at least 25 m thick (Figure 6).

Results from this site clearly illustrate the impacts of land clearing on permafrost conditions. In the cleared field, the test pit, ERT profile and GPR survey all suggest permafrost degradation and the development of a supra-permafrost talik 3 to 5 m deep, which likely developed over the ~10 years since site clearing and disturbance. In contrast, results indicate that the active layer beneath the forest is thin and no talik is present. Generally, rapid initial permafrost degradation following surface disturbance is expected in this area and comparable locations. Degradation will slow down over the years, but will likely be compounded by the on-going impacts of regional climate warming.

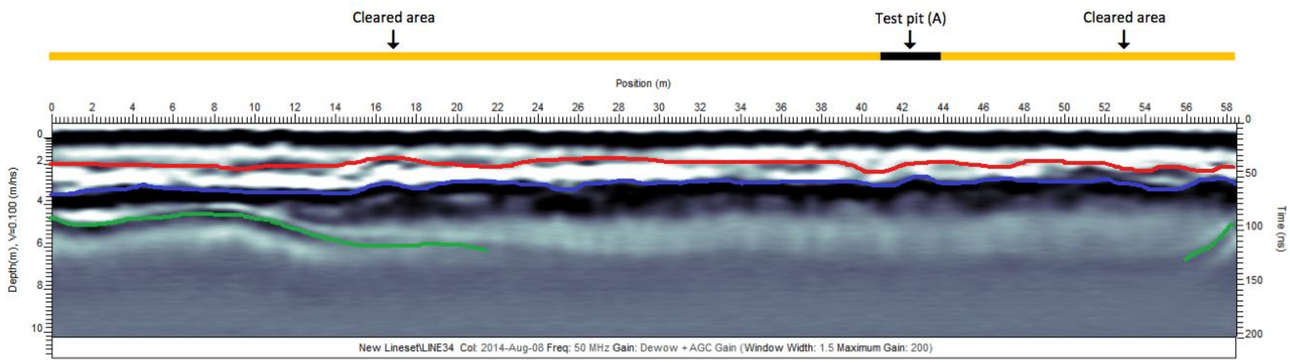

Figure 5. 59 m-long GPR profile A conducted in a cleared field in the Dawson City region. Survey had a penetration depth of 7 m at a speed of 0.1 m/ns. Stratigraphic contacts are present at 2 m (red line), 4 m (blue line) and 5-7 m (green line).

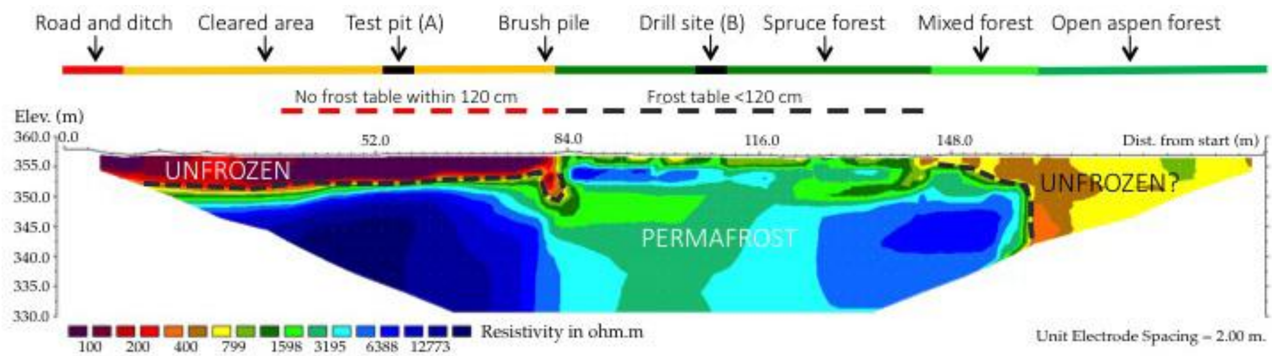

Figure 6. 200 m-long resistivity profile running across a cleared field and into a relatively undisturbed forest in the Dawson City region. The boundary between frozen and unfrozen materials (dashed line) is interpreted to be at about 800 Ohm m (between the yellow and green shades).

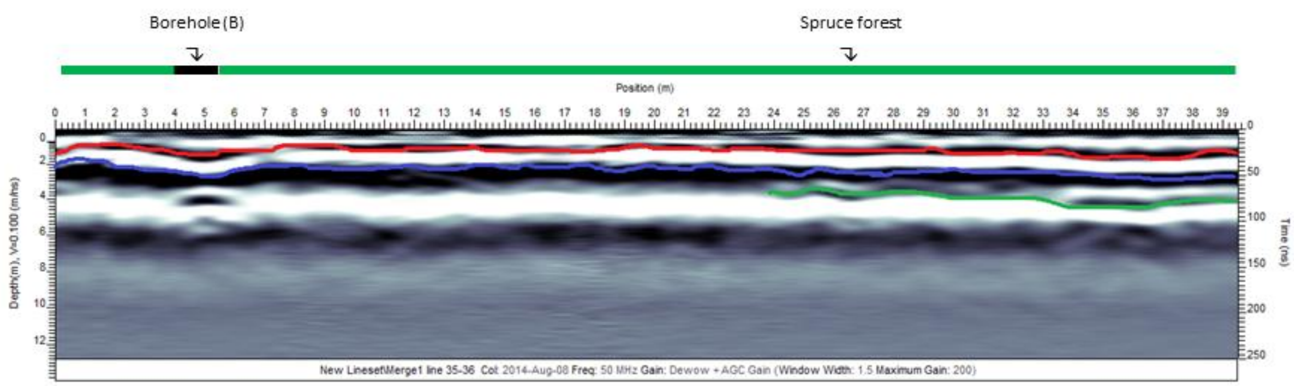

Figure 7. 40 m-long GPR profile B conducted in a forest in the Dawson City region. Survey had a penetration depth of 6 m at a speed of 0.1 m/ns. Stratigraphic contacts are present at 0.5-1 m (red line), 2 m (blue line) and 4-6 m (green line).

3.4 Dawson City Region – Agricultural Development

Henderson's Corner is a small subdivision, 22 km southeast of Dawson City, which was developed for agricultural purposes. It is positioned on a fluvial fan and composed mainly of silt and sand that was deposited on the Klondike River floodplain at the base of Alki Creek (a north-flowing tributary to the Klondike River). The fluvial fan formed after the McConnell glaciation (McKenna and Lipovsky 2014) but the exact timing of development remains unknown. The fan deposits were affected by periglacial processes, and ice-wedge polygons are common, especially along the base of the nearby hill.

Archival airphotos were used to reconstruct past land use history (Figure 8). Air photos from 1977 and 1990 show evidence of land clearing for agriculture, although residents explained that some parts of Henderson's Corner area were left forested until the late 1980s and early 1990s, at which point the land was divided into smaller residential lots. Air photos also indicate that additional clearing was done between 1990 and present.

At the time of site investigations, cleared areas were covered by 30 cm-tall grasses.

Ice wedges have degraded in cleared areas (polygon A on Figure 8), and troughs associated with ice wedge polygons are visible in the landscape (Figure 9). Thermokarst ponds and lakes have formed at the southern edge of the study area (polygons B-D on Figure 8).

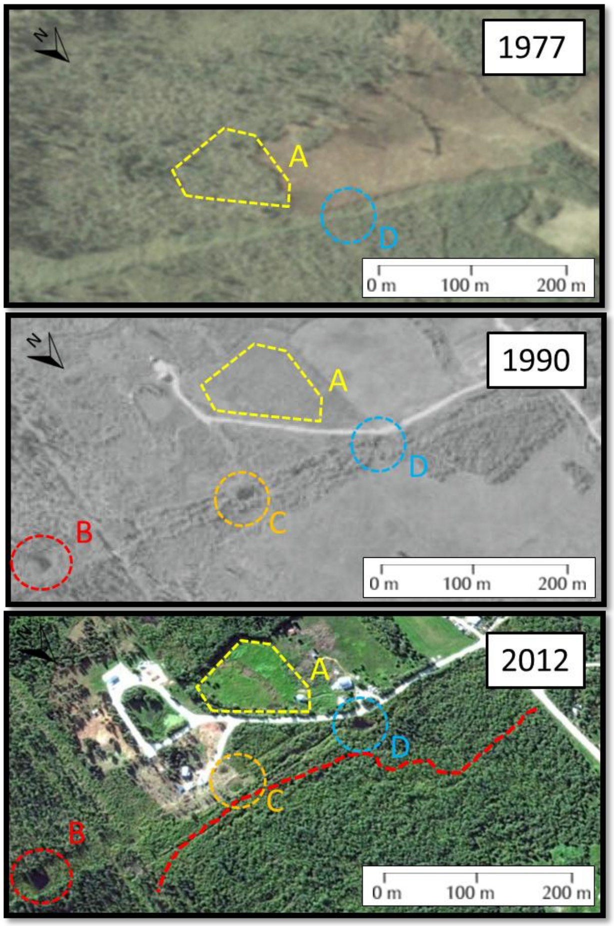

Figure 8. Henderson's Corner site evolution from 1977 to 2012. A) Zone showing degradation of ice wedges; B, C, D) inception and growth of thermokarst ponds and lakes; red line: regrowth of forest over agricultural field

A 215-cm-deep borehole was drilled in the trough of an ice wedge polygon, where ponded water was present, and a second 120-cm-deep borehole was drilled in the centre of the same polygon. In both cases, the soil stratigraphy revealed saturated silt deposits. The boreholes did not reach the permafrost table. This is consistent with other investigations in the area, which also found no near-surface permafrost. A nearby borehole off the Klondike Highway close to the Klondike River revealed an 80 cm-thick organic layer over an 80 cm-thick layer of silt and a 30 cm-thick sand deposit, followed by gravel to the base of the core (350 cm). No permafrost was encountered in this borehole and the water table was reached at 330 cm (R. Trimble, Tetra Tech EBA, pers. comm.).

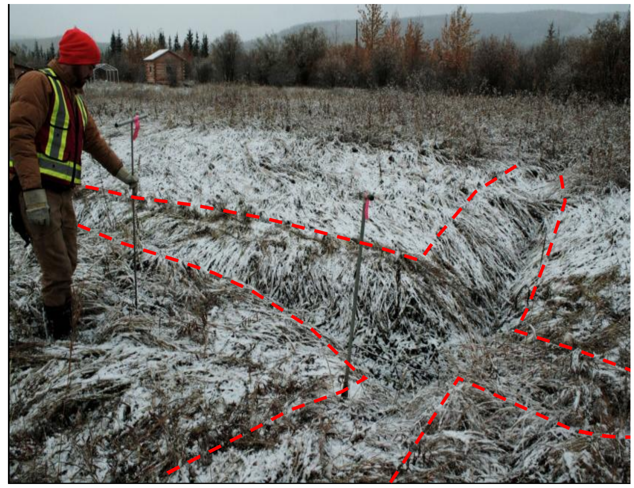
Figure 9. Troughs associated with ice wedge degradation in the cleared portions of the Henderson's Corner area.

As with results from Burwash Landing, field studies demonstrate the notable impact of anthropogenic disturbance and vegetation removal on permafrost landscapes. Here, forest clearing for agriculture led to the deterioration of ice wedge polygons, triggering the creation of linear ponds and thermokarst lakes, impairing intended land use (e.g. residents describe tractors getting stuck in polygon troughs). Careful investigation of permafrost conditions prior to agricultural development is warranted due to the notable impact ground ice degradation can have on drainage and subsequent agricultural viability.

4 CONCLUSION

In the discontinuous permafrost zones of the Yukon, notable vegetation removal and/or disturbance results in significant deepening of the active layer and the development of supra-permafrost taliks that can reach depths of several metres.

In Burwash Landing, field investigations showed that the degree of vegetation removal impacts the degree of permafrost degradation. In a FireSmart zone, light alteration to vegetative cover (e.g., stand thinning for fire protection) does not appear to have altered permafrost presence or distribution. The selective removal of plant species had little impact on the permafrost state - the active layer remained thin, and permafrost conditions were similar to relatively undisturbed sites nearby. Along an adjacent firebreak, vegetation removal has had a greater impact on the ground thermal regime, resulting in a deepening of the active layer, the development of a supra-permafrost talik up to 8 m deep, and potential warming of underlying permafrost. Additional studies should be conducted to determine the threshold, over which vegetation removal triggers permafrost degradation.

In the Dawson City region, anthropogenic disturbance has had notable effects on permafrost conditions. For example, site clearing for placer mining operations has disrupted the natural state of permafrost by removing the top layers of soil and vegetation to access the gold-bearing material beneath. As a result, the active layer has thickened and a supra-permafrost talik has developed, with ice-rich permafrost degradation inferred to have occurred at an average rate of 0.5 to 1 m per year over the past ~10 years. This has resulted in differential thaw settlement, the development of depressions, and poor drainage locally. In the adjacent forested zone, which was generally undisturbed, a shallow (~50 cm) active layer persists, and is underlain by ice-rich permafrost.

In the nearby agricultural area, forest was cleared for agricultural purposes over the past four decades, resulting in the degradation of near-surface permafrost containing relict massive ice wedges and ground ice. This in turn created linear water channels around ice wedge polygons, and thermokarst ponds and lakes, which impaired intended land use and have likely exacerbated climate change impacts on the local ground thermal regime.

Interestingly, previous studies have suggested that under the current climate conditions the permafrost of Dawson City has the potential to recover from disturbances inherited from the Klondike Gold Rush (1896-1899) and subsequent decades (Calmels et al. 2012). Continued thermal, physical and geochemical monitoring of existing taliks and underlying frozen ground could help determine whether comparable recovery is occurring, in the context of a warming climate. This would help evaluate long-term trajectories of permafrost biogeosystems affected by anthropogenic disturbances, especially vegetation removal, under continued climate change.

ACKNOWLEDGEMENTS

The authors are grateful to the Kluane First Nation, the Tr’ondëk Hwëchin, and the City of Dawson for supporting this project and for allowing access to their Traditional Territories and lands. Project partners include the Yukon Geological Survey (Yukon Government), University of Montreal, University of Ottawa, and Northern Climate ExChange (Yukon Research Centre, Yukon College). Funding for this project was provided by Aboriginal Affairs and Northern Development Canada and in-kind contributions by project partners.

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