Permafrost as a unifying discipline for northern environmental change research: Environmental Studies across treeline, Mackenzie Delta region, NWT

S.V. Kokelj
Renewable Resources and Environment, Indian and Northern Affairs Canada, Yellowknife NT.

ABSTRACT
A research program in the Mackenzie Delta region was initiated through the study of vegetation, snow and thermal regimes across the treeline. The scope of study was expanded to investigate the impacts of permafrost degradation on terrestrial and aquatic environments. Retrogressive thaw slumps, which are large-scale permafrost degradation features, modify soil chemistry and microclimate, accelerating tall shrub growth and modifying plant communities. Thaw slumps also have significant impacts on water quality and sediment loads in streams. The associated thermal disturbance, talik enlargement and thawing of underlying ice-rich permafrost can drive initiation and polycyclic behaviour of lakeside thaw slumps. This model relates rising permafrost temperatures with the recent increase of thaw slump activity. The central relevance of permafrost in the study of northern environments and engineering makes the discipline a potential focal point around which to develop integrated monitoring and research programs.

RÉSUMÉ
Un programme de recherche dans la région du Delta de Mackenzie a été initier en étudiant les régimes thermiques et les régimes de végétation et de neige à travers la limite arctique des arbres. Le périmètre d'application de l'étude a été agrandi pour examiner l'impacte de la dégradation du pergélisol sur l'environnement terrestre et aquatique. Les glissements de terrains de fonte régressive modifient la chimie du sol et le microclimat, ce qui accélère la croissance de grands buissons et modifient les communautés de plantes. Les glissements de terrains de fonte ont aussi des impactes considérables sur la qualité de l'eau et la teneur de sediment en suspension. La pértubation thermique, l'élargissement de talik et le dégel de pergélisol sous-jacent riche en glace peut engendrer l'initiation de glissements de terrains polycyclique. Ce model fait le rapprochement entre les températures de pergélisol croissantes et l'accélération récente d'activité de glissement de fontes régressive. La pertinence centrale du pergélisol dans l'étude des environnements du nord et de génie établi la discipline comme point focal autour du quelle la surveillance intégrée et les programmes de recherches peuvent être développer.

1 INTRODUCTION

Multidisciplinary approaches are required to understand northern environmental systems and distinguish normal variation from the effects of climate change, and natural or anthropogenic disturbance (Burn and Kokelj 2009; Smol 2009). The thermal state of permafrost is strongly influenced by climate, vegetation and snow (Smith et al. 2005; Burn and Kokelj 2009). The development and degradation of ground ice has both geotechnical and ecological implications (Lewkowicz 1987; Lantz et al. 2009). The strong links between permafrost and other components of the environment places the discipline of permafrost science in a unique position to serve a unifying role in the investigation of northern physical and biological processes and their responses to global change (Hinzman et al. 2005). The high priority of permafrost issues in development and management of northern infrastructure highlights the importance of the discipline in engineering and northern geoscience (Haley and Horn 2008).

This paper presents a body of research on environmental conditions across treeline in the Mackenzie Delta region (Figure 1). The research was initiated to fill knowledge gaps related to the assessment and management of the impacts of northern oil and gas development (Burn and Kokelj 2009). The study of vegetation, snow and thermal regimes provided a

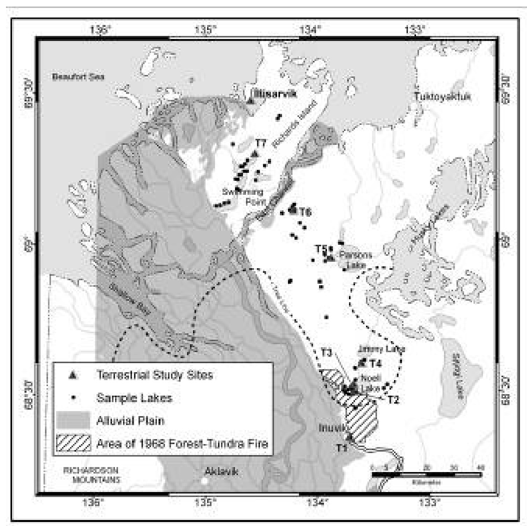

Figure 1. Map of the Mackenzie Delta study region..

platform upon which a broader collaborative program was built to investigate the variability of environmental systems across treeline and the impacts of climate change and disturbance. An overview of this approach and a summary of research results provide the context for discussing northern research frameworks.

2 THE RESEARCH CONTEXT

The ecological, cultural and development significance of the Mackenzie Delta area have made this a priority region for northern research and monitoring (Mackay 1963; Burn and Kokelj 2009). The contrasting conditions between subarctic boreal and tundra zones and deltaic and upland environments lead to variations in the direction and strength of relationships between various environmental components (Burn and Kokelj 2009). Local and regional-scale environmental gradients have often been integrated into research designs investigating the factors which influence ground thermal and ground ice conditions (e.g.: Smith 1975; Taylor et al. 1996; Kokelj and Burn, 2005a). Research in the region also tremendously benefits from the benchmark geoscience work of Dr. J.R. Mackay (see: Permafrost and Periglacial Processes, 2007, 18(1)) and the long-term presence of the Geological Survey of Canada (Dyke and Brooks 2000). During the last half century, the western Arctic has been one of the most rapidly warming regions on the planet (Burn and Kokelj 2009), providing additional impetus to investigate ecosystem responses to global environmental change. The Mackenzie Delta is underlain by significant discovered and anticipated hydrocarbon reserves (Dixon et al. 1994), and the recent proposal to develop the Mackenzie Gas Project invigorated Federal government research and monitoring activities.

3 STUDY REGION

The research summarized in this paper was undertaken within upland terrain east of Mackenzie Delta (Figure 1). The region is underlain by glaciogenic deposits dominated by fine-grained tills (Rampton 1988). Continuous permafrost is up to several hundreds of meters thickness and mean ground temperatures range from about -1 °C to -8°C (Burn and Kokelj 2009). The permafrost is ice-rich and may host massive ice to depths of 10 m or more (Mackay 1971).

The region has numerous small to medium sized lakes (Figure 2). Lakes and ponds deeper than the maximum thickness of winter ice are underlain by taliks or unfrozen zones. As such, water bodies have profound influence over permafrost distribution (Burn 2002) and ground thermal regimes (Kanigan et al. 2008) throughout the region. The most dynamic components of the geomorphic system in this ice-rich terrain are related to the interfaces between frozen and unfrozen ground. Deep thawing of the active layer can cause surface subsidence, influence surface microtopography and cause the development or degradation of earth hummocks (Mackay 1995; Kokelj et al. 2007a). Lakes in the region are thought to have developed due to regional thawing of ice-rich permafrost during the Holocene Climate Optimum (Rampton 1988). Some of these lakes continue to expand by thermokarst processes. Lakes may also rapidly drain when ice-rich permafrost adjacent to the basin is thermally or mechanically eroded (Mackay 1992; Marsh et al. 2009).

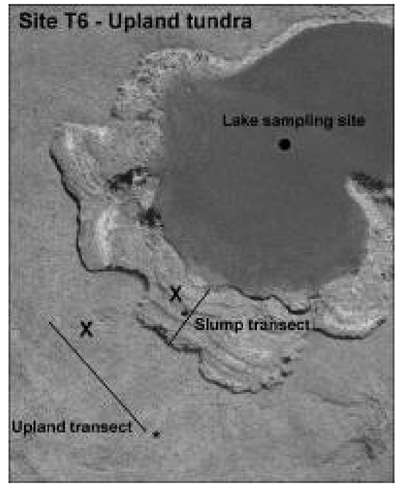

Figure 2 Aerial view of a typical research site showing transects on tundra and in thaw slumps where data on soils, vegetation, snow and ground temperatures were collected. The (X) indicates deep ground temperature measurement sites and the (*) indicates active layer and air temperature sensors. The aquatic impacts of slumping were examined in adjacent lakes. The slump transect is 150 m for scale.

Climate throughout the region is characterized by long, cold winters and short summers. Climate normals show that average precipitation and temperatures at Inuvik (248 mm; -8.8 °C) are significantly higher than at Tuktoyaktuk (139 mm; -10.2 °C) (Environment Canada 2009). The lower air temperatures at Tuktoyaktuk can be attributed in part to cooler early summer temperatures due to persistence of sea ice. The northward decrease in mean annual temperature and precipitation is reflected by the transition from subarctic boreal forest near Inuvik to low shrub tundra at the coast (Figure 1) (Lantz et al. 2010a).

4 STUDY DESIGN

To investigate ground thermal conditions across treeline, several sites were established on upland surfaces ranging from the subarctic forest tundra in Inuvik to low shrub tundra at the Beaufort Sea coast (Figures 1). Vegetation, soils and snow data were collected from across the regional ecological gradient to examine the relative influence of these factors on the ground thermal regime (Palmer 2007). Installation of thermistors to 10-m depth at these sites was facilitated through collaboration with the Geological Survey of Canada. These locations were also core ecological sites where detailed information on vegetation structure and community composition was collected to examine relationships between vegetation, regional climate and disturbance (Lantz et al. 2010a; 2010b).

Each site was located in close proximity to a small lake affected by retrogressive thaw slumping (Figure 2). This provided the opportunity to examine impacts of permafrost degradation on the chemistry of soils and surface runoff and on ground thermal regimes (Kokelj et al. 2005; Kokelj et al. 2009a). This research stimulated further investigations on the impacts of thaw slumping on lake chemistry and shrub dynamics, and paleolimnology. These studies have been contextualized by characterization and regional scale mapping of lakes, thaw slump disturbances, and plant communities (Lantz and Kokelj 2008; Kokelj et al. 2009b; Lantz et al. 2010a).

5 RESEARCH SUMMARY

Ground thermal regimes across treeline

The boreal tundra transition zone is characterized by a steep gradient in mean summer air temperature which relates closely to a northward decrease in cover and patch size of shrub tundra (Lantz et al. 2010a). The structural complexity and height of shrubs declines abruptly with winter snow accumulation only about 20 km north of Inuvik (Figure 3) (Palmer 2007).

Snow insulates the ground and inhibits ground cooling in winter (Smith 1975). The dominant role of snow in controlling permafrost temperatures is reflected by the significant variation in the winter ground thermal conditions between sites with varying shrub and snow characteristics (Figure 4) (Smith 1975; Kokelj et al. 2007b). Differences in snow cover can also explain a large portion of regional variation in mean annual ground temperatures (MAGT) (Burn and Kokelj 2009; Figure 8). Ground temperatures range from -1^{o}C to -3^{o}C around Inuvik and decrease northwards with shrub and winter snow cover, to less than -6^{o}C on Richards Island.

A comparison of regional ground temperatures compiled from 2000-2008 (Burn and Kokelj 2009; Figures 10, 11) with earlier data from Mackay (1974) show that ground temperatures in uplands have increased by as much as 2^{o}C over the last 30 years. The relationships between snow, vegetation and ground temperatures (Figures 3, 4) imply that the northward migration of the tall-shrub tundra will influence snow redistribution and retention and compound the effects of climate warming on the ground thermal regime. Although the consequences and feedbacks of increasing tundra shrub cover can be inferred from field observations (Sturm et al. 2005), there remain gaps in understanding thresholds between shrub patch size and density, snow accumulation and warming ground.

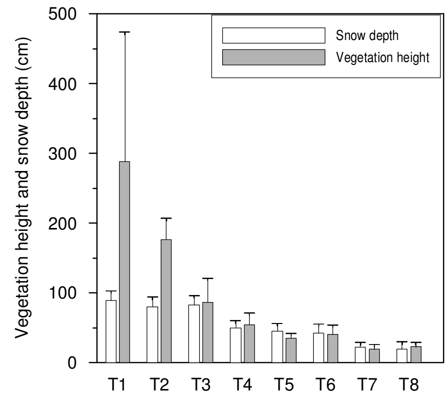

Figure 3 Graphic showing the northward decrease in vegetation height and snow depth from subarctic boreal forest (T1-Inuvik) to low shrub tundra (Illisarvik).

Thaw slumps and environmental impacts

Areas impacted by retrogressive thaw slumping provide the opportunity to examine the environmental implications of permafrost degradation. In ice-rich environments, permafrost thawing can lead to the development of thaw slumps which comprise a steep headwall of ground ice and a footslope of lower gradient (Figure 5). Stabilized slumps appear ecologically distinct from the surrounding tundra as they are often colonized by tall shrubs (Figure 5). The widespread occurrence of thaw slumps in the region, the perception that these disturbances are becoming more prevalent and recent permafrost warming stimulated several foci for research, including: a) an examination of the distribution and growth rates of slumps; b) investigations of slump impacts on the chemistry of soils, runoff and lake water; c) study of the microclimatic conditions and vegetation composition of slumps; and d) determination of mechanisms of slump initiation and rejuvenation. Addressing these questions required collaboration amongst several disciplinary experts and the application of a range of methods (see Lantz et al. 2009; Thompson et al. 2008; Kokelj et al. 2009a, b).

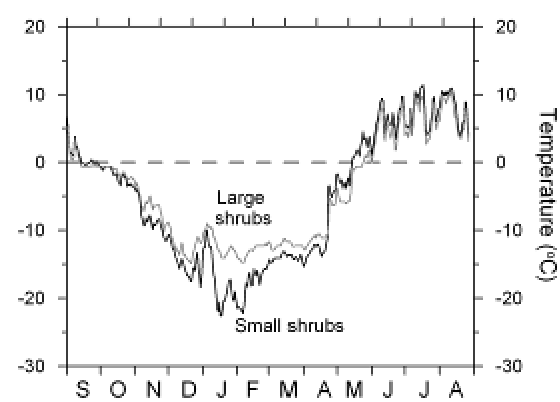

Figure 4 Ground surface temperatures for two adjacent tundra sites with and without tall alder shrubs.

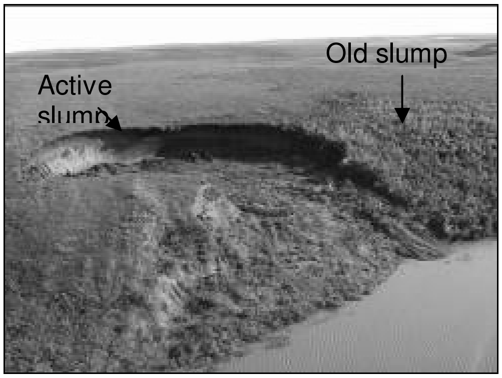

Figure 5 Area of retrogressive thaw slumping adjacent to a small lake in the Mackenzie Delta region. The headwall is about 10 m height. Note the adjacent stabilized slump with tall shrubs.

Regional mapping of slumps revealed that the disturbances are closely related to tundra lakes (Lantz and Kokelj 2008; Kokelj et al. 2009a). A 3500 km^2 study area defined by a 20 km buffer around proposed pipeline infrastructure between Inuvik and the Beaufort Sea coast contained over 500 retrogressive thaw slumps. More than 90% of the active disturbances were associated with areas of previous slumping (Figure 5). Analysis of sequential aerial photographs revealed that both the aerial extent and growth rates of slumps have increased with accelerated climate warming since the 1970s (Lantz and Kokelj 2008).

Aquatic impacts

Knowledge of the chemical contrast between the active layer and underlying permafrost (Kokelj and Burn 2003, 2005b) and the physiographic and hydrologic impacts of slumping (Lewkowicz 1987) led to the development of study designs to evaluate the environmental impacts of thaw slumping. Soils and runoff from slumps were characterized by elevated soluble ion concentrations and lower pH than adjacent undisturbed areas (Kokelj et al. 2005). Over 70 upland lakes, half of which were impacted by permafrost degradation, were sampled from across a range of surficial materials and ecological zones (Figure 1). A principal components analysis on the lake water quality data showed that almost 60% of the total variability in the dataset was described by PC1. The first principal component scores distinguish lakes affected by slumping from those which are undisturbed on the basis of ionic strength (Figure 6) (Kokelj et al. 2009b). The intensity of aquatic impacts was explained by the proportion of the catchment affected by slumping and relative age of disturbance. Lakes impacted by thaw slumps were also characterized by clear water in contrast with tea coloured waters of undisturbed lakes. Microcosom experiments showed that the addition of slumped sediments to coloured lake water increased clarity likely due to adsorption and sedimentation of DOC (Thompson et al. 2008).

Permafrost degradation can be expected to accelerate with future warming and increase in importance as a driver of chemistry and optical properties of northern lakes (Kokelj et al. 2009b). The studies presented above have also served as a platform for research investigating the impacts permafrost degradation on lake productivity (Mesquita et al. 2008) and utilizing paleolimnological techniques to examine timing, magnitude and effects of contemporary and past thawing events.

Terrestrial impacts

Research on the terrestrial impacts of slumping explored the hypothesis that thaw slumps provide an important microenvironment for colonization and dispersal of shrubs and other plant species onto the tundra. Sampling variously aged thaw slumps across the treeline transition showed increased nutrient availability, soil pH, snow pack, ground temperatures and active layer thickness in comparison with undisturbed terrain (Lantz et al. 2009). The ameliorated conditions in slumps were associated with altered plant community composition, increased productivity, catkin production and seed viability of green alder compared with the undisturbed tundra (Figure 5). Results suggest that permafrost disturbances may provide seed sources for plant and shrub colonization of undisturbed tundra (Lantz et al. 2009).

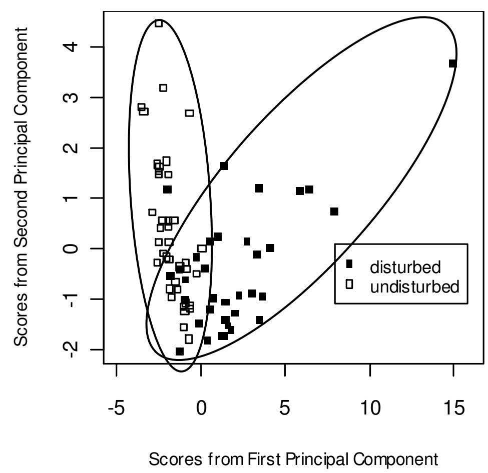

Figure 6. First and second principle components scores on the lake chemistry data set from 74 lakes across treeline in the Mackenzie Delta region. Disturbed lakes are impacted by retrogressive thaw slumping. Redrawn from Kokelj et al. 2009b.

The cumulative effects of numerous disturbances could drive broad scale changes in vegetation. A regional scale analysis of disturbance and ecological change is warranted because both natural (slumps, drained lakes, fire) and anthropogenic (abandoned sumps, well sites, seismic) disturbances are common throughout the Delta region (Jenkins et al. 2008; Lantz and Kokelj 2008; Marsh et al. 2009; Kemper and MacDonald 2009). Regional ecological change is critical to predicting both permafrost and wildlife responses to future climate warming.

Mechanisms that cause slumping
Previous research focused on the impacts of permafrost degradation on aquatic and terrestrial environments, but the mechanisms driving thaw slump activity remained speculative (Lantz and Kokelj 2008). Fundamental questions persisted in relation to why slump initiation and reactivation processes, commonly attributed to mechanical erosion, have been so active in the low energy environments of small tundra lakeshores (Figure 5) (Lantz and Kokelj 2008).

It was hypothesized that slump initiation is associated with talik expansion into ice-rich sediments subadjacent to the lakeshore (Figure 7) (Kokelj et al. 2009a). Ground thermal data from thaw slumps showed that mean annual near-surface temperatures were at least several degrees higher than in the adjacent tundra. A two-dimensional thermal model, utilizing field data to define boundary conditions, showed that increasing permafrost temperatures caused either by climate warming (Burn and Kokelj 2009) or thaw slumping (Lantz et al. 2009) can lead to rapid near-surface lateral talik expansion (Figure 7) (Kokelj et al. 2009a). Talik growth into ice-rich sediments subadjacent to the lakeshore is likely to yield lake bottom subsidence which can cause initiation or rejuvenation of shoreline slumping. The observation of depressions and tension cracks on lake bottoms adjacent to areas of slumping provides empirical evidence that talik adjustment, permafrost degradation and lake bottom subsidence may drive both the initiation and long-term polycyclic behavior of lakeside thaw slumps (Kokelj et al. 2009a). These findings highlight the importance of considering changes in lake and permafrost temperatures, lake levels and/or changing ice-thickness on the thermal and physical stability of lakeshores throughout permafrost terrain.

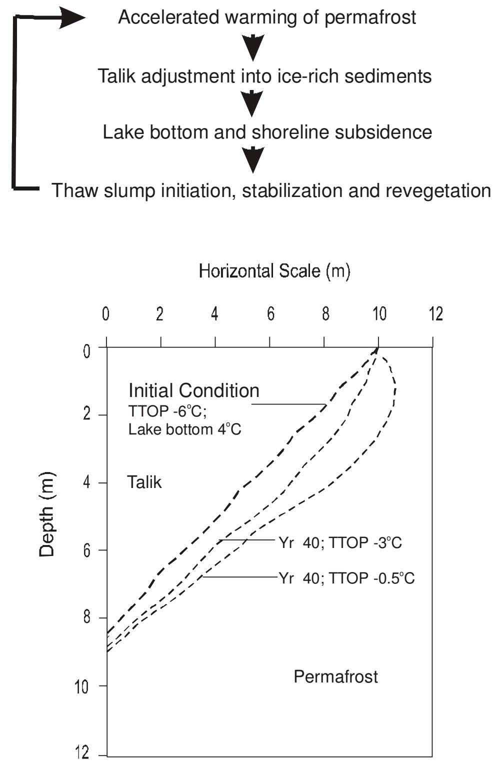

Figure 7. Conceptual model of slump initiation and polycyclicity and a graphic showing modeled talik growth after 40 years elapsed time where adjacent permafrost is increased in step fashion from -6 °C to -3 °C and -0.5 °C, respectively (Kokelj et al. 2009a). The dotted lines represent the position of the 0°C isotherms for equilibrium talik conditions and different modeled scenarios.

6 MODELS FOR POLICY RELEVANT RESEARCH

In our experience, a regional scale, multidisciplinary research program that emphasizes partnerships with northerners has been an effective way to develop a scientific knowledge base that can be applied in northern decision making. Regional approaches have also proven effective in engaging northern communities and producing results relevant to environmental management agencies.

The importance of building partnerships and maintaining communication with communities, regulators and land management agencies is becoming more broadly recognized as a key component of monitoring and research in northern Canada. Community engagement prior to initiating research and monitoring projects is invaluable as the researchers develop an appreciation for community concerns and local knowledge related to environmental context and study logistics. Partnerships are also strengthened through hiring local field assistants, training community monitors to conduct independent data collection and making efforts to communicate results in formats relevant to decision makers. Strong partnerships are likely to facilitate permitting, encourage feedback and identify future research needs.

Delta communities and regulators frequently expressed concerns regarding the disposal of drilling wastes to sumps in permafrost. This stimulated our involvement in sump-related research where we were able to apply our research experience examining interactions between vegetation, snow and thermal regimes in natural environments (Figures 3 and 4) towards understanding the long-term ecological and thermal evolution of drilling-mud sumps (Jenkins et al. 2008; Johnstone and Kokelj 2008; Kokelj et al. in press). This research has supported recommendations regarding sump construction and reclamation practices, the development of monitoring guidelines and assessment of the viability of permafrost as a long-term waste containment medium.

7 SUMMARY

The broad relevance of permafrost in the study of northern environments and in the engineering design and maintenance of infrastructure makes the discipline a potential focal point around which to develop integrated monitoring and research programs. The research presented here was focused around the study of permafrost and terrain conditions across treeline and served to fill environmental information gaps around the assessment, planning and management of proposed pipeline infrastructure. A multidisciplinary approach was adopted to evaluate the terrestrial and ecological impacts of retrogressive thaw slumping, the results of which were relevant to understanding potential ecosystem changes under future climate warming. The multidisciplinary knowledge base also enabled the development and testing of a physically based model of slump initiation and rejuvenation. The research was contextualized by characterization and regional mapping of disturbances, lakes and ecological conditions.

In areas like the Mackenzie Delta region where multiple interests overlap, there is growing acknowledgement that the coordination of diverse research and monitoring efforts is vital to determine impacts of global environmental change and cumulative impacts of northern development. The scope of our work was possible through fostering collaboration amongst researchers and northern communities and leveraging support from various sources. The central relevance of permafrost in understanding northern environmental change and in planning and managing northern development and infrastructure provides the permafrost science and engineering community with great opportunities to play leadership roles in northern research for many decades to come.

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