Permafrost loss and a new approach to the study of subarctic ecosystems in transition

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Abstract This study uses remote sensing to demonstrate the rate and spatial pattern of land-cover change resulting from permafrost loss in a subarctic region that typifies the southern boundary of permafrost. Permafrost occupied 0.70 km^2 of a 1.0 km^2 area in 1947, but by 2008 occupied only 0.43 km^2. This study also explains the need for an Earth Systems approach to properly examine the integrated mechanisms, interactions and feedbacks among physical, chemical and biological components of warming subarctic ecosystems.

Key words permafrost thaw; ecosystem change; subarctic; peatlands.

INTRODUCTION

Land-cover change induced by permafrost thaw introduces considerable uncertainty to the future availability of freshwater resources in northern Canada where permafrost controls water storage and drainage processes by limiting the amount of water infiltration to that which can be stored in the active layer, and by restricting hydrological interaction between near-surface supra-permafrost water and deep sub-permafrost groundwater. Along the wetland-dominated southern boundary of permafrost, permafrost typically occurs in the form of tree-covered plateaus that rise above the surrounding treeless and permafrost-free wetland terrain. As such, permafrost plateaus obstruct and redirect surface and near-surface drainage in the surrounding terrains. Thawing and subsidence of permafrost plateaus has led to increasing interconnectivity of drainage networks (Beilman & Robinson, 2003), and to changes in the local hydrological cycle due to changes in soil thermal and moisture regimes (Hayashi *et al.*, 2007), surface energy balances, and snow accumulation and melt rates and patterns (Wright *et al.*, 2009).

Northwestern North America is one of the most rapidly warming regions on Earth (Johannessen *et al.*, 2004). Climate warming and its environmental consequences are unlikely to proceed in an easily predictable manner due to complex responses and feedbacks. Permafrost thaw is one of the most important and dramatic manifestations of climate warming in Canada, and is strongly influenced by feedback processes (Jorgenson *et al.*, 2010). It also has the potential to alter other key aspects of ecosystems such as runoff and snow cover, forest composition, biodiversity and habitat for keystone species, surface–atmosphere interactions including greenhouse gas fluxes, forest fire regimes, and the quantity and quality flows to downstream ecosystems and the Arctic Ocean (Rowland *et al.*, 2010). While permafrost and ecosystem responses to warming occur in varying degrees throughout the North, the discontinuous permafrost zone of the subarctic is where the most dramatic permafrost thaw and landscape transformations are currently observed (Quinton *et al.*, 2011). Forecasted dramatic changes in temperature and moisture are expected to affect the processes governing the release of carbon dioxide and methane from the vast stores of carbon in northern peatlands (Lenton *et al.*, 2008). There are strong indications that the hydrology and hydrochemistry of the subarctic are changing as a result of permafrost thaw, yet little is known about the interactions and feedbacks among climate, water, biogeochemistry and the ecology of subarctic ecosystems. As a result, ecosystem consequences of warming and the impacts of thaw cannot be predicted with confidence (Frey *et al.*, 2007). Further, the implications of these feedbacks are not only prevalent within the subarctic region, but also to downstream aquatic and terrestrial ecosystems and the Arctic Ocean, the settled regions of southern Canada, due to downwind movement of water vapour in weather systems, and to global climate systems through changes to greenhouse gas fluxes, forest fire regimes and ground surface albedo.

The lack of knowledge on the mechanisms and rates of land-cover change induced by permafrost thaw, the impact on hydrological processes and resulting ecosystem impacts, and appropriate mitigation strategies, underscores the need for scientific research to provide the knowledge base needed for informed and sustainable water resource management. This article presents a selection of published and unpublished material for the purpose of: (1) demonstrating a clear example of the rate and spatial pattern of permafrost loss over the last ~60 years in the southern boundary of permafrost in the Northwest Territories, Canada, and (2) recommending an approach to examining subarctic ecosystem responses and feedbacks to permafrost thaw.

STUDY SITE

This study was conducted in the 152-km^2 Scotty Creek basin (61°18'N, 121°18'W; 285 m a.s.l.), which lies within the 140 000 km^2 Hay River Lowland of the Northwest Territories, Canada. Scotty Creek typifies the southern extent of permafrost in much of Canada where a high density of peatlands helps to preserve discontinuous permafrost due to the large thermal offset created by the dry, insulating peat covering the ground surface (Robinson & Moore, 2000; Smith & Riseborough, 2002). The peatlands in this region are dominated by a mosaic of permafrost plateaus, channel fens and ombrotrophic flat bogs (Quinton *et al.*, 2009). Unlike bogs and fens, the permafrost plateaus support a tree cover (*Picea mariana*) and are underlain by ~5–10 m thick permafrost (Burgess & Smith, 2000). Their crests rise 1 to 2 m above the surfaces of the surrounding bogs and fens (Robinson & Moore, 2000). Channel fens take the form of broad, 50 to >100 m wide channels. Unlike the floating peat mat characterising the surface of fens, flat bog surfaces are relatively fixed. Most flat bogs are small features that occur within permafrost plateaus, while others are relatively large, contain numerous permafrost plateaus, and are connected to channel fens.

METHODOLOGY

The forest cover distribution in the study area mirrors that of the permafrost, since the forest occurs only on the permafrost plateaus. This offers a unique opportunity to monitor permafrost thaw rates since such thaw transforms permafrost plateaus into treeless wetlands (i.e. bogs or fens), a change easily detected on the ground and from aerial and satellite imagery (Jorgenson *et al.*, 2001). Field observations at Scotty Creek (Quinton *et al.*, 2009) and elsewhere in the Hay River Lowland (Robinson & Moore, 2000) indicate that permafrost thaw leads to local inundation and water-logging, causing death of the tree cover within one or two years.

IKONOS multispectral satellite imagery (4-m resolution) from August 2000 and four sets of aerial photographs taken between 1947 and 2008 were obtained for Scotty Creek. The aerial photographs include high resolution (0.55-m to 1.22-m) historic black and white (visible) aerial photography (acquired July to September, 1947, 1970, 1977) and mosaiced near-infrared aerial photography (0.18-m resolution) acquired in August 2008 coincident with an airborne survey using light detection and ranging (LiDAR). The historical aerial photographs were ortho-rectified using the 2008 aerial photography and a LiDAR-derived digital elevation model (DEM) (resolution = 1 m) (Chasmer *et al.*, 2011). A 1 km × 1 km subset area was chosen, corresponding to the area covered by the LiDAR survey and also containing linear disturbances visible in all images (requirement of aerial triangulation and ortho-rectification processes). The three cover types (permafrost plateaus, wetlands (i.e. bogs and channel fens) and open water were classified based on land-cover spectral properties (Chasmer *et al.*, 2011). Using the time series of images, sequential maps were developed that show changes in the spatial distribution of the tree-covered area and, by proxy, the area underlain by permafrost. Errors in plateau edge detection/delineation range from between 8% and 12% (and up to 25% using IKONOS imagery). These errors are due to variable pixel resolutions between images, image geometry, and edge delineation at the boundary between forest and bog/fen. Due to the mismatch in pixel resolution, accuracy of aerial triangulation and ortho-rectification, ability to detect plateau features within aerial photographs, and forest/plateau edge delineation, the uncertainty in the delineation of the boundaries between different land covers results in error that ranges between 8% and 12% in the land cover area estimates from the air photos and up to 26% from the IKONOS imagery (Chasmer *et al.*, 2011). All linear disturbances were digitised using the IKONOS image to obtain an estimate of their total length within the Scotty Creek basin.

RESULTS AND DISCUSSION

Image analysis

Remote sensing analysis of the 1.0 km^2 subset area (Fig. 1) indicates that permafrost occupied 0.70 ± 0.06 km^2 in 1947 and decreased with time to 0.43 ± 0.03 km^2 by 2008, as evidenced by the expansion and merger of wetlands (i.e. bogs and fens) and the shrinkage and disappearance of the forest cover (i.e. permafrost plateaus). This loss rate of 38% loss (±8%) of the permafrost present in 1947 is similar in magnitude to that reported by Beilman & Robinson (2003) over the same period for other sites in the region. The 2008 imagery indicates 133 km of linear disturbance (i.e. winter roads and seismic cutlines) within the 152-km^2 basin, approximately five times greater (0.875 km^{-1}) than the basin's natural drainage density (0.161 km^{-1}) (Quinton *et al.*, 2003).

Need for an Earth-systems approach

For the past few decades, researchers have studied permafrost ecosystems in a compartmentalised fashion, focusing on individual components (e.g. water, terrestrial ecology) of the ecosystem. However, it has become clear that the integrated ecosystem response to climate change and anthropogenic disturbances in the subarctic cannot be addressed adequately by this approach. Instead, an Earth-systems approach is needed to properly examine the integrated mechanisms, interactions and feedbacks among physical, chemical and biological components of warming subarctic ecosystems. This would require the gathering of expertise from the diverse fields of hydrology, terrestrial ecology, biogeochemistry and wildlife ecology to address the common overarching goal of developing a comprehensive understanding of subarctic ecosystem responses and feedbacks to climate warming, and a new capacity to predict the rate and impact of permafrost loss in the subarctic. Such an approach will by necessity, bridge disciplinary boundaries and forge new collaborations.

Unlike the high-arctic, which was the major focus of the International Polar Year (IPY), there has been no large interdisciplinary research programme targeted to the subarctic, which has relatively thin, discontinuous and therefore sensitive permafrost. It is also the permafrost region with the highest population density, land disturbance and rate of resource development. This is also the region with extensive peatlands, and the deepest snow depth outside of the western cordillera, and as such represents an important runoff generation zone for freshwater flow to the Arctic Ocean. The co-occurrence of permafrost and extensive peatlands means that this region contains the largest soil carbon stocks in Canada, though this is not well quantified.

Wholesale ecosystem change in the subarctic will have wide-ranging effects from global climate forcing to regional socio-economic impacts as this region is at the forefront of mineral resource development and a northward expanding commercial forestry. An integrated, Earth-systems approach will reveal new insights on the effects of a warming global climate on biodiversity, trace element cycling and exposure/toxicity to living systems, and water resources and greenhouse gas fluxes in northern ecosystems. It will also specifically isolate the climate drivers of systems changes in ecology, hydrology and chemistry, and will reveal the existence of thresholds with respect to the structure and function of plant, microbial and animal species that are important to subarctic food webs, including species at risk such as woodland caribou.

IPY provided an excellent opportunity to intensify scientific research activity in the arctic and subarctic regions, resulting in new knowledge on permafrost ecosystems. For example, permafrost

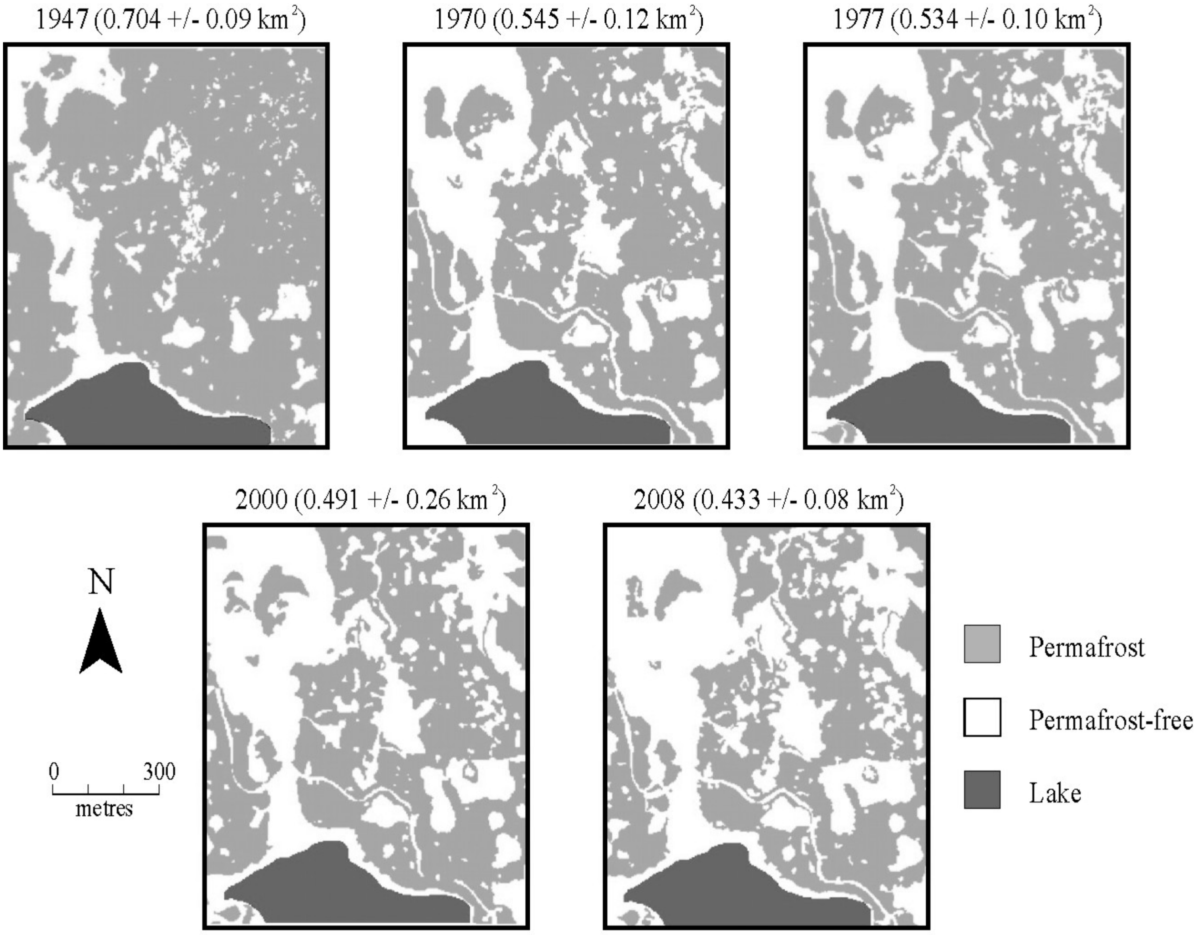

Fig. 1 The area of the 1-km^2 subset area of Scotty Creek, Northwest Territories, Canada underlain by permafrost in 1947, 1970, 1977, 2000 and 2008 (modified from Quinton *et al.*, 2011).

thaw in the southern Yukon is enhanced by shrub tundra expansion and height increases, which result in much deeper snowpacks and more rapid snowmelt that both work to further accelerate permafrost thaw (Quinton & Carey, 2008). In another example, Kemper & Macdonald (2009) indicated that plant communities in the low Arctic may not be in equilibrium with the present climate, but that disturbance associated with seismic exploration triggers a succession towards a new equilibrium. These and other individual research projects laid the foundation for the approach recommended in this report, in which the integrated ecosystem response is studied in a truly interdisciplinary manner.

REFERENCES

Beilman, D. W. & Robinson, S. D. (2003) Peatland permafrost thaw and landform type along a climate gradient. In: *Proceedings Eighth International Conference on Permafrost* (ed. by M. Phillips, S. M. Springman & L. U. Arenson) (Zurich, Switzerland), vol. 1, 61–65. A.A. Balkema.

Burgess, M. M. & Smith, S. L. (2000) Shallow ground temperatures. In*: The Physical Environment of the Mackenzie Valley, Northwest Territories: A Base Line for the Assessment of Environmental Change* (ed. by L. D. Dyke & G. R. Brooks), 89–103. Geological Survey of Canada Bulletin 547, Ottawa, Canada.

Chasmer, L., Hopkinson C. & Quinton, W. L. (2011) Quantifying errors in permafrost plateau change from optical data, Northwest Territories, Canada: 1947 to 2008. *Canadian J. Remote Sensing – CRSS Special Issue* **36**(2), S211–S223.

Frey, K. E., Siegel, D. I. & Smith, L. C. (2007) Geochemistry of west Siberian streams and their potential response to permafrost degradation. *Water Resour. Res*. **43**, W03406, doi:10.1029/2006WR004902.

Hayashi, M., Goeller, N. T., Quinton, W. L. & Wright, N. (2007) A simple heat conduction method for simulating the frost-table depth in hydrological models. *Hydrol. Processes* **21**, 2610–2622.

Johannessen, O. M., Bengtsson, L.. Miles, M. W., Kuzmina, S. I., Semenov, V. A., Alekseev, G. V., Nagurnyi, A. P., Zakharov, V. F., Bobylev, L. P., Pettersson, L. H., Hasselmann, K. & Cattle, A. P. (2004) Arctic climate change: observed and modelled temperature and sea-ice variability. *Tellus Series—Dynamic Meteorology and Oceanography* **56**(4), 328–341.

Jorgenson, M. T., Racine, C. H. Walters, J. C. & Osterkamp, T. E. (2001) Permafrost degradation and ecological changes associated with a warming climate in central Alaska. *Climatic Change* **48**, 551–579.

Jorgenson, M. T., Romanovsky, V., Harden, J., Shur, Y., O'Donnell, J., Schuur, E. A. G., Kanevskiy, M. & Marchenko, S. (2010) Resilience and vulnerability of permafrost to climate change. *Canadian J. Forest Research* **40**, 1219–1236, doi:10.1139/X10-060.

Kemper, J. T. & Macdonald, S. E. (2009) Directional change in upland tundra plant communities 20–30 years after seismic exploration in the Canadian low-arctic. *J. Vegetation Science* **20**, 557–567, doi: 10.1111/j.1654-1103.2009.01069.x.

Quinton, W. L. & Carey, S. K. (2008) Towards an energy-based runoff generation theory for tundra Landscapes. *Hydrol. Processes* **22**, 4649–4653. doi: 10.1002/hyp.7164.

Quinton, W. L., Hayashi, M. & Pietroniro A. (2003) Connectivity and storage functions of channel fens and flat bogs in northern basins. *Hydro.l Processes* **17**, 3665–3684.

Quinton, W. L., Hayashi, M. & Chasmer, L. (2009) Peatland hydrology of discontinuous permafrost in the Northwest Territories: overview and synthesis. *Canadian Water Resour. J.* **34**, 311–328.

Quinton, W. L., Hayashi, M. & Chasmer, L. (2011) Permafrost-thaw-induced land-cover change in the canadian subarctic: implications for water resources. *Hydrol. Processes* **25**, 152–158, doi: 10.1002/hyp.7894.

Robinson, S. D. & Moore, T. R. (2000) The influence of permafrost and fire upon carbon accumulation in High Boreal peatlands, Northwest Territories, Canada. *Arc. Antarc. Alp. Res.* **32**, 155–166.

Rowland, J. C., Jones, C. E., Altmann, G., Bryan, R., Crosby, B. T., Geernaert, G. L., Hinzman, L. D., Kane, D. L., Lawrence, D. M., Mancino, A., Marsh, P, McNamara, J. P., Romanovsky, V. E., Toniolo, H., Travis, B. J., Trochim, E., Wilson, C. J. (2010) Arctic Landscapes in transition: responses to thawing permafrost. *EOS*, *Trans. Am. Geophys. U.* **91**(26), 229–230, doi:10.1029/2010EO260001.

Smith, M. W. & Riseborough, D. W. (2002) Climate and the limits of permafrost: A zonal analysis. *Permafrost Periglacial Proc.* **13**, 1–15.

Wright, N., Hayashi, M., & Quinton, W. L. (2009) Spatial and temporal variations in active layer thawing and their implication on runoff generation in peat-covered permafrost terrain. *Water Resour. Res*. **45**, W05414.