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Wetland-Forest Transition at the Edge of Permafrost: Roles of Water and Energy Transport Process

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1. Introduction

The permafrost region of Canada (**Fig. 1**) is one of the most rapidly warming regions on the planet . Large-scale modelling studies predict pole-ward shift of the discontinuous permafrost zone due to the warming (e.g. Delisle, 2007. *Geophys. Res. Lett.*, 34, L09503). This may cause major changes in the distribution of permafrost within the discontinuous permafrost zone (**Fig. 2**).

Questions: **1) How will the permafrost distribution change with the warming?**
2) How does vegetation influence the thawing of permafrost?
3) What are the eco-hydrological implications of permafrost thaw?

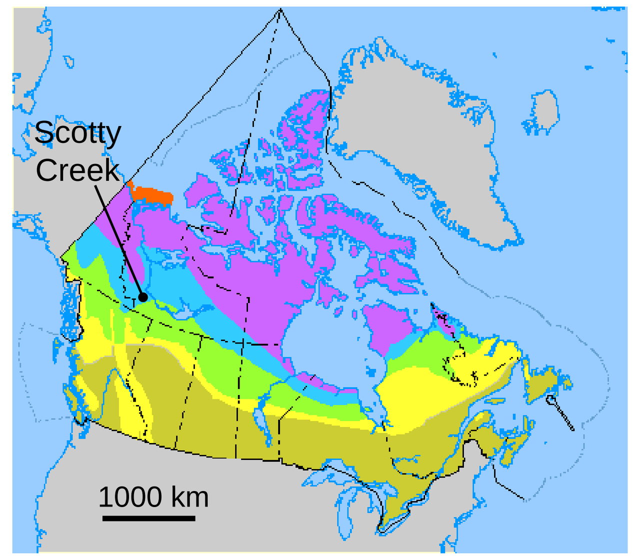


Fig. 1 Permafrost distribution in Canada. (Natural Resources Canada, http://atlas.nrcan.gc.ca/site/english/maps/environment/land/permafrost)

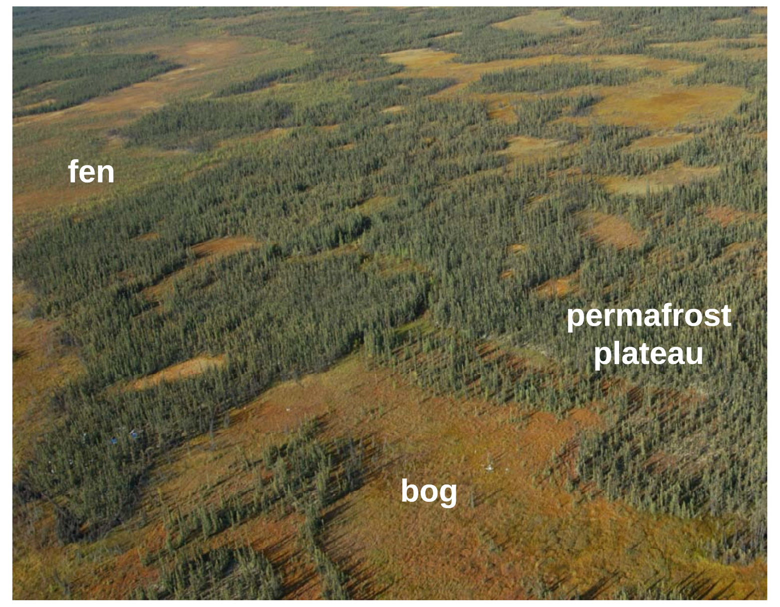


Fig. 2 Scotty Creek represents typical peatlands in the Northwest Territories. Discontinuous permafrost occurs as a mosaic of non-permafrost wetlands and permafrost plateaus that supports trees. The thawing of permafrost may causes a major change in landscape and hydrological pathways.

2. Study Site – Scotty Creek Research Basin

Scotty Creek is in the Northwest Territories (NWT) of Canada (**Fig. 1**), and is covered with a thick (2-3 m) layer of peat.

Three distinct landcover types with different hydrological functions exist as a complex mosaic (**Fig. 2**):

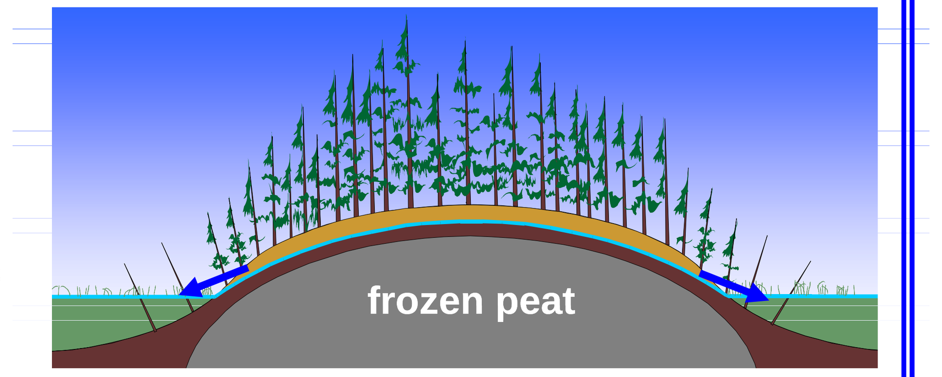
(1) **Permafrost plateaus** rise 1-2 m above the surrounding wetlands and generate runoff that feeds fens and bogs (**Fig. 3**). They support black spruce forests.

(2) **Channel fens** provide drainage network, and support vascular aquatic plants.

(3) **Flat bogs** store water and occasionally drain to channel fens. They are dominated by *Sphagnum* moss and contain acidic water.

Thawing of permafrost plateaus may change the relative proportion of forests and wetlands, and connectivity of hydrological pathways.

Fig. 3 Schematic cross section of a permafrost plateau. The active layer develops during summer months. Snowmelt and storm runoff mainly occur as subsurface flow (blue arrows) through the saturated zone within the active layer. The plateau is surrounded by bogs or fens.



3. Methodology

- Annual frost table (FT) surveys on a transect across a permafrost plateau (**Fig. 4**) since 1999. (Wright et al., 2009. *Water Resour. Res.* 45, W05414)
- Four meteorological stations near FT transect. (Wright et al., 2009)
- Soil temperature/moisture monitoring stations. (Hayashi et al., 2007. *Hydrol. Process.* 21: 2610-2622)
- High-resolution (4 m) satellite image in 2000. (Hayashi et al., 2004. *J. Hydrol.*, 296: 81-97)
- High-resolution (1 m) LiDAR survey in 2008. (Quinton et al., 2009, *Can. Water Resour. J.*, in press)
- Electrical resistivity imaging (ERI) in 2009.

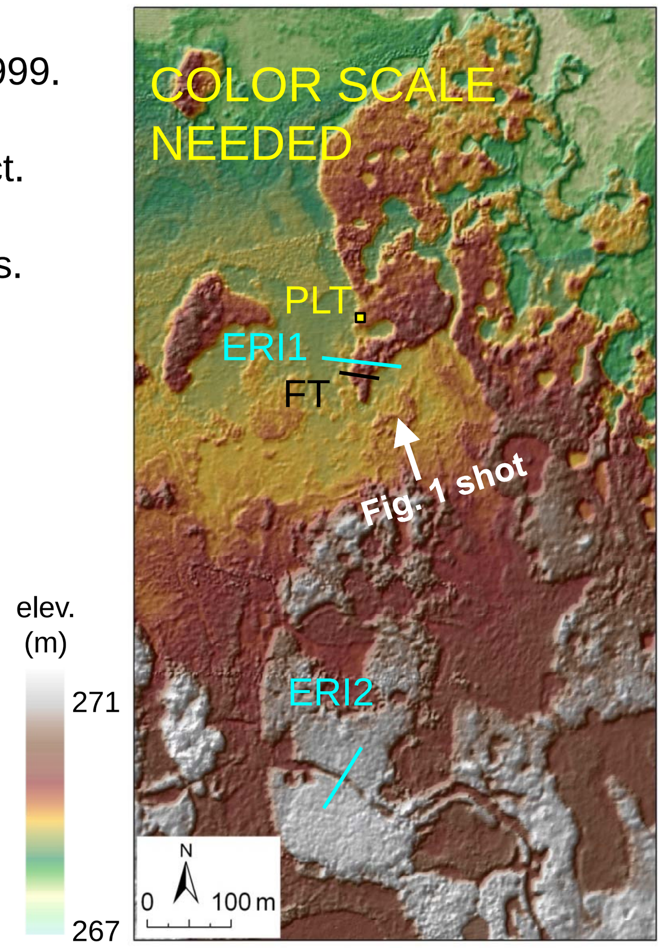
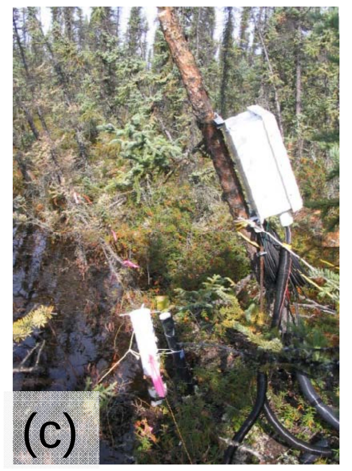


Fig. 4 Study areas in the Scotty Creek watershed. Frost-table survey transect (FT), frost-table mapping plot (PLT), and electrical resistivity imaging (ERI) lines are shown.

4a. Results: Frost Table Dynamics

Annual frost surveys on the same line every year in the permafrost plateau (**Fig. 4**) revealed a steady shrinkage of plateau due to the lateral thawing from both sides (**Fig.5a**). Elevation surveys from 2006 and 2009 indicate that the plateau is subsiding as the active layer deepens (**Fig. 5b**).

This results in the encroachment of fens and bogs into black spruce forest (**Fig. 5c**). As the trees die and fall, the plateau edges are exposed to radiation inputs and the contact with relatively warm surface water in the wetlands, thereby sustaining the continued shrinkage of permafrost and expansion of non-permafrost.



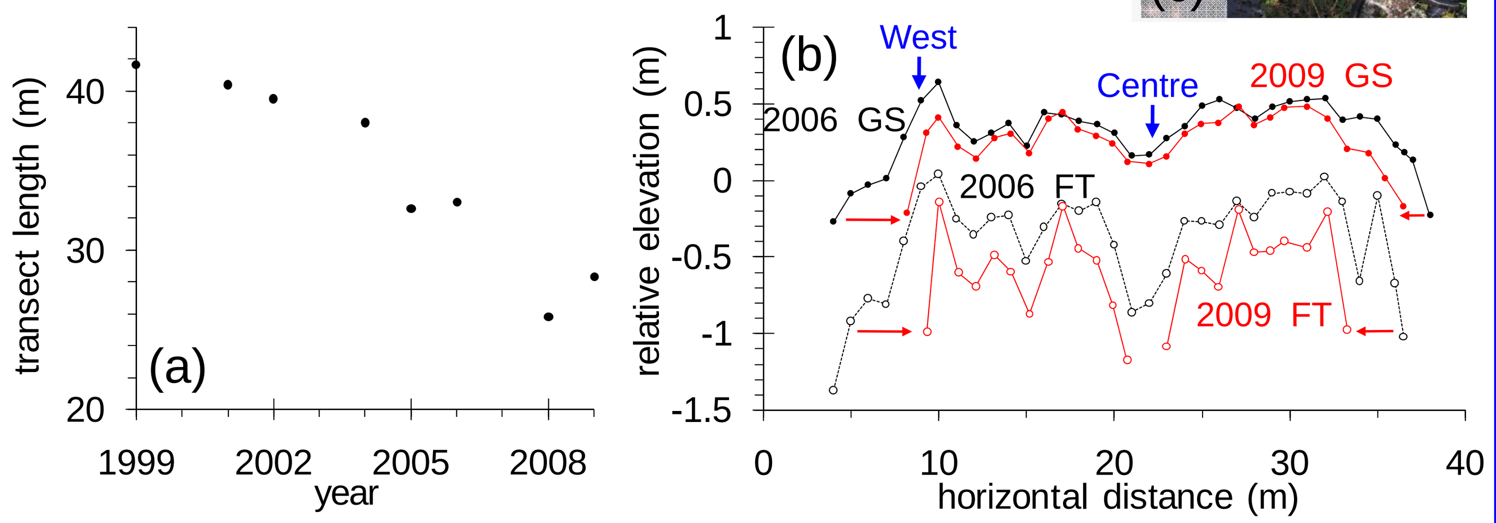


Fig. 5 (a) Length of the annual frost table (FT) survey transect indicating the lateral shrinkage of permafrost. (b) Elevation of the ground surface (GS) and the FT surveyed in the late August of 2006 and 2009 showing the lateral shrinkage of permafrost (red arrows) and the deepening of the active layer. Elevation is measured relative to a stable datum anchored to the mineral soil. Blue arrows show the location of soil monitoring instrumentation sites. (c) A 2008 photograph of a monitoring station, which had been located inland but was nearly submerged.

The frost table is generally deep under topographic lows (**Fig. 5b**). The lowering of the frost table was much faster in the Centre than the West site (**Fig. 6a**). The Centre site is in a depression (**Fig. 5b**) and has a wet condition (**Fig. 6b**) due to subsurface flow convergence, whereas the West site is higher and has a dryer condition.

The thermal conductivity of peat is strongly dependent on water content as water is much more conductive than air and organic material. Enhanced deepening of the active layer under depressions is due to the positive feedback, in which the convergence of water during thawing seasons enhances the vertical heat conduction.

This concept is demonstrated on a detailed frost-table map (**Fig. 7**), surveyed on a rectangular plot (PLT in **Fig. 4**) in June 2006. A two-dimensional flow model based on the Dupuit-Forchheimer equation was used to simulate the distribution of the saturated thickness in the active layer after a hypothetical rainfall of 15 mm. The model shows thicker saturated zones in the areas of deeper frost table (**Fig. 7**).

Fig. 6 (a) Depth to the frost table (FT) at Centre and West soil monitoring site (see Fig. 5b) in 2004. Observed data (symbols) are based on frost-probe measurements and soil temperature monitoring, and lines show simulated frost table using a vertical heat transfer model. (b) Liquid volumetric water content at 0.2-m depth (Hayashi et al., 2007).

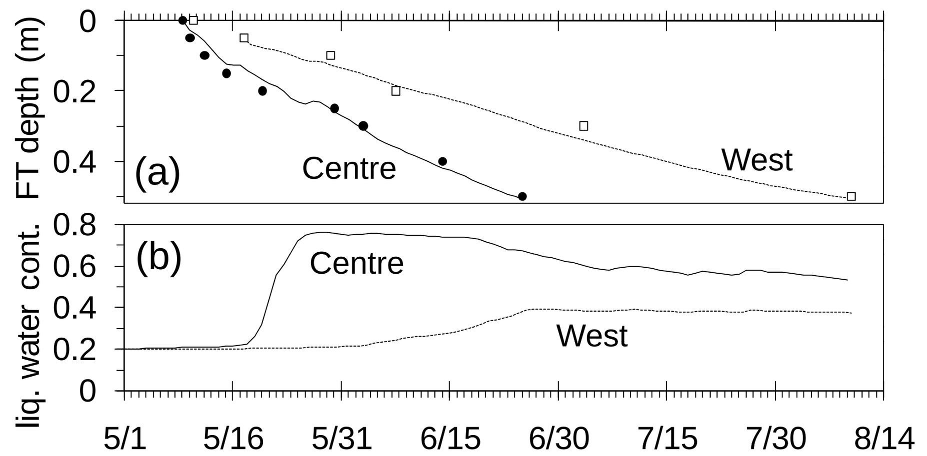
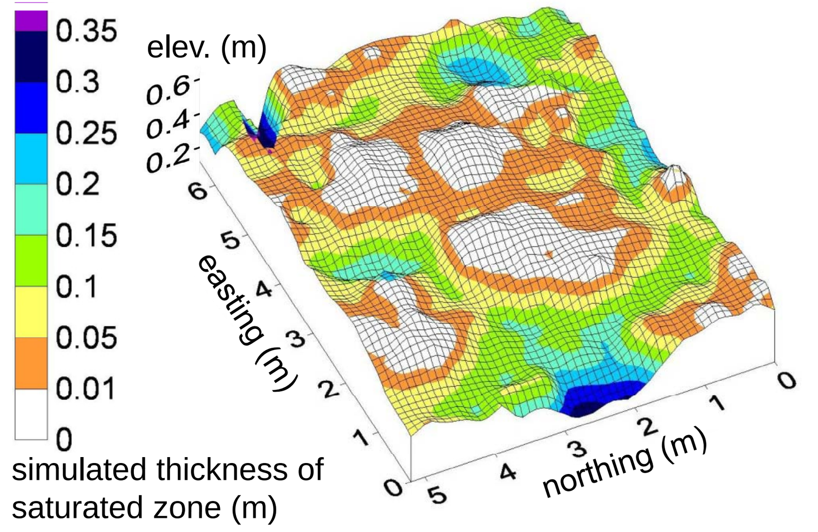


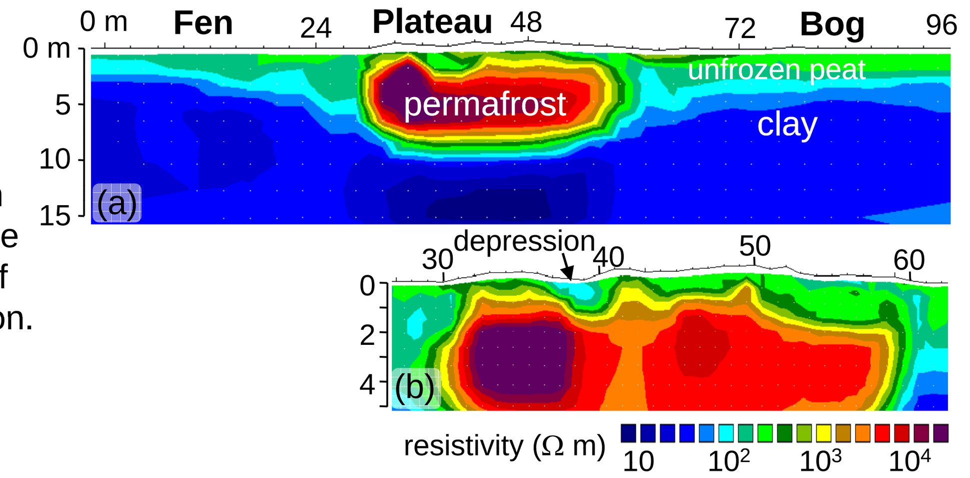
Fig. 7 Frost-table elevation in a detailed survey plot (PLT in Fig. 4) in June 2006, measured on 0.25-m grids and interpolated by krigging (Wright et al., 2009). Elevation is relative to an arbitrary datum. The colors indiate the thickness of the saturated zone within the active layer after a 15-mm rain event, simulated using a two-dimensional flow model. The frost table represents an impermeable boundary of unconfined aquifer, which evolves during a thawing season.



4b. Results: Permafrost Imaging and Mapping

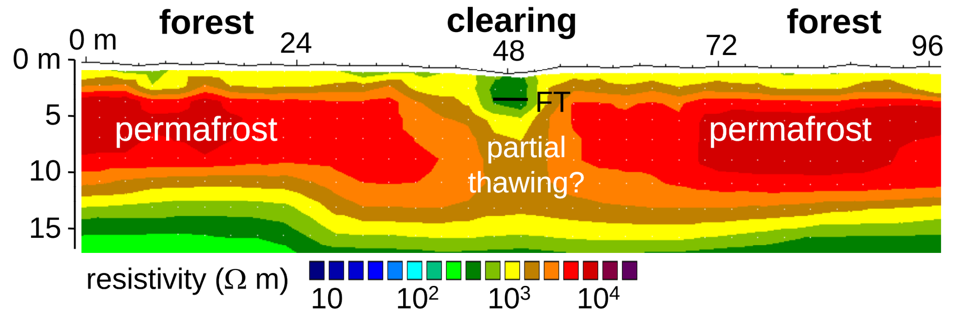
Resistivity survey along ERI1 (see **Fig. 4**) clearly delineated permafrost under the peat plateau (**Fig. 8a**) . ERI was also effective for delineating the peat/clay boundary, which was confirmed using a hand auger. The sharp, vertical boundary between the permafrost and adjacent wetlands may indicate the importance of lateral heat transfer . The high-resolution survey showed the deepening of the active layer under a depression (**Fig. 8b**), providing further evidence for the feedback mechanism.

Fig. 8 Resistivity image for ERI1 in Fig. 4. (a) Image obtained with 3-m electrode spacing, showing the clear definition of the permafrost bottom. (b) Image with 1-m electrode spacing showing the details, including the deepening of the active layer below a depression.



ERI was also conducted across a winter road (ERI2 in **Fig. 4**) to examine the effects of canopy removal, which took place in the1950's . The active layer was much deeper (ca. 2.5 m) under the road cut, and relatively low resistivity indicates the presence of liquid water in the permafrost underneath (**Fig. 9**). The ground surface has subsided along the road cut due to the deepening of the active layer.

Fig. 9 Resistivity image for ERI2 in Fig. 4, obtained with 3-m electrode spacing. The frost table (FT) under the road clearing was determined using a hand auger.



The high-resolution satellite image from 2000 and the LiDAR data from 2008 were used to delineate the distribution of permafrost plateaus and wetlands.

Figure 10 shows the 2008 extent of plateaus in brown and the loss of plateau areas during 2000-2008 in red. Clearly, permafrost plateaus are thawing from the edges, which is consistent with the interpretation of the ERI data.

Since the permafrost degradation is occurring both laterally and vertically, it is very important to consider the lateral heat transfer and the water-energy feedback processes at a "sub-grid" scale (i.e. 100-1,000 m) in modelling of climate-permafrost interaction in the discontinuous permafrost regions.

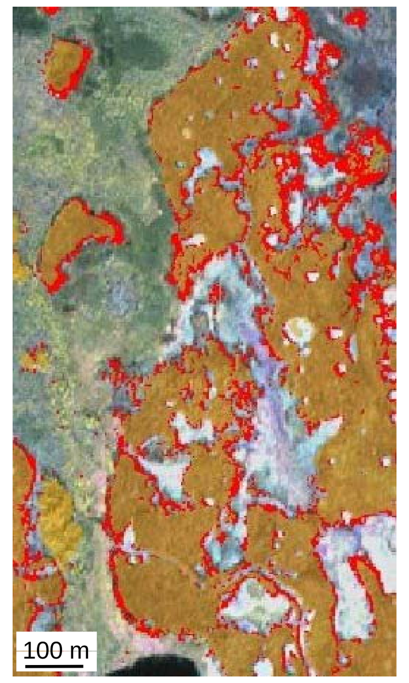


Fig. 10 Permafrost degradation (shown in red) between 2000 and 2008 (Quinton et al., 2009).

5. Conclusions

The peat-covered, discontinuous permafrost of Scotty Creek watershed is thawing with the climate warming, which is consistent with model prediction in the literature.

However, the thawing does not occur as a result of uniform reduction in thickness as assumed in large-scale, vertical model. It occurs as:

- Preferential deepening of the active layer in topographic depressions.
- Shrinkage at the edges of plateaus due to the exposure to radiation and the lateral heat transfer from the neighbouring wetlands.
- Thawing along the lines of canopy removal (roads, seismic cutlines).

In all these cases, the positive feedback between water and energy transfer sustains progressive thawing.

Effects of these sub-grid scale processes, and impacts of local disturbances need to be considered in future modelling efforts.

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