GEOPHYSICAL RESEARCH LETTERS, VOL. 31, L18208, doi:10.1029/2004GL020358, 2004

Accelerated thawing of subarctic peatland permafrost over the last 50 years

Serge Payette, Ann Delwaide, Marco Caccianiga, and Michel Beauchemin
NSERC Northern Research Chair, Centre d'Études Nordiques, Université Laval, Québec, Québec, Canada

Received 26 April 2004; revised 5 August 2004; accepted 19 August 2004; published 25 September 2004.

[1] In this study we provide a quantification of the main patterns of change of a subarctic peatland caused by permafrost decay monitored between 1957 and 2003. Up-thrusting of the peatland surface due to permafrost aggradation during the Little Ice Age resulted in the formation of an extensive peat plateau that gradually fragmented into residual palsas from the 19th century to the present. Only about 18% of the original surface occupied by permafrost was thawed in 1957, whereas only 13% was still surviving in 2003. Rapid permafrost melting over the last 50 years caused the concurrent formation of thermokarst ponds and fen-bog vegetation with rapid peat accumulation through natural successional processes of terrestrialization. The main climatic driver for accelerated permafrost thawing was snow precipitation which increased from 1957 to present while annual and seasonal temperatures remained relatively stable until about the mid-1990s when annual temperature rose well above the mean. Contrary to current expectations, the melting of permafrost caused by recent climate change does not transform the peatland to a carbon-source ecosystem as rapid terrestrialization exacerbates carbon-sink conditions and tends to balance the local carbon budget. *INDEX TERMS:* 1630 Global Change: Impact phenomena; 1823 Hydrology: Frozen ground; 1824 Hydrology: Geomorphology (1625); 1854 Hydrology: Precipitation (3354); 1851 Hydrology: Plant ecology. **Citation:** Payette, S., A. Delwaide, M. Caccianiga, and M. Beauchemin (2004), Accelerated thawing of subarctic peatland permafrost over the last 50 years, *Geophys. Res. Lett.*, *31*, L18208, doi:10.1029/2004GL020358.

1. Introduction

[2] Boreal and subarctic peatlands have been a major carbon sink [*Gorham*, 1991] throughout their Holocene history, until the advent of the Little Ice Age when extensive peat surfaces froze almost completely because of permafrost expansion [*Allard and Seguin*, 1987; *Lagarec*, 1982; *Payette and Rochefort*, 2001; *Worsley et al.*, 1995]. The permanently frozen peat surfaces take the form of large peat plateaus or confined palsas [*Luoto and Seppälä*, 2003; *Sollid and Sørbel*, 1998; *Zoltai*, 1972; *Zoltai and Tarnocai*, 1975] where ecosystem productivity is greatly reduced because of the shift from wet sedge-fen and/or *Sphagnum*-bog to dry lichen-heath conditions.

[3] Several studies have reported temporal changes in permafrost distribution during the 20th century in northern Europe [*Christensen et al.*, 2004; *Luoto and Seppälä*, 2003; *Sollid and Sørbel*, 1998; *Thorhallsdottir*, 1994; *Zuidhoff*, 2002] and North America [*Allard and Rousseau*, 1999; *Dionne*, 1978; *Laprise and Payette*, 1988; *Laberge and Payette*, 1995; *Thie*, 1974]. The changes were related to the reduced surface occupied by permafrost in boreal and subarctic peatlands due to recent global change. The evaluation of permafrost decay is generally deduced from air photographs. However, field measurements over an extended period of time can yield more information on the patterns and the processes associated with permafrost thawing. The main objective of this study is to report on permafrost evolution of a subarctic peatland during the past 50 years, and more specifically permafrost decay caused by recent climate change and the concurrent changing cover of the main components of the peatland, i.e., thermokarst ponds, residual permafrost mounds, and frost-free fen/bog vegetation. Indeed, the long-term monitoring of climate-sensitive ecosystems and biological data covering large geographic areas are among the best tools to identify the direct responses of organisms and ecosystems to recent climate change [*Lloyd and Fastie*, 2003; *Parmesan and Yohe*, 2003; *Pounds et al.*, 1999; *Southward et al.*, 1995].

2. Methods

[4] We have followed the fate of permafrost from 1957 (enlarged aerial photographs taken in 1957, starting date)

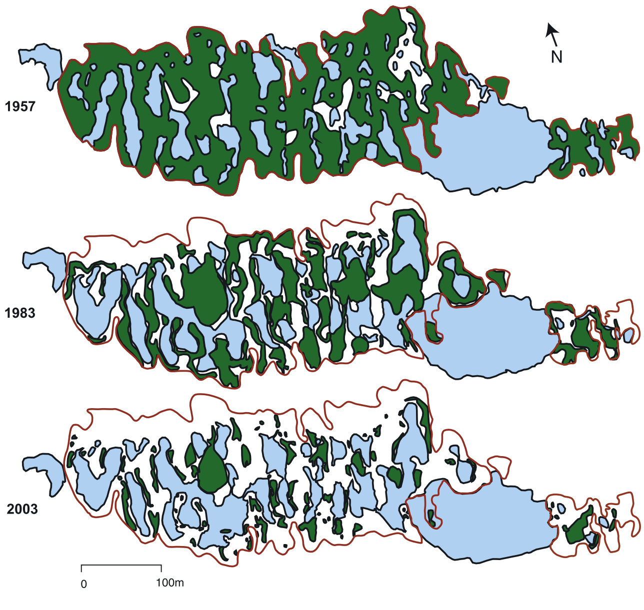

Figure 1. Peatland changes associated with permafrost thawing between 1957 and 2003. Changing patterns of permafrost (green), thermokarst ponds (blue) and fen vegetation (white) in 1957, 1983 and 2003.

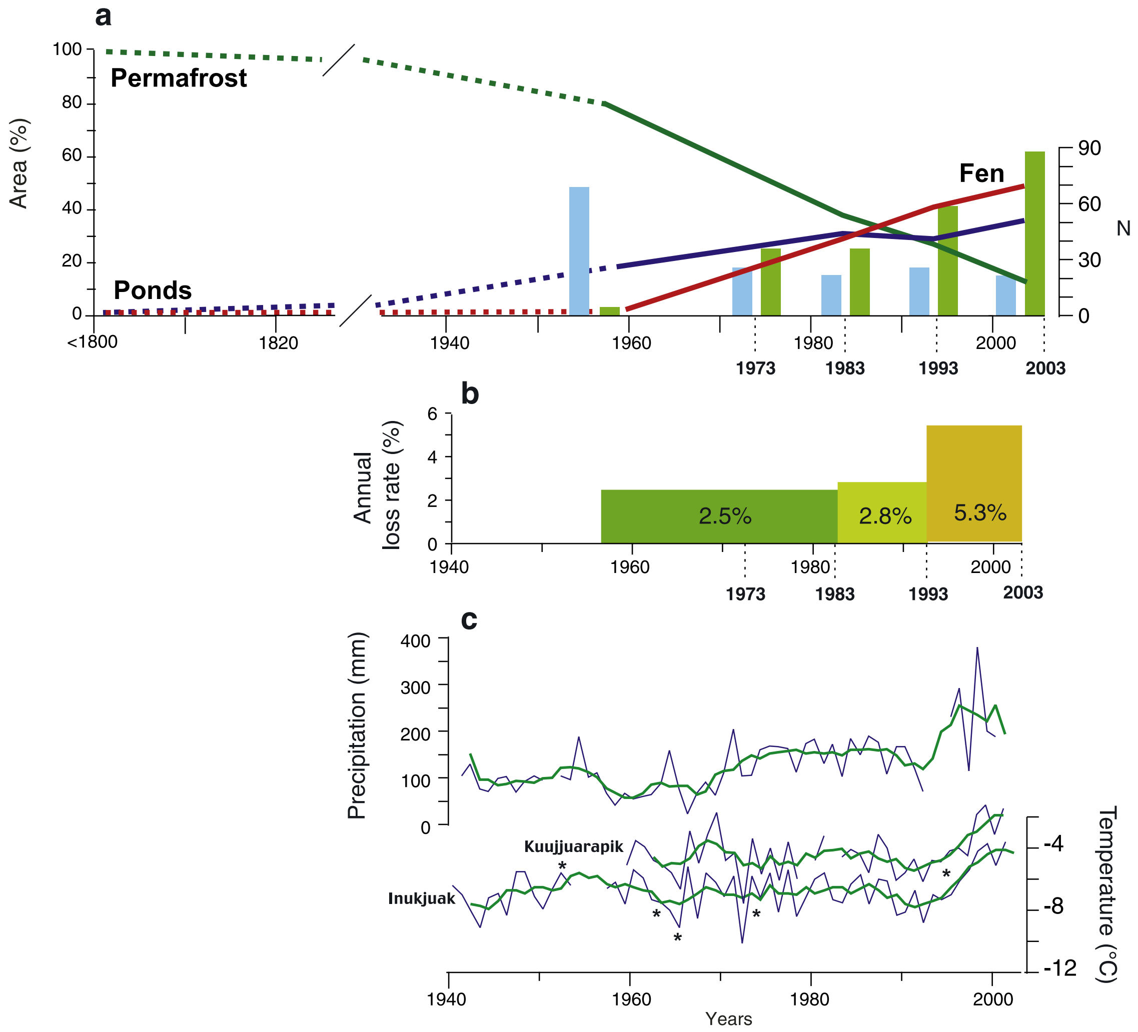

Figure 2. In A, changing cover (%) of permafrost (green line) thermokarst ponds (blue line) and fen vegetation (red line). Vertical bars correspond to number of thermokarst ponds (blue) and palsa mounds (green). In B, annual rate of permafrost loss. Calculation of loss rate is based on the proportion of permafrost lost from one survey (100%) to the other (remaining proportion in %). (C) Mean annual temperature (blue) with 5-year running mean (green) and winter precipitation (October to April) (blue) with 5-year running mean (green). Precipitation data are from the Inukjuak weather station, and temperature data are from the Inukjuak and Kuujjuarapik weather stations. Asterisks on the Inukjuak curve indicate interpolated temperature values based on data from Kuujjuarapik weather station. The Inukjuak weather station is 150 km north of the study site and the Kuujjuarapik weather station is 125 km south of the study site.

to 2003 based on the detailed monitoring of a subarctic peatland (56°11′N/75°55′W: eastern coast of Hudson Bay, northern Québec, Canada) using four field surveys at 10-year intervals in 1973, 1983, 1993 and 2003, respectively. The peatland investigated is in a pristine area of the discontinuous permafrost zone of northern Canada [*Payette and Rochefort*, 2001]. The site is representative of the extensive permafrost peatlands developed over clay-silt marine sediments along the eastern Hudson Bay coast between 53°N and 58°N [*Allard and Seguin*, 1987; *Lagarec*, 1982; *Payette and Rochefort*, 2001]. Peatland monitoring was based on the distribution of all permafrost landforms (palsas, collapse scars, thermokarst ponds) and permafrost-free sedge-shrub lawns within the geographical limits of the permafrost peatland. A dense grid of geographic coordinates was laid out for landform mapping in 1973 [*Samson*, 1974], whereas an optical prism was used in 1983 [*Laprise and Payette*, 1988] and a total station in 1993 [*Laberge and Payette*, 1995] and 2003. Field measurements were made between early and mid-summer. Permafrost inception and development cause the up-thrusting of the peat surface due to the growth and piling of lenses of segregation ice in peat and more particularly in mineral deposits [*Allard and Rousseau*, 1999]. Tree colonization occurs sometime after up-thrusting of the peat surface because of well-drained soil conditions. Thus the age distribution of the oldest black spruce (*Picea mariana* (Mill.)B.S.P.) trees (n = 15) growing on palsa mounds was used to determine the minimum age of permafrost development.

3. Results and Discussion

[5] Permafrost inception likely occurred during the Little Ice Age, and corresponds to maximum age of black spruce trees (350 years: from AD 1680 to present) colonizing the frozen peat plateau protruding above the peatland surface.

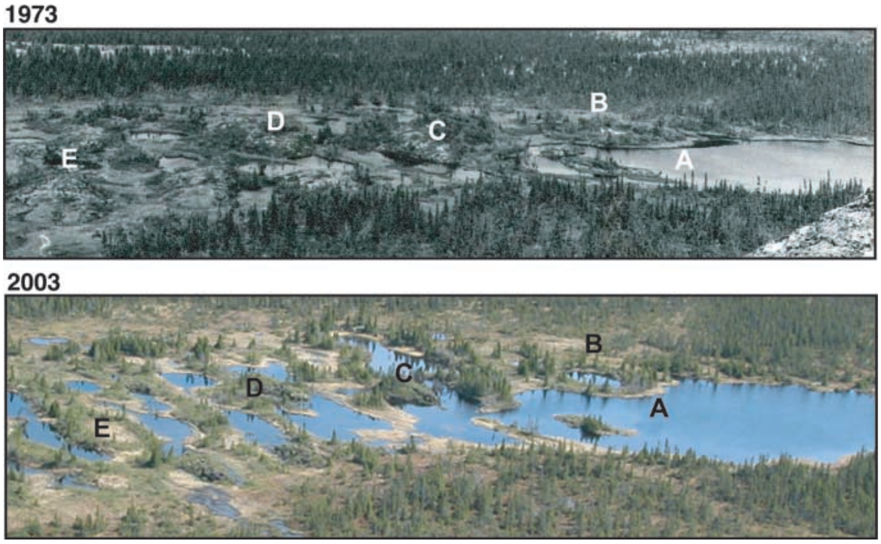

Figure 3. Photographs of the peatland in 1973 (taken by H. Samson) and 2003 showing major cover changes in permafrost, ponds and fen/bog vegetation. Island formed in A and thermokarst ponds formed in A and B. C, D and E: several shifts from palsa to fen/bog vegetation, and fen/bog vegetation to ponds.

Several dead trees distributed in thermokarst ponds indicate recent decay of permafrost bodies. The overall distribution and life span of pond trees and tilted (reaction wood) living trees [*Laprise and Payette*, 1988] on palsa mounds suggest continuous permafrost thawing during the 20th century. About 18% of the initial frozen peatland surface was melted in 1957 (Figure 1). Thereafter accelerated thawing occurred with only 38%, 28% and 13% of the original frozen surface still remaining in 1983, 1993 and 2003, respectively (Figure 2a). However, the annual loss of permafrost from one survey to the other (Figure 2b) indicates increasing decay rates from 1957–1983 (2.5% yr^{-1}), to 1983–1993 (2.8% yr^{-1}) and 1993–2003 (5.3% yr^{-1}). Assuming a loss rate equivalent to that of the last decade, permafrost will disappear completely in less than 20 years from now.

[6] From 1957 to 2003, permafrost loss was compensated by a concurrent gain in thermokarst ponds and fen/bog vegetation (Figures 1 and 2a). The decadal trends in the area occupied by ponds and fen/bog vegetation indicate active hydroseral processes towards terrestrialization of the peatland with fast sedge (*Carex aquatilis* Wahlenb.) and *Sphagnum riparium* Angstr. invasion and establishment. Shallow thermokarst ponds and slow subsidence of palsa sides likely provided propitious conditions for effective terrestrialization. Over the last 10 years, permafrost subsidence (as measured from 10 palsa mounds in 1993 and 2003) was of the order of 40% of the original height (about 1–1.5 m height decrease) which corresponds to substantial inflow of water from melting ice within palsas. Transformation of the peatland surface shows the fen/bog vegetation to assume dominance progressively, but reversion to pond conditions occurred during the survey period (Figure 3) which suggests important fluctuations of the water table through time. Old-aged thermokarst ponds (i.e., >20 years old) also are probably the deepest of all ponds, as they are at the centre of large sunken palsas where the largest volume of segregation ice was located.

[7] The overall spatial pattern of permafrost degradation from 1957 to 2003 shows the progressive fragmentation of the peat plateau, with most residual palsas and thermokarst ponds having their longest axis north-south oriented (Figure 1). This repetitive pattern of elongated palsas and ponds sets the ideal topographic conditions for snow trapping from dominant westerly winds. Increased snow precipitation from the late 1960s to present (Figure 2c) facilitated permafrost thaw along palsa margins exposed from the north-east to the south-east as also indicated by the main orientation of tilted trees [*Laprise and Payette*, 1988]. Over the last 30 years, the fragmentation process associated with continuous permafrost thawing caused a three-fold increase of the number of residual palsas (Figure 2a) along with a sharp decrease of the size of individual palsas. The progressive fragmentation and isolation of residual palsas and development of thermokarst ponds resulted in the loss of physical inertia of the initial peat plateau, and rapid decay began after 1957 when increased snow precipitation reduced frost penetration [*Seppälä*, 1990, 1994] although air temperature remained rather stable until the mid-1990s. Since 1996, accelerated thawing was facilitated by the dramatic increase of precipitation and temperature (Figure 2c).

4. Conclusion

[8] Long-term ecosystem monitoring provides baseline information on the patterns and processes of ecosystem changes associated with recent ecological changes in pristine northern environments. Two major findings here are the rapid permafrost thawing based on well documented melting rates over the last 50 years and the resulting formation of compensatory successional trajectories relative to the global carbon budget [*Christensen et al.*, 2004], i.e., the concurrent development of thermokarst ponds (C-source) and peat accumulation through terrestrialization (C-sink). Also of interest are the successive patterns of permafrost/thermokarst distribution and change after 1957 which suggest that the degradation of permafrost was a fast, one-way, self-organized process. Long-term ecosystem monitoring is

important for realistic predictions of future behaviour of subarctic peatlands as warmer and wetter conditions are anticipated in this century for high-latitude areas [*Houghton et al.*, 2001]. The dramatic decay of peatland permafrost since the mid-1950s is on line with several other accelerated ecosystem changes during the past 50 years across the northern and southern biomes [*Crutzen and Steffen*, 2003].

[9] **Acknowledgments.** We are most grateful to NSERC (Canada) and FQRNT (Québec) for financial support. We thank M. Seppälä and two anonymous reviewers for thoughtful comments on an earlier draft.

References

Allard, M., and L. Rousseau (1999), The internal structure of a palsa and a peat plateau in the rivière Boniface region, Québec: Inferences on the formation of ice segregation mounds, *Geogr. Phys. Quat.*, *53*, 373–387.

Allard, M., and M. K. Seguin (1987), The Holocene evolution of permafrost near the tree line, on the eastern coast of Hudson Bay (northern Quebec), *Can. J. Earth Sci.*, *24*, 2206–2222.

Christensen, T. R., T. Johansson, H. J. Akerman, and M. Mastepanov (2004), Thawing sub-arctic permafrost: Effects on vegetation and methane emissions, *Geophys. Res. Lett.*, *31*, L04501, doi:10.1029/2003GL018680.

Crutzen, P. J., and W. Steffen (2003), How long have we been in the Anthropocene era?, *Clim. Change*, *61*, 251–257.

Dionne, J. C. (1978), Formes et phénomènes périglaciaires en Jamésie, Québec subarctique, *Geogr. Phys. Quat.*, *32*, 187–247.

Gorham, E. (1991), Northern peatlands: Role in the carbon cycle and probable responses to climatic warming, *Ecol. Appl.*, *1*, 182–195.

Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, and D. Xiaosu (2001), *Climate Change 2001: The Scientific Basis*, Cambridge Univ. Press, New York.

Laberge, M.-J., and S. Payette (1995), Long-term monitoring of permafrost change in a palsa peatland in northern Quebec, Canada: 1983–1993, *Arct. Alp. Res.*, *27*, 167–171.

Lagarec, D. (1982), *Proceedings of the Fourth Canadian Permafrost Conference*, *The R. J. E. Brown Memorial Volume*, edited by H. M. French, pp. 43–48, Natl. Res. Counc. of Canada, Ottawa, Ont.

Laprise, D., and S. Payette (1988), Évolution récente d'une tourbière à palses (Québec subarctique): Analyse cartographique et dendrochronologique, *Can. J. Bot.*, *66*, 2217–2227.

Lloyd, A. H., and C. L. Fastie (2003), Recent changes in treeline forest distribution and structure in interior Alaska, *Ecoscience*, *10*, 176–185.

Luoto, M., and M. Seppälä (2003), Thermokarst ponds as indicators of the former distribution of palsas in Finnish Lapland, *Perm. Perigl. Proc.*, *14*, 19–27.

Parmesan, C., and G. A. Yohe (2003), A globally coherent fingerprint of climate change impacts across natural systems, *Nature*, *421*, 37–42.

Payette, S., and L. Rochefort (Eds.) (2001), *Écologie des Tourbières du Québec-Labrador*, Presse de l'Université Laval, Québec, Québec, Canada.

Pounds, J. A., M. P. Fogden, and J. H. Campbell (1999), Biological response to climate change on a tropical mountain, *Nature*, *398*, 611–615.

Samson, H. (1974), Évolution du pergélisol en milieu tourbeux en relation avec le dynamisme de la végétation, golfe de Richmond, Nouveau-Québec, M.S. thesis, Université Laval, Québec, Québec, Canada.

Seppälä, M. (1990), Depth of snow and frost on a palsa mire, Finnish Lapland, *Geogr. Ann.*, *72A*, 191–201.

Seppälä, M. (1994), Snow depth controls palsa growth, *Perm. Perigl. Proc.*, *5*, 283–288.

Sollid, J. L., and L. Sørbel (1998), Palsa bogs as a climatic indicator: Examples from Dovrefjell, southern Norway, *Ambio*, *27*, 287–291.

Southward, A. J., S. J. Hawkins, and M. T. Burrows (1995), Seventy years' observations of changes in distribution and abundance of zooplankton and intertidal organisms in the western English Channel in relation to rising sea temperature, *J. Thermal Biol.*, *20*, 127–155.

Thie, J. (1974), Distribution and thawing of permafrost in the southern part of the discontinuous permafrost zone in Manitoba, *Arctic*, *27*, 189–200.

Thorhallsdottir, T. E. (1994), Effects of changes in groundwater level on palsas in central Iceland, *Geogr. Ann.*, *76A*, 161–167.

Worsley, P., S. D. Gurney, and P. E. F. Collins (1995), Late Holocene mineral palsas and associated vegetation patterns: A case study from Lac Hendry, northern Québec, Canada and significance for European Pleistocene thermokarst, *Quat. Sci. Rev.*, *14*, 179–192.

Zoltai, S. C. (1972), Palsas and peat plateaus in central Manitoba and Saskatchewan, *Can. J. For. Res.*, *2*, 291–302.

Zoltai, S. C., and C. Tarnocai (1975), Perennially frozen peatlands in the western Arctic and Subarctic of Canada, *Can. J. Earth Sci.*, *12*, 28–43.

Zuidhoff, F. S. (2002), Recent decay of a single palsa in relation to weather conditions between 1996 and 2000 in Laivadalen, northern Sweden, *Geogr. Ann.*, *84A*, 103–111.

M. Beauchemin, M. Caccianiga, A. Delwaide, and S. Payette, NSERC Northern Research Chair, Centre d'Études Nordiques, Université Laval, Québec, Québec, Canada G1K 7P4. (serge.payette@bio.ulaval.ca)