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Collapse of permafrost mounds along a subarctic river over the last 100 years (northern Québec)

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Abstract

Widespread permafrost decay is currently occurring in the northern hemisphere. In subarctic Québec, most permafrost mounds are located in peatlands in the form of palsas and peat plateaus. The formation and degradation of these periglacial landforms are influenced by several regional and local factors including air temperature, depth of snow cover, and peat insulation. Mineral palsas are another type of permafrost landforms found along river shores in subarctic Canada. Due to their peculiar position near or in the river floodplain, the dynamics of these palsas are influenced by water level fluctuations. This study examines palsa dynamics along a subarctic river, the Boniface River, in northern Québec. Mapping of palsas and thermokarst ponds over a 44-year period, i.e., from 1957 (from aerial photographs) to 2001 (from field surveys) was used to evaluate changes in the distribution and area covered by permafrost landforms. Also the decay of 14 palsas was assessed using the mortality dates of black spruce trees as determined by tree-ring analysis. Between 1957 and 2001 the area occupied by palsas decreased by 23% whereas 76% of the present-day thermokarst area formed since 1957. No new palsas developed during this period. For the 14 palsas studied, degradation began at the end of the 19th century and accelerated during the 20th century. Palsa degradation was closely related to distance from the river channel. Palsas located in the river floodplain were the most affected by thawing and showed a 48% reduction in area. Degradation was less severe for palsas located 1 to 15 m from the river margin, which experienced a 19% reduction in area. The spatiotemporal distribution of palsas suggests that changes in water level are among the most important factors influencing the dynamics of riparian palsas, particularly for those palsas directly in contact with the river water.

Keywords: Permafrost; Palsas; Thermokarst; Climate change; Subarctic; Landform changes

1. Introduction

In northern regions, permafrost is one of the main ground characteristics directly related to climatic conditions (Brown, 1979). Permafrost development in eastern North America occurred primarily during cold periods of the Holocene with a maximum distribution attained during the Little Ice Age (Allard and Seguin, 1987a; Payette and Delwaide, 2000; Arlen-Pouliot and Bhiry, 2005). Currently, the distribution of permafrost in the northern hemisphere is decreasing due to recent warming (Thie, 1974; Dionne, 1978; Kershaw and Gill, 1979; Dionne, 1984; Laberge and Payette, 1995; Matthews et al., 1997; Sollid and Sørbel, 1998; Camill,

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1999; Osterkamp et al., 2000; Beilman et al., 2001; Lloyd et al., 2003; Payette et al., 2004; Smith et al., 2005). With forecasted warming of 1.4 °C to 5.8 °C (Houghton et al., 2001), given the fact that high latitude regions are expected to experience more warming, it is necessary to determine the relative importance of the factors that influence permafrost dynamics.

In the discontinuous permafrost zone, palsas (permafrost mounds) and peat plateaus (flat topped palsas that cover a large area) are the most abundant periglacial forms. They develop in soils with a negative thermal balance that promotes the development of segregation ice and subsequent frost heaving (Seppälä, 1986). The formation and degradation of palsas are influenced by various regional and local factors including air temperature, peat thickness, drainage, vegetation, and snow regime (Seppälä, 1986, 1990). Palsas are primarily found in peatlands and they are generally covered by a *Sphagnum* and/or sedge peat layer colonized by lichens and small shrubs. However, mineral palsas are another category of palsas that do not have a surficial peat layer. The formation of mineral palsas is closely associated with the inception and expansion of segregation ice distributed in the form of ellipsoid to lamellar ice lenses within loamy to silty and clayey fluvial, fluvio-marine and marine deposits. Contrary to peat materials, fine mineral deposits are ice-prone materials able to produce thick segregation ice lenses under wet site conditions along arctic and subarctic rivers. Mineral palsas bordering rivers in northern Québec are widespread, and their position close to running waters suggests that their dynamics are in part or totally controlled by changing

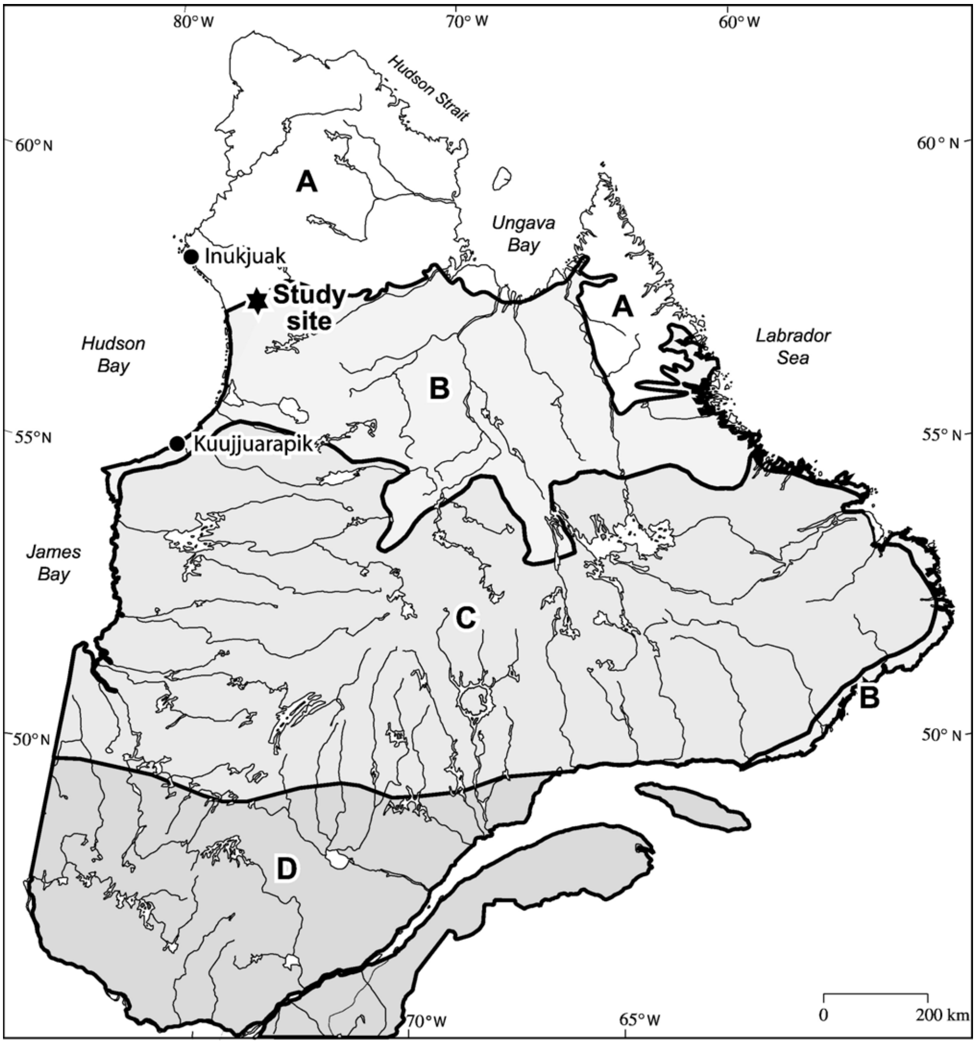

Fig. 1. Location of the study area (star) and permafrost distribution in Québec–Labrador. A — Continuous permafrost. B — Discontinuous permafrost. C — Sporadic permafrost. D — Seasonal frost. (Modified after Payette, 2001).

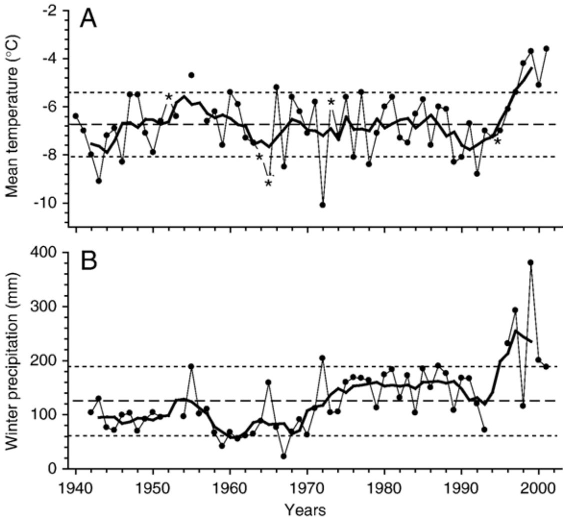

Fig. 2. Annual mean temperature (A) and winter precipitation (B) at the Inukjuak weather station. Thick lines correspond to 5-year running means. Missing values of annual mean temperature were estimated from data at the Kuujjuarapik weather station (250 km south of the study area) (shown by asterisks). Broken lines and dotted lines correspond to the overall mean and standard deviation, respectively.

water levels. Changes of the water level could modify the thermal dynamics of palsas and thus palsa development. Low water levels favour the development of riparian palsas while periods of high water levels initiate their degradation (Payette and Delwaide, 2000; Luoto and Seppälä, 2002).

The main objective of this study is to evaluate the relationship of subarctic riparian palsas located on the shores of the Boniface River in northern Québec with variations in precipitation and temperature. More specifically, the study aims to measure the degree of permafrost degradation that has occurred over the last 100 years, and in particular the last 50 years, and evaluate the relative influence of precipitation and temperature on riparian palsa dynamics. We hypothesize that the palsas situated along the Boniface River have degraded at least since the 1950s in response to increased precipitation and temperature. This degradation should also be directly influenced by variations in river water levels related to fluctuations in annual precipitation.

2. Study area

The study area is located in the Boniface River region (57° 45′ N; 76° 20′ W), 130 km south of Inukjuak and 35 km east of Hudson Bay (Fig. 1). The study area is within the shrub subzone of the forest tundra (Payette, 1983), and is approximately 10 km south of the tree limit. Hill tops are typically colonized by lichens with some prostrate black spruce (*Picea mariana* (Mill.) B.S.P.). Forests are found within humid protected areas such as depressions and valleys. Black spruce is the principal tree species in the region with dwarf birch (*Betula glandulosa* Michx.) being the dominant shrub species. The closest weather station is located within the village of Inukjuak. The mean annual temperature at the station is −7 °C. The mean temperature of the warmest month (July) is 9 °C, while that of the coldest month (February)

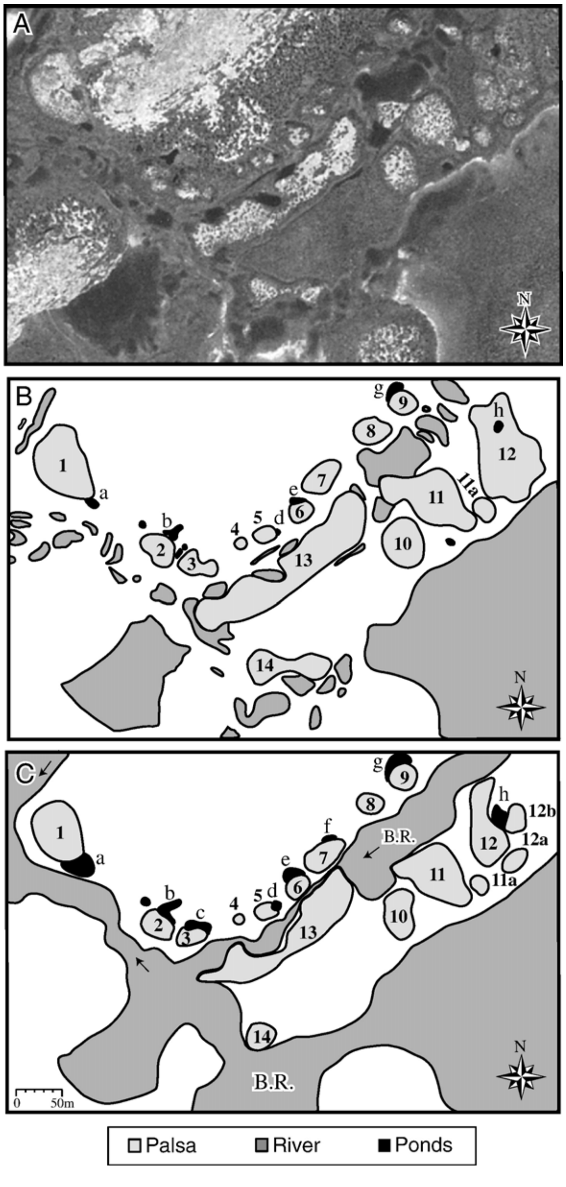

Fig. 3. Permafrost change since 1957. (A) Aerial photography in July 1957. (B) Permafrost landforms and river delineation in 1957. (C) The same area in 2001 based on field mapping. B.R. corresponds to the Boniface River. Arrows indicate direction of the river current.

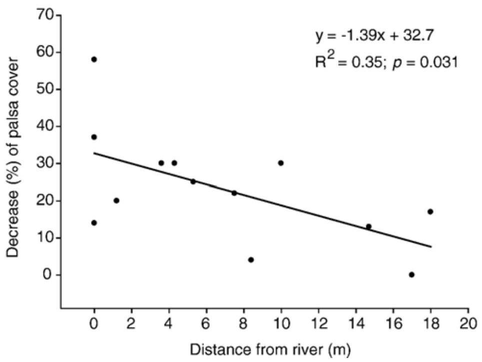

Fig. 4. Relation between distance of palsas from the river shore and decrease of palsa cover between 1957 and 2001.

is −26 °C. The mean frost free period is 60 days and the growing season extends from mid-June to the end of August. The average annual precipitation varies between 500 and 550 mm with 40% falling in the form of snow (Environment Canada, 2003).

The study area is situated at the northern limit of the discontinuous permafrost zone (Fig. 1; Allard and Seguin, 1987b; Payette, 2001). Permafrost is widespread and covers at least 50% of the sites, principally occupying minerotrophic peatlands. In addition, mineral palsas are found on the shores of the Boniface River. These include intact palsas located on the riparian borders, as well as completely degraded or relic palsas situated on the present river floodplain. Relic palsas are generally found in the form of thermokarst ponds (ponds resulting from the thawing of permafrost) surrounded by a residual rim colonized by planeleaf willow (*Salix planifolia* Pursh). Current palsas are colonized by a vegetation cover containing different mosses (*Pleurozium*, *Dicranum* ssp. and *Polytricum* ssp.), lichens (*Cladina stellaris* (Opiz) Pouz. & Vezda, and *C. rangiferina* (L.)), bushes (*B. glandulosa*, *S. planifolia*, *Rhododendron groenlendicum* (Oeder) Kron & Judd. and *Vaccinium vitis-idaea* L.), and black spruce. The perimeters of the palsas are principally colonized by planeleaf willow and dwarf birch, as well as several herbaceous and moss species.

3. Methods

Site selection was based on a general survey of periglacial formations bordering a 10-km section of the Boniface River. The site was chosen based on the diversity, abundance and developmental stages of mineral palsas and thermokarst ponds. The selected criteria included their spatial relationship to the river (i.e., the requirement to have palsas directly in contact with the river, as well at various distances from it) and the presence of black spruce on the palsas and in the ponds.

Meteorological data from the Inukjuak station was used in order to observe temperature and precipitation variations during the 1941–2001 period. Daily meteorological data before this period were not used because of a large number of incomplete values. Incomplete data for the 1941–2001 period were estimated using meteorological data from the Kuujjuarapik station (Fig. 1) when they were available. The two principal factors that influence permafrost, mean annual temperature and total winter precipitation (November to April), were then compiled. According to Wang et al. (2001), the climatic data recorded at the Inukjuak station are representative of the climate that prevails over the Boniface River region.

In order to evaluate recent permafrost dynamics, a map was made in July 2001 with the aid of a total station (Leica T1010 theodolite) that delimited mineral palsas, thermokarst ponds and the river shores. These elements were then identified on aerial photographs (1:40 000) of the region taken 29 July 1957. The portion representing the study site was first enlarged 10× and then digitized. The outlines of the different morphological elements were then identified and traced. The areas covered by palsas and thermokarst ponds were calculated on the two maps. The superimposition of

Table 1
Area covered by palsas (a) and thermokarstic ponds (b) in 1957 and 2001

a)

Palsa	Area in 1957 (m^2)	Area in 2001 (m^2)	Decrease (%)
1	4019	2832	30
2	817	814	0
3	821	711	13
4	171	142	17
5	422	338	20
6	709	498	30
7	1304	1022	22
8	760	528	30
9	749	722	4
10	1963	1475	25
11	3849	3306	14
13	7846	4882	37
14	2118	887	58

b)

Pond	Area in 1957 (m^2)	Area in 2001 (m^2)	Increase (%)
a	94	565	501
b	170	281	65
c	0	275	–
d	16	40	150
e	46	307	567
f	0	25	–
g	152	447	194
h	94	302	221

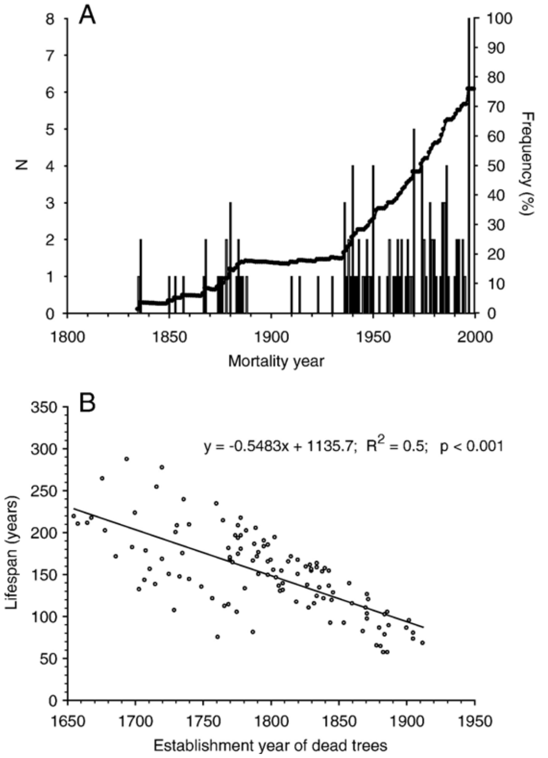

Fig. 5. (A) Mortality years of spruce stems in thermokarst ponds and on slopes (columns) and cumulative mortality frequency (solid line). (B) Relation between lifespan and year of establishment of dead stems.

the 2001 map onto the 1957 map allowed changes in the permafrost features to be determined for the 44-year period.

The 1957 aerial photographs were geo-referenced with the 2001 map using 30 control points surveyed by a theodolite. The control points were distributed throughout the site and consisted of positions that have not moved since 1957 (hill border, lake centre, black spruce clone). Superimposing the two maps assured that the area measurements were exact and comparable. All of the study site's palsa delimitations except one (palsa 12) were easily identifiable on aerial photographs. That is why the area of palsa 12 was not used for further analysis.

The thermokarst ponds of the study area were also analyzed. The three ponds containing the largest number of black spruce were temporarily drained with a water pump in order to sample the trees and determine their age and year of mortality. Before sampling, black spruce stems were first described and then unearthed in order to determine their parenthood. The type of peat in which each individual grew was identified in order to ensure that the sampled trees were growing on the palsa before it degraded into a pond. Each stem was mapped in its living position and then sampled at the root collar. In the laboratory, stem discs were dried and finely polished for tree-ring counting and dating. Then tree establishment and mortality dates were determined by cross dating using a well-dated light ring chronology (Filion et al., 1986). A curve presenting the mortality dates of the sampled trees was then constructed. Only samples that still possessed bark were used in order to ensure the exact year of mortality.

4. Results

4.1. Meteorological data

Throughout the 1900s, the mean annual temperature in the region fluctuated between −10 and −5 °C (Fig. 2A). Since the mid-1990s, a significant increase in mean temperature occurred and culminated in 2001. In addition, two large changes in variations of total winter precipitation were recorded. The period from 1940 to 1970 has been characterized by small snow accumulation, while the

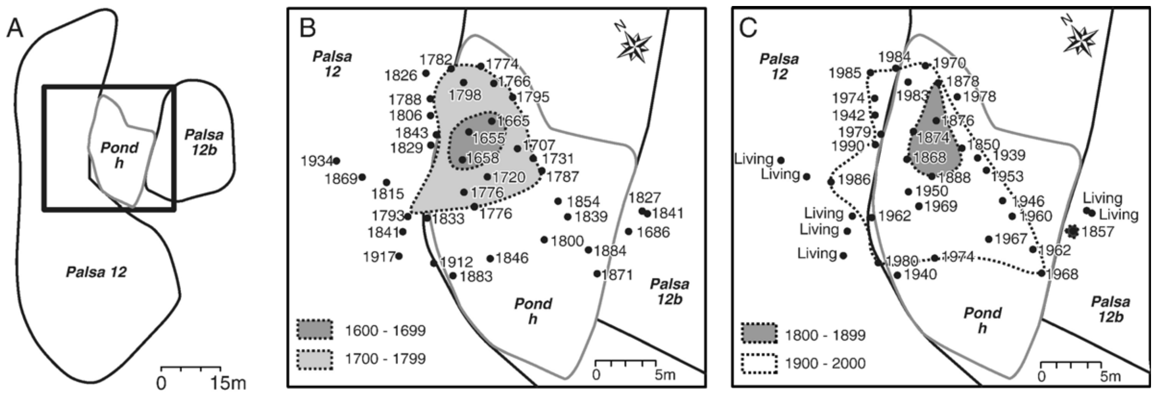

Fig. 6. (A) Simplified map of palsa 12 and pond h. (B) Establishment dates of spruce in pond h and part of palsa 12 (black box in A), enlarged 3×. (C) Mortality dates of spruce in pond h and part of palsa 12 enlarged 3×.

period from 1970 to 2001 was more humid (Fig. 2B). Total winter precipitation increased sharply between 1993 and 1996.

4.2. Permafrost development

A comparison of the 1957 and 2001 maps indicates that permafrost degraded and the size of the river channel increased during the 44-year period (Fig. 3). A 23% reduction in total palsa area was observed over this period with palsas located closer to the river being more severely degraded than those at a distance (Fig. 4). No new palsas developed after 1957. Total thermokarst pond area increased by 76% with all ponds present in 1957 increasing in area (Table 1).

Tree-ring analysis of black spruce located within the thermokarst ponds allowed the identification of two periods of increased mortality. The first period is from 1870 to 1890, while the second one extends from 1935 to the present time (Fig. 5A). There are two possible explanations for distribution of mortality rates: natural senescence or drowning following permafrost degradation. The negative linear relationship between tree lifespan and the dates of establishment of the dead trees (Fig. 5B) eliminates the possibility of natural senescence. Indeed, the trees that established during the 19th and 20th centuries possessed an average lifespan well shorter than those of the 18th century. The 19th and 20th century trees therefore died prematurely due to the collapse of the palsas. The plateau in the mortality curve between 1890 and 1935 is likely a result of a decrease in palsa degradation during this period.

4.3. Spatiotemporal distribution of black spruce

The black spruce in the present-day pond and degradation tallus of palsas 12 and 12b established first in the centre and then spread outwards (Fig. 6). Three individuals were established in the centre of the pond in the mid-17th century, 12 near the end of the 18th century, and 16 during the 19th century. The mortality pattern follows the order of establishment, with the trees that were the first to establish being the first to die. The first mortality phase occurred in the centre of the present-day pond around the end of the 19th century, followed by a second period beginning in the mid-20th century. This type of spatiotemporal pattern suggests that palsas 12 and 12b were linked for more than 200 years. Subsidence likely started around the end of the 19th century and accelerated after 1950.

The establishment pattern of trees for palsas 2 and 3 show similar tendencies to those observed for palsa 12

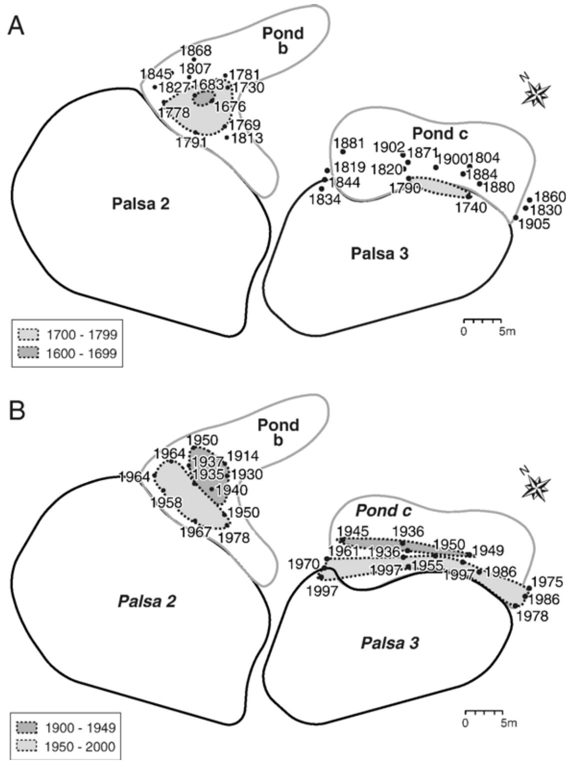

Fig. 7. Maps of palsas 2 and 3 (with ponds b and c) showing establishment dates (A) and mortality dates (B) of spruce.

(Fig. 7). The oldest stems, located in the centre of the pond, established near the end of the 17th century, with tree establishment then proceeding outwards from 1750 to 1850. Tree mortality occurred in a centripetal pattern. Mortality dates become older with distance from the palsa border. Black spruces found in the ponds therefore represent older palsa boundaries that subsequently degraded between 1935 and 1990.

5. Discussion

Permafrost degradation beginning in the 20th century has been observed in several subarctic regions of North America (Thie, 1974; Laberge and Payette, 1995; Osterkamp et al., 2000; Beilman et al., 2001; Jorgenson et al., 2001) and Europe (Sollid and Sørbel, 1998; Zuidhoff and Kolstrup, 2000; Zuidhoff, 2002; Luoto and Seppälä, 2003). However, some studies show that permafrost degradation stabilized during the 20th century (Seppälä, 1998), while others indicate that permafrost can develop or degrade under the current climatic conditions. During the last 50 years at the study site, the surface occupied by palsas decreased by 23%, whereas thermokarst pond area increased by 76%, and no new palsas developed. This loss in permafrost surface area is less than that observed at another subarctic Québec site where more than 80% of a palsa peatland's permafrost mounds disappeared over the last 50 years (Payette et al., 2004). The more northerly position of the Boniface River riparian palsas compared to the palsa peatland studied by Laberge and Payette (1995) and Payette et al. (2004) (57° 45′ N versus 56° 11′ N), explains this difference. Indeed, the probability of permafrost degradation increases along a north–south gradient (Luoto and Seppälä, 2003).

A comparison of the 1957 and 2001 maps indicates that the palsas and the areas directly in contact with the river water (palsas 11, 13, and 14) are more degraded than those protected by the riparian shores occupied by dense willow stands. A significant relationship exists between the distance of the palsas from the river channel and the degree of their degradation. The high water levels recorded for the Boniface River since the 1970s (Payette and Delwaide, 1991) have eroded the borders of the palsas and increased their thermal conductivity, thus favouring their degradation during summer. Luoto and Seppälä (2002) have observed elsewhere that palsas were absent along riparian borders where water at the level of the active layer contributed to permafrost degradation. Conditions of the regional hydrology thus seem to be one of the factors explaining the dynamics of palsas directly in contact with the river.

Palsas that were not directly in contact with the river also degraded but with reduced surface areas between 4 and 30%. In these cases, variations in water level cannot be the principal factor causing their degradation, as the palsas are protected by the riparian shores with a width that varies between 1.2 and 14.7 m. The degradation of these palsas is principally in the form of thermokarst ponds, which are generally situated on the northeast slopes of the palsas. The spatial distribution of the ponds suggests that snow dynamics play an important role in the degradation of the palsas and their transformation into thermokarst ponds. Soil temperature is largely influenced by the thickness of snow cover. A recurring pattern of snow accumulation can be identified from one winter to the other in spite of annual differences (Filion and Payette, 1982). This pattern depends principally on vegetation, topography, and wind redeposition. The study site is exposed to dominant westerly winds, which leave a thin snow layer covering the exposed palsa summits and slopes and a thick cover of snow on their protected northeast sides. The differential snow cover insulates the protected sides of the palsas during winter and leaves the unprotected areas exposed to the cold. The marked increase in winter precipitation after 1970 at the Inukjuak weather station, also probably recorded in the study site, was likely instrumental in the recent decrease in palsa area.

Although snow cover is an important factor influencing palsa degradation (Smith, 1975; Nicholson, 1979; Lévesque et al., 1988), air temperature has also been observed to play a role (Osterkamp et al., 2000). According to the meteorological data from the Inukjuak station, the mean annual temperature has remained relatively stable throughout the 20th century and has risen only recently during the 1990s. These results suggest that winter precipitation has played a primary role in influencing permafrost degradation by favouring a rise in the river level and by increasing the quantity of snow on the non-exposed palsa slopes. The sharp increase in temperatures during the 1990s also likely amplified the degradation process.

The formation of thermokarst ponds at the borders and centres of palsas at the end of the 19th century probably accelerated the melting process. The spatio-temporal distribution of black spruce in the ponds allowed the reconstruction of the degradation processes of three palsas. The degradation of palsas 2 and 3 follows a centripetal pattern, as generally observed in palsa peatlands (Thie, 1974; Laberge and Payette, 1995), riparian environments (Payette and Delwaide, 2000), and coastal areas. However, the degradation of palsa 12 follows a centrifugal pattern. This melting pattern can be explained by a greater accumulation of snow in the centre of the closely associated palsas 12 and 12b with their merging borders forming a topographic depression. The creation of ponds at the border or centre of palsas modifies their thermal balance and increases the transfer of heat towards their frozen cores (Laprise and Payette, 1988).

6. Conclusions

This study evaluated the dynamics of subarctic riparian palsas situated on the shores of the Boniface River in relation to climatic conditions. A chronology of degradation periods for 14 riparian palsas was constructed and indicates that degradation began in the middle of the 19th century and accelerated near the end of the 20th century. This degradation is associated with the climatic warming that began near the end of the 19th century. However, winter precipitation also appears to have played an important role in the dynamics of riparian palsas during the warming period by modulating the water level of the river. Palsas situated near the river and subject to fluctuations in water level were more degraded than those further away from the water line. In addition to variations in the river's water level, an increase in winter precipitation also contributed to the formation of thermokarst ponds bordering the protected sides of the palsas. The surface area of the palsas diminished by 23% between 1957 and 2001, while the area of ponds increased by 76%. Riparian palsas are very sensitive to climatic variations, as they are influenced by both air temperature and water level. With regards to future research, it would be interesting to compare riparian palsas with those found in an upland location (i.e. no contact with water) at the same latitude. This comparison would allow the influence of the river on palsa dynamics to be directly verified.

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