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Recent Permafrost Dynamics in a Subarctic Floodplain Associated with Changing Water Levels, Québec, Canada

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Abstract

We have reconstructed from tree-rings the dynamics of mineral frost mounds on the floodplain of a subarctic river (Rivière Boniface, northern Québec) likely associated with snow precipitation and temperature changes during the past centuries. Due to their peculiar location in the river bed, we have postulated that the inception and decay of frost mounds (thermokarst ponds) were associated with snow-controlled water levels of the river. The periods of establishment, growth, and mortality of spruce around and in two thermokarst ponds on the shore zone were identified. The oldest tree-ring dates show that permafrost mounds formed during a period of water lowering in the 17th century, likely in a long-enduring sequence of low waters initiated around cal AD 1150 (910 yr BP), which persisted for at least 200 yr until the beginning of the 20th century. Two main periods of spruce mortality were identified, in the late 19th century and early 20th century and in the 1950s–1960s, which corresponded to a rising river level probably due to greater snow precipitation. The patterns of spruce establishment and mortality were strikingly similar in the studied sites. The first spruce to establish were all located along the pond's edges and they were also the first ones to die; most of the youngest spruce established later in the central part of each feature, i.e., in the early to mid-1850s to 1910, and died during the 1950s–1960s. The sequence of events reported here suggests an important lowering of the Rivière Boniface during the first part of the Little Ice Age (end of the 16th century–17th century) which was drier and cold. During the second part of the Little Ice Age (mainly 19th century), greater precipitation occurred and climaxed in the 20th century when climate warmed and the river stage reached its maximum level. Changes in snow precipitation were probably more instrumental than temperature changes in the rise and fall of permafrost landforms because of the snowpack's direct influence on the soil thermal regime and river level during snowmelt.

Introduction

Long-term changes in global climate indicate sustained gradual cooling from the early to late Holocene culminating during the last major excursion of the Little Ice Age (Grove, 1988; Bradley and Jones, 1992). Since the end of the 19th century, warming affected the Northern Hemisphere, although with much geographic variability (Houghton et al., 1996). Recent changes in climate in northern areas involve temperature variability (Overpeck et al., 1997) but also precipitation variability which influences profoundly the global environment.

Proxy data from different sources (terrestrial, aquatic, marine, etc.) generally lead to different interpretations of the role of specific climatic parameters in ecosystem dynamics. In response to climate change terrestrial ecosystems with a pronounced hydrologic component (e.g., lake shores, riparian environments, peatlands and other wetlands) are probably more sensitive to precipitation than to temperature, despite the fact that precipitation is largely controlled by temperature. In the Subarctic, for instance, winter conditions are critical for the functioning of whole ecosystems. The survival and growth of land plants, in particular trees and shrubs, are often determined by the winter climate (Lavoie and Payette, 1992). The amount of snow on the ground and its spatial distribution dictated by topography and plant cover are key factors (Filion and Payette, 1982) influencing ecosystem development, providing protection against detrimental saltating snow abrasion and insulation from deep frost penetration in soils (permafrost aggradation), as well as water availability for terrestrial and aquatic plant growth and production.

Long-term precipitation changes are attributed to changing atmospheric circulation patterns (Kutzbach and Street-Perrot, 1985; COHMAP members, 1988). The identification of periods of low and high water levels in lakes and rivers helps greatly to partition the respective role of precipitation and temperature in ecosystem dynamics (Berglund, 1983; Digerfeldt, 1986; Payette and Filion, 1993; Lavoie, 1998). Despite recent advances in this direction (Almquist-Jacobson, 1994; Lavoie, 1998), the direct impact of precipitation variability relative to temperature variability has been so far difficult to evaluate in climate-sensitive ecosystems like permafrost peatlands and wetlands. However, only recently have there been some opportunities to study the development of such ecosystems under field conditions that highlights the contributing role of precipitation in a period of known climatic deterioration like the Little Ice Age (Payette and Delwaide, 1991). In this paper, our objective is to evaluate the dynamics of permafrost mounds located in the floodplain of a subarctic river associated with precipitation and temperature changes during the past centuries. Due to their peculiar position

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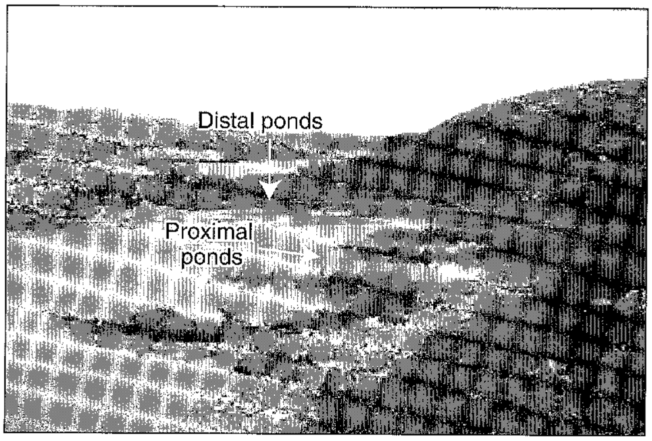

FIGURE 1. Aerial view of the studied thermokarst ponds (former mineral frost mounds) in the Rivière Boniface area. At the foreground, the two proximal features located in the river bed. The two distal features are in the background, at the contact between the river bed and the shore zone.

in the river bed, we postulated that the rise and fall of permafrost mounds were closely associated with precipitation-controlled water levels of the river. To reconstruct the dynamics of riparian permafrost mounds, we have used macrofossil and tree-ring analyses.

Methods

STUDY AREA

The studied permafrost landforms are degraded mounds forming collapse scars located in the floodplain of Rivière Boniface (57°45′N; 76°20′W, Fig. 1), 110 m above sea level. The area is in the zone of discontinuous but widespread permafrost (Allard and Seguin, 1987), 10 km south of the arctic treeline (Payette, 1983). Climatic data from the Inukjuak weather station (150 km northwest of the study area) indicate that the mean annual temperature is −7°C, ranging from −26°C (in February) to 9°C (in July) with a mean frost-free period of about 60 d. Annual precipitation totals 500–550 mm, 35% of which falls as snow (Environnement Canada, 1989). The growing season extends from mid-June to mid-August.

Permafrost mounds (height of 1–2 m above the mean water level) are conspicuous along the Rivière Boniface floodplain. Large permafrost plateaus co-occur with individual mounds of the same height and composed of similar mineral sediments. Permafrost mineral mounds are often bordered by wooded palsas and lichen-shrub-covered palsas. The top of the mounds are currently colonized by mosses, herbs, and shrubs, and often black spruce (*Picea mariana*) trees. As in the present case, however, several permafrost mineral mounds are heavily disturbed by thermokarst processes in the form of collapse scars. The most degraded mounds, located on the present river bed, are thermokarst ponds delineated by raised rims colonized by large old-aged willows (*Salix planifolia*). The borders of the other degraded mounds, in the landward part of the river bed, are covered by shrubs including *Salix planifolia, S. argyrocarpa, Betula glandulosa,* and black spruce.

SAMPLING

According to the distribution of crustose lichens (for example *Rhizocarpon geographicum*) on rocky cliffs bordering the river, the water level was 1 m below the mean river level at the time of sampling (mid-July 1998). Indeed, the water level of the Rivière Boniface has been well below the mean for the past 5 yr due to reduced snow precipitation, thus largely facilitating the present study.

Four degraded permafrost mounds (or thermokarst ponds) were studied, i.e., two exposed, proximal ponds relative to the river thalweg, and two protected, distal ponds located within the shore zone (Fig. 1). Because of abundant spruce in growth position the two ponds of the shore zone were studied in detail for the reconstruction of permafrost dynamics. The topographic profile of the river bed was made with a hand level at 50-cm intervals, from the dry river bed to the present shore zone. Living and dead spruce around and in the two ponds were mapped. The ponds were drained with a water pump to map and sample all the drowned spruce. The spruce samples were drawn to scale and morphological features, such as presence of scars, exposed roots or stem anomalies indicating former reiterative events, were noted. Cross sections were taken at the base of the stem and along the stem and main branches when possible. The wood sections were sanded for tree-ring analysis. Tree-ring counts and crossdating were performed to ensure proper dating of the samples using light rings (Filion et al., 1986) or skeleton plots and checked with the COFECHA program (Holmes, 1983). Ring widths were measured under a binocular microscope at 40× with a Velmex micrometer (±0.002 mm) interfaced with a computer to record the data. Two indexed black spruce series were built to detrend tree growth according to age. The ring-width series were standardized using linear regression for most radii or horizontal line fit for two samples. The two chronologies correspond to spruce samples located along the pond's edges and the pond's centers, respectively.

Soil profiles were examined along the transect and in the ponds to look for ancient shore zones represented by buried soil horizons and organic beds. A buried organic bed was sampled, cleaned of rootlets and processed in the laboratory for radiocarbon dating at the ^{14}C laboratory of the Centre d'études nordiques (Université Laval, Québec). The radiocarbon date has been calibrated from a probability distribution using the Stuiver and Reimer (1993) program.

Results

DESCRIPTION OF THE THERMOKARST PONDS

The two proximal ponds on the riparian bed (Fig. 1) were well-delineated circles with a diameter of 20 and 25 m, respectively. The ponds within the willow-covered rims were 2.6 m deep. No subfossil wood was found in the ponds, and the bottom was covered by sparse plant detritus and fine sand.

Scattered living and dead spruce surrounded the two distal ponds, but many more individuals were located below the water level (Figs. 2, 3). The north pond was currently colonized by patches of *Sparganium hyperboreum* and extensive mats of floating, peat-producing brown mosses (*Drepanocladus exannulatus*). The shape of the pond was irregular—about 11 m long in the east-west direction, 8 m wide in the north-south direction, and 76 cm deep with about 30 cm of loose peat at the bottom (Fig. 2b). The south pond (Fig. 3), 1.55 m deep, was free of floating vegetation. The elliptic shape of the pond is 8 m long in the east-west direction and 12.5 m in the north-south direction (Fig. 3b). Drowned dwarf birch and *Salix planifolia* thickets and black spruce shrubs, partially or completely buried by moss peat, were conspicuous on the pond bottom, particularly on the east

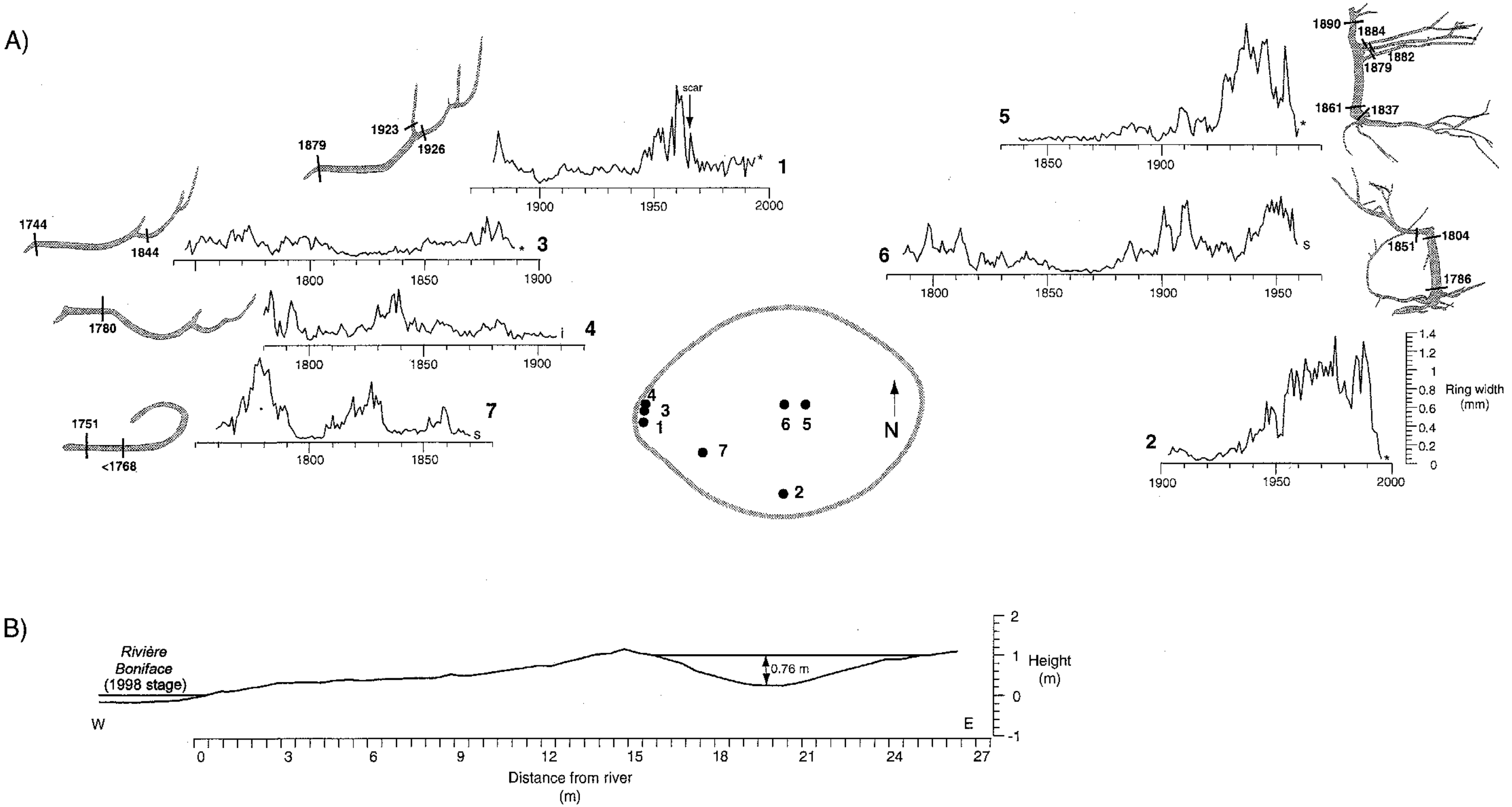

FIGURE 2. *A) Distribution and tree-ring growth of spruce (including six growth forms) in the north feature's pond. B) Topographic profile of the north feature at the contact between the river bed and the shore zone. *: stem with bark; i: irregular stem surface (i.e., missing rings); s: smooth stem surface.*

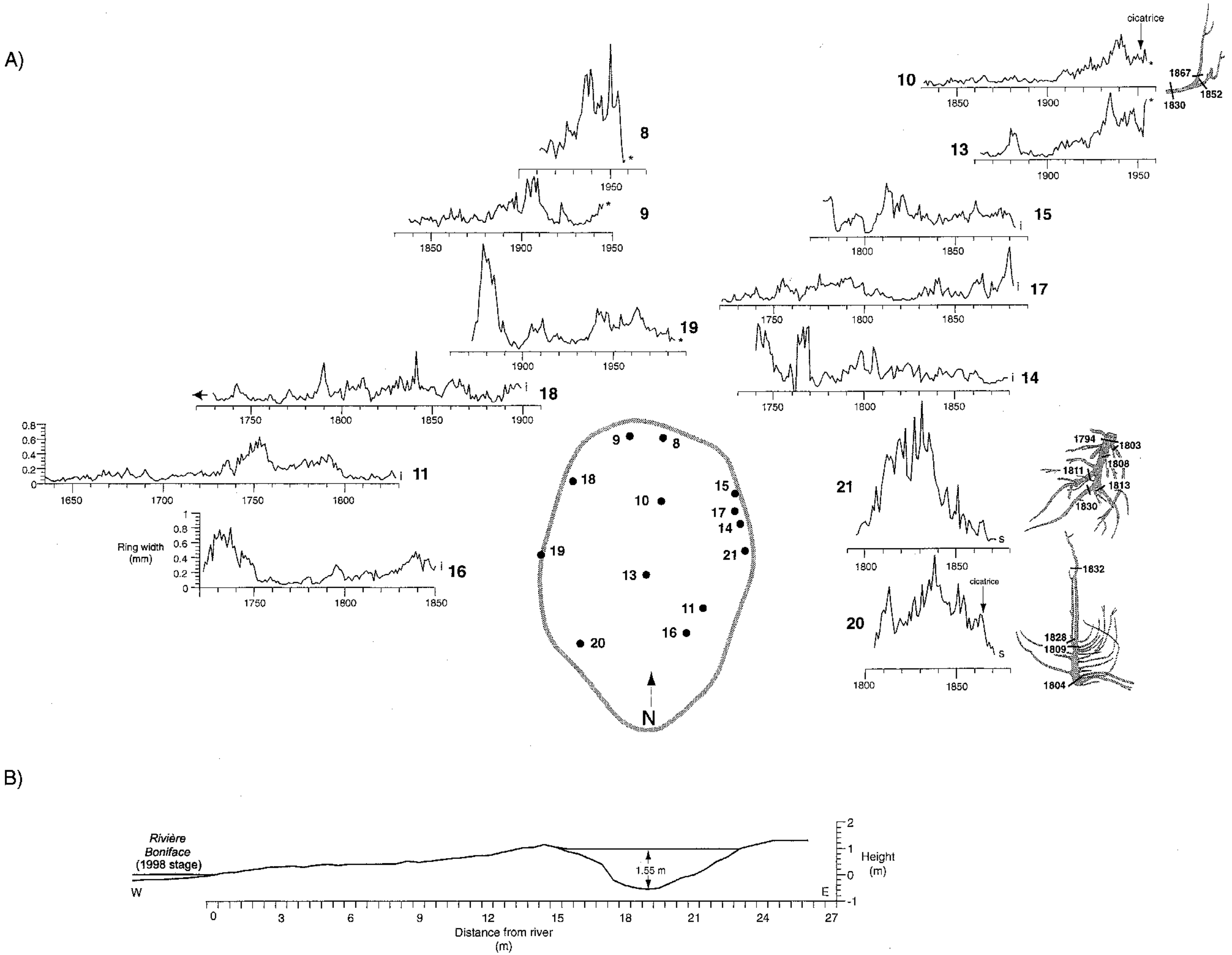

FIGURE 3. *A) Distribution and tree-ring growth of spruce (including three growth forms) in the south feature's pond. B) Topographic profile of the south feature at the contact between the river bed and the shore zone. *: stem with bark; i: irregular stem surface (i.e., missing rings); s: smooth stem surface.*

side. A similar but less dense vegetation cover was present on the bottom of the north pond, indicating former permafrost mounds colonized by woody vegetation. All the stems and branches of the drowned woody plants were oriented towards the pond's edges, which suggests that permafrost degradation first occurred at the borders of the frost mounds.

SPRUCE DISTRIBUTION IN TIME AND SPACE

Spruce distribution around and within the two distal ponds were used to reconstruct the process of permafrost aggradation and degradation. Only two living spruce had colonized the edges of the north feature, whereas no living spruce were present around the south feature.

North Pond

Seven spruce were recovered along the ponds' rims and centers. The first spruce established in the second part of the 18th century (samples 3, 4, 6, and 7; Fig. 2a). One shrubby spruce (sample 1), <2 m high, was currently growing on the exposed rim after establishing at the end of the 1870s. It co-occurred with two other shrubby spruce (samples 3 and 4) established in the early and late 18th century and which died in the late 19th and early 20th centuries. The radial growth of these spruce shrubs was low (<0.25 mm yr^{-1} on average). Interestingly, spruce (sample 3) that established in the early 18th century rooted 10 cm below the rooting zone of the currently living spruce (sample 1), and the roots of the other spruce (samples 3 and 4) were air-exposed likely due to wave action. The other living spruce (sample 2) was a small moribund tree about 3 m high with all the basal branches oriented vertically (orthotropic branches); it was growing within the inundated south border of the feature with the stem base currently sinking slowly into the pond. Three drowned spruce were recovered from the pond bottom, two at the center and one near the border (samples 5, 6, and 7). Sample 7 was a prostrate spruce with a large trunk lacking any vertical stems or leaders; this spruce likely established in the mid-18th century and died in the 1870s. The two former spruce (samples 6 and 5) were well-preserved, small bushy trees with very long branches that established in the late-18th and mid-19th centuries, respectively; both died in the late 1950s–early 1960s. Radial growth of samples 5 and 6 increased markedly at the end of the 19th century when the three spruce located on the west rim died (samples 3, 4, and 7). High radial growth was recorded by spruce 5 and 6 beginning in the 1930s and the exposed living spruce (sample 1) between 1940 and 1960.

South Pond

Most spruce (n = 13) were distributed concentrically on the pond bottom. Only one spruce established during the 17th century (sample 11, Fig. 3a) in the southeastern part of the feature; this spruce had a very slow growth (0.16 mm yr^{-1} on average), except between 1730 and 1760. Several spruce (samples 14, 16–18) invaded the border of the feature at this time, with spruce 14 and 16 experiencing rapid growth during the establishment period. Only one spruce (sample 19), about 100 yr old, was present on the west-exposed rim; it was the largest tree of all the studied spruce. It established on the uppermost edge in the 1870s and died in the 1980s. It was completely uprooted, with the basal stem broken and the upper stem submerged into the pond. Sample 21 located on the other side of the pond established in the late 18th century and died in the 1870s; this spruce was also uprooted, in an upside down position, with orthotropic branches submerged in the pond. The tree was turned down at the time of its death because no reaction wood was recorded in any of the analyzed sections. The oldest (17th and early 18th centuries) and most decomposed spruce were all located towards the edges of the feature (samples 11, 14–21), and they all died during the 19th century (except sample 19). Whereas most drowned spruce were prostrate, slow growing, clonal shrubs, two individuals were fast growing, small trees with distinct orthotropic basal branches which experienced declining growth in the 1840s until they died in the 1870s (samples 20 and 21). The youngest and most recently dead spruce (between 1940 and 1960) were in the cental area of the feature in connection with the central axis of the north pond (samples 8–10 and 13). Spruce 9, 10, and 13 were slow-growing shrubs before 1900, but experienced faster growth thereafter.

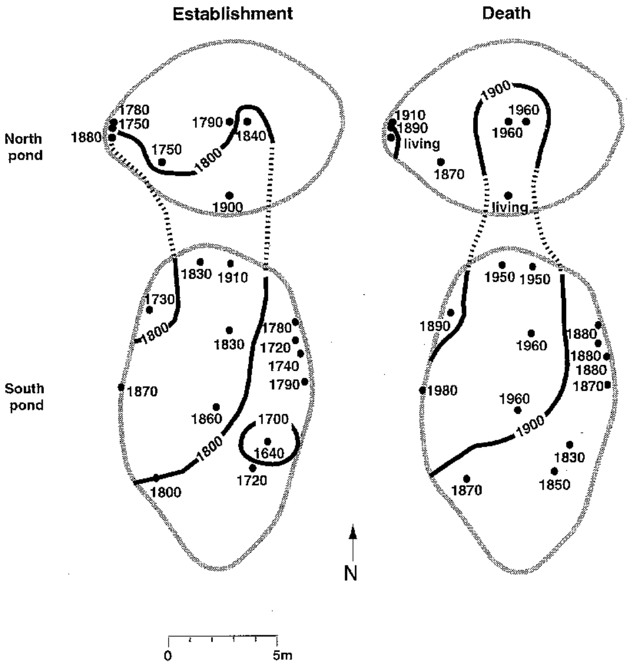

FIGURE 4. Patterns of spruce establishment and mortality on the two features. Dots correspond to location of sampled spruce (see Figs. 2, 3). Numbers refer to dates (decades) of establishment and death of sampled spruce. Solid black lines correspond to isochrones of establishment (1800) and death (1900).

INDEXED SPRUCE CHRONOLOGIES

Spruce were separated into two different groups based on location, i.e., along the pond edges and at the center of the features. These two locations also corresponded to distinct periods of establishment and mortality likely associated with permafrost dynamics (Fig. 4). Therefore, two tree-ring chronologies were constructed based on spruce distribution (Fig. 5). The first chronology (n = 12 spruce, 19 radii) shows the oscillating growth pattern of spruce along the feature's edges with high mortality from the late 19th century to 1910, with only one spruce surviving to the late 20th century. This contrasts with the second chronology (n = 8, 15 radii) based on spruce distribution at the center of the features: a suppressed growth period during the 19th century (excluding the first part of the chronology because of the small number of samples) and high growth beginning in the 1930s. A large part of the chronology was sychronous with

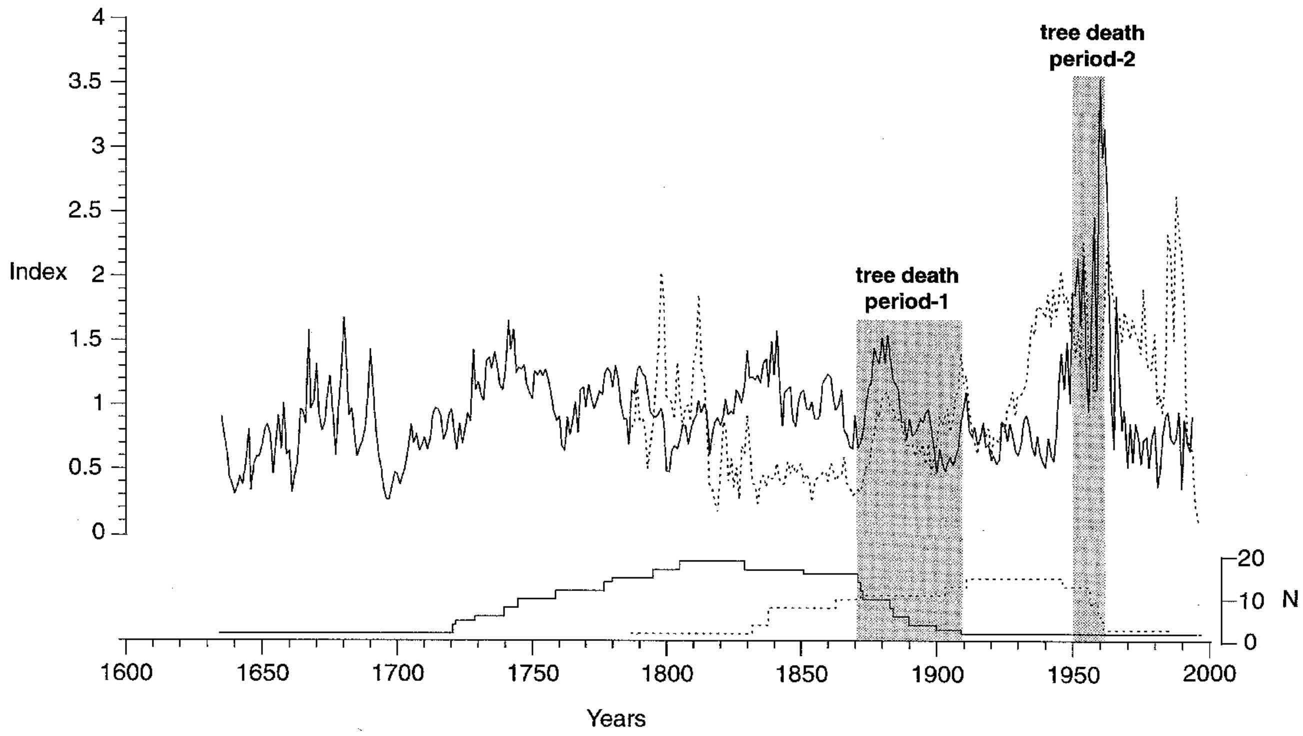

FIGURE 5. Tree-ring chronologies based on spruce distribution in the two thermokarst ponds resulting from degradation of mineral frost mounds. The first chronology (solid line) corresponds to spruce distributed along the pond's borders. The second chronology (dotted line) corresponds to spruce distributed at the center of the ponds. Two periods of spruce mortality are shown, i.e., period 1 ranging from the late 19th century to 1910 and period 2 in the 1950s–1960s. The number of radii used to construct the two chronologies is indicated below the indexed curves.

the first chronology. High spruce mortality occurred in the 1950s–1960s during a period of high ring growth.

BURIED ORGANIC LAYER

An organic layer 8-cm-thick was sampled 30 cm below the exposed rims of the two ponds. The organic layer was made of decomposed mosses and twigs. This layer was radiocarbon dated to 910 ± 90 BP (UL-1994), e.g., calibrated date A.D. 993–1280 (2 sigmas) or mean cal A.D. 1156, which indicates a former lower shoreline at that time. This organic layer was buried by fine sand alternating with several thin organic layers and then by thicker layer of fine sand draping to the surface.

Discussion

The shape, size, and water depth of the four ponds are likely attributable to thermokarst processes which affected former mineral frostmounds developed in the river floodplain. Permafrost aggraded during a period of water lowering during the 17th century in a long sequence of low waters likely initiated around 900 BP as suggested by the radiocarbon date of the buried organic layer 30 cm below the surface of the present water level. Whereas it is not possible to portray the rise and fall of permafrost from the two proximal ponds because of a lack of datable material, the developmental history of permafrost from the two distal ponds in the present shore zone can be reconstructed based on living spruce and spruce wood remains. A synoptic of the life period of the studied spruce (Fig. 4) indicates that spruce establishment started as early as the 17th century and lasted for at least 200 yr until the beginning of the 20th century. Two main periods of spruce mortality were identified, the first one in the late 19th century and early 20th century and the second in the 1950s–1960s (Figs. 4, 5). Moreover, the patterns of spruce establishment and mortality was strikingly similar for the two features (Fig. 4): the first spruce to establish were all located on the rims and they were also the first to die; most of the youngest spruce established later in the early to mid-1850s to 1910 and most died during the 1950s–1960s. The thermokarst process was still in progress with one moribund spruce in the south-central part of the north feature currently sinking into the thermokarst pond. The pattern of spruce mortality reveals the pattern of degradation of the mounds with the first stage of degradation along the edges of the mounds exemplified by sinking spruce (several spruce having orthotropic basal branches) and the last stage of degradation at the center of the features. Thus the shift from frost mounds to thermokarst ponds proceeded centripetally, a pattern commonly observed in other permafrost wetlands (Thie, 1974; Kershaw and Gill, 1979; Laberge and Payette, 1995).

The establishment and growth of spruce associated with the features indicate a former period of low river stage when they were able to colonize well-drained substrates. Similarly, drowning and death of spruce suggest one or several periods, or an incremental and continuous change of excessive waterlogged conditions of the same substrates. Such contrasting conditions illustrate the impact of dramatic local soil changes indirectly associated with a changing water level of the river, i.e., low river stage permitting aggradation of permafrost inducing frost mounds thus facilitating spruce establishment and growth, to a high river stage and deeper snow causing permafrost degradation and spruce death. The geomorphic processes involved in the shift from spruce establishment and growth to spruce death appear to be closely associated with the rise and fall of permafrost mounds developed in a river bed larger than it is today. The lowering of the river stage, and the ensuing permafrost aggradation and upthrusting of the river bed, spruce establishment, permafrost degradation, and spruce death are all linked stages of a large domino effect induced by the lowering and then the rising of the river level. Water lowering is likely caused by dry and cold winter conditions with below-average snow precipitation. By exposing the river bed and the associated shoreline to cold air the water-saturated fluvial substrates were affected by permafrost aggradation and concurrent upthrusting due to the formation of ice lenses.

Several centuries ago, as suggested by the radiocarbon date of the buried organic layer below the rims of the two distal ponds, the water level of the river retreated (at least 30 cm below the current water level) in response to reduced precipitation, probably snow precipitation which is the major contributor of water input in arctic and subarctic river and lake basins (Bégin and Payette, 1988). With a thinner snowpack, the exposed but water-saturated bottom of the river and its associated low-lying shore zone were subjected to permafrost aggradation, and ice formation. The resulting frost mounds began to form at the start of the Little Ice Age several centuries after initial lowering of the river at around AD 1150. Because of well-drained soil conditions associated with frost mound emergence spruce were able to colonize the ground surface during the 17th and 18th centuries.

The sequence of events reported here supports earlier contentions on climatic trends from the Little Ice Age to present in this area (Payette and Delwaide, 1991; Payette and Filion, 1993). The major lowering of the Rivière Boniface at 900 BP was followed by small oscillations in water levels below the current river stage during the first part of the Little Ice Age (end of the 16th century–17th century) which was drier and cold. During the second part of the Little Ice Age (mainly 19th century), greater precipitation occurred and climaxed in the 20th century when climate warmed (as also shown by the development of small trees in the central parts of the ponds) and the water level in the river reached its maximum stage. Permafrost degradation started at the end of the 19th century when the climate warmed and the river stage rose appreciably. Unfortunately there is no field data to date the rise and fall of the two proximal permafrost mounds, but it is likely that permafrost degraded sooner and more rapidly than that of the two distal mounds because they were in direct contact with the rising water level of the river (and maybe for a longer period of time).

The collapse of mineral frost mounds in the floodplain of Rivière Boniface was contemporaneous with the widespread decay of palsas in the boreal and subarctic regions across the northern hemisphere, events which are likely attributable to recent climatic warming (Spolanskaya and Evseyev, 1973; Sollid and Sorbel, 1974; Thie, 1974; Samson, 1975; Kershaw and Gill, 1979; Brown, 1980; Lagarec, 1980; Mathieu, 1983; Dionne, 1984; Pissart and Gangloff, 1984; Seguin and Allard, 1984; Laprise and Payette, 1988, Laberge and Payette, 1995; Halsey et al., 1995). However, temperature rise is probably not the sole factor responsible for permafrost degradation. Changes in snow precipitation were probably more instrumental than temperature in the rise and fall of permafrost landforms because of their direct influence on the soil thermal regime and river stage/discharge level.

Acknowledgments

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