Global Ecology and Biogeography, (Global Ecol. Biogeogr.) (2005) **14**, 307–313

RESEARCH PAPER

Late Holocene opening of the forest tundra landscape in northern Québec, Canada

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ABSTRACT

Aim Previous studies conducted at the tree line in northwestern Québec suggested that the forest tundra was created over the last 3000 years by deforestation as a result of the combined action of forest fires and climatic cooling. Our objectives were to: (1) validate at a larger spatial scale the time frame of the last 3000 years; (2) verify if the opening process was more pronounced during particular time periods; and (3) confirm that fire was the triggering mechanism.

Location Seventeen lakes from the forest tundra of northern Québec.

Methods Pollen records were analysed to determine the date of landscape opening, as interpreted by the time of decrease towards present-day values of the ratio of *Picea* pollen percentage to pollen percentage of the taxa typical of open forest tundra landscapes (*Betula*, Ericaceae, Cyperaceae and Poaceae).

Results Landscape opening in northern Québec started *c.* 3220 cal. BP (calibrated years before present) and was more pronounced between *c.* 2040 and 890 cal. BP. No spatial pattern was observed in the dates of landscape opening.

Main conclusions The suggestion that landscape opening in the forest tundra occurred over the last 3000 years was validated at the scale of northern Québec. A period of more pronounced opening was identified between 2040 and 890 cal. BP and could be related to increased fire occurrence. Absence of a spatial pattern in the dates of landscape opening provides further confirmation that fire was the triggering mechanism.

Keywords
Black spruce, climate change, fire, forest tundra, landscape opening, *Picea mariana*, pollen.

RÉSUMÉ

Objectif Des études antérieures menées à la limite des arbres dans le nord-ouest du Québec ont suggéré que la toundra forestière aurait été créée au cours des derniers 3000 ans par la déforestation résultant de l'action combinée des feux de forêt et d'un refroidissement climatique. Nos objectifs étaient de (1) valider à une échelle spatiale plus importante la période des derniers 3000 ans; (2) vérifier si le processus d'ouverture du paysage a été plus prononcé à certaines périodes; et (3) confirmer que le feu a été le mécanisme déclencheur.

Localisation Dix-sept lacs de la toundra forestière du nord du Québec.

Méthodes Les enregistrements polliniques ont été analysés pour déterminer la date d'ouverture du paysage, telle qu'interprétée par le moment où survient une baisse marquée vers les valeurs actuelles du ratio du pourcentage de pollen de *Picea* sur le pourcentage de pollen de taxons typiques des milieux ouverts de la toundra forestière (*Betula*, Ericaceae, Cyperaceae et Poaceae).

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  DOI: 10.1111/j.1466-822x.2005.00157.x

Résultats L'ouverture du paysage dans le nord du Québec a débuté vers 3220 cal. BP et s'est exprimée de façon plus marquée entre 2040 et 890 BP cal. Aucun patron spatial n'a été observé dans les dates d'ouverture du paysage.

Principales conclusions La suggestion selon laquelle l'ouverture du paysage dans la toundra forestière aurait eu lieu au cours des derniers 3000 ans a été validée à l'échelle du Québec nordique. Une période plus marquée d'ouverture du paysage a été identifiée entre 2040 et 890 cal. BP et pourrait être reliée à des fréquences de feux plus élevées. L'absence de patron spatial dans les dates d'ouverture du paysage est une confirmation supplémentaire que le feu a été le mécanisme déclencheur.

Mots-clés
Changement climatique, épinette noire, feu de forêt, ouverture du paysage, *Picea mariana*, pollen, toundra forestière.

INTRODUCTION

The forest tundra of northern Québec is a large ecotone between the boreal forest and the treeless tundra (Payette, 1983). This biome, accounting for 15% of Québec's territory (224,700 km^2; Lavoie & Payette, 1996), is characterized by a sparse black spruce [*Picea mariana* (Mill.) B.S.P.] cover and can be further divided into two subzones: a southern forest subzone, and a northern shrub subzone (Payette, 1983). Lichen-covered hilltops are scattered throughout a forest matrix in the southern subzone, whereas in the northern subzone, a lichen-heath matrix dominates and is interrupted by scattered forest islands located in protected sites (Payette *et al.*, 2001). The forest islands are remnants of a once more extensive forest cover (Payette & Morneau, 1993). Deforestation resulting from the combined action of forest fires and climatic cooling has opened the landscape over the last 3000 years (Payette & Gagnon, 1985; Gajewski *et al.*, 1993; Payette *et al.*, 2001). Gajewski *et al.* (1993; p. 441) suggested that 'A progressive cooling would inhibit reproduction of *Picea*, but trees would continue to persist until removed by fire … ; thus the timing of late Holocene spruce decline would not be expected to follow a consistent pattern and would not be registered as a north-south movement of treeline'.

The recent global warming trend, mainly caused by anthropogenic overuse of fossil fuels (IPCC, 2001), will probably have major repercussions on the dynamics of the forest tundra. Indeed, climate change effects are expected to be more pronounced at higher latitudes (IPCC, 2001). One result may be that the forest cover could eventually become denser in these regions as a warmer climate would favour black spruce regeneration in the forest tundra (Sirois, 2000). Higher temperatures and densification of the forest cover might lead to increased fire frequency, although this relationship is not straightforward [see, for example, the contrasting results for northeastern North America in Flannigan *et al.* (2000) and Flannigan *et al.* (2001)].

To better assess the potential impacts of future climate change on the northernmost forests, it is important to document the past dynamics of the forest tundra, especially the mechanisms that led to its formation. In this study, we investigated the phenomenon of landscape opening of the forest tundra, considering both the spatial and temporal scales. Seventeen lakes from across northern Québec were studied to determine the timeframe of landscape opening. Previous studies conducted at the tree line in northwestern Québec showed the process to have occurred over the last 3000 years, in association with climate cooling (Payette & Gagnon, 1985; Gajewski *et al.*, 1993; Payette *et al.*, 2001). Here we wanted to: (1) validate the timeframe of the last 3000 years at a larger spatial scale; (2) determine if the opening process was more pronounced during particular time periods; and (3) verify the assumption of Gajewski *et al.* (1993) that if fire was the triggering mechanism, there should be no clear spatial pattern in the dates of landscape opening.

METHODS

Seventeen forest tundra lakes in which long-term pollen records were available were selected in northern Québec (Fig. 1). Pollen data were obtained from the North American pollen database (<http://www.ngdc.noaa.gov/paleo/napd.html>) and the Canadian pollen database (<http://www.uottawa.ca/academic/arts/geographie/lpcweb/>). Vegetation surveys conducted by Asselin and Payette (2005) on a deforested forest tundra hilltop showed that it was dominated by *Betula glandulosa* Michx., ericaceous shrubs (*Vaccinium vitis-idaea* L. and *Ledum decumbens* (Ait.) Lodd.), Cyperaceae, and Poaceae. These taxa account for more than 98% of the vegetation cover on the hilltop. Thus, in the present study, the date of landscape opening was determined as the moment when the '*Picea*:open ratio' – the ratio of *Picea* (cf. *mariana*) pollen percentage to pollen percentage of taxa typical of open forest tundra landscapes (*Betula*, Ericaceae, Cyperaceae, Poaceae) – fell to present-day values. Although Sugita *et al.* (1999) warned that the percentage of non-arboreal pollen should be used with caution in studies of landscape opening, the situation is facilitated in northern Québec by the fact that only one tree species is usually present (*Picea mariana*). Pollen percentages (instead of accumulation rates) are used, as exotic pollen counts required to calculate accumulation rates were only available for five of the

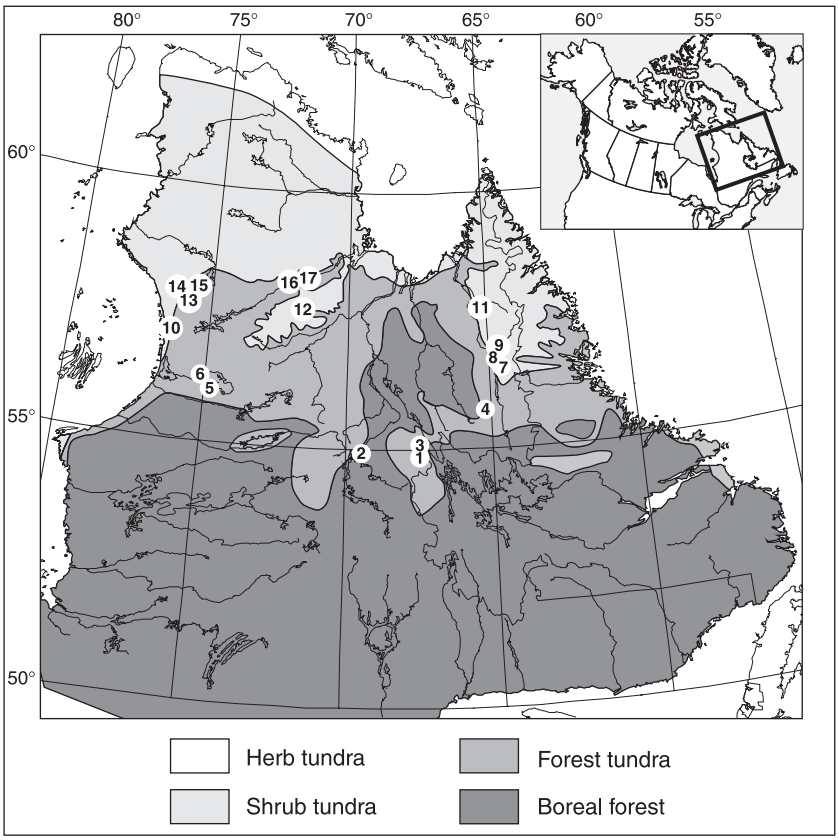

Figure 1 Map showing the location of the 17 lakes discussed in this study. Lakes are identified with the same numbers as in Table 1.

17 data sets. Using the *Picea*:open ratio instead of only *Picea* pollen percentage circumvented the problem of differences between sites due to the proximity of the closed boreal forest to the sites in the southern and northeastern forest tundra, and to the proximity of shrub tundra to the sites in the northwestern forest tundra. Indeed, modern *Picea* pollen percentages are somewhat different for these three regions, with means (± 1 SD) of 46 ± 11, 33 ± 10, and 24 ± 9 for southern, northeastern, and northwestern forest tundra, respectively. The overall mean (33 ± 13) is not so different, however, from the 30% value suggested as typical of the forest tundra landscape (Richard, 1981; Anderson *et al.*, 1991; Gajewski, 1991). The pollen grains found in lake sediments come from local, as well as regional sources (Sugita, 1994) and it could be argued that this might prevent landscape opening from showing up in the pollen record. However, as landscape opening has persisted for several centuries in the forest tundra landscape of northern Québec, it is reasonable to assume that it will show clearly in the pollen records used in the present study.

To verify the presence of a spatial pattern in landscape opening at the scale of northern Québec, each lake was assigned to one of the following regions: (1) southern forest tundra; (2) northeastern forest tundra (east of 70° W); and (3) northwestern forest tundra (west of 70° W), and a linear regression of the date of landscape opening against latitude was computed. All radiocarbon dates used in this paper were calibrated using version 4.3 of the CALIB program (Stuiver & Reimer, 1993). Dates for the remaining portions of each core were inferred using the same interpolation models as those used by the original authors.

RESULTS

Charcoal data from five sites (Daumont, EC1, Karinbou, B2, LB1) show that landscape opening as inferred from the decrease in the *Picea*:open ratio is closely associated with fire occurrence (Fig. 2). These five sites all recorded a fire episode just prior (B2), at the same time (LB1, Karinbou, Daumont), or just after (EC1) the inferred landscape opening date (Fig. 2). Previous fire episodes were recorded at Daumont, EC1, and LB1, but were apparently followed by black spruce re-colonization. Fire episodes were also recorded after landscape opening at LB1, B2, and EC1 (Fig. 2).

The *Picea*:open values (Fig. 2) were used to infer the dates of black spruce arrival and landscape opening for the 17 northern Québec lakes. Lakes from the southern forest tundra show a slow increase in the *Picea*:open ratio after postglacial colonization, reaching peak values sometime between 4850 and 3950 cal. BP (calibrated years before present), depending on the site. Landscape opening, as inferred by a sustained decrease in the *Picea*:open ratio, occurred between 3220 and 990 cal. BP in the southern forest tundra. Lakes in the northeastern forest tundra were colonized at the same time or soon after those from the southern forest tundra, between 4590 and 3080 cal. BP. Landscape opening dates for these sites range from 2290 to 310 cal. BP. Lakes from the northwestern forest tundra were colonized at the same time or soon after those from the northeastern forest tundra, between 3970 and 1870 cal. BP. Landscape opening occurred in this region between 2620 and 890 cal. BP. For the combined 17 northern

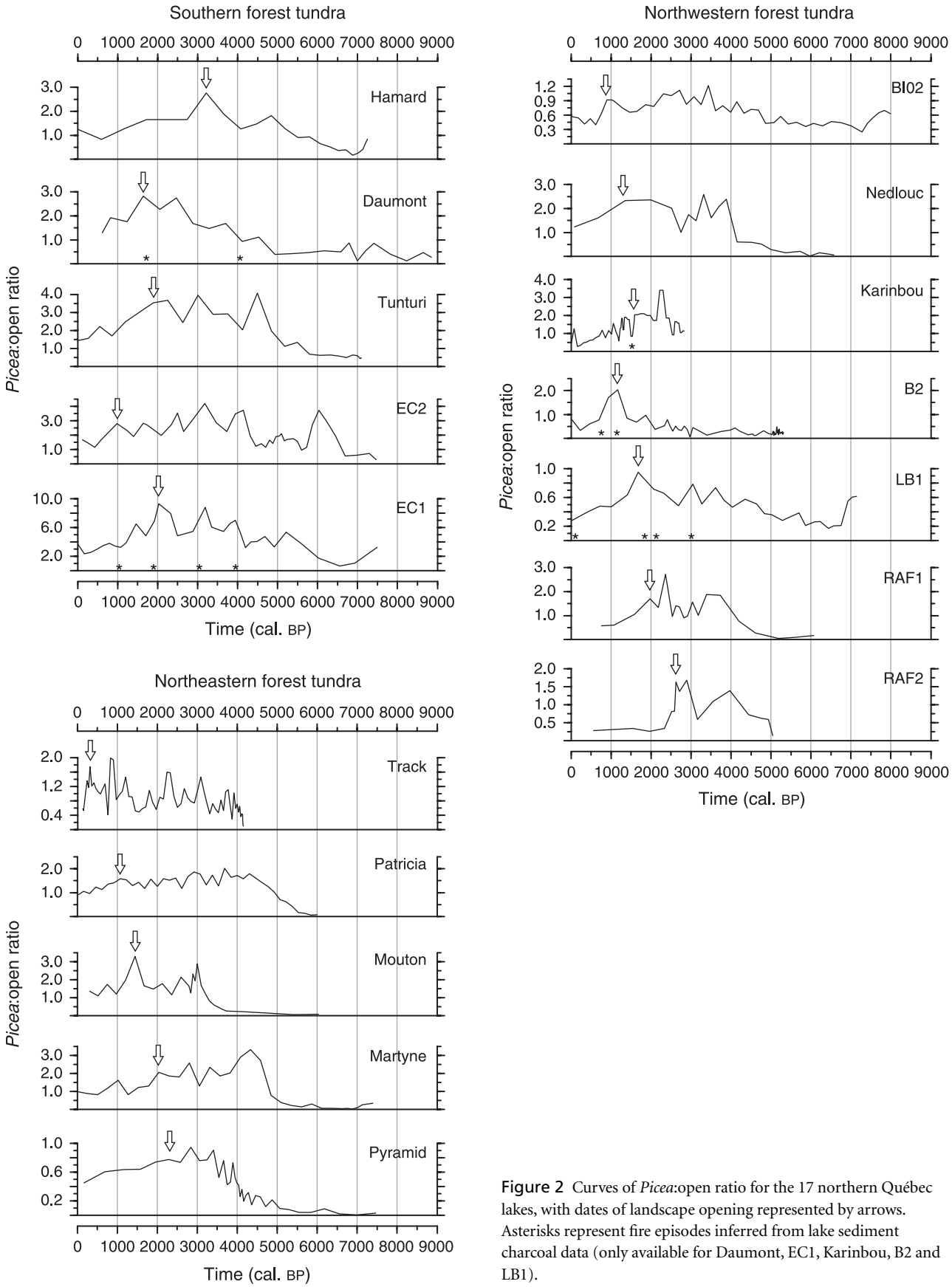

Figure 2 Curves of *Picea*:open ratio for the 17 northern Québec lakes, with dates of landscape opening represented by arrows. Asterisks represent fire episodes inferred from lake sediment charcoal data (only available for Daumont, EC1, Karinbou, B2 and LB1).

Table 1 Dates of landscape opening for the 17 forest tundra lakes considered in this study. Landscape opening was interpreted as the moment when the ratio of *Picea* pollen percentage to pollen percentage of species typical of open forest tundra landscapes (*Betula*, Ericaceae, Cyperaceae, Poaceae) fell to present-day values

No.	Name	Latitude	Longitude	Elevation (m)	Region*	Date of opening (cal. BP)†	Reference
1	Hamard	54.48	67.30	564	SFT	3220	Stravers (1981)
2	Daumont	54.53	69.24	607	SFT	1650	Richard *et al.* (1982)
3	Tunturi	55.01	67.30	610	SFT	1890	Stravers (1981)
4	Track	55.46	65.10	442	NEFT	310	Short & Nichols (1977)
5	EC2	56.01	74.56	260	SFT	990	Gajewski *et al.* (1996)
6	EC1	56.17	75.06	250	SFT	2030	Gajewski *et al.* (1993)
7	Patricia	56.40	64.40	538	NEFT	1080	Samson (1983)
8	Mouton	56.46	64.49	410	NEFT	1440	McAndrews & Samson (1977)
9	Martyne	56.47	64.50	365	NEFT	2040	Samson (1983)
10	BI02	57.07	76.22	210	NWFT	890	Gajewski & Garralla (1992)
11	Pyramid	57.38	65.10	381	NEFT	2290	Short & Nichols (1977)
12	Nedlouc	57.39	71.39	330	NWFT	1350	Richard (1981)
13	Karinbou	57.44	76.08	135	NWFT	1580	Ponader *et al.* (2002)
14	B2	57.46	76.18	115	NWFT	1170	Asselin & Payette (submitted)
15	LB1	57.55	75.37	200	NWFT	1680	Gajewski *et al.* (1993)
16	RAF1	58.13	72.04	205	NWFT	1970	Richard (1981)
17	RAF2	58.13	71.57	225	NWFT	2620	Richard (1981)

*SFT: southern forest tundra; NEFT: northeastern forest tundra; NWFT: northwestern forest tundra.
†Rounded to the nearest 10 years.

Québec lakes, the dates of landscape opening inferred from the *Picea*:open ratio ranged from 3220 to 310 cal. BP and tended to be more concentrated (13/17) in the period 2040–890 cal. BP (Fig. 3). The regression of the date of landscape opening against latitude yielded no significant result (Fig. 4), indicating the absence of a north to south progression of the landscape opening phenomenon.

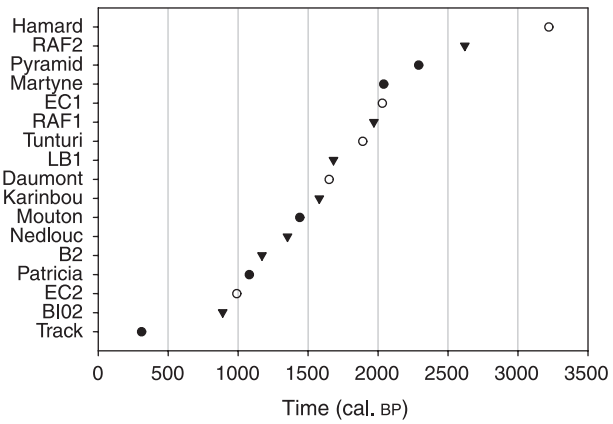

Figure 3 Dates of landscape opening for the 17 forest tundra lakes discussed in this study. Sites from the three regions are identified by different symbols: open circles = southern forest tundra; closed circles = northeastern forest tundra; triangles = northwestern forest tundra.

DISCUSSION

The close association between landscape opening as inferred from a decrease in the *Picea*:open ratio and fire occurrence as evidenced by sedimentary charcoal data (Fig. 2) legitimizes the use of the *Picea*:open ratio.

A reduction of the *Picea*:open ratio was recorded after 3220 cal. BP in 17 northern Québec lakes (Table 1; Fig. 2), confirming the timeframe of the last 3000 years for landscape opening of the forest tundra (Payette & Gagnon, 1985; Gajewski *et al.*, 1993; Payette *et al.*, 2001). More than 75% of the sites (13/17) recorded landscape opening in the interval 2040–890 cal. BP (Fig. 3). Most of the fires that burned prior to 2040 cal. BP were probably followed by a certain amount of black spruce regeneration. This is supported by charcoal data for lakes LB1, Daumont and EC1, showing multiple fire episodes with only one causing landscape opening (Fig. 2). The climate deterioration of the last 3000 years (Filion, 1984) progressively impoverished the seed bank (Elliott, 1979; Sirois, 2000). Then, between 2040 and 890 cal. BP, climatic conditions were more conducive to fire (Arseneault & Payette, 1997; Pitkänen & Huttunen, 1999; Arseneault & Sirois, 2004). The fairly depleted black spruce seed bank did not ensure post-fire re-colonization, leading to the creation of what is now known as the forest tundra ecotone. A subsequent decrease in the intensity of the deforestation process between 890 cal. BP and present-day might be explained by reduced fire activity during this period. This reduced fire activity might be attributable to a cooler and wetter climate, less conducive to fire (Filion, 1984), and to the open nature of the forest tundra being less favourable to fire ignition and spread.

Gajewski *et al.* (1993) suggested that there should be no clear north to south pattern in the dates of landscape opening if fire

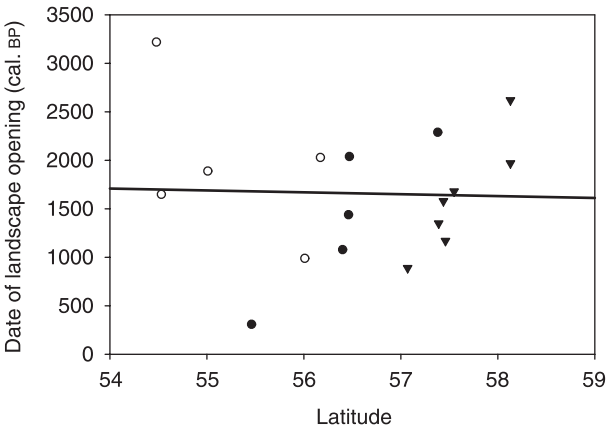

Figure 4 Regression of the date of landscape opening against latitude for the 17 forest tundra lakes ($R^2 = 0.001$; $P > 0.05$). Sites from the three regions are identified by different symbols: open circles = southern forest tundra; closed circles = northeastern forest tundra; triangles = northwestern forest tundra.

was the triggering mechanism. Accordingly, our results did not show any particular spatial pattern in the dates of landscape opening (Table 1; Fig. 4). Dates varied within each of the three regions and there was significant overlap between the date ranges from one region to the other (Fig. 4). This is further evidence of the link between fire occurrence and opening of the forest tundra landscape.

CONCLUSION

The opening of the forest tundra landscape in northern Québec started around 3220 cal. BP and was more pronounced between 2040 and 890 cal. BP as a result of higher fire frequencies. The fact that landscape opening of 17 northern Québec lakes did not proceed in a clear north to south fashion is further evidence that the process is mainly the result of fire occurrence.

AKNOWLEDGEMENTS

We would like to express our gratitude to Sébastien Champagne, Tamsin Laing and Reinhard Pienitz for their help during fieldwork. Many thanks to Élisabeth Robert for pollen counts, and to Mathieu Durette and Claudia Zimmerman for sample preparation (lake B2). We are also grateful to the numerous authors who made their pollen data available through the North American pollen database and the Canadian pollen database. Yves Bégin, Ian Campbell, Paul Jasinski, Violaine Lafortune, Martin Lavoie and Warwick Vincent made thoughtful comments on earlier drafts of the manuscript. This study was financially supported by the Natural Sciences and Engineering Research Council of Canada, the Canadian Department of Indian Affairs and Northern Development and the Ministère de la Recherche, de la Science et de la Technologie du Québec (FCAR program).

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