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Late Holocene deforestation of a tree line site: estimation of pre-fire vegetation composition and black spruce cover using soil charcoal

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Anatomical identification of soil charcoal fragments was used to reconstruct the pre-fire vegetation composition of a tree line site that burned ca 930 cal. AD in northern Québec, Canada. Soil charcoal was also used as a proxy to estimate black spruce *Picea mariana* palaeo-cover. The site (a low-elevated hilltop) is presently devoid of spruce trees and dominated by dwarf birch *Betula glandulosa*, lichens, ericaceous shrubs (*Ledum decumbens*, *Vaccinium vitis-idaea*) and sedges. In contrast, black spruce dominated before the fire with an understory of *Empetrum nigrum* and *Vaccinium vitis-idaea*. Pre-fire black spruce cover was estimated at 32%, giving an indication of the potential for warming-induced natural reforestation of the forest-tundra.

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The circumboreal forest-tundra biome is characterised by intermingled patches of forest and tundra. In northern Québec (Canada), this pattern has been attributed to black spruce *Picea mariana* post-fire regeneration failure due to low viable seed production under cool climate over the last 3000 yr (Payette and Gagnon 1985, Sirois and Payette 1991, Payette et al. 2001). Since lightning strikes tend to hit hilltops, black spruce forest patches are located in the wetter, protected valleys, while deforested hilltops are covered with lichens, sedges, ericaceous shrubs, and dwarf birch *Betula glandulosa*. The resulting toposequence – from wet, forested valleys to dry, deforested hilltops – forms the basic unit of the forest-tundra landscape (Payette et al. 2001).

Little evidence is yet available regarding the density of the "palaeo-forests" that once covered the hilltops of the forest-tundra. As a denser forest cover is expected in the forest-tundra under climate warming (Scott et al. 1997, Skre et al. 2002), pre-fire forests could be used as analogues to determine the direction of vegetation change on hilltops of the forest-tundra. Soil charcoal can be used to reconstruct the vegetation composition of pre-fire forests. Anatomical properties of different wood species allow their identification, and these characters are maintained after the wood is charred (Sander and Gee 1990, Thinon 1992, Heinz and Thiébault 1998, Figueiral and Mosbrugger 2000, Heinz et al. 2004). Furthermore, we argue that the spatial distribution of charcoal fragments can be used as a "palaeo-cover" proxy to estimate pre-fire black spruce cover. This can have important applications in the calculation of the potential effect of climate warming on the carbon sequestration capacity of the forest-tundra.

The goal of the present study was to reconstruct pre-fire vegetation composition and estimate pre-fire black spruce cover using soil charcoal at a tree line site known to have burned in the 10th century AD, a period when opening of the forest-tundra landscape was particularly important (Asselin and Payette 2005).

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Material and methods

The study site is located at the tree line, in the Rivière Boniface area of northern Québec (57°45′N, 76°20′W). Soil charcoal were sampled every meter in a 15 × 15 m quadrat randomly positioned in a flat area, on top of a low-elevated hill that burned ca 930 cal. AD (radiocarbon date obtained from wood charcoal, Beta-35519: 1110 ± 50 BP, calibrated using version 4.4 of the CALIB program (Stuiver and Reimer 1993)). The site is part of a larger area (ca 150 ha) where many hilltops burned ca 1000 yr ago (Payette unpubl.). A few clonal black spruce krummholz (shrubby growth form) have re-colonised the hilltop margins after the fire. The age of these clones can be estimated by measuring their size (or circumference) which is a function of the time elapsed since the last fire to have occurred at the site (Laberge et al. 2000); this method confirms that no other fire occurred at the study site since the 930 cal. AD event. A palaeoecological investigation of the late Holocene dynamics of a peatland adjacent (< 100 m) to the present study site did not show evidence of fire prior to the 930 cal. AD event (Asselin and Payette unpubl.). Thus, all soil charcoal sampled at the study site can be attributed to the 930 cal. AD fire event.

Before sampling for charcoal, present vegetation composition was determined by evaluating the relative abundance of each species present at each sampling point using the line-intercept method (Mueller-Dombois and Ellenberg 1974), i.e. by noting the species intercepting the line at each cm along five 20 cm lines spaced by 5 cm. Soil charcoal were sampled in 20 × 20 cm pits. In the poorly developed podzols of the forest-tundra hilltops, charcoal are found at the interface between the organic horizon and the Ae (eluviated) mineral horizon (soil nomenclature following Expert Committee on Soil Survey (Anon. 1987)). Thus, the 20 × 20 cm pits were sampled down to the first cm of the B (illuviated) horizon to make sure that all charcoal were included. The samples were put in plastic bags and kept in the refrigerator until lab processing.

In the lab, each sample was left in a dispersing solution (sodium hexametaphosphate – $(NaPO_3)_6$ – 2.5%) for at least 3 h before wet sieving (2 mm mesh size). The > 2 mm fraction was oven-dried at 60°C. Charred material (wood, flower parts, needles, cone scales) was sorted by hand under a dissecting microscope (6.4 ×). Charcoal fragments were identified to the genus or species level with an incident light microscope (1000 ×), using wood anatomy characters (Schweingruber 1978, Panshin and de Zeeuw 1980, Richter et al. 2004) and a reference collection. The rationale for using 2 mm as a minimum size is that, according to previous studies (Thinon 1992, Ohlson and Tryterud 2000, Benedict 2002, Bégin and Marguerie 2002), particles with geometric-mean diameters > 2 mm generally are not transported by wind. Secondary transport of charcoal fragments can have resulted from surface flow, strong winds or caribou *Rangifer tarandus* trampling. Following Benedict (2002), we fixed at 80 charcoal fragments (for a volume approximated to 400 cm^3, i.e. a 20 × 20 cm quadrat with ca 1 cm thickness) the threshold below which secondary transport cannot be ruled out. Ohlson and Tryterud (2000) found a mean value of 85 charcoal fragments inside an experimental burn, compared to < 1 fragment outside the burn. Because fragmentation of the charcoal pieces over time probably varied between sampling points, a regression of the number of charcoal fragments over total charcoal weight was computed for the 225 samples (Fig. 1). The regression equation yielded a value of 0.34 g for 80 charcoal fragments and it is this value that was used as a threshold. After removal of the effect of secondary transport, it is reasonable to suppose that the spatial distribution of spruce charcoal fragments can be used as a palaeo-cover proxy.

Results

The vegetation surveys showed that litter (mostly dead lichens) covered 28% of the quadrat, with bare rock and exposed mineral soil accounting for 6 and 1%, respectively (Table 1). When considering only vegetation, 5 taxa dominate the hilltop, their relative abundance totalling ca 98% (Table 1). The most important species is dwarf birch, followed by lichens (mostly *Cladina* spp., with some *Alectoria* spp., *Cetraria* spp., *Cladonia* spp. and *Sphaerophorus* spp.), ericaceous shrubs (*Vaccinium*

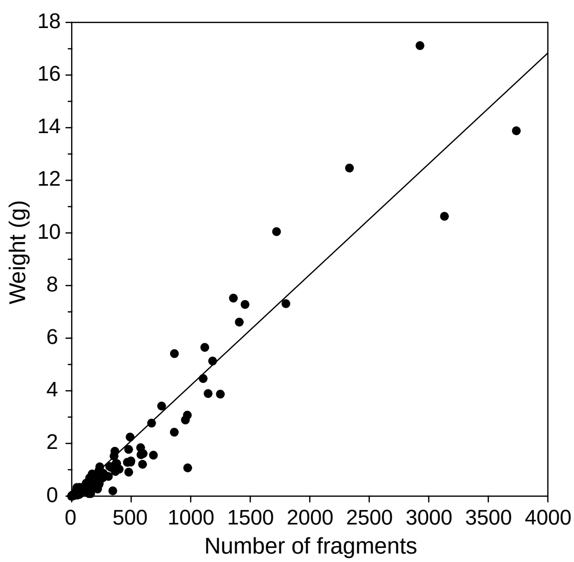

Fig. 1. Number of black spruce charcoal fragments versus weight for the 225 samples. The regression equation is $y = 0.0042x$ ($R^2 = 0.92$; $p < 0.001$).

Table 1. Results of the vegetation surveys conducted in the 15 × 15 m quadrat. RA = relative abundance (%).

	Total counts	RA	RA vegetation only	RA woody species only
Litter	7684	28		
Betula glandulosa	6958	26	40	56
Lichens	4277	16	24	
Vaccinium vitis-idaea	3014	11	17	24
Ledum decumbens	2267	8	13	18
Rock	1611	6		
Cyperaceae	620	2	4	
Mineral soil	311	1		
Poaceae	135	<1	<1	
Bryophytae	111	<1	<1	
Empetrum nigrum	46	<1	<1	<1
Salix planifolia	29	<1	<1	<1
Hepaticae	26	<1	<1	
Ledum groenlandicum	30	<1	<1	<1
Rubus chamaemorus	3	<1	<1	<1
Picea mariana	0	0	0	0

vitis-idaea and *Ledum decumbens*), and sedges (*Carex bigelowii*). Black spruce is absent from the quadrat, and the relative abundance of black crowberry *Empetrum nigrum* is <1%.

Only three taxa were present in the charcoal assemblages: *Picea mariana* represented on average 95% of the fragments found in any one sample (range 51–100%) and only small amounts of *Empetrum nigrum* and *Vaccinium vitis-idaea* charcoal were found. Although the latter two species cannot always be differentiated based on wood anatomy (Schweingruber 1978), charred pistils of both species were found in the quadrat (98 for *Empetrum* and 8 for *Vaccinium*). A few carbonised *Cladina* lichen fragments were also found, but not counted. Total charcoal weight (excluding lichens, angiosperm species pistils, and black spruce needles and cone scales) varied between 0.00 and 17.19 g. Figure 2 shows black spruce charcoal weight for each sample. Pre-fire black spruce cover was estimated by counting the number of samples with >0.34 g black spruce charcoal. This value was obtained by a linear regression of black spruce charcoal weight against the number of fragments (Fig. 1), where the threshold value of 80 fragments corresponds to a weight of 0.34 g. Of the 225 samples, 72 were found to be above the threshold, giving a pre-fire black spruce cover of 32% (Fig. 2). Combined *Empetrum* and *Vaccinium* charcoal weights varied from 0.00 to 0.20 g.

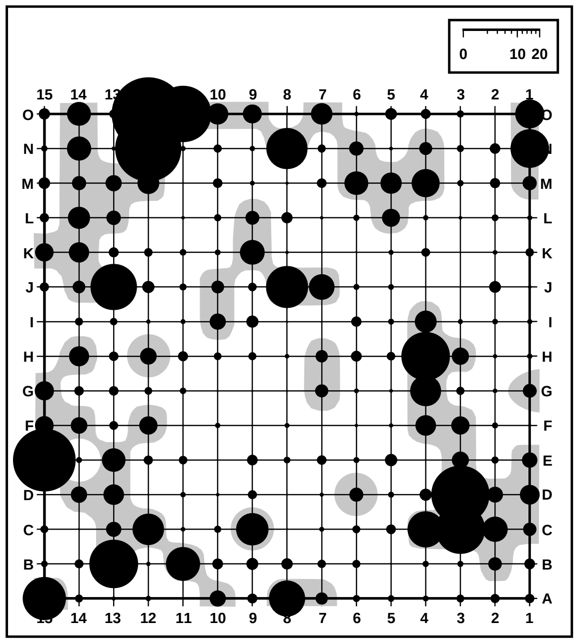

Fig. 2. Bubble plot showing black spruce charcoal weight for each sample of the quadrat. The shaded areas represent black spruce palaeo-cover, i.e. the samples with black spruce weights above the 0.34 g threshold accounting for secondary transport (72 out of 225, i.e. 32%). Note that angiosperm species charcoal are not represented because of their low weights (varying from 0.00 to 0.20 g).

Discussion

Vegetation surveys showed that the quadrat is presently occupied mostly by dwarf birch, lichens, ericaceous shrubs, and sedges (Table 1). In contrast, almost all charcoal pieces were identified as *Picea mariana*. Differentiation of *Picea mariana* from *Picea glauca* and *Larix laricina* can be difficult (Marguerie et al. 2000). In the present study, however, several lines of evidence point towards *Picea mariana*: 1) many cones, cone scales and needles were found, all from *Picea mariana*; 2) an important difference between *Larix* and *Picea* is the frequency of biseriate punctuations on the tracheids (Marguerie et al. 2000, but see Talon 1997). Although this data was not quantified during the identification process, a qualitative evaluation clearly showed the *Picea* type to be dominant; 3) there is no white spruce (*P. glauca*) in the area today, and probably never was

(Payette 1993); and 4) there are presently only three tamarack trees *L. laricina* in the whole Boniface river area and most of the species distribution is east of 74°W (Payette 1993).

While dwarf birch was absent from the charcoal samples, charred pistils and wood from *Empetrum nigrum* and *Vaccinium vitis-idaea* were present. More *Empetrum* pistils were found (98) compared to *Vaccinium* (8), suggesting the former species was more abundant. Very low weights of angiosperm charcoal (never exceeding 0.20 g) can be partially explained by the fact that small twigs of ericaceous shrubs produce charcoal pieces <2 mm in diameter. Furthermore, angiosperm wood is generally more porous than gymnosperm wood in the boreal forest, and thus more fragile and susceptible to breakage. Nevertheless, although differential preservation might have affected our results (Lasker 1976), the contrast between the present vegetation (dominance of dwarf birch and absence of black spruce) and the pre-fire vegetation reconstruction (dominance of black spruce and absence of dwarf birch) is too drastic to be spurious.

Important fluctuations in the amount of charcoal pieces were seen from one sample to another (varying from 0 to 3736 pieces, and from 0 to 17.19 g). Ohlson and Tryterud (2000) stated that such a pattern can be explained by a combination of small amounts of fuel, fuel that produces no charcoal (i.e. lichens, mosses and grasses) and low fire intensity, as the relationship between fuel accumulation and fuel consumption is the key determinant of charcoal production (Clark et al. 1998). This lends support to our assertion that spatial distribution of charcoal pieces can be interpreted as a proxy for pre-fire black spruce cover. Judging from variations in the amount of charcoal present in the 225 samples, pre-fire black spruce cover was ca 32%. This is slightly less, but comparable to a nearby site that never burned since its initial establishment (no soil charcoal >2 mm) and shows a 40% black spruce cover. Such very old black spruce forest islands are characterised by absence of *Betula glandulosa* and a high cover of *Empetrum nigrum* (Payette unpubl.), also in agreement with our results.

If climate warming continues, an increase of the forest cover could proceed in the forest-tundra by black spruce re-colonisation of presently deforested hilltops (Gamache and Payette 2005). Newly established forests would eventually reach 30-40% cover, thus increasing the carbon sink capacity of northern Québec forest-tundra (Apps et al. 1993, Myneni et al. 2001, Harding et al. 2002). However, modelling studies suggest that this new sink could be offset by a positive feedback loop acting on climate warming and attributable to decreased surface albedo (Bonan et al. 1992, Foley et al. 1994, Betts 2000, Harding et al. 2002). These studies were conducted by replacing tundra patches with closed-crown, tall boreal forests (as in the lowlands). Our results show that black spruce cover on forest-tundra hilltops might not reach >30–40% under a warmer climate. Furthermore, hilltop black spruce would most likely grow as krummholz, since leaf and twig abrasion by snow and ice particles would prevent the development of erect growth forms (Pereg and Payette 1998).

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