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Reconstruction of the long-term fire history of an old-growth deciduous forest in Southern Québec, Canada, from charred wood in mineral soils

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Abstract

Charcoal particles are widespread in terrestrial and lake environments of the northern temperate and boreal biomes where they are used to reconstruct past fire events and regimes. In this study, we used botanically identified and radiocarbon-dated charcoal macrofossils in mineral soils as a paleoecological tool to reconstruct past fire activity at the stand scale. Charcoal macrofossils buried in podzolic soils by tree uprooting were analyzed to reconstruct the long-term fire history of an old-growth deciduous forest in southern Québec. Charcoal fragments were sampled from the uppermost mineral soil horizons and identified based on anatomical characters. Spruce (*Picea* spp.) fragments dominated the charcoal assemblage, along with relatively abundant wood fragments of sugar maple (*Acer saccharum*) and birch (*Betula* spp.), and rare fragments of pine (*Pinus* cf. *strobus*) and white cedar (*Thuja canadensis*). AMS radiocarbon dates from 16 charcoal fragments indicated that forest fires were widespread during the early Holocene, whereas no fires were recorded from the mid-Holocene to present. The paucity of charcoal data during this period, however, does not preclude that a fire event of lower severity may have occurred. At least eight forest fires occurred at the study site between 10,400 and 6300 cal yr B.P., with a dominance of burned conifer trees between 10,400 and 9000 cal yr B.P. and burned conifer and deciduous trees between 9000 and 6300 cal yr B.P. Based on the charcoal record, the climate at the study site was relatively dry during the early Holocene, and more humid from 6300 cal yr B.P. to present. However, it is also possible that the predominance of conifer trees in the charcoal record between 10,400 and 6300 cal yr B.P. created propitious conditions for fire spreading. The charcoal record supports inferences based on pollen influx data (Labelle, C., Richard, P.J.H. 1981. Végétation tardiglaciaire et postglaciaire au sud-est du Parc des Laurentides, Québec. Géographie Physique et Quaternaire 35, 345-359) of the early arrival of spruce and sugar maple in the study area shortly after deglaciation. We conclude that macroscopic charcoal analysis of mineral soils subjected to disturbance by tree uprooting may be a useful paleoecological tool to reconstruct long-term forest fire history at the stand scale.

Keywords: Forest fire history; Forest dynamics; Old-growth deciduous forest; Charcoal; ^{14}C dating; Tree fall; Tree uprooting; Holocene; Conifer; Climate change; Podzol

Introduction

Stand disturbances vary greatly in origin, intensity, severity, duration, and size (Huston, 1994). Stand disturbances are factors of diversity and stability at the landscape scale and maintain the regional vegetation at equilibrium (Godron and Forman, 1983; Pickett and White, 1985). In temperate and boreal regions, fire is one the most important disturbance factors at the stand and landscape scales (Johnson, 1992; Niklasson and Granström, 2000; Payette, 1992; Whelan, 1995). Most forests dominated by conifer trees are prone to fire disturbance (Spurr and Barnes, 1980; Wright and Bailey, 1982), whereas hardwood stands are less so. Different fire regimes produce a large spectrum of seral stands, including old-growth forests in areas less frequently affected by fire.

The dynamics of old-growth deciduous forests are regulated by small- and large-scale disturbances driven by

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hurricanes, strong winds, glaze storms, and also fires causing tree fall and uprooting of medium- and large-sized trees (Canham and Loucks, 1984; Henry and Swan, 1974). Tree fall and uprooting are major forest and soil processes favoring soil renewal and forest regeneration (Brown, 1977, 1979; Clinton and Baker, 2000; Lutz, 1940; Stephens, 1956). Tree uprooting contributes largely to soil mixing, down slope soil movement, and burial of organic materials from the forest floor (Bormann et al., 1995; Brown and Martel, 1981; Lutz, 1940). As a result, post-disturbance windthrow tends to increase the organic content of the soil, particularly after a forest fire when uprooting of large burned trees incorporates variable amounts of charcoal from coarse woody debris and litter. When buried, charcoal is among the most resistant organic materials (Carcaillet, 2001; Filion, 1984a; Schneour, 1966).

Several methods exist to evaluate the historical role of fire in forest growth and development at different spatial and temporal scales. Direct field evidence for the recent impact of fire comes from fire-scar and post-fire tree age data (Arseneault, 2001; Bergeron et al., 2001; Heinselman, 1973; Johnson, 1992; Larsen, 1997; Payette et al., 1989). Also discrete charcoal layers in peat (Kuhry, 1994; Pitkänen et al., 2003; Wein et al., 1987) and eolian (Filion, 1984b) deposits are reliable indicators of old and recent in situ fires. Indirect field evidence of recent and past fire occurrences are based on pollen-slide and thin-section methods (Clark, 1988; Clark and Royall, 1996; Cwynar, 1978; Patterson et al., 1987; Swain, 1980; Whitlock and Bartlein, 2004) where microscopic and macroscopic charcoal from lake sediments are used to infer local and regional fire events. Charcoal buried in lake sediments are particularly relevant for the reconstruction of the fire ambiance during a given period of time, in particular the Pleistocene and the Holocene. However, lake charcoal cannot give an accurate account of past fire events, except in particular instances where detailed macroscopic charcoal counts are compared to known fire events within the lake catchment area (Whitlock and Millspaugh, 1996). Another method to reconstruct the long-term fire history at a particular site, and based on direct evidence, is the use of radiocarbon-dated, macroscopic charcoal buried in mineral soils (Bassini and Becker, 1990; Carcaillet, 2001; Carnelli et al., 2004; Filion, 1984a; Gavin, 2001; Gavin et al., 2003; Piperno and Becker, 1996; Ohlson and Tryterud, 2000). The method of soil charcoal analysis is based on the systematic sampling, botanical identification, and absolute dating of charcoal fragments buried in organic and mineral soils (Carcaillet and Talon, 1996; Filion, 1984a; Thinon, 1978). Sometime after a forest fire, charcoal pieces are fragmented and buried beneath the soil surface due to several factors (frost action, solifluction, soil fauna, tree uprooting, etc.). Most charcoal particles persist at a forest site but some may be transported to considerable distances according to their size, weight, and form. The spatial and temporal resolution of charcoal analysis relies heavily on the fact that charcoal fragments recorded at a site were formed in situ or transported: microscopic charcoal is generally transported over long distances (Clark, 1988; Whitlock and Millspaugh, 1996), whereas macroscopic (>0.5 mm) charcoal stays at or near its place of origin (Ohlson and Tryterud, 2000).

The nature and amounts of organic matter in forest soils are largely a function of the long-term dynamics of tree uprooting since initial afforestation of post-glaciated sites. As a consequence, mineral forest soils are forming extensive repositories of generations of mesophilous and/or xerophilous tree species which occupied the sites in the recent and distant past. When focusing on a detailed study of the charcoal content of mineral soils at a given forest site, charcoal analysis that includes counting, botanical identification, and dating of charcoal fragments represents a paleoecological method most useful for the reconstruction of the chronology of local fire events and post-fire development of forest vegetation through time. Based on a relatively large number of sampling soil pits, macroscopic charcoal data can give a reliable estimate of the minimum number of past fire events and past fire-tree interactions in a given stand. This approach also is relevant in the broader context of fire reconstructions at the landscape scale where comparisons are made with data based on indirect evidence of fire influence using charcoal buried in lake sediments.

The main objective of this study was to evaluate the potential of charcoal analysis in mineral soils as a paleoecological tool to reconstruct the long-term fire history of local forest sites. To do so, we analyzed the charcoal content of well-drained podzolic soils from an old-growth deciduous forest currently dominated by sugar maple (*Acer saccharum* Marsh.) and yellow birch (*Betula alleghaniensis* Britton) located at its northern range limit in southern Québec. The potential of the method of charcoal analysis in mineral soils is based on the assumption that the common characteristic of all forest sites is the typical soil development and forest renewal closely tuned to the uprooting process caused by all-sized windthrows and tree falls. It is hypothesized that the long-term fire history of a particular forest site can be deciphered by studying the charcoal assemblage of the local mineral soils, focusing on the botanical identification and radiocarbon-dating of charcoal fragments.

Study area

The study site is a pristine, cold-temperate deciduous forest located in the Tantaré Ecological Reserve ca. 460 m above sea level (47°04′ N, 71°32′ W; slope: 5°–12°) north of Québec City (Fig. 1), in the northernmost part of the Mixed Forest Zone, between the Deciduous Forest Zone and the Boreal Forest Zone (Grandtner, 1966). It is part of the Great Lakes – St. Lawrence Section (Rowe, 1972) and more particularly the Laurentian sugar maple forest and yellow birch – sugar maple forest ecoregion (Grandtner, 1966). The

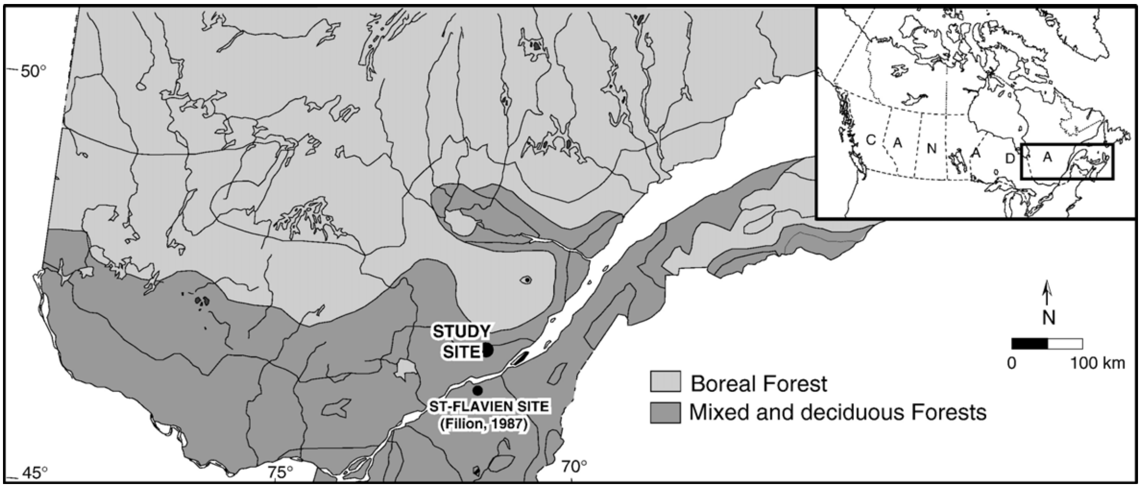

Figure 1. Location of the study forest site and the St. Flavien site in southern Québec, Canada.

forest is dominated by sugar maple and yellow birch (also very scattered paper birch, *Betula papyrifera* Marsh.), with subdominant conifers such as balsam fir (*Abies balsamea* (L.) Mill.), white spruce (*Picea glauca* (Moench) Voss), red spruce (*Picea rubens* Sarg.), and occasionally white pine (*Pinus strobus* L.). Below the canopy, small trees are common, particularly mountain maple (*Acer spicatum* Lam.) and striped maple (*Acer pensylvanicum* L.). The structure and current dynamics of the sugar maple—yellow birch stand were described in an earlier paper (Payette et al., 1990) based on a permanent 0.25-ha quadrat (50 m × 50 m) subdivided into 100 squared plots (5 m × 5 m) arranged in a checkerboard pattern. The soil of the forest site is a ferro-humic podzol developed in a sandy loam deposit with gravels and boulders of glacial origin. The soil profile is relatively well-drained with gleyed material and water table at a depth of about 1.5 m in the C horizon. The soil horizons are heavily disturbed by tree uprooting and contain small charcoal fragments to a depth of about 1.35 m. All the soil horizons are very acidic in the organic topsoil (pH of 3.6–3.8) and B (pH of 4.0–4.3) horizons. The nutrient content of both the organic and mineral horizons is also very low with a deficit in nitrogen and base cations.

Methods

Charcoal analysis was based on the sampling of 50 of the 100 plots within the forest quadrat. Plot selection was based on a systematic sampling design where one of the two plots located in the lower right corner of the quadrat was chosen at random; then the other 49 plots were selected every two plots according to the checkerboard pattern. Two cores at the center of each plot were extracted with a soil auger after eliminating the litter and the organic topsoil. The soil volume analyzed in each plot corresponded to 750 cm^3 of mineral soil. We have restricted the analysis of macroscopic charcoal to the uppermost 10 cm of the mineral horizons, although tree uprooting disturbs the soil to a depth of 1 m (Lutz and Griswold, 1939) or more. Contrasting views exist on the impact of tree uprooting on soil properties, i.e., uprooting

Table 1
Distribution, number and botanical identification of charcoal fragments within the study quadrat (n = 50 plots)

	1					2					3					4					5				
	A	C	E	G	I	B	D	F	H	J	A	C	E	G	I	B	D	F	H	J	A	C	E	G	I
Picea sp.	3	2					2	1							1	4	1	1			4	3	1	2	
Taxus canadensis		2		2			1									1									
Pinus cf. *strobus*																									
Thuja																									
Und. Conifer														1			1				2				
Acer saccharum	2				2						3										2				
Acer sp.						2																			
Betula sp.	1						3						2		3	1			1						
Cf. *Populus*																									
Cf. *Corylus*																							1		
Rosaceae																									
Undeterminable	2			1					1									2		3			3		
Total	8	4	0	3	2	2	6	1	1	0	3	0	2	1	4	6	2	3	1	3	8	3	5	2	0

See Figure 2 for alphanumeric coordinates.
Each plot is identified by an alphanumeric coordinate.

tends to homogenize the soil (Bormann et al., 1995) and also to increase local soil variability (Brown, 1979). The charcoal content was relatively homogenous and evenly distributed within the soil profile as checked in several soil pits across the forest stand. The large number of sampled plots used in this study increases the probability of recording most buried charcoal associated with the main fire events.

Each soil core was immersed for 12 hours in a solution of sodium hexametaphosphate to disperse the soil aggregates and to facilitate sieving. The cores then were washed with water in sieves with mesh sizes of 2 mm and 800 μm. Charcoal was extracted from the mineral fraction by flotation followed by manual sorting under a binocular microscope. An incident-light microscope was used for charcoal identification under magnifications of 200, 500 and 1000×. The surfaces of charcoal fragments were cut for observations of the three anatomical planes (i.e., transversal, longitudinal-tangential, and longitudinal-radial). Identification of charcoal fragments was based on published descriptions of wood anatomy (Jacquiot, 1955; Jacquiot et al., 1973; Panshin and de Zeeuw, 1980) and a reference collection of charred wood at the Centre d'études nordiques (Université Laval, Québec City, Canada). Charcoal fragments were identified at the genus level, and sometimes at the species level, based on state of preservation and size of fragments. Maple species are difficult to distinguish on the basis of wood anatomy because of their very uniform anatomy. However, *A. saccharum* can be differentiated from the other species (i.e., *A. rubrum* L.; *A. spicatum* and *A. pensylvaticum*): rays are larger (about 1 mm and 5–8 cells wide) but smaller rays (about 0.5 mm and 2–4 cells wide) are also frequent, particularly in branch wood. A single very large ray is enough for proper identification of *A. saccharum*. *A. pensylvaticum* can be differentiated from *A. spicatum* by the number of vessels per mm^2 in transversal section.

During sieving and sorting, several non-charred fragments were recovered from the cores. These fragments were not considered in the macrofossil assemblage, although they corresponded to burial events associated with stand dynamics during fire-free periods. Several resistant, well-preserved seeds of pin cherry (*Prunus pensylvanica* L.) were found, along with other non-charred wood fragments.

Sixteen individual charcoal fragments were radiocarbon dated by the AMS technique at IsoTrace Lab (University of Toronto, Ontario, Canada) and Beta Analytic Inc. (Miami, Florida, USA). Selection of charcoal fragments was based on dry weight of C, location in the quadrat (dated samples were distributed uniformly across the quadrat) and tree species. Nine dates came from spruce (*Picea* spp.), the most abundant tree taxon of the charcoal assemblage, four from sugar maple, and three from birch (*Betula* spp.). Calibration of conventional radiocarbon age to calendar years was based on the Stuiver and Reimer (1993) program and the calibration data set intcal98.14c of Stuiver et al. (1998). The dating of a greater number of AMS dates was not possible because of the small quantity of C of the other charcoal fragments. In sites experiencing frequent fires, the radiocarbon dates of charcoal approximate the actual dates of fires in dry boreal forest sites influenced by fire-induced eolian activity (Filion, 1984b), whereas charcoal may be much older than the fire dates in sites with infrequent fires and long-lived trees as in humid, old-growth forests of the western US and Canada (Gavin, 2001). The determination of fire events was based on a statistical weight method where each radiocarbon date of charcoal was represented by a histogram with a normal distribution and a width of 2 standard deviations (95% confidence). Each histogram was divided into 50-year classes (about half of the average standard deviation from all the dates). A statistical weight was computed for each class interval from probability tables for a normal distribution. Each histogram represents the sum of statistical weights for each 50-year interval.

Results

The macrofossil charcoal assemblage of the 50 plots contained 289 fragments (Table 1). Most fragments had

6					7					8					9					10					Total
B	D	F	H	J	A	C	E	G	I	B	D	F	H	J	A	C	E	G	I	B	D	F	H	J	
7	1	1	3		2	3	2		1	6	9	7	3		30	7	3	5	1	13	4	8	5		146
				1		1															2		1		11
			1																						1
					1												3								*4*
			2				1			3		2	2		2	4				2		1	1		24
	1						1			4	1	1					1				2		1		21
	1																		1						4
2						1				4		2			1				1		12		2		36
												1													1
																									1
	1																								1
2								1			2	3		1	2	6		2		2	3	2		1	39
11	4	1	6	1	3	5	4	1	1	17	12	16	5	1	35	17	7	7	3	17	23	11	10	1	289

well-preserved anatomical structures, but some charcoal had ferruginous inclusions making botanical identification difficult. Of the 50 plots sampled, only four had no charcoal, and the large majority of charcoal fragments were from plots located in the lower part of the quadrat, likely resulting from soil movements associated with tree uprooting and post-fire runoff (Fig. 2). Whereas six tree species are present today in the study stand (i.e., sugar maple, yellow birch, balsam fir, white spruce, red spruce, and one dead stem of paper birch), six tree taxa (i.e., spruce, white pine, white cedar, sugar maple, birch, and cf. *Populus*) were recorded in the charcoal assemblage, including three species/genera absent from the present forest stand. Based on anatomical characters, it has not been possible to identify species of spruce and birch. Spruce charcoal was by far the most abundant (50% of all fragments recorded). Unidentifiable charcoal (because of too small size or damaged fragments) corresponded to 22% of all fragments. About 8% of all fragments recorded were unidentifiable conifers. Canada yew (*Taxus canadensis* Marsh.), which is common today on the forest floor, also was relatively abundant in the charcoal assemblage, whereas balsam fir, a widespread companion species, was absent from the charcoal assemblage.

Radiocarbon dating of charcoal fragments indicates early- to mid-Holocene fire events (Table 2). The oldest dates come from spruce charcoal with six dates ranging between 10,400 and 10,200 cal yr B.P. Sugar maple and birch charcoal dates range between 9900 and 6300 cal yr B.P. According to the temporal distribution of the dates (based on the statistical weight of each date), a minimum of eight fires were identified in the site during the Holocene, with most fires pre-dating 10,000 cal yr B.P. (Fig. 3).

Table 2
List of radiocarbon dates

No.	Laboratory No.	^{14}C yr B.P.	Calibrated age* (cal yr B.P. ± 2 sigma)	Species
8F1	Beta-191510	9300 ± 50	10,360 (10,436) 10,583	*Picea* sp.
9G2	Beta-19151	9260 ± 50	10,357 (10,444) 10,559	*Picea* sp.
9A2	Beta-189871	9120 ± 60	10,186 (10,238) 10,426	*Picea* sp
8D1	Beta-191509	9080 ± 40	10,178 (10,222) 10,285	*Picea* sp.
10F2	Beta-189869	9020 ± 60	10,108 (10,197) 10,248	*Picea* sp.
8H1	Beta-189868	8950 ± 60	9906 (10,162) 10,222	*Picea* sp.
5C2	Beta-191508	8770 ± 70	9551 (9853) 9959	*Betula* sp.
10J1	Beta-191512	8670 ± 70	9529 (9575) 9870	*Picea* sp.
1A1	TO-7649	8350 ± 180	8927 (9402) 9741	*Picea* sp.
3A1	TO-7650	8030 ± 90	8626 (9000) 9131	*Acer saccharum*
9E2	TO-7653	7200 ± 80	7917 (7991) 8174	*Picea* sp.
1A2	Beta-189870	7190 ± 50	7930 (7993) 8062	*Betula* sp.
8B2	Beta-189867	6120 ± 40	6866 (6990) 7033	*Acer saccharum*
2D1	TO-7651	6060 ± 80	6724 (6815) 7096	*Betula* sp.
5A1	TO-8134	5660 ± 90	6289 (6422) 6642	*Acer saccharum*
1I1	TO-7652	5480 ± 90	6166 (6287) 6412	*Acer saccharum*

* Calibrated ages include intercept date (median if more than one intercept) in brackets and 2 sigma range.

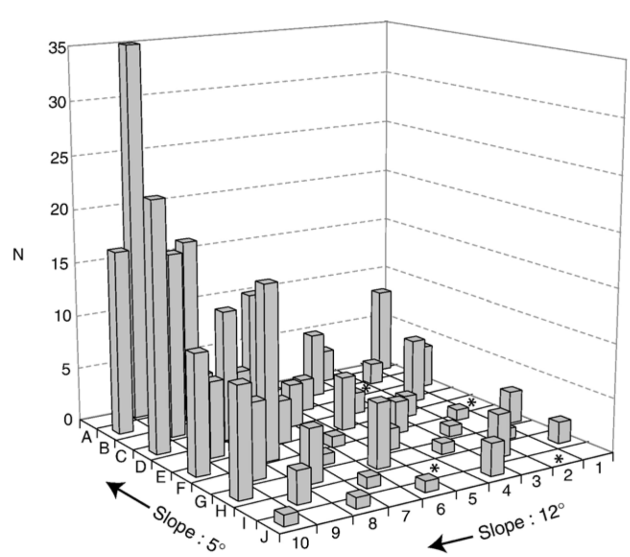

Figure 2. Distribution and number of charcoal fragments in the 50 plots of the study quadrat. Each plot is identified by an alphanumeric coordinate (ex. plot J10, J8, J6, etc.). Asterisks correspond to plots with no charcoal fragments (J2, I5, E1, and C3).

Discussion

Charcoal buried in mineral soils of the old-growth deciduous forest of the Tantaré Ecological Reserve give a record of the minimum number of fires that occurred at the site during the Holocene. Buried charcoal fragments likely come from large, uprooted burned trees. Forest fires not followed by tree uprooting are less likely to be recorded in the charcoal assemblage. Because of frequent tree uprooting in forest environments, there is no stratification of charcoal particles in the soil compared to sand dune deposits associated with long-term fire disturbance (Filion, 1984b). Given the large number of radiocarbon dates of charcoal within a rather small area (0.25 ha), it is likely that they correspond to the dates of at least eight fire events that occurred at the site since initial afforestation, at the beginning of the Holocene. It is possible that the sampling

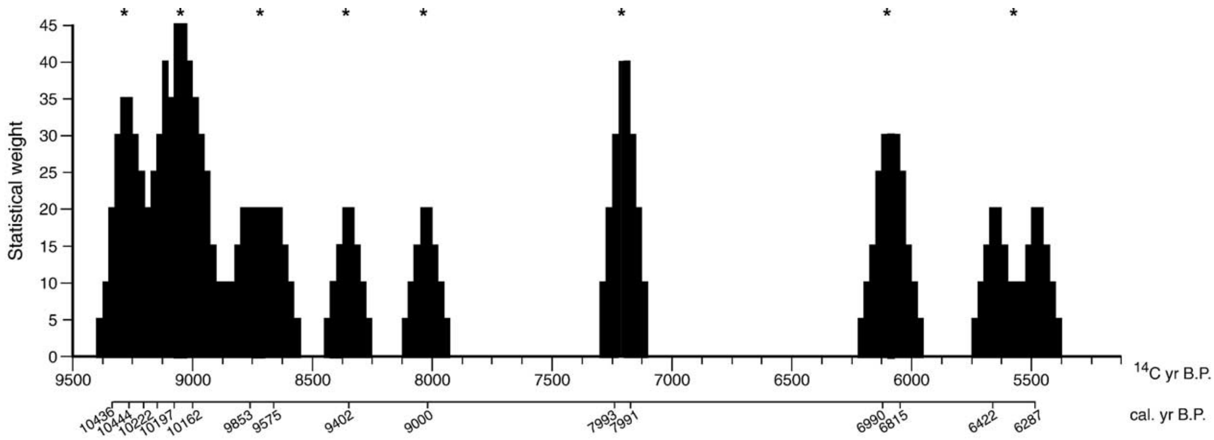

Figure 3. Occurrence of at least eight fires at the Tantaré site based on the main modes of statistical weight of the 16 radiocarbon dates. Note age scales are in both uncalibrated ^{14}C yr B.P. and calibrated cal yr B.P.

of charcoal at a greater depth (>10 cm) would have yielded similar results because tree uprooting tends to homogenize the soil profile (Bormann et al., 1995). Although it would have been preferable to date more charcoal fragments in order to consolidate the fire chronology, the quality of the remaining charcoal pieces and the small amount of C available were insufficient for proper AMS dating.

The radiocarbon age of charcoal is older than the age of the fire event proper (Filion, 1984b; Gavin, 2001; Talon et al., 1998). Charcoal is produced by dead wood burned during a given fire, and the time elapsed since death may vary considerably according to site and climatic conditions. However, in boreal and temperate forests of eastern North America, dead trees usually decompose rapidly at the soil surface. In contrast to organic matter buried by windthrow which decomposes rapidly, buried charcoal resists decomposition (Filion, 1984a; Schneour, 1966; Talon et al., 1998). On the other hand, a high frequency of tree uprooting reduces the rate of carbon accumulation in the soil (Bormann et al., 1995), and exposes the buried organic materials to rapid decomposition.

Deglaciation of the Tantaré forest area occurred around 13,500 cal yr B.P. (11,600 ^{14}C yr B.P. in Lasalle et al., 1977). Our macrofossil charcoal assemblage yielded relatively old radiocarbon dates of the presence of tree species sometime after deglaciation. Labelle and Richard (1981) have studied the post-glacial vegetation history at a nearby site (Lac Marcotte) based on pollen analysis. Lac Marcotte is located a few km east of our study site and at a roughly similar altitude of 500 m above sea level. Black spruce seeds buried in basal gyttja of Lac Marcotte indicated that this species was present in the area ca. 10,150 cal yr B.P. along with other boreal tree species as evidenced by macrofossils of paper birch, balsam fir, white spruce, and eastern larch (*Larix laricina* (DuRoi) K. Koch). According to Labelle and Richard (1981), black spruce and jack pine (*Pinus banksiana* Lamb.) were more abundant in the Lac Marcotte area during the early Holocene (i.e., between 10,150 and 9500 cal yr B.P., and 10,150 and 8200 cal yr B.P., respectively).

The charcoal assemblage of the Tantaré site shows direct evidence of early presence of boreal trees and rapid post-glacial forest development. The oldest spruce charcoal is contemporaneous with spruce trees buried by eolian sands in the St. Flavien area about 50 km southwest of the Tantaré site (Filion, 1987; see location of St. Flavien site in Fig. 1). The buried trees were from a fossil forest with stems in original growth position dated between 11,200 and 10,200 cal yr B.P. According to Filion (1987), the burial of forest trees and also small peatlands by eolian sands between 11,700 and 8300 cal yr B.P. in the St. Flavien area was caused by dry and temperate conditions. The long-term fire history of the Tantaré forest also indicates that site conditions north of Québec City were temperate but rather dry in early Holocene times. Carcaillet and Richard (2000) also showed from microfossil charcoal influx data that the early Holocene in eastern Canada was characterized by high fire incidence. On the other hand, it is possible that fire conflagrations at this site during this period were facilitated by conifer trees which were probably more abundant during this period as suggested by the charcoal record.

Our charcoal record shows that conifers dominated the site from 10,400 to 9000 cal yr B.P., and then conifer and deciduous tree species between 9900 and 6300 cal yr B.P. It was not possible to date the only charcoal fragment of white pine extracted from the Tantaré soils because of its small size. According to several radiocarbon-dated tree macrofossils, white pine arrived in the Québec City area (St. Flavien site) at about 6800 cal yr B.P. (Filion and Quinty, 1993). Pollen influx values suggest that sugar maple established in the Lac Marcotte basin 8800 ^{14}C yr B.P. (~10,000 cal yr B.P.), and the species was more abundant between 5700 and 4200 cal yr B.P., and also around 2300 and 900 cal yr B.P. (interpolated and calibrated dates from Labelle and Richard, 1981). The charcoal data show direct evidence for the presence of sugar maple at the Tantaré site at 9000 cal yr B.P. Sugar maple occupied the site continuously despite recurrent fires during the first half of the Holocene. The increased abundance of sugar maple after 5700 cal yr B.P. (interpolated and calibrated date from Labelle and Richard, 1981) also coincides with the complete cessation of fire as suggested by the charcoal record in the Tantaré soils. However, it is important to emphasize the fact that the absence of fire evidence from the mid-Holocene to present in the Tantaré soils does not proved that fire never occurred at the site during this period. It is possible that the evidence has been obscured by less severe fires that produced smaller amounts of charcoal and also less frequent and less intense post-fire uprooting. Overall, the ultimate cause for the absence of fire evidence in the Tantaré site after 6300 cal yr B.P. is not known. It is not known to what extent the present sugar maple—yellow birch forest is the modern analogue of the original deciduous forest that established after 5700 cal yr B.P. (Labelle and Richard, 1981) because of cessation of fire incidence. Although more humid conditions prevailed in the area thereafter (Filion, 1987; Labelle and Richard, 1981), it is also possible that the dominance of deciduous hardwood trees since mid-Holocene times reduced greatly the probability of fire spreading.

Conclusions

Our study is the first one to use charcoal macrofossils buried in mineral soils for the reconstruction of the long-term fire history of a well-drained forest site. Our main findings are the early presence of forest tree species after deglaciation in close association with fire activity. Also a minimum of eight fire events were recorded, particularly in the first half of the Holocene. No charcoal fragments younger than 6300 cal yr B.P. were recovered, which indicates that fire activity in the Tantaré forest site was minimal if not absent since mid-Holocene.

Charcoal analysis of mineral soils based on radiocarbon-dated charcoal fragments identified at the genus/species levels is a powerful paleoecological tool to reconstruct from direct evidence (charcoal macrofossils) the long-term forest fire history at the stand scale. The reconstruction of the long-term forest fire history of well-drained forest stands is possible mostly in sites affected by tree uprooting as the main burial process. Macroscopic charcoal fragments buried in mineral soils by tree uprooting give direct evidence of fire events and presence of tree species/genus at different periods since deglaciation. Macrofossil charcoal in forest soils also yield dates of presence and relative abundance of tree species that complement other paleoecological tools used in pollen-based studies of lake and peatland environments.

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