Quaternary Science Reviews 25 (2006) 1489–1500

Fire and soil erosion history in East Canadian boreal and temperate forests

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Received 7 January 2005; accepted 7 January 2006

Abstract

Fire-made soil erosion should trigger (i) an increase of inorganic sedimentation within lake-basins and (ii) a change of magnetic susceptibility if the burn depth is strong enough to reach the mineral soil and to modify the magnetism of mineral particles. Magnetic susceptibility will also change with the flux of mineral sediments even without a change of their magnetism. Here, we test the role of fire on soil erosion by measuring the mineral accumulation and the magnetic susceptibility in sediments from seven small lakes' and two dunes' profiles from East Canada over the Postglacial. Four sites are located in the boreal forest south of James Bay, two in the eastern maritime Quebec and one in the cold temperate south-eastern Ontario. Charcoal accumulation rate is used as a proxy of biomass burning based on the assumption that higher the biomass burning, higher is the charcoal accumulation. The mineral accumulation, deduced from loss-on-ignition residues, is a proxy of erosion process in the lake catchment areas. No relationship is observed between sediment types, sedimentation, magnetic susceptibility and charcoal concentrations in lakes. The patterns of erosion proxies do not match with those of fire, except in dunes. The results suggest that fires have no significant impact on soil erosion in East Canadian forest ecosystems, except in dry-sandy areas. This fact can result from fire severity that is not strong enough to completely burn the humus layer, especially in northern boreal forest characterized by thick soil organic layers. Fire is thus not a significant process affecting the lake sedimentation by soil material input, nor a factor of soil dynamics by rejuvenation of top most soil centimeters over the Postglacial, except in dry sandy areas where dune activity is obviously controlled by burning.

1. Introduction

Fire frequency has globally changed several times during the Postglacial, at different periods and in different ways depending on vegetation, air masses and human impact (e.g. Clark et al., 1989; Swetnam, 1993; Carcaillet, 1998; Flannigan et al., 2001; Long and Whitlock, 2002; Gavin et al., 2003; Lynch et al., 2004). Because fire is expected to trigger erosion (Wright and Heinselman, 1973) or to control the tree recruitment when humus is consumed (Johnson, 1992; Greene et al., 2004), it is crucial to estimate the precise role of fire on soil dynamics to improve the understanding of postglacial environmental changes and eventual feedbacks. Erosion resulting from fire is due to a total destruction of litter and humus layers by severe surface fires. Low severity surface fires do not cause erosion because the litter layer survives and protects the soil. However, it is classically assumed that erosion is strongly stimulated by fires (Soto et al., 1995; Legleiter et al., 2003; Wondzell and King, 2003; Meyer et al., 2004), although the linkage between the processes are rarely demonstrated on long-term perspectives, i.e. over more than 100 yr.

In eastern Canada, the fire regime deduced from sedimentary charcoal records changed at least twice during the Holocene (Carcaillet and Richard, 2000). During the early Holocene, the fire frequency was high until 7500–7200 cal. yr BP, then low with intervals generally

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doi:10.1016/j.quascirev.2006.01.004

longer than 300 yr between 7200 and 2200 cal. yr BP. Since 2000 yr, the frequency is generally high with fire intervals shorter than 150 yr in the boreal forest (Carcaillet et al., 2001a). The increase of fire frequency is assumed to be driven by higher occurrence of droughts during the fire season, due to more frequent presence of Pacific dry air masses over East Canada (Carcaillet and Richard, 2000). The fire history reported in the eastern Canadian peninsula by ^{14}C dating of charcoal from dunes and from soils (Payette and Gagnon, 1985; Filion et al., 1991; Bussières et al., 1996; Talon et al., 2005) complete the regional pattern of fire history previously deduced from a charcoal database of 37 lakes (Carcaillet et al., 2002).

In the present paper, we propose to test the hypothesis that changes in fire frequency during the Postglacial in eastern Canadian plains and hills have controlled the soil erosion dynamics. To analyze this hypothesis, we reconstruct the fire and the sedimentation history of seven lakes from Ontario and Quebec by continuous high-resolution charcoal and loss-on-ignition (LOI) analyses, respectively. Magnetic susceptibility is used along with LOI residues (inorganic matter) to highlight the soil erosion. We assume that modifications of sediment type and rate are expressed by changes in inorganic sedimentation and magnetic susceptibility. Finally, we explore the role of the regional aeolian activity on the local mineral matter sedimentation by comparing the Holocene sand accumulation pattern of two dunes with the observed cumulative LOI residues in three lakes within the same region.

The seven lakes (Fig. 1) are situated in the southeastern Ontario cold temperate biome and in the Quebec boreal biome. Two lakes from the boreal forest are from a hilly landscape in the eastern maritime Quebec (Gaspé Peninsula) and four from Abitibi, a plain region of western Quebec, south of James bay (Abitibi). The two dunes are from the Abitibi boreal forest. The diversity and the number of situations should allow the identification of trends and generalities on the links between fire and erosion. The lakes are distributed along a vegetation gradient, with the southernmost, in the mixed–temperate forest. Three lakes are in closed-crown mixed–boreal forests and three others are in closed-crown coniferous–boreal forests.

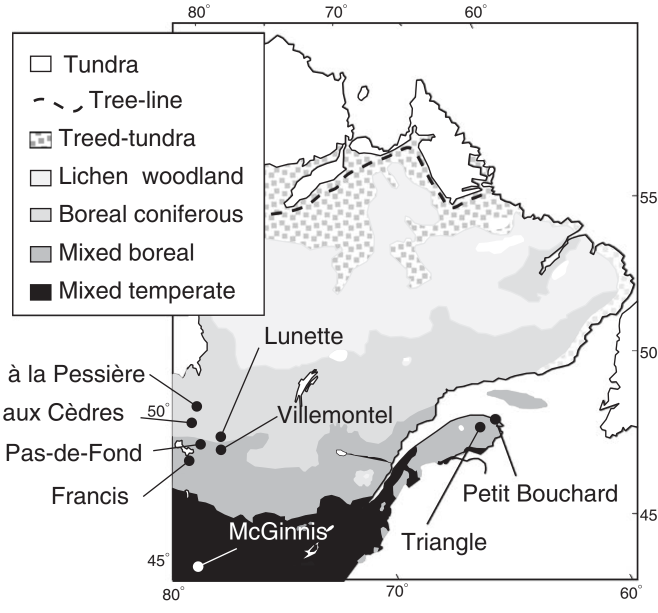

Fig. 1. Location of study sites in East Canada.

2. Study sites

Table 1 provides details on geographic coordinates (latitude, longitude, elevation), on ecological characteristics (vegetation, topography), on lacustrine properties (surface, depth, presence of inlet or outlet) and on sampling (type of corer, core length, presence of laminae) of each sites. The presence of laminae is an indication of a sedimentation not disturbed by bioturbation. Slopes around lakes are rather flat (L. Francis, L. Pas-de-Fond, L. à la Pessière, L. aux Cèdres) to gentle (McGinnis L., Petit L. Bouchard, L. Triangle), unfavorable to soil erosion if humus is not entirely removed or deteriorated.

2.1. Lakes description

Lac Francis, L. Pas-de-Fond, L. aux Cèdres and L. à la Pessière are kettle lakes located in western Quebec, South of James Bay (Fig. 1). In this area, till outcrops are scattered within a more or less uniform and flat landscape. The lakes lie on eskers covered by clay sediment from the proglacial lake Ojibway that deposited the ‘‘Northern Clay Belt’’, covering a large area south of James Bay. In Abitibi, the vegetation is mixed boreal in the southern part where Lac Francis and L. Pas-de-Fond are situated, and closed crown coniferous in the northern part where L. aux Cèdres and L. à la Pessière are located. The mixed southern boreal forest is characterized by balsam fir (*Abies balsamea*), eastern white cedar (*Thuja occidentalis*), Jack pine (*Pinus banksiana*), white spruce (*Picea glauca*), black spruce (*Picea mariana*), paper birch (*Betula papyrifera*) and, aspen and poplar (*Populus tremuloides* and *P. balsamifera*). The northern boreal forest is dominated by black spruce and, secondly, by Jack pine, paper birch and aspen. In the southern mixed boreal forest, the humus layer is rather shallow, (<centimeters), and in the northern coniferous the humus layer is thick (20–50 cm), and generally covered by a carpet of mosses (Hypnaceae).

Lac Triangle and Petit L. Bouchard are located in eastern Quebec along the Atlantic coast, in the region called Gaspé Peninsula. The climate has strong maritime influences. A steep relief characterizes the region with summits around 1300 m a.s.l. Lac Triangle is situated in the interior plateau at 465 m a.s.l. in the closed-crown balsam fir and black spruce belt typical of the northern maritime boreal forest, and Petit L. Bouchard near the coast at 145 m a.s.l. in a mixed boreal forest characterized by balsam fir, white spruce, paper birch and red maple (*Acer*

Table 1
Description of lakes and sampling methods

Name	McGinnis	Francis	Pas-de-Fond	aux Cèdres	à la Pessière	Petit Bouchard	Triangle
Latitude (N)	44°36′26″	48°31′35″	48°48′30″	49°20′45″	49°30′30″	48°51′14″	48°42′36″
Longitude (W)	78°02′23″	79°28′20″	78°50′00″	79°12′30″	79°14′25″	64°35′52″	65°24′50″
Elevation (m)	256	305	290	315	280	145	465
Topography around lake	Hills with gentle slopes	Flat	Flat	Gentle flat on the side of an esker	Flat	Flat	Hilly
Vegetation zone	Mixed temperate	Mixed boreal	Mixed boreal	Coniferous boreal	Coniferous boreal	Mixed boreal	Coniferous boreal
Lake surface (ha)		0.8	2.0	2.0	~4.0	2.0	1.5
Max. lake depth (m)	>18	6	11	15	16	1.4	1.6
Inlet/outlet	Yes/Yes	Yes (intermittent)/No	No/Yes	No/Yes	No/Yes	No/Yes	No/Yes
Type of corers[a]	KB + L	KB + L	KB + L	KB + McK	KB + McK	KB + L	L
Laminated	Yes (pro parte)	Yes (pro parte)	Yes (100%)	No	Yes (100%)	No	Yes (pro parte)
Total length of sediment (cm)	194	302	368	600	584	330	387

[a] KB—Kajak-Brinkhurst; L—Livingstone; McK—McKereth.

rubra). The two lakes are shallow headwater lakes. The sediments of Lac Triangle are partially laminated, indicating that no bioturbation occurred during most of the Postglacial, and that sediments are appropriate for high-resolution analyses.

McGinnis Lake is a headwater lake, located in south-eastern Ontario, in the Petroglyphs Provincial Park, at the southern limit of the Canadian shield. The climate is cold temperate to continental. The vegetation surrounding the lake is mixed and diverse, composed of pines (*Pinus strobus*, *P. resinosa*), balsam fir, eastern white cedar, hemlock (*Tsuga canadensis*), American beech (*Fagus grandifolia*), red maple, red oak (*Quercus rubra*), paper birch (*Betula papyrifera*) and yellow birch (*Betula alleghaniensis*). The relief is hilly and rocky. The soil is superficial with a thin humus layer of needles and Cladina-type lichens, which dries quickly in summer. The sediment core has been recovered at 18 m depth. The sediments are light-gray, carbonated and partially laminated.

2.2. Dune locations

The two dunes have been excavated in Abitibi, western Quebec, in the "Northern Clay Belt". The dune of Villemontel is located at 48°41′59″N and 78°21′38″W, and the dune of Lac Lunette is at 48°47′57″N and 78°23′19″W, i.e. about 30 km east from Lake Pas-de-Fond.

These dunes are situated at the transition between the mixed and the closed-crown coniferous boreal forests. The Villemontel dune has a parabolic shape and is at the top of an esker. The dune of Lac Lunette corresponds to a wide area of dunes interrupted by forest islands at about 1.2 km west of the esker. Both dunes are about 5 m high. The woody vegetation is composed of *Pinus banksiana-Kalmia angustifolia* forest with scattered *Picea mariana*, *Betula papyrifera* and *Populus tremuloides*. The under-storey is composed of *Cladina* sp., *Polytrichum piliferum*, *Vaccinium* spp., *Hudsonia tomentosa* and herbs.

2.3. Present-day fire regime

The fire cycle depends on the observed period. Today, the mean fire cycle (and associated confidence interval) around Lac aux Cèdres and L. à la Pessière, located in the coniferous northern boreal forest, is 398 yr (302–527). In the mixed southern boreal forest where L. Francis, L. Pas–de-Fond and the two dune fields are located, the frequency is 326 yr (250–426) (Bergeron et al., 2004). However, these values have considerably increased since AD 1850 where the mean fire cycles were 101 yr (79–129) and 83 yr (65–105), respectively. In Gaspesie, where L. Triangle and L. Bouchard are situated, the mean fire cycle would range between 200 and 500 yr over the 20th century (Gauthier et al., 2001). No estimates are available for the region of McGinnis Lake in southern Ontario.

3. Material and methods

3.1. Lake sampling, sediment and charcoal measurements, chronologies

At Lac Francis, L. Pas-de-Fond, McGinnis L., L. Triangle and Petit L. Bouchard, the lacustrine sediments were recovered from the frozen surface with a Livingstone-type corer, whereas a Mackereth sampler equipped with a 6-m-long tube was used at L. à la Pessière and L. aux Cèdres. Because neither corer allows sampling of the more recently accumulated material, the water–sediment interface was sampled using a Kajak–Brinkhurst (KB) gravity corer, except for L. Triangle. The pair of cores for each site was cross-correlated by pollen analyses and LOI to estimate the thickness of the sediment missing from the surface of Livingstone or Mackereth cores.

Three lakes were analyzed for charcoal from pollen-slides (L. Francis, L. Triangle, Petit L. Bouchard) and five by sediment sieving (L. Francis, L. Pas-de-Fond, L. McGinnis, L. Pessière, L. Cèdres), according to Carcaillet et al. (2001b). The cores were sliced into centimeter sections. At each section, 1 cm^3 samples were taken along the longitudinal axis of the core.

For sieving-charcoal, sediment samples were sieved through a 150 μm mesh. Sediments were deflocculated in a 3% $Na_4P_2O_7$ solution for a minimum of 2 days before a gentle manual water spray was used to aid sieving. The remaining particles were bleached in a 10% water solution of sodium hypochlorite (NaOCl) for a few minutes to clearly distinguish charcoal from dark organic matter. The area of each charcoal fragment was estimated microscopically at 40 × magnification using a graticule with 400, 0.0144 mm^2 squares, and was classified into one of ten exponential size-classes. The total surface area of charcoal in a sample was obtained by summing the mean surface area of each size-class, multiplied by the number of particles in that size-class over all classes. Charcoal measurements are reported as charcoal areal concentration (mm^2/cm^3).

For tallying pollen-slides charcoal, 1 cm^3 was removed, and exotic pollen grains (*Eucalyptus*) were added to each sample to estimate the charcoal concentration. Samples were soaked with 10% hot KOH and sieved with a 700 μm mesh size. Each residue was observed to detect and tallied any charcoal fragment larger than 700 μm. Carbonate, silicate and a fraction of organic material were eliminated with 10% HCl, 48% HF and acetolysis, respectively. Samples were mounted on glass slides with glycerine. A drop was randomly sampled, and charcoal fragments were tallied at 400 × magnification using a grid with 400 squares of 156 μm^2 surface area. The total surface of each pollen-slide was scanned. Charcoal fragment estimates were divided into ten exponential size-classes. Results are express in areal charcoal concentration (mm^2/cm^3).

The LOI analysis is a proxy measurement of the organic matter content of the sediment when consumed at 600 °C during 30 min, and of the carbonate content at 1000 °C during 60 min (Dean, 1974). Residues of ignition are assumed to be ashes, but mainly inorganic particles such as silt, clay and sand, supply from soil erosion of catchment area and from aeolian activity.

Samples for LOI were collected using a 1 cm^3 volumetric sub-sampler. LOI at 600 °C was carried out continuously along the cores at every centimeter, while LOI at 1000 °C was generally performed at every 5 cm, except in sequences with high carbonate content, e.g. in the clay–gyttja interface, in the clay sections and at McGinnis Lake and Lac Triangle in the entire postglacial sequences. In such sequences LOI at 1000 °C was carried out at each centimeter to clearly determine the onset of the organic accumulation.

Magnetic susceptibility is used to assess (i) the changes of the total input of mineral particles from the catchment area (quantitative process, mass erosion) or (ii) the magnetism changes of iron-rich particles incorporated in the sediment, both of which are associated to the fire activity (Le Borgne, 1960; Longworth et al., 1979; Oldfield et al., 1981). The qualitative process might be recorded only if the burn depth reaches the mineral soil, completely consumes the humus layer and, finally, modifies the magnetism of soil particles. In such processes, the mass erosion is not critical; only discrete erosion of iron-rich particles which might change the magnetism of sediment. Measurement of magnetic susceptibility was carried out at the Department of Geography of the University of Ottawa (Ontario). The total magnetic susceptibility reading was performed using a Barrington MS2. Measurements were done at each centimeter in the same median depth as the charcoal sampling. Values are expressed in CGS (i.e., G/cm^3 Oe).

The data comparison is based on the organic content (LOI concentration), LOI-residues and charcoal. The concentration-based comparison is preferred to influx, because influx is strongly constrained by the sediment accumulation rate modeled by isotopic dating. The comparison of two independent influx values from the same stratigraphic level holds a constant value that is the sediment accumulation rate. Consequently, it is not necessary to use influx in the same core, but only concentration. Such argument is not acceptable along the temporal axis, because the sediment accumulation rate varies along this axis, and of course for comparisons among sites.

Table 2 provides a synthesis on the chronology for each lake and on the deposition time obtained by modeling the age/depth relationship. The chronologies of Lac Francis and L. Pas-de-Fond are based on ^{210}Pb and AMS ^{14}C dating (terrestrial plant macro-remains). The chronologies of L. aux Cèdres, L. à la Pessière, L. Triangle and Petit L. Bouchard are based on ^{14}C measurements, AMS on assemblages of terrestrial macro-remains or conventional on bulk sediment. No ^{14}C date is available for McGinnis Lakes, but we assume that the 2-m-long profile is less than 10,000-years-old, based on the short length of the core.

3.2. Dunes sampling and chronology

The profiles were dug until the base of the dune was reached (e.g. the initial soil at Villemontel) or until no traces of pedogenesis activity was observed (e.g. Lunette). The dunes profiles were cleared to 1 m width. Each sedimentary sequence is composed of mineral sandy soil interbedded with charred organic accumulation. Each organic layer corresponds to a past stabilized soil that burned, and sand accumulation is attributed to aeolian activity potentially following fire events (Filion, 1984).

Only organic soil can be dated by ^{14}C measurements. In total, 13 ^{14}C measurements were performed at Villemontel (8) and at Lunette (5) to establish a chronology, i.e. about

Table 2
Details on lacustrine chronologies

Lakes names	McGinnis	Francis	Pas-de-Fond	aux Cèdres	à la Pessière	Petit Bouchard	Triangle
Post-glacial chronology	Undated	6800 cal yr	7450 cal yr	7296 cal yr	7650 cal yr	11,128 cal yr	11,164 cal yr
Mean deposition time ± s.d. (SE)	Unknown	26 yr cm^{-1} ±11.7 (0.67)	23 yr cm^{-1} ±8.7 (0.49)	12 yr cm^{-1} ±6.4 (0.26)	13 yr cm^{-1} ±2.7 (0.11)	33 yr cm^{-1} ±14.0 (0.79)	25 yr cm^{-1} ±9.2 (0.50)
Reference	Unpub.	Carcaillet et al., 2001b	Carcaillet et al., 2001a	Capece, 2003	Carcaillet et al., 2001a	Asnong and Richard, 2003	Asnong and Richard, 2003

half of the observed charcoal layers. The ^{14}C dates are calibrated against dendrochronological years using the CALIB 4.4.2 program based on the data set INTCAL98 (Stuiver et al., 1998), and reported as intercept with a 2σ range at $p > 0.95$. The age/depth model is then applied to all charred organic layers to deduce the age of the fires, and to estimate the aeolian accumulation rate.

4. Results

4.1. Sedimentation pattern

Each lake shows a pattern of accumulation of organic matter (LOI at 600 °C), of carbonates (LOI at 1000 °C) and of inorganic residues (LOI residues) different from each other (Figs. 2 and 3). However, general trends can be highlighted. The maximum of LOI residue concentration occurs during periods of clay sedimentation, and is generally associated with high concentration of carbonates and the lowest charcoal concentration (L. à la Pessière, L. Pas-de-Fond and L. Francis, Fig. 3). Two lakes show carbonate accumulation, i.e. McGinnis L. and L. Triangle, highlighted by high values of LOI at 1000 °C (Figs. 2(A) and (D)). These lakes with carbonate accumulation show important fluctuations in the organic content (LOI) and LOI residues (Figs. 2(A),(B),(D), and (E)). Lac Francis and L. Pas-de-Fond display low carbonate concentration, except in the sequence with clay sediment (Fig. 3(G) and (J)), but record important fluctuations of the LOI residues (Figs. 3(H) and (K)), i.e. of the inorganic input in the lake basin. This could result from a mineral matter erosion, because L. Francis and L. Pas-de-Fond are kettle lakes located on eskers. However, L. aux Cèdres and L. à la Pessière are also kettles situated on eskers, but do not show such large fluctuations of LOI residues (Figs. 3(B) and (E)). Lake Francis and L. Pas-de-Fond are located in the mixed southern boreal forest with moderately thick humus layers, while at L. aux Cèdres and L. à la Pessière, which are in the black spruce northern boreal forest, the humus layers are generally thick and well-protected by a layer of mosses. These observations suggest that the geomorphological context is not a key element to explain the pattern of inorganic input (LOI residues), while the structure of the humus layer and of its cover could be decisive for soil protection against the erosion of mineral particles.

On average, the LOI residues of L. Pas-de-Fond and of L. Francis are between 150 and 200 mg/cm^3 above the clay sediments (Figs. 3(H) and (K)). At McGinnis Lake, which is situated in a hilly landscape covered by a thin humus layer, the inorganic residues range between 150 and 200 mg/cm^3, as well as in L. Pas-de-Fond and L. Francis. Because the bedrock is composed of hard rock comprising the Canadian shield, the mineral soil is also thin surrounding the lake catchment at McGinnis. The nature of the bedrock probably explains the relatively low input of inorganic residues in McGinnis Lake, despite the fact

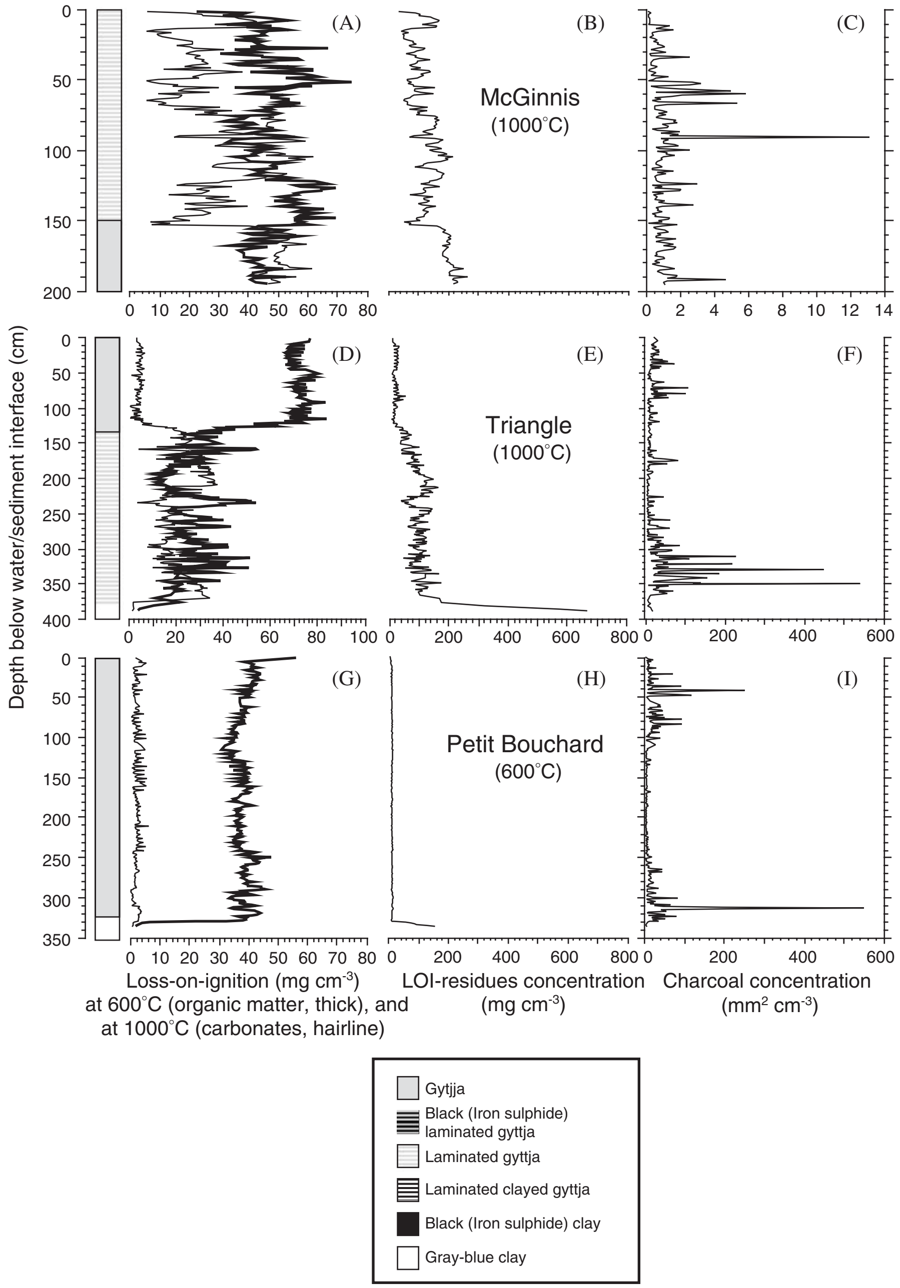

Fig. 2. Stratigraphy, loss-on-ignition (LOI) concentration at 600 and 1000 °C for organic matter and carbonates ($CaCO_3$), respectively (A,D,G), ignition residues (B,E,H) and charcoal concentration (C,F,I) in lacustrine sediments from temperate lake (McGinnis Lake [A,B,C], southeast Ontario), and boreal lakes (Lac Triangle [D,E,F] and Petit L. Bouchard [G,H,I], East Quebec).

its humus layer is highly susceptible to complete consumption at each fire.

4.2. Charcoal and inorganic matter (LOI residues): long-term pattern

Charcoal concentrations increase with decreasing depth in lakes Francis and Pas-de-Fond, but LOI residue concentrations do not show the same pattern: LOI residues decrease in L. Pas-de-Fond and no clear trend associated with the charcoal curve in L. Francis (Figs. 3(H) and (K) vs. Figs. 3(I) and (L), respectively). At lakes aux Cèdres and à la Pessière, the curves of charcoal concentrations show a high variability, which does not occur in LOI residues (Figs. 3(B) and (E) vs. Figs. 3(C) and (F), respectively). At McGinnis, the curve of charcoal concentration is rather flat with decreasing depth and, those of LOI residues fluctuate a lot (Figs. 2(B) vs. (C)). The charcoal curves of L. Triangle and L. Petit Bouchard show elevated values at the base and very low values in the middle of the core. No apparent relationship is observed with LOI residues (Figs. 2(F) and (I)), particularly for L. Petit Bouchard that displays extreme low LOI-residues (Figs. 2(E) and (H)).

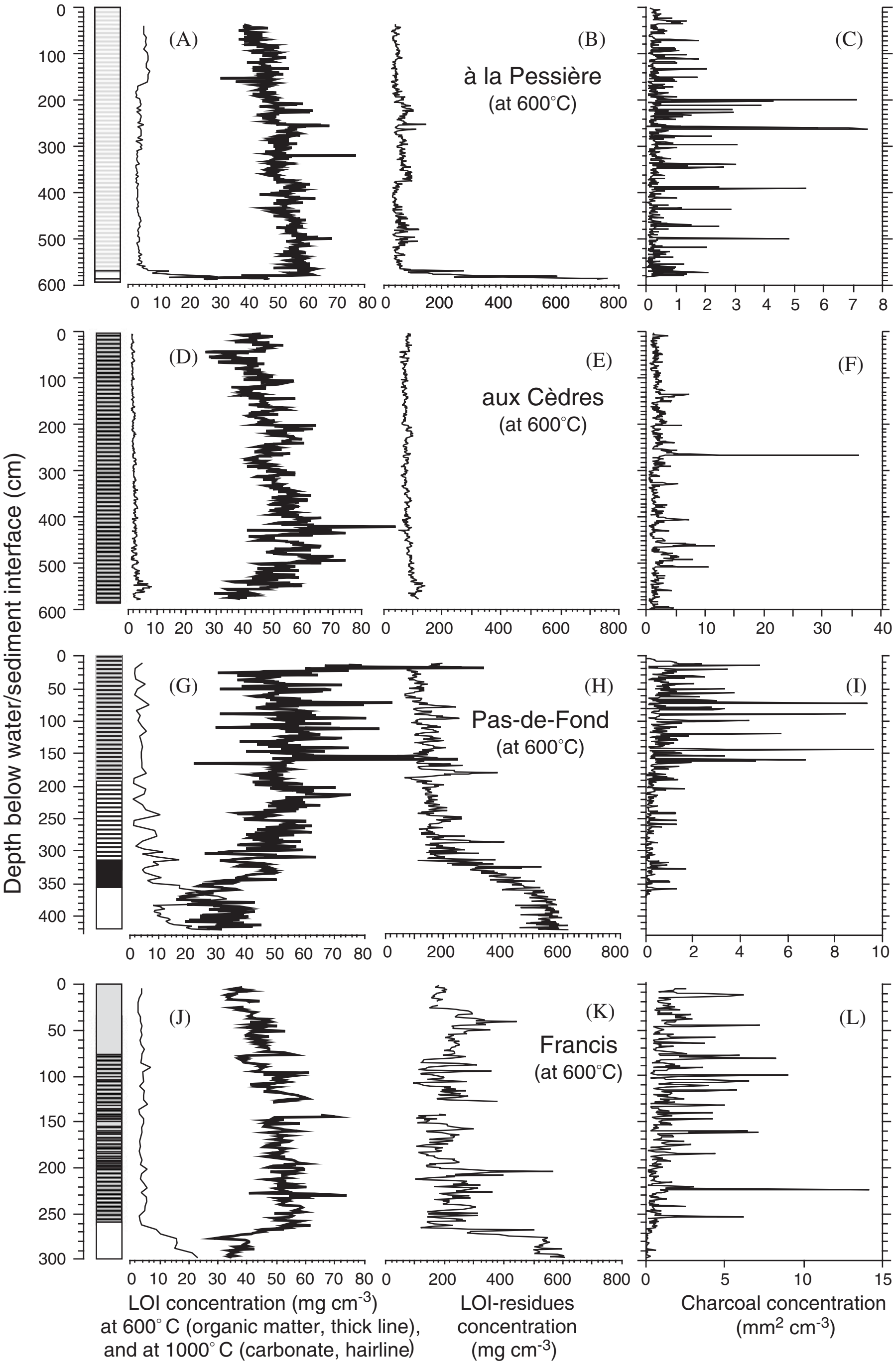

Fig. 3. Stratigraphy, loss-on-ignition (LOI) concentration at 600 and 1000 °C for organic matter and carbonates ($CaCO_3$), respectively (A,D,G,J), concentration of ignition residues (B,E,H,K) and charcoal concentration (C,F,I,L) in lacustrine sediments from four boreal lakes (western Quebec). For the legend of stratigraphy, see Fig. 2.

4.3. Charcoal and organic matter (LOI): long-term pattern

At McGinnis L. and L. Triangle, there are no clear trends in charcoal concentration, while there are extreme fluctuation in LOI at 600 and at 1000 °C (Figs. 2(A) and (D)). At L. Francis, the LOI concentrations are decreasing with decreasing depth, and charcoal concentrations are increasing (Fig. 3J). At L. aux Cèdres and L. à la Pessière, the LOI concentrations are decreasing, and charcoal concentrations do not show any decreasing or increasing trends (Figs. 3(A) and (D)). These results show that the organic concentration deduced from LOI at 600 °C is not linked to the concentration of charcoal that is embedded into sediments, suggesting no direct relationship between fire and lacustrine organic productivity.

4.4. Charcoal, magnetic susceptibility and LOI residues

The total magnetic susceptibility values are low and fluctuate between –0.56 and 3.12 CGS (Fig. 4). The highest values correspond to the bottom of the core. The negative values are explained by the fact that the measurements were done on fresh material. Negative values, thus, correspond to the effect of components such as H_2O, SiO_2 or carbonates that are diamagnetic (King et al., 1982; Banerjee, 1989; Verosub and Roberts, 1995).

The curve of total magnetic susceptibility appears independent of the charcoal concentration curve, but matches rather well the curve of LOI residues at 600 °C, in L. à la Pessière (Fig. 4). This observation suggests that changes of magnetic susceptibility in lacustrine sediments through time are independent of fire activity in the lake

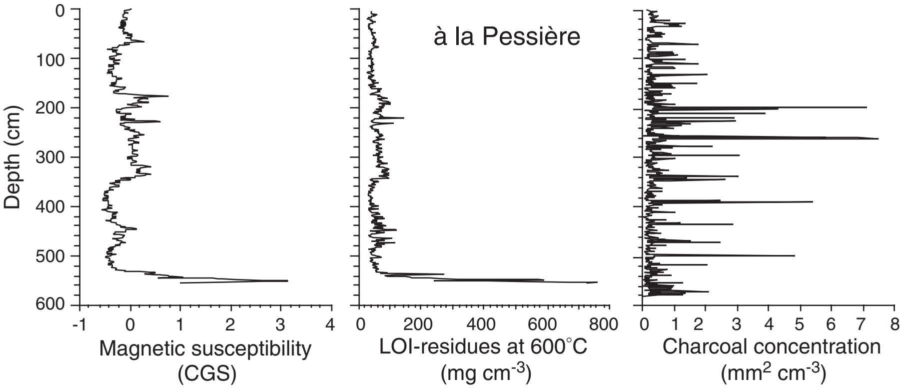

Fig. 4. Magnetic susceptibility series expressed in CGS (G/cm^3 Oe) compared to ignition residues and charcoal series at Lac à la Pessière (boreal zone, West Quebec).

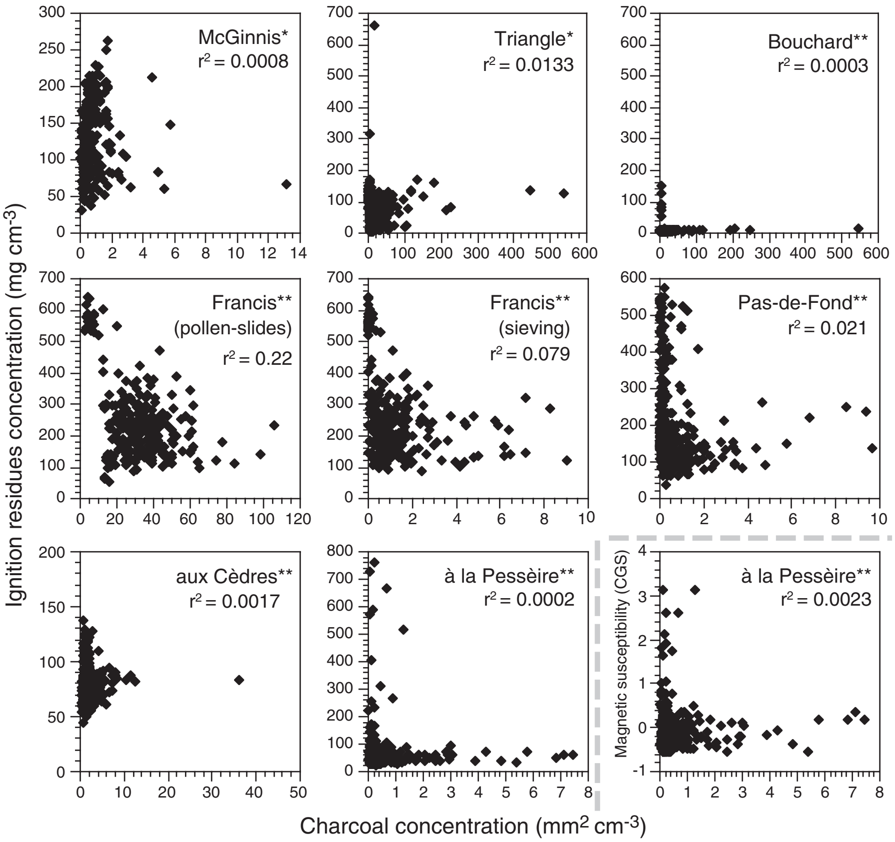

Fig. 5. Erosion proxies (ignition residues and magnetic susceptibility) plotted against fire proxy data measured at the same depth. Residues are deduced from ignition at 1000 °C (*) in the lacustrine sediments with carbonates accumulation during the Postglacial (McGinnis Lake and Lac Triangle), and at 600 °C (**) in the other sediments.

area, but are linked to the amount of mineral particles in the sediment. The qualitative effect of fire on the magnetism of sediment is not supported by the data. Only the accumulation rate of mineral particles, a quantitative process, controls the total magnetic susceptibility.

4.5. High-resolution relationship between charcoal and erosion proxies

Fig. 5 presents the results of erosion proxies (*y* axis), i.e. LOI residues and magnetic susceptibility, plotted against the fire proxy (charcoal concentration, *x* axis) at the same depth. If fire triggers erosion, the charcoal values should exhibit correlation between charcoal concentration and LOI residues. None of these graphs shows a relationship between charcoal concentrations, and LOI residues or magnetic susceptibility, indicating a lack of functional links between fire and inorganic inputs in the lacustrine sediments.

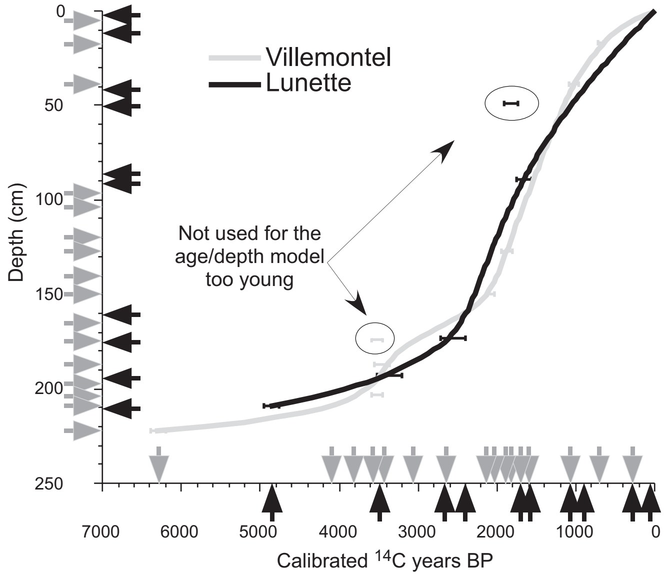

Fig. 6. Age/depth distribution of charcoal layers in two dunes from Abitibi. The gray (Villemontel dune) and the black (Lunette dune) arrows indicate the charcoal layers on the depth axis (*y*) and on the radiocarbon axis (*x*).

4.6. Dunes dynamics and fire history

Fig. 6 displays the distribution of charcoal layers within dunes plotted against the depth (*y*) and the age axes (*x*). At Villemontel, seven of the eight radiocarbon dates are used to establish the age/depth model, and four on the five at Lunette. Two ^{14}C dates are too young according to the other radiocarbon dates obtained beneath: UQ-2117 at Villemontel and UL-1268 at Lunette (Table 3).

The pattern of sand accumulation is illustrated by the smoothed distribution of the ^{14}C dates (age/depth model). The two distributions follow the same pattern, i.e. a low rate of accumulation until 3000 cal. yr BP, then a gentle rise until 2500 cal. yr BP, rapidly followed by a strong rise until the present-day (Fig. 6). The number of observed charcoal layers increase since approximately 2500 cal. yr BP in the two dune profiles. First, the synchronicity between sites and, second, between fire history and the increase of sand accumulation in each site suggest that fire and sand accumulation dynamics are linked at the stand level in dry sites.

5. Discussion

5.1. Fire, LOI residues and magnetic susceptibility: non-linked proxies

The present results obtained in different ecosystems and climates (cold temperate, boreal maritime, boreal) from eastern Canada do not support our working hypothesis

Table 3
Radiocarbon dating of charcoal layers of the Villemontel and the Lunette dunes in Abitibi, West Quebec

Depth (cm)	Lab code	Age (^{14}C yr BP)	Age (cal. yr BP)	Dated material
Villemontel				
17	UQ-2121	785±52	671–792	Wood charcoal
39	UQ-2122	1144±68	931–1183	Wood charcoal
127	UQ-2125	1933±59	1720–1995	Wood charcoal
150	UQ-2126	2125±45	1989–2303	Wood charcoal
175	UQ-2117	3316±85	3362–3722	Wood charcoal
187	UL-1632	3270±100	3318–3723	Wood charcoal
203	UQ-2116	3319±88	3361–3725	Wood charcoal
222	UQ-2113	5525±72	6173–6451	Wood charcoal
Lunette				
49	UL-1268	1870±80	1608–1952	Plant macro-remains
89	UL-1629	1760±100	1506–1891	Wood charcoal
173	UL-1630	2520±70	2361–2749	Wood charcoal
193	UL-1631	3130±79	3157–3550	Wood charcoal
209	UQ-2114	4314±89	4612–5279	Wood charcoal

UQ corresponds to measurements performed at the GEOTOP laboratory (Université du Québec à Montréal) and UL to the Centre d'Études Nordiques laboratory (Université Laval).

that fires trigger erosion in the lake catchment areas. The charcoal concentrations are not correlated to mineral matter concentration and of magnetic susceptibility both on long-term (Figs. 2–4) and at high resolution (Fig. 5).

The present observations do not echo the conclusions of studies carried out in the mountains of the US Cordillera (Millspaugh and Whitlock, 1995) or of the Swiss Alps (Gedye et al., 2000). These studies suggest to secure the detection of past fire events using both changes in magnetic susceptibility and occurrence of charcoal peaks. This hypothesis implicitly suggests that charcoal concentration is linked with fire severity (Clark et al., 1996). The fire severity, which is defined as the depth of burn (in biomass, humus or soil) or the fire size, depends on several factors, e.g. the drought severity, the quality and the quantity of fuel and the landscape connectivity. However, Fig. 5 does not show any link between charcoal concentration and LOI residues concentration or magnetic susceptibility. The charcoal concentration cannot be used together with either LOI residues or magnetic susceptibility to pinpoint the severity of fires. The more or less flat terrain and the thick humus layer in the forests of our study sites might be the explanation of this discrepancy with the conclusion of Millspaugh and Whitlock (1995) and of Gedye et al. (2000).

Based on our records, it seems not possible to use magnetic susceptibility or any other erosion proxies to secure the reconstruction of fire history in lacustrine sediments, because erosion and fire history appear independent processes on long-term perspectives at both low- (Figs. 2–4) and high-resolution (Fig. 5). Our conclusion may certainly result from the lack of significant slopes around the lakes.

5.2. *Fire and aeolian input of clastic particles*

In North America and Fennoscandia, charcoal layers are frequently embedded in tree-covered dunes (Filion, 1984; Käyhkö et al., 1999; Arbogast and Packman, 2004). Their occurrences would result from postglacial fire events triggered by dry climate, followed by periods of fire-made erosion and aeolian activity that accumulate dune material. Holocene aeolian dune activity would thus be linked to fire history (Filion et al., 1991). Our results strongly support this interpretation at the stand to local scale (Fig. 6). However, the lack of rise of inorganic accumulation in lakes regionally closed to the dune of Villemontel and Lunette, i.e. L. à la Pessière, L. Pas-de-Fond and L. Francis, suggests that fire-made aeolian activity does not act on the regional lacustrine sedimentation, but acts on the dune activity in dry sandy areas. Indeed, the fire frequency rises once, significantly, at about 2200–2000 cal yr BP at L. Pas-de-Fond and L. Francis, and in the Villemontel and the Lunette dunes (Figs. 7(B) and (C)), but does not show any changes in LOI residues accumulation corresponding to mineral particles (Fig. 7A), while sand accumulation rises at the same time (after 2500 cal. yr BP) with the same pattern both at Lunette and Villemontel (Fig. 7B). Fire can thus impact the dry areas stimulating the local aeolian dynamics, but this process cannot be extrapolated at the regional scale to explain sedimentary processes such as those occurring in lakes basin.

5.3. *Fire, erosion and soil protection by humus layer*

Our records present strong arguments to defend the hypothesis that processes of inorganic inputs in small lake sediments (i.e. mineral matter from long-distance air transportation or from local soil erosion) are independent of fire activity on a long-term perspective. Indeed, the results have been obtained in seven different lakes with different physiographical contexts—in the coniferous boreal forest (three lakes), in the mixed boreal forest (three) and in the mixed cold temperate forest (one). One lake is located in a hilly plateau (L. Triangle), two in hilly landscape (McGinnis L and Petit L. Bouchard) and three are in an almost totally flat terrain (L. Francis, Pas-de-Fond, à la Pessière).

The low level of inorganic inputs in the sites from the coniferous boreal forest (L. à la Pessière, L. aux Cèdres, L. Triangle) is easy explained by the thick humus of several tens centimeters covered by mosses that provides a good protection against erosion, if the fire severity (i.e. depth of burn) is low. Where the humus layer is thin to moderately thick (L. Pas-de-Fond, L. Francis), the soil appears less-protected, as reported by the higher values of LOI residues that are located in the southern mixed boreal forest. However, McGinnis Lake has the thinnest humus layer, highly susceptible to complete burning during fire, whereas its LOI residues curve exhibits values comparable to those of L. Pas-de-Fond and L. Francis with thicker and wetter humus. This apparent discrepancy is explained by the extremely thin soil surrounding McGinnis Lake. The input of inorganic matter (mineral material) depends both on the soil protection by humus and the soil thickness in the catchment area. Soils covered by thick humus layers are better-protected against soil erosion (e.g. in the coniferous boreal forest), and thin soils do not provide enough material to stimulate the input of mineral material in the lake basin.

A positive result would have important consequences to explain observed vegetation changes during the Holocene (e.g. Liu, 1990; Richard, 1994; Carcaillet et al., 2001a), because fire severity measured as the depth of humus burn has crucial relationships with the recruitment of trees (Johnson, 1992). The best conifer recruitment is observed where mineral soil appears after fire (Greene et al., 2004). Unfortunately, the data presented here do not help to explain the observed vegetation dynamics around these sites in eastern Canada by changes in burn depth or humus removal (Carcaillet et al., 2001a; Asnong and Richard, 2003; Capece, 2003).

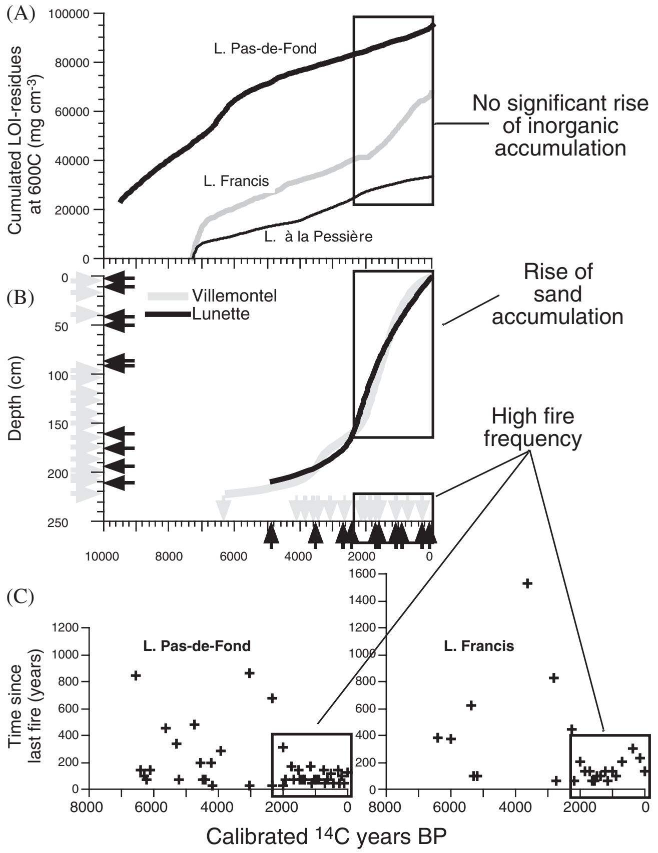

Fig. 7. Regional synthesis of fire frequency and of dynamics of inorganic matter in lakes and dunes (Abitibi, West Quebec). The pattern of inorganic matter concentration in lacustrine sediment (**A**) is independent of the increasing fire frequency that regionally starts ca 2500–2200 cal. yr BP according to sites (**C**), whereas the sand accumulation rises in dune with the increasing fire frequency (**B**). The data show that fire frequency follows the same pattern at the regional scale, but aeolian sand accumulation is a product of stand to local processes (e.g., fire event, geomorphology, soil-type). Sand and other inorganic matter are not airborne on long distance because lakes and dunes inorganic accumulation are independent.

6. Conclusion

No significant relationship has been recorded between proxies of fire and those of soil erosion or aeolian activities in sediments of seven small lakes from boreal and temperate forests in eastern Canada. Fire and erosion/aeolian processes appear independent from each other over long time periods and at the regional scale while, at the stand to local scale, high fire frequency stimulates the aeolian erosion and accumulation in sandy dry areas. This observed lack of relationship is likely due to the fact that humus layer is rarely totally consumed during fire, and thus protects soil against erosion in boreal and temperate forests, except in dune areas where dryness and thin humus layers are removed by burning and enhanced aeolian activity. This conclusion does not rule out that one single fire can provoke erosion because of its extreme severity, if followed by rains; but it cannot be generalized to all fires over the Postglacial.

Acknowledgements

Financial support was provided by the Natural Sciences and Engineering Research Council (NSERC, Canada), program entitled "Networks of Centres of Excellence in Sustainable Forest Management", and by post-doctoral grants from the Ministère de l'Éducation (Québec) and from La Fondation de l'Université du Québec À Montréal (to C.C.). We thank K. Gajewski (U. of Ottawa) for magnetic susceptibility facilities, M. Desponts (Direction de la recherche forestière, Ministère des Ressources naturelles du Québec) for the dune analysis, B. Fréchette (U. de Montréal) for the help at laboratory, Y.T. Prairie (UQAM) for the help during L. aux Cèdres and L. à la Pessière sampling and, J.N. Haas, J. McAndrews (U. of Toronto) and S. Müller (U. de Montréal) for the help during the MacGinnis Lake sampling.

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