Calculating long-term fire frequency at the stand scale from charcoal data

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Abstract. Fire frequency is a statistical metric used to evaluate long-term fire activity at stand and landscape scales. Fire frequency is defined as the number of fires occurring per unit time in a given area. In this study a method to calculate fire frequency at the stand scale is described, based on direct fire evidence of radiocarbon-dated macrocharcoal fragments (>2 mm diameter) at the soil surface and buried in the mineral soil. A jack pine (Pinus banksiana Lamb.) stand was used as a model site to calculate the long-term fire frequency. The number of fires recorded at the soil surface is a function of fire activity and residence time of charcoal, the fewer fires occurring in the site the longer the residence time of charcoal. The residence time of charcoal at the surface of the study site totals 1710 calibrated years (calibrated age in years before 2010). Fourteen fire events occurred over the last 1000 years, i.e., an average fire interval of 75 years, a situation facilitating the long-term maintenance of jack pine. When considering the late Holocene period covered by the dated charcoal in the surface and soil compartments, the average fire interval was 165 years over the last 3565 cal. years. Botanical identification of dated charcoal fragments indicated the arrival of jack pine about 2400 cal. years ago, i.e., the minimum arrival date of the species near its northeasternmost limit in North America. Although longer fire intervals prevailed before the last millennium, jack pine was able to maintain in the site or nearby, given that most fire intervals where shorter than the species maximum lifespan. Self-perpetuation of jack pine illustrates the effectiveness of recurrence dynamics over the last thousand years. It is concluded that detailed analysis of radiocarbon-dated macrocharcoal fragments at the surface and in the soil allows the calculation of the long-term fire frequency and reconstruction of fire history at the stand scale. Given the long residence time of charcoal in fire-prone sites, there is an opportunity to reconstruct local fire histories when focusing only on macrocharcoal fragments at the soil surface.

Key words: black spruce; charcoal; fire frequency; fire history; jack pine; Picea mariana; Pinus banksiana; radiocarbon dating; recurrence dynamics; succession.

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INTRODUCTION

There is a growing interest in fire frequency studies because of the importance of fire in shaping vegetation assemblages at the stand and landscape scales and in driving ecosystem dynamics in close association with environmental and climatic changes (Clark 1988a, 1990, Johnson and Larsen 1991, Johnson 1992, Payette 1992, Swetnam 1993, Arsenault and Sirois 2004). According to Johnson and Gutsell (1994), one of the most difficult aspects of fire frequency studies
has been to understand what frequency really means. Fire frequency is a term commonly used in fire studies, but its meaning varies greatly (Heinselman 1973, 1981, Romme 1980, Romme and Knight 1981, Payette et al. 1989, Johnson and Gutsell 1994, Bergeron et al. 2001). Fire frequency refers to the number of fires occurring per unit time in a given area which may be a single point, a forest stand or a landscape (Romme 1980). Fire frequency and fire area per unit of time are the main fire metrics to evaluate accurately the fire regime at different spatiotemporal scales (Heinselman 1973, 1981, Romme 1980, Johnson 1992, Johnson and Gutsell 1994).

Several methods are used to calculate fire frequency as well as the other attendant metrics like fire rotation (Heinselman 1973) or its equivalent the fire cycle (Van Wagner 1978) in a given area. The most commonly used method consists of recording the number of all dated fires (fire dates obtained from tree-ring counts of fire scars and post-fire trees, archival documents, etc.) occurring in a relatively large area (e.g., >100 km²) over a given period of time (e.g., 50, 100, 200 years or more). The rationale here is based on an approach derived from the space-for-time substitution approach which is extensively used in chronosequence and long-term ecological studies (Pickett 1988). The assumption behind this approach is that fire dates from different sites allow the calculation of fire frequency and fire rotation at the regional scale but for a relatively short period of time, i.e., below the longevity of most forest trees (uncovering the last 100 to 200 hundred years or so), except in areas harbouring long-lived tree species and old-growth forest stands where fire frequency and fire rotation can be extended to several hundred years (Payette et al. 1989, Swetnam 1993, Niklasson and Granström 2000). This approach implies that older fires are progressively reduced in size and even «killed» by the most recent fires, a situation producing a bias in the calculation of local and regional fire frequencies. Caution must be exercised when using this method as a surrogate for long-term fire frequency because present fire frequency (the last 50, 100 or 200 years) based on this approach is not necessarily representative of the historical and recent fire regimes at the site scale and the landscape scale.

Paradoxically the most common and extensively used method to evaluate the long-term recurrence of fire is based on the study of continuous lacustrine sequences (Patterson et al. 1987, Clark 1990, Whitlock and Larsen 2001), i.e., from fire-free environments. Ponds and lakes accumulate with time all-sized charcoal pieces, both microscopic and macroscopic, falling onto the water surface from long- and short-distance transport (Clark 1988, Whitlock and Larsen 2001). Intensive field and laboratory work was done to calibrate lacustrine charcoal sequences with present and recent fire occurrences based on direct fire evidence (fire scars and age of postfire trees) at the watershed scale (Clark 1990, Whitlock et al. 2004, Higuera et al. 2005). Research priorities are given on determining the distance of the source area of charcoal pieces (generally the 125–250 μm fraction; Whitlock and Larsen 2001). Sedimentary charcoal sequences from ponds and lakes are used at the Holocene time scale to evaluate the long-term fire activity both at the watershed and the regional scales.

Fire-prone environments like forest stands growing on mineral soils may be good candidates for the calculation of present and long-term fire frequency at the site scale (e.g., area of 1 ha). 14C dating of a large number of macrocharcoal fragments (>3–5 mg, >2 mm diameter) distributed at the soil surface and buried in the mineral soil matrix, defined here as the terrestrial macrocharcoal approach (TMA), may allow a realistic evaluation of present and long-term fire frequency at the stand scale. The assumptions behind the TMA are the followings: (1) Charcoal is produced by incomplete wood combustion during natural and man-made fires, particularly dry wood which died a few years or several years before the fire (Payette and Lajeunesse 1980, Gavin 2001, Marguerie et al. 2010). (2) In fire-prone ecosystems with fast carbon turnover (decomposition rate) and composed of short-lived tree species, a fire date follows the 14C charcoal date by a few years or tens of years (de Lafontaine and Payette 2011) which is probably less so in the pluvial forests of western USA and Canada according to Gavin (2001). (3) Charcoal produced by a given fire may be buried during or immediately after the fire event or several decades or hundred years after the passage of another fire or another soil disturbance event. (4)
Surficial charcoal lays at the soil surface since its inception by a given fire, whereas charcoal located in mineral soil was buried by tree fall and uprooting during periods of blowdown due to wind velocity and also mass tree mortality caused by fire and other primary disturbances affecting soil stability (Filion 1984a, Thinhon 1992, Carcailllet 2001, Talon et al. 2005). In forest environments, charcoal buried in mineral soil is not stratified because of uprooting processes producing mixed soil horizons up to 1 m deep (Lutz 1940, Brown and Martel 1981, Bormann et al. 1995). Only ombrotrophic peatlands, superposed eolian paleosols in sand dunes, lakes and other similar geomorphic environments, as well as archeological deposits, produce stratified, sequential macrocharcoal horizons or layers (Filion, 1984a, b, Wein et al. 1986, Vernet and Thiébault 1987, Desponts and Payette 1993, Kahry 1994, Figueiral and Mosbrugger 2000, Elliott and Parker 2001, Whitlock and Larsen 2001, Magnan et al. 2012). (5) The residence time of charcoal at the soil surface is a function of the number and intensity of fire occurrences through time. (6) Charcoal already buried into the soil can also be surfaced during another soil disturbance event. (7) In sites of high fire occurrences, for example in jack pine (Pinus banksiana Lamb.) stands, the residence time of charcoal at the soil surface should be relatively short given that charcoal produced by ancient fires is at risk to burn several times and, hence, to degrade into ashes in contrast to charcoal produced in sites less prone to fire recurrence like in humid forests of western USA and Canada (Gavin 2001). (8) Charcoal buried in the mineral soil should have a very long residence time compared to surficial charcoal, because it is protected from the influence of recurrent fires and all the other ecological events occurring at the soil-air interface. Theoretically, charcoal preserved in the soil matrix may yield most if not all the spectrum of fire events that occurred at the site since initial forest establishment after deglaciation or post-glacial marine transgression in glaciated areas and also unglaciated areas. (9) Macroscopic charcoal with unaltered anatomical traits can be identified botanically, thus allowing insights into the past dominance of specific tree species and forest types (Filion, 1984a, b, Desponts and Payette 1993, Heinz and Thiébault 1998, Carcailllet and Talon 1996, Talon et al. 2005, de Lafontaine and Payette 2011, 2012).

Given the above assumptions, TMA could be used to evaluate the long-term frequency of fire events at the local scale, for example, forest stands covering 1 ha. The main objectives of this study are (1) to calculate current (using fire scars, tree-ring dated post-fire trees) and long-term fire frequency (using macrocharcoal fragments at the soil surface and buried into the soil) at the stand scale, (2) to evaluate the residence time of charcoal at the soil surface in fire-prone ecosystems like jack pine stands, (3) to determine the date of arrival of jack pine at the site and (4) to examine the successional processes behind the maintenance and survival of this species at the site since its initial establishment. To do so, we have used jack pine as a model of one of the few forest tree species in North America fully adapted to recurrent fires, in a particular site that is located near the northeasternmost limit of the species in North America.

**METHODS**

**Study site**

The study jack pine stand (hereafter «Moisie site») is growing on well-drained, deltaic sands of the Moisie river (50°14’55” N, 66°05’78” W, at an elevation of 50 m above sea level), about 10 km east of the Sept-Îles airport, in the Québec North Shore area (Fig. 1). The Sept-Îles climate corresponds to cold, humid, subarctic conditions prevailing throughout the year (Environment Canada 2012). Mean annual temperature for the 1971–2000 period was 0.8°C, with January as the coldest month (−15.3°C) and July as the warmest month (15.3°C). Annual precipitation during the same period of record totalled 1156 mm, including 412 cm of snow. The Moisie site is a 94-year-old postfire stand (relative to the year 2010) regenerating from a 1916 fire (fire-scar date). The scar-bearing pine was 144 years old, and established in 1866 likely after a mid-19th century fire. Mean height of pine trees varies between 8.5 and 12 m.

The pine stand was delineated by a 500-m² plot (10 m × 50 m) where the frequency distribution of stem diameter (2-cm classes) of all tree species was calculated (Fig. 2). The stand is dominated by jack pine, and accompanied by
black spruce (*Picea mariana* (Mill.) B.S.P.) and balsam fir (*Abies balsamea* (L.) Mill.); white birch (*Betula papyrifera* (Marsh.)) was present in small numbers but outside the plot. Jack pine and black spruce regenerated readily after fire, whereas balsam fir established several years later. Current post-fire regeneration occurs only in black spruce and balsam fir whereas jack pine has no viable regeneration (except 2–3 deformed saplings). The plant cover of all species recorded within the plot (Table 1) was determined based on Braun-Blanquet’s cover classes (+ = <1%; 1 = 1–10%; 2 = 10–25%; 3 = 25–50%; 4 = 50–75%; 5 = 75–100%, from Mueller-Dombois and Ellenberg 1974), and shows that the ground layer is composed predominantly of fire-adapted ericaceous species (*Kalmia angustifolia*, *Rhododendron groenlandicum*, *Vaccinium angustifolium* and *Arctostaphylos uva-
ursi) and lichen species (Cladonia stellaris and Cladonia rangiferina).

The jack pine stand is growing on acidic (pH: 4.15 at the mineral soil interface), well-drained sands (90% sand) developing a podzolic profile classified as eluviated dystric brunisol (0.32% of C, 0.24% of (Fe + Al)pyro and ratio of 4.7 of organic C/Fe pyro in the B horizon), all soil analyses as in CSSC (1998).

Charcoal sampling and dating
Charcoal fragments were sampled systematically on 25 points distributed over the 500-m² plot (Fig. 3). At each point located every 5 m along the two 50-m lines delineating the plot and at the middle of the plot, 3–4 charcoal pieces laying at the soil surface were recovered for botanical identification and radiocarbon dating. A 10-cm long mineral soil core (750 cm³) was also extracted with a soil auger sampled at each point after removing completely the organic layer, for a total of 25 cores. At the laboratory, the mineral deposit of each core was immersed for 12 hours in a solution of sodium hydroxide (NaOH 1%) to disperse soil aggregates. The mineral material was then washed with water in sieves with mesh sizes of 2 mm and 4 mm. Only charcoal fragments ≥2 mm were considered in sampling, botanical identification and dating, given the evidence that charcoal fragments ≥0.5 mm are of local origin (Ohlson and Tryterud 2000). Charcoal was extracted from the mineral fraction by flotation and manual sorting under a binocular microscope. Charcoal particles were dried at room temperature, weighed, and particles >3 mg were identified to the genus level based on wood anatomy under an optical microscope. Botanical identification of charcoal was based on a charred wood reference collection at the Centre d’Études Nordiques (Université Laval, Québec) and botanical keys (Panshin and de Zeeuw 1980, Marguerie et al. 2000). A total of 52 charcoal fragments were radiocarbon dated by the AMS (Accelerator Mass Spectrometry) technique, 25 from the soil surface and 27 from the mineral soil. Selection of charcoal fragments to be dated was based on dry weight of the particles (>3 mg), botanical identification, and spatial distribution of the 25 sampling microsites. Radiocarbon dating was performed at the Centre d’Études Nordiques (Universite Laval, Quebec, Canada) and Keck Carbon Cycle AMS Facility (University of California, Irvine, CA, USA) laboratories. The radiocarbon dates were calibrated (Stuiver and Reimer 1993) using calibration dataset IntCal09.14c (Reimer et al. 2009) implemented in the CALIB (version 6.0.1) software.

The date of each fire event and the calculation of the long-term fire frequency, i.e., the construction of fire chronology at the stand scale, were based on the comparative analysis of all calibrated charcoal dates according to the following procedure:

The determination of the calibrated age of each radiocarbon date was based on the weighted average of the highest probability distribution within the 2-sigma ranges of the starting and ending calendar dates. Because of the large excursions of atmospheric ¹⁴C through time, probability distributions within the 2-sigma ranges vary greatly in particular during recent periods of maximum and minimum variations of solar activity (Solanski et al. 2004), resulting in the partitioning of the probability distribution over time for a given date. In this study we always selected the highest probability distribution of each calibrated ¹⁴C date. However, when a particular calibrated date included two relatively high probability distributions, both distributions were incorporated in two separate fire-

| Plant class | Species | Abundance |
|-------------|---------|-----------|
| Trees       | Pinus banksiana | 4 |
|             | Picea mariana | 2 |
|             | Abies balsamea | + |
| Shrubs      | Kalonia angustifolia | 3 |
|             | Rhododendron | 2 |
|             | groenlandicum | |
|             | Vaccinium angustifolium | 2 |
|             | Chiogenes hispidula | 2 |
|             | Alnus viridis var. crispa | 1 |
|             | Salix humilis | 1 |
|             | Arctostaphylos uva-ursi | 1 |
|             | Vaccinium vitis-idaea | 1 |
|             | Epigaea repens | 1 |
|             | Juniperus communis | 1 |
|             | var. depressa | |
| Herbs       | Cornus canadensis | 2 |
| Mosses and hornworts | Pleurozium schreberi | 3 |
|             | Ptilidium ciliare | + |
| Lichens     | Dicranum undulatum | + |
|             | Cladonia stellaris | 3 |
|             | Cladonia rangiferina | 2 |
|             | Cladonia mitis | + |
event scenarios of the long-term fire frequency. Because no significant differences existed between the two scenarios, we have used the first scenario with the highest probability distribution. Given that a $^{14}$C age refers to radiocarbon years before present (BP), i.e., AD 1950, 60 years were added to each calibrated date in order to reflect present time, i.e., 2010. Thus, in this study, all fire dates are reported as years before AD 2010.

It was assumed that the fire-event date exceeded by a relatively small number of years (<15–25 years) the calibrated date of the wood that produced the dated charcoal. An examination of the very narrow rings forming most charcoal fragments in our samples suggests that they were coming from burned branches and twigs, an indication that the wood material was probably dead and dry. During a forest fire, jack pine produces more charcoal fragments than black spruce, and dead branches along the living stems are burned readily (Bégin and Marguerie 2002). According to Stocks (1987, 1989), the fuel consumed during a jack pine crown fire is predominantly composed of fine material made of litter, foliage and small branches and twigs. Furthermore, given that jack pine stands are recurrently impacted by fire at relatively short time intervals (Desponts and Payette 1992, Le Goff and Sirois 2004), it is likely that a rather small number of years separate the date of wood and the date of the fire which produced the charcoal. The determination of the exact number of years separating the date of the wood fragment and the fire proper remains complex, and there is presently no satisfactory method to solve the so-called inbuilt age (Gavin 2001) problem. Given the current state of the art in the interpretation of charcoal dates, an extended knowledge and experience on the structure and dynamics of forests stands are keys to evaluate realistically the discrepancy between the age of the wood and the age of the fire event.

It must be acknowledged that the uncertainties inherent to radiocarbon dating of recent or modern samples limit our capacity to evaluate accurately the age difference between the age of the charcoal-bearing wood and the age of the fire proper. However, the collection of several radiocarbon dates having the same age, for example in young charcoal samples, is probably an indication of the close proximity existing between the age of the wood producing the charcoal and the age of the fire. In this study, all the radiocarbon-dated charcoal fragments ($n = 8$ $^{14}$C dates) originating from the most recent fire (1916, i.e.,
94 years) have a cal. age ranging from 111 to 118 years, i.e., an age difference of 17–24 years between the age of the wood that produced the charcoal and the age of the fire proper. This situation should be expected frequently at the soil surface where charcoal produced by the most recent fires are more abundant than charcoal of much older fires. Similar differences (7–17 years) exists between the age of the wood and the age of the fire proper for the previous fire that occurred in the mid-19th century (i.e., 144 years old jack pine established immediately or a few years after the fire and cal. age ranging from 152 to 161 years). As a result, the determination of the age of a fire event in a jack pine site like the Moisie site was based on a maximum difference of 30–40 years between calibrated radiocarbon charcoal samples. Furthermore, it is not possible to assign to a particular fire event a charcoal date having a difference of 20–25 years with two adjacent charcoal dates separated by 40–45 years. This charcoal fragment has 50% chance to belong to each fire event.

In order to test the value and representativeness of the data set, an accumulation curve of all the 14C dates was constructed to evaluate the expected maximum number of fire events to have occurred in the study site. The rationale behind the construction of the accumulation curve is that is allows one to estimate the actual number of fire events at the site and to see if there are fire events missed by the sampling depth. In its simplest form one can say that the actual number of fire events at the site is a finite number in comparison to the number of fire events deduced by the number of 14C dates currently available in a given site. Although we have used a large set of 14C dates the accumulation curve remains an extrapolation device to evaluate the completeness of the fire record at the stand scale, and it does not indicate by all means the actual number of fire events having characterized the complete fire history of the site. The accumulation curves were constructed as follow: the number of recorded fire events \([F(n)]\) was plotted as a function of the number of 14C-dated charcoal fragments \((n)\), and an expected number of fire events \((F_{\text{max}})\) was then extrapolated by fitting an asymptotic, negative exponential function

\[
F(n) = F_{\text{max}} (1 - e^{Kn})
\]

where \(F_{\text{max}}\) is the asymptote, i.e., the expected number of fire events, and \(K\) is a fitted constant controlling the shape of the accumulation curve (de Lafontaine and Payette 2011). The parameters of the equation were calculated based on a curve fitting website (http://zunzun.com). When plotting the data with the negative exponential model one may interpret the trend taken by the cumulative distribution of all radiocarbon-dated fire events: a linear trend may indicate that a certain number of fire events still remain to be inventoried whereas a trend approaching or running on the asymptote may suggest that most fire events having impacted the site were indeed inventoried. The accumulation curve remains a useful tool to better record, in a conservative but objective manner, the fire history of the study site.

Based on all the fire events identified, a long-term fire-frequency history was constructed for the Moisie site. All the calibrated radiocarbon dates were pooled in a cumulative probability analysis using the sum-probabilities option in CALIB 6.0.1 to plot the probability that a given event occurred at a particular time in order to visualize the fire chronology on the Holocene time scale (Meyer et al. 1992, Lafortune et al. 2006). This method sums the probabilities of all dates and therefore takes into account the uncertainties inherent to radiocarbon dating.

Because of the intrinsic nature of forest stands plagued by continuous disturbance events, the distribution of charcoal in the surface compartment and in the soil compartment is not stratified as it is for sedimentary environments of dunes, peatlands and lakes (Filion 1984b, Kuhry 1994, Whitlock and Larsen 2001). It is thus necessary to obtain the greatest number of charcoal fragments possible in order to track most of the fire events that occurred at the site; in some cases this implies a very large number of dates like in fire-prone sites (this study), and a small number of dates in less fire-prone sites like balsam fir stands growing in humid areas (Couillard 2011, de Lafontaine and Payette 2011). The approximate number of fire events occurring at a site since initial forest establishment should be obtained with the radiocarbon dating of all charcoal fragments present at the site, given that a certain number of fire events was lost from the record because of repeated burning as well as in the case
of light fires which produce small amounts of charcoal. It is currently not possible to date all the charcoal fragments due to the high costs of AMS dating.

RESULTS

Charcoal data

A total of 162 charcoal fragments >2 mm were recovered in the plot, i.e., 49 fragments at the soil surface and 113 fragments buried into the mineral soil (Table 2). Charcoal fragments at the soil surface were heavier (20 ± 26.5 mg) and significantly different (Z test, \( p < 0.01 \)) than those buried into the soil matrix (9.5 ± 8.6 mg). Sixty-eight charcoal fragments (42%) were identified to the genus level. Pine charcoal (40.8 ± 41.8 mg) was heavier (Z test, \( p < 0.01 \)) than spruce charcoal (10.9 ± 7.0 mg) in the surface compartment whereas it was the reverse (spruce = 14.3 ± 15.6 mg, pine = 9.3 ± 7.2 mg) in the soil compartment. Sixty-two out of the 162 charcoal fragments belong to tree species (42% of the charcoal population, including 21% spruce, 19% pine, 1.2% birch and 0.6% larch) whereas the remaining material is made of ericaceous and other shrub wood fragments, with the exception of the non-identified charcoal fragments (29% of the charcoal population, with a large proportion of unidentified tree species). Fifty-two out of the 68 identified charcoal fragments were radiocarbon-dated (i.e., 32% of the whole charcoal population; 49 fragments identified and 3 fragments unidentified); when extracting deciduous wood (mostly ericaceous wood) of the record, it is 45% of all charcoal pieces that were dated (Table 3). They were selected according to their relative abundance, representativeness and location within the quadrat. Most \(^{14}C\) dates are coming from conifer species, i.e., jack pine and black spruce.

Long-term fire frequency of the Moisie site

About the same number of pine and spruce charcoal fragments were dated in the surface and the soil compartments, i.e., 11 pine and 14 spruce fragments at the soil surface and 14 pine and 10 spruce fragments in the soil matrix. Three unidentified glazed samples of the soil compartment were dated and they were among the oldest charcoal fragments dated, i.e., 2810, 2468 and 3565 cal. years. Spruce and jack pine are present at the site at least since 1880 and 2400 cal. years, respectively.

Based on the accumulation curve of the 52 charcoal dates, a minimum of 22 fire events occurred during the last 3565 cal. years of fire history (Fig. 4). The overall trend of the accumulation curve is approaching the asymptote. The partitioning of the charcoal dates in the two compartments gives a more qualified picture relative to the fire-event record. The distribution of the 25 charcoal dates of the surface compartment tends toward an asymptote which suggests that the number of fire events recorded is near the actual number of fires having passed in the site during the residence time period of surficial charcoal. The linear trend identified in the soil compartment suggests the number of fire events having impacted the Moisie site to be probably greater than the data set indicates. A maximum of 11 and 19 different fire events were depicted in the surface and the soil compartments, respectively. Interestingly, 8 out of the 11 fire events recorded in the surface compartment were also recorded in the soil compartment. The 3 «missing» fires of the soil compartment refer to fires that occurred ca. 228, 260 and 895 cal. years ago. The oldest fire event inventoried in the surface compartment (which was also recorded in the soil compartment) was about 1710 cal. years of age, a figure corresponding to the minimum residence time of charcoal at the soil surface. As expected the residence time of charcoal in the soil compartment is greater (two times greater in this study), i.e., about 3565 cal. years.

Because of differential charcoal survival, the surface compartment yielded a shorter (less than 1710 years), more recent (predominantly the last 1000 years) but more complete record of the last 1000 years of the site fire history. The data set from the soil compartment extends significantly the fire record to a large part of the late Holocene period and it is complementary to the data set of the surface compartment. Indeed, 5 different fire events recorded in the soil compartment over the last 1710 cal. years were not depicted in the surface compartment, i.e., ca. 570, 600, 975, 1020 and 1520 cal. years ago. According to the fire record of both compartments, 14 different fire events occurred in the jack pine site over the last millennium (from ca. 1020 cal. years to present),
which corresponds to a long-term mean fire interval of 70–75 years. However, the finer distribution of all the fire events during this period suggests a fire interval of 65 and 50 years during the last 250–260 cal. years and the first half of the last millennium, respectively. Accordingly a fire-free episode of 235–250 years affected the Moisie site from the middle of the last millennium to about 250 years ago. When considering the late Holocene period of fire activity covered by both compartments, the average long-term fire interval of the jack pine site was 160–165 years. This figure is not representative of the fire situation that prevailed during the period 1020–3565 years ago when only 9 fire events were recorded, and corresponding to a mean fire interval of 280–285 years. The fire data of the soil compartment is probably incomplete, making the calculated fire interval longer that the actual number of fires would give if all the supposed missing fires were recorded in a more detailed charcoal dating program.

**DISCUSSION**

The first objective of this study was to calculate the long-term fire frequency at the stand scale based on macrocharcoal evidence, using a jack pine site as a model. The mean fire interval is a major metric of the fire regime that was applied here at the scale of a forest stand covering less than 1 ha. The large data set used at the Moisie site was necessary to overcome the problem of non-stratified environments where frequent windthrows and other geomorphic events are disturbing the original soil sequence. Jack pine is a well adapted tree species to post-fire regeneration because of its serotinous cones enclosing a large quantity of seeds that are released after an intense fire (Cayford and McRae 1983, Gauthier et al. 1993a). It is generally agreed that jack pine cannot reproduce in the absence of fire, and a high frequency of fires is necessary for long-term self-perpetuation (Day and Woods 1977, Heinselman 1981, Carroll and Bliss 1982, Desponts and Payette 1992, Gauthier et al. 1993b). The calculated mean fire interval at the study site during the late Holocene (since 3565 cal. years) was rather short (ca. 165 years). The reconstructed fire record of the last millennium indicated an average fire interval <75 years in line with current fire frequencies across the geographical range of jack pine (Heinselman 1973, Rowe et al. 1974, Carroll and Bliss 1982, Desponts and Payette 1992, Gauthier et al. 1993b). It is probable that the number of fires having affected the Moisie site is greater than our fire record indicates.

The second objective of our study was to evaluate the residence time of charcoal at the soil surface. Of the 25 charcoal dates, only one was older than 1000 cal. years, i.e., ca. 1700 cal. years. A large hiatus separates both dates, but one fire event was recorded in the mineral compartment at 1520 cal. years, and it is not known if other fires occurred during the period of 500 years between 1520 and 1020 cal. years. The rather long residence time of surficial charcoal in the Moisie site is a neat indication that reconstruction of fire history over several thousand years is possible when using surficial charcoal. A closer examination of charcoal distribution at the soil surface

Table 2. Number and weight (mg) of botanically-identified and unidentified charcoal fragments in the surficial compartment and the soil compartment of the jack pine stand.

| Metric                              | **Picea sp.** | **Pinus banksiana** | **Larix laricina** | **Betula sp.** | **Unidentified deciduous species** | **Unidentified** | **Total** |
|-------------------------------------|---------------|---------------------|--------------------|----------------|-----------------------------------|-----------------|-----------|
| Mineral soil charcoal fragments     |               |                     |                    |                |                                   |                 |           |
| **N**                               | 19            | 16                  | 1                  | 2              | 35                                | 40              | 113       |
| **Average weight (mg)**             | 14.3          | 9.3                 | 41.5               | 7.6            | 7.6                               | 8.1             | 9.5       |
| **SD**                              | 15.6          | 7.2                 | 3.8                | 3.5            | 4.6                               | 8.6             |           |
| **%**                               | 16.8          | 14.2                | 0.9                | 1.8            | 31                                | 35.4            | 100       |
| Surface charcoal fragments          |               |                     |                    |                |                                   |                 |           |
| **N**                               | 15            | 15                  |                    | 12             | 7                                 | 49              |           |
| **Average weight (mg)**             | 10.9          | 40.8                |                    | 8.2            | 6.7                               | 20.0            |           |
| **SD**                              | 7.0           | 41.8                |                    | 7.9            | 6.1                               | 26.5            |           |
| **%**                               | 30.6          | 30.6                |                    | 24.3           | 14.3                              | 100             |           |
Table 3. $^{14}$C dates (year BP) and calibrated $^{14}$C dates (cal. yr BP) of macrocharcoal in the surface compartment and in the mineral soil compartment. Probability distribution (Prob.) and calibrated age of fire events (calculated from the year 1950 + 60 years) based on 2 scenarios of occurrence of fire events. Numbers in estimated fire event column refer to Fig. 4A.

| Laboratory number (UCIAMS) | Botanical charcoal identification | 2-sigmas interval (yr BP) | Scenario 1 | Scenario 2 |
|-----------------------------|--------------------------------|---------------------------|------------|------------|
| Surface                     |                                |                           | Calibrated age of fire† | Estimated fire event |
| 8001                         | Pinus banksiana Modern         | Modern                    | 1950–1970   | 1950–1970  |
| 8009                         | Picea sp.                      | 45 ± 15                   | 41–60      | 0.67       | 111        | 1|
| 8010                         | Pinus banksiana Modern         | 20 ± 20                   | 20–22      | 0.76       | 111        | 1|
| 8007                        | Picea sp.                      | 75 ± 15                   | 73–77      | 0.58       | 113        | 1|
| 78266                       | Pinus banksiana Modern         | 80 ± 20                   | 78–82      | 0.65       | 118        | 1|
| 78264                       | Pinus banksiana Modern         | 90 ± 15                   | 88–92      | 0.44       | 113        | 1|
| 78265                       | Picea sp.                      | 135 ± 15                  | 133–137    | 0.31       | 152        | 2|
| 78279                       | Picea sp.                      | 120 ± 15                  | 118–122    | 0.60       | 158        | 2|
| 78269                       | Picea sp.                      | 205 ± 20                  | 203–207    | 0.49       | 228        | 4|
| 80873                       | Pinus banksiana Modern         | 15 ± 15                   | 13–17      | 0.31       | 152        | 2|
| 78261                       | Pinus banksiana Modern         | 155 ± 15                  | 153–157    | 0.49       | 254        | 4|
| 78264                       | Pinus banksiana Modern         | 145 ± 20                  | 143–149    | 0.33       | 260        | 4|
| 78084                       | Pinus banksiana Modern         | 375 ± 15                  | 373–379    | 0.76       | 526        | 5|
| 78094                       | Picea sp.                      | 680 ± 15                  | 678–682    | 0.78       | 720        | 8|
| 78095                       | Pinus banksiana Modern         | 750 ± 15                  | 748–752    | 0.99       | 743        | 9|
| 78262                       | Picea sp.                      | 850 ± 15                  | 848–852    | 1.00       | 819        | 10|
| 90877                       | Pinus banksiana Modern         | 960 ± 20                  | 958–964    | 1.00       | 895        | 11|
| 80012                       | Picea sp.                      | 900 ± 15                  | 898–902    | 0.50       | 939        | 12|
| 78085                       | Pinus banksiana Modern         | 900 ± 15                  | 898–902    | 0.50       | 939        | 12|
| 78267                       | Picea sp.                      | 1730 ± 15                 | 1728–1732  | 0.94       | 1706       | 16|
| Mineral soil                |                                |                           | Calibrated age of fire† | Estimated fire event |
| 81184                       | Pinus banksiana Modern         | Modern                    | 1950–1970   | 1950–1970  |
| 81182                       | Picea sp.                      | 20 ± 15                   | 19–21      | 1.00       | 111        | 1|
| 81171                       | Picea sp.                      | 135 ± 15                  | 133–137    | 0.31       | 152        | 2|
| 80021                       | Pinus banksiana Modern         | 405 ± 15                  | 403–407    | 1.00       | 545        | 6|
| 81173                       | Pinus banksiana Modern         | 455 ± 15                  | 453–457    | 1.00       | 571        | 6|
| 81186                       | Picea sp.                      | 545 ± 20                  | 543–549    | 0.75       | 600        | 7|
| 81185                       | Picea sp.                      | 550 ± 15                  | 548–552    | 0.74       | 602        | 7|
| 81181                       | Pinus banksiana Modern         | 670 ± 15                  | 668–674    | 0.62       | 718        | 8|
| 90876                       | Pinus banksiana Modern         | 760 ± 20                  | 758–764    | 1.00       | 759        | 9|
| 90877                       | Pinus banksiana Modern         | 765 ± 20                  | 763–769    | 1.00       | 759        | 9|
| 81171                       | Picea sp.                      | 780 ± 15                  | 778–784    | 1.00       | 767        | 9|
| 90880                       | Pinus banksiana Modern         | 800 ± 20                  | 798–802    | 1.00       | 769        | 9|
| 80023                       | Picea sp.                      | 810 ± 15                  | 808–814    | 1.00       | 773        | 9|
| 80022                       | Picea sp.                      | 860 ± 20                  | 858–864    | 0.97       | 821        | 10|
| 81707                       | Picea sp.                      | 905 ± 15                  | 903–909    | 0.57       | 936        | 12|
| 81178                       | Pinus banksiana Modern         | 980 ± 20                  | 978–984    | 0.58       | 977        | 13|
| 81715                       | Picea sp.                      | 1065 ± 15                 | 1063–1069  | 0.89       | 1018       | 14|
| 83490                       | Pinus banksiana Modern         | 1555 ± 20                 | 1553–1559  | 1.00       | 1518       | 15|
| 81706                       | Pinus banksiana Modern         | 1745 ± 20                 | 1743–1749  | 0.98       | 1716       | 16|
| 81183                       | Picea sp.                      | 1765 ± 20                 | 1763–1769  | 1.00       | 1731       | 16|
| 81172                       | Picea sp.                      | 1875 ± 15                 | 1873–1879  | 0.92       | 1882       | 17|
| 83489                       | Pinus banksiana Modern         | 1990 ± 20                 | 1988–1994  | 1.00       | 2002       | 18|
| 81714                       | Picea sp.                      | 2310 ± 20                 | 2308–2314  | 1.00       | 2395       | 19|
| 83491                       | Unidentified                   | 2390 ± 20                 | 2388–2394  | 1.00       | 2468       | 20|
| 81708                       | Unidentified                   | 2620 ± 15                 | 2618–2624  | 1.00       | 2810       | 21|
| 81176                       | Unidentified                   | 3275 ± 20                 | 3273–3279  | 1.00       | 3565       | 22|

† Years before 2010.
would help to extend significantly the fire chronology provided a greater number of charcoal dates.

The third objective of our study was to determine when jack pine arrived at the site during the Holocene. This objective has not been fulfilled satisfactorily because of several factors, in particular the glazed charcoal fragments which yielded the oldest radiocarbon dates but without knowing if they were indeed pine fragments. The presence of jack pine 2400 cal. years ago corresponds to the minimum date of arrival of the species in this coastal area. Late Wisconsin ice appears to have extended south of the present coastal line to about the 300 m bathymetric contour (Dredge 1983) and to the south coast of the western part of Anticosti Island (Painchaud et al. 1984). Deglaciation occurred about 11,800 cal. years ago (10,200 yr BP) according to a marine-shell date east of Sept-Îles (Dubois 1977). The immediate vicinity of the Sept-Îles area was the last part of the Québec North Shore to become ice free about 10,600 cal. years ago (9400 yr BP) (Dubois 1977, Dubois and
the area north of Sept-Îles 4300 cal. years ago (King 1986). Jack pine pollen (5–10% pollen) arrived in the area north of Sept-Îles 4300 cal. years ago (3900 yr BP) at Pine Lake (51°08' N, 69°16' W) and 2200 cal. years ago (2200 yr BP) at Gras Lake (52°15' N, 67°04' W). Pine pollen remained relatively low in the region, and jack pine populations were probably small at these sites (King 1986). Open and dry sites favourable for germination of jack pine seeds are few in the area because of frequent and extensive peatlands. Although jack pine is present in the Sept-Îles area today, neither the pollen stratigraphy at Petel Lake nor the pollen stratigraphy at LD Lake, several tens of km from the Moisie site, record its arrival there (Mott 1976). Future research using high-resolution pollen analysis could provide more information about the arrival of jack pine in the area, as recent work in the James Bay area (northern Québec) shows of an earlier arrival of the species based on macrofossil evidence despite a 1% pine pollen recorded in Holocene eolian sediments (Lacroix et al. 2011). Given the lack of data on the potential absence/presence of jack pine before 2400 cal. BP, it is not possible to evaluate satisfactorily the successional dynamics of the species during the complete Holocene period of the Moisie site.

The fourth objective of our study was to examine the successional processes behind the maintenance and survival of jack pine at the site since its initial establishment, at least over the last 2400 cal. years. According to the temporal distribution of jack pine and black spruce, the tree species that are currently dominating the Moisie site, they both regenerated repeatedly during this long period in close association with recurrent fires. The last millennium has been a period of high fire recurrence, with a mean fire interval of less than 80 years on average, favourable for the self-perpetuation of jack pine stands. The predominance of short fire intervals in well-drained sites, like the study site situated on the dry sandy terrace of the Moisie river, suggests that a strong control is exerted by topography and drainage conditions on fire ignition and spread (Arseneault 2001) despite the fact that the Sept-Îles climate is dominated by cold and humid conditions. On the other hand, the long fire free interval of 235–250 years at the middle of the last millennium possibly contributed to reduce the abundance of the species, even causing its local extinction. Black spruce may overgrow jack pine 100–150 years after fire, but mixed stands also can self-perpetuate during long periods, particularly on exposed, open sites. After more than 130–150 years most jack pine trees are dying or become senescent. Desponts and Payette (1992) observed open mixed stands of black spruce and jack pine that have self-perpetuated for more than 200 years. Post-fire stand simulations suggest the extinction of jack pine when fire intervals are longer than 220 years (Le Goff and Sirois 2004). The results of the simulations emphasize the adaptation of jack pine to a regime of short to moderately long fire frequencies. However, Heinselman (1973), Desponts and Payette (unpublished data) and D. Arseneault (pers. comm.) reported the occurrence of scattered jack pines 245 to 275 years old on dry soils. Old jack pine trees are currently growing in open stands associated with exposed sandy substrates which are favourable for its maintenance because the species has almost continually reproduced from seeds disseminated from non-serotinous cones (Gauthier et al. 1993a, b). This type of reproduction is opportunistic and helps the species to survive long quiescent periods. There is also the possibility for jack pine to survive at low densities and then to resume dominance in the following post-fire stands (Sirois 1993, Lavoie and Sirois 1998) because of higher rates of seed germination and seedling survival than any other tree species on blackened seedbeds (Sirois, 1993, Thomas and Wein 1985). It is also known that jack pine is an opportunistic species able to invade poorly drained sites like peatlands during dry, fire-prone periods (Pellerin and Lavoie 2003). The long-term maintenance and self-perpetuation of jack pine in the Moisie site is a direct illustration of an effective ecosystem process of recurrence dynamics over
a period of several thousand years where classical successional trajectories (Huston 1994) changing the vegetation assemblage were not operative.

**Conclusion**

The detailed analysis of macrocharcoal (>2 mm) at the soil surface and buried into the mineral soil of a jack pine site has been used as a model to calculate the long-term frequency of fire at the local scale. The Moisie site is a typical forest environment developed on well-drained substrate and continuously affected by disturbance processes such that standard stratigraphical analysis is not possible. In order to reconstruct the fire history and the attendant fire metrics, a large number of macrocharcoal fragments must be analyzed and processed. In this study, several botanically identified charcoal pieces were dated and ordered chronologically in an in situ chronosequence of 3565 cal. years where mixed jack pine and black spruce stands self-perpetuated. The fire frequency over the last millennium was on average less than 80 years, a common and basic ecological trait facilitating the long-term maintenance and growth of jack pine populations. The terrestrial macrocharcoal approach (TMA) used in this study documented the pattern and tempo of tree populations influenced by fire over the late-Holocene period. Thanks to the TMA, it has been possible to show that succession as a directional process of vegetation change through time has not been the main driver of the ecological dynamics of the jack pine site. On the contrary, repetitive fires during the late-Holocene period were responsible for the prevalence of a recurrence-dynamics process where the same tree species self-perpetuated through time without any substantial ecosystem changes. TMA may be applied to forest environments with low fire frequencies or fire intervals longer than the time resolution given by the AMS method of 14C dating. Further refinements of TMA also may include charcoal sampling from deeper soil horizons located beneath the mineral cores currently recovered at the soil surface. Given that TMA at the stand scale can be applied to a variety of ecological situations, a comparative study between riparian well-drained sites and small lake environments should be encouraged to calibrate and validate the reconstruction of the fire history deduced from lacustrine sediments.

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