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Evaluating the persistence of post-fire residual patches in the eastern Canadian boreal mixedwood forest

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In boreal forest ecosystems, wildfire severity (i.e. the extent of fire-related tree mortality) is affected by environmental conditions and fire intensity. A burned area usually includes tree patches that partially or entirely escaped fire, called 'residual patches'. Although the occurrence of residual patches has been extensively documented, their persistence through time, and thus their capacity to escape several consecutive fires, has not yet been investigated. Macroscopic charcoal particles embedded in organic soils were used to reconstruct the fire history of 13 residual patches of the eastern Canadian boreal mixedwood forest. Our results display the existence of two types of residual patches: (i) patches that only escaped fire by chance, maybe because of local site or meteorological conditions unsuitable for fire spread (random patches), and (ii) patches with lower fire susceptibility, also called 'fire refuges' that escaped at least two consecutive fires, probably because of particular site characteristics. Fire refuges can escape fire for more than 500 years, up to several thousand years, and probably burn only during exceptionally severe fire events. Special conservation efforts could target fire refuges owing to their old age, long ecological continuity and potential specific biological diversity associated to different microhabitats.

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Fire is the main natural disturbance shaping boreal forest landscapes (Zackrisson 1977; Payette 1992). In North American boreal ecosystems, wildfires contribute to the creation of a complex mosaic of stands of varying age, composition and structure, within which other disturbances and processes can interact (Payette 1992). The boreal forest is characterized by intense crown wildfires covering large areas (Kafka *et al.* 2001). Fire severity, i.e. the extent of fire-induced tree mortality, depends on environmental conditions, forest structure and fire intensity. A burned area usually includes tree patches that partially or entirely escaped fire, called post-fire residual forests (Gluck & Rempel 1996; Wallenius *et al.* 2004, 2005; Burton *et al.* 2008). Residual patches have so far been largely ignored in forest management planning in the North American boreal forest (Gauthier *et al.* 2009).

The proportion of post-fire residual boreal forest can vary between 1 and 25% of the area burned (Delong & Tanner 1996; Dragotescu & Kneeshaw 2012). The maximum size of residual patches is usually less than 10 ha (Eberhart & Woodard 1987; Gluck & Rempel 1996). Their number may vary from 0 to 10.4 patches per 100 ha of area burned (Eberhart & Woodard 1987; Delong & Tanner 1996; Gluck & Rempel 1996; Kafka *et al.* 2001). It is still unclear whether the number and size of residual patches varies with fire size (Eberhart & Woodard 1987; Fortin & Payette 2002).

Although residual patches represent a small proportion of the area burned, they could represent significant and unique habitats in post-fire successional landscapes (Burton *et al.* 2008). Such patches can be refuges for disturbance-sensitive species, and can thus constitute biodiversity hotspots (Amaranthus *et al.* 1994; Segerström 1997; Hörnberg *et al.* 1998; Gandhi *et al.* 2001). Residual patches also constitute seed banks providing propagules for recolonization of burned areas (Asselin *et al.* 2001). Furthermore, being older than the surrounding landscape, residual patches can include 'biological legacies' such as large diameter trees, snags and coarse woody debris, which are important in the long-term ecological functioning of forest ecosystems (Amaranthus *et al.* 1994).

Although the occurrence of post-fire residual patches has been extensively described, their persistence through time, and thus their capacity to escape several consecutive fires has not yet been investigated in North America. The presence of fire refuges has mostly been documented in Fennoscandia, where so-called swamp forests can escape fire for several millennia (Hörnberg *et al.* 1998; Segerström 1997; Wallenius *et al.* 2004). However, there is a lack of detailed data on ecosystem continuity in North American boreal forests. Potential long-term ecological continuity in post-fire residual patches could provide refuges for species with specific biodiversity signatures associated with older successional stages (Selva 2003; Rivas Plata *et al*. 2008) that could be taken into account in biological conservation strategies in boreal ecosystems (Angelstam 1998). Hence, the objective of this study was to assess the persistence through time of post-fire residual patches in the eastern Canadian boreal mixedwood forest. To test the hypothesis that some post-fire residual forest patches can display long continuity, we reconstructed the fire histories of 13 such patches using macroscopic wood charcoal particles (>250 µm) embedded in the organic soil layer.

Material and methods

Study area

The study area is located within the Lake Duparquet Research and Teaching Forest (Fig. 1), in the eastern Canadian boreal mixedwood forest characterized by *Abies balsamea* (L.) Mill. (balsam fir), *Betula papyrifera* Marsh. (paper birch), *Picea glauca* (Moench) Voss. (white spruce), *Populus tremuloides* Michx. (trembling aspen) and *Thuja occidentalis* L. (eastern white cedar) as the main tree species (Dansereau & Bergeron 1993; Bergeron 2000). *Abies balsamea*, *Thuja occidentalis* and *Picea glauca* are late-successional species, whereas *Populus tremuloides* and *Betula papyrifera* initiate forest succession after stand-replacing disturbances (Bergeron 2000). The local geomorphology is characterized by a massive glaciolacustrine clay deposit left by proglacial lake Ojibway, which covers most of the area below 300 m elevation (Vincent & Hardy 1977). Hills with partially reworked or eroded morainic deposits are interspersed in the landscape (Bergeron *et al*. 1982). The climate is cold with a mean annual temperature of 0.7°C (1971–2000) and mean annual precipitation of 889.8 mm (Environment Canada 2011). The closest meteorological station is located in La Sarre, 42 km north of the study area.

Identifying residual patches

The post-fire residual forest patches were selected within young matrix forest burned for the last time in AD 1944 or 1923, as revealed by previously published fire history based on dendrochronological research (Dansereau & Bergeron 1993; Bergeron 2000; Fig. 1). Areas affected by the 1944 and 1923 fires had previously burned in AD 1717 and 1760, respectively (Dansereau & Bergeron 1993; Bergeron 2000). Post-fire residual patches were distinguished from the surrounding forest matrix based on forest structure and composition retrieved from ecoforestry maps (Ministère des Ressources naturelles http://www.mrn.gouv.qc.ca/forets/inventaire/produits-donnees-inventaire.jsp). These patches were identified as old-growth coniferous patches (with *Abies balsamea* or *Thuja occidentalis*) embedded in a matrix of younger deciduous forests (with *Populus tremuloides* or *Betula papyrifera*). Thirteen post-fire residual forest patches with thick organic matter layers (mean: 39 cm; range 8–149 cm) were sampled (Fig. 1). A Russian corer was used to sample organic matter when it was more than ~50 cm thick (five patches, Table 1), otherwise organic matter monoliths were extracted using a shovel and a knife (eight patches, Table 1). All the organic matter was sampled at each site, down to the mineral soil.

Dating and age-depth models

Radiocarbon (^{14}C) dating by accelerator mass spectrometry (AMS) was conducted on plant macroremains and charcoal fragments by Beta Analytic Inc. (Miami, FL, USA), Poznań Radiocarbon Laboratory (Poznań, Poland) and Laboratoire de mesure du Carbone 14 (LMC14) (Saclay, France). Profiles with less organic matter accumulation were poor in plant macro-remains, and thus AMS ^{14}C dates were obtained from macroscopic charcoal fragments sampled from the charcoal layer representing the last fire (see below). Radiocarbon age determinations of wood charcoal are commonly used to date past forest fire events, even though such fire ages can be overestimated because of the phenomenon of inbuilt age resulting from dating wood material that could have been dead for a long time before it burned (Gavin 2001). However, dead trees usually decompose rapidly in wet boreal forests (Naesset 1999), and thus the inbuilt age effect was probably restricted to a few decades at most. A total of 26 AMS ^{14}C dates was obtained (nine from charcoal, 17 from macro-remains; Table 2). We developed age-depth models for the five sites with the thickest organic matter accumulations. Age-depth models were based on calibrated ages and the age of the surface was established at –61 calibrated years before present (cal. a BP, i.e. AD 2011; present = AD 1950 by convention). All ^{14}C age determinations were converted to cal. a BP using version 6.1 of the CALIB software (http://calib.qub.ac.uk/calib/), and reported as intercepts with 2σ ranges (Table 2). Age-depth models were constructed assuming vertical accumulation as a continuous monotonic process applying linear interpolation between dated levels. Only one date was available for site Venteux, but linear interpolation using this date and the surface (present time) yielded a realistic sedimentation rate (see Results).

Laboratory analyses

Contiguous 1- and 0.5-cm-thick slices were cut from the sampled organic soil profiles. A 1-cm^3 subsample was

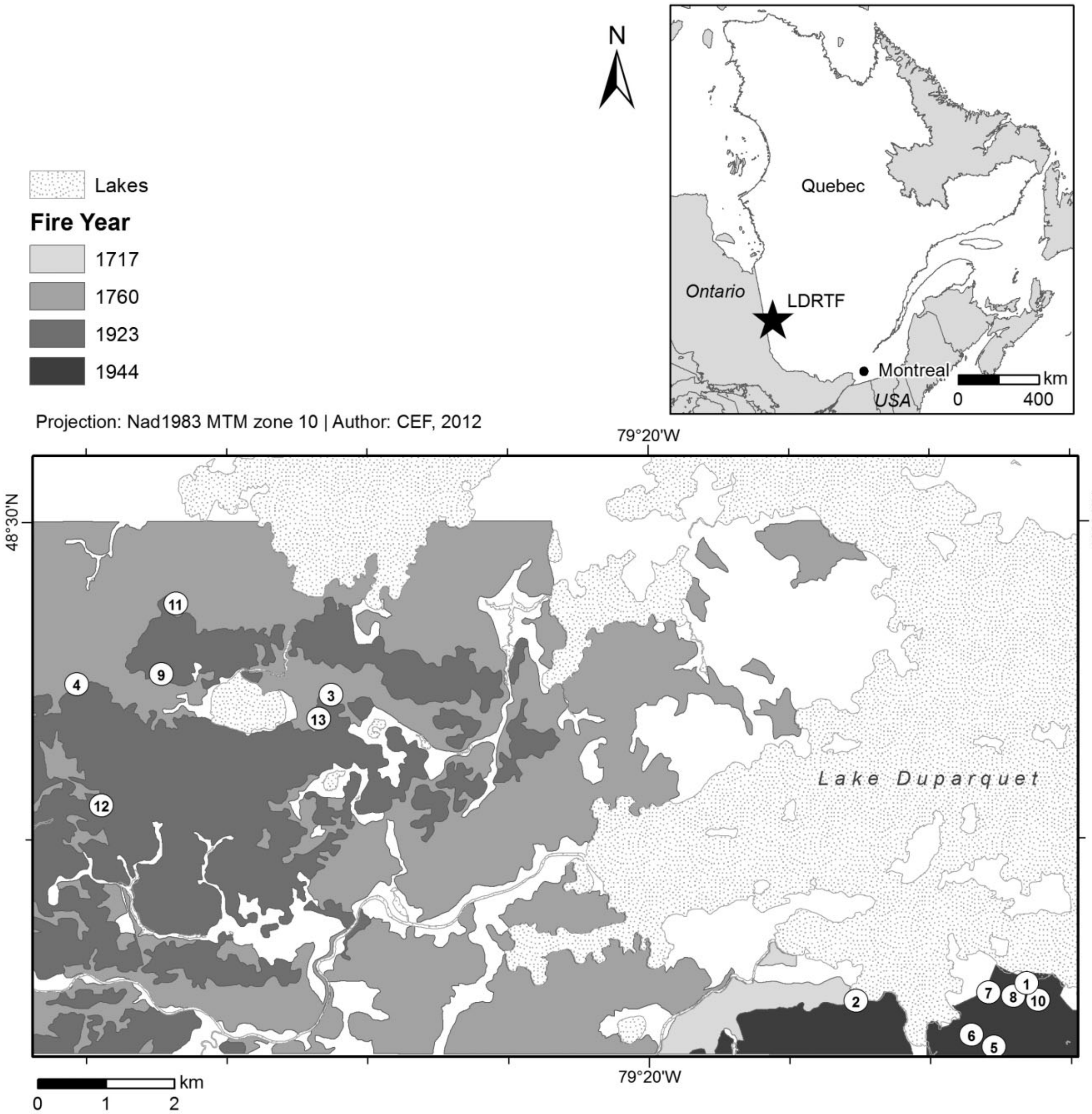

Fig. 1. Location of the studied post-fire residual forest stands in the eastern Canadian boreal mixedwood forest (Lake Duparquet Research and Teaching Forest: LDRTF). 1 = Georges; 2 = Limite; 3 = Mosquito1; 4 = Surprise; 5 = Venteux; 6 = Cadeau; 7 = Lauriane; 8 = Jennifer; 9 = Expérience; 10 = Falaise; 11 = Barrage; 12 = Monsabrais; 13 = Mosquito2. Areas burned by the AD 1717, 1760, 1923 and 1944 fires are shown in different shades of grey.

retrieved from each slice and left for at least 1 h in a 3% $(NaPO_3)_6$ dispersing solution, before gentle wet-sieving through 2- and 0.25-mm meshes. Macroscopic charcoal fragments from each subsample were counted and sorted under a dissecting microscope.

Determining the distance of the charcoal source is not a trivial issue because dispersal and deposition mechanisms are spatially and temporally variable (Clark *et al*. 1998; Ohlson & Tryterud 2000; Lynch *et al*. 2004). Charcoal fragments larger than 2 mm are a good proxy of *in situ* fire events because they usually do not travel more than a few metres from the flame front (Ohlson & Tryterud 2000; Asselin & Payette 2005) and resist fragmentation for millennia in soil deposits (de Lafontaine & Asselin 2011). Moreover, 94% of the charcoal mass produced in an *in situ* fire consists of particles ≥2.0 mm (Ohlson & Tryterud 2000). Charcoal deposition can vary substantially within a burned area

Table 1. Characteristics of the 13 sampled post-fire residual stands.

Name	Site number (as in Fig. 1)	Density (trees ha^{-1})	Organic matter thickness (cm)	Slope (°)
Georges	1	3373	49	0
Limite	2	585	22	0
Mosquito1	3	1517	8	0
Surprise	4	670	9	3
Venteux	5	1211	50.5	0
Cadeau	6	2354	98	0
Lauriane	7	514	9	5
Jennifer	8	576	14	7
Expérience	9	1049	9	3
Falaise	10	618	11	4
Barrage	11	1271	59	1
Monsabrais	12	1551	149	2
Mosquito2	13	757	25	0

– with some samples even being devoid of charcoal – when tree density is low, such as in a stand following partial logging (Ohlson & Tryterud 2000) or in the forest tundra (Asselin & Payette 2005). However, we sampled stands in the closed-crown boreal mixedwood forest, where tree density was high enough that charcoal would have been deposited more evenly on the ground after fire. Charcoal fragments larger than 0.25 mm but smaller than 2 mm were used to identify extra-local fires, i.e. wildfires that occurred in the surrounding forest matrix. Such particles can travel several hundred metres from the flame front (Ohlson & Tryterud 2000).

Fire history reconstructions

For the five sites having the thickest organic matter accumulation (>50 cm: Monsabrais, Cadeau, Georges, Barrage, Venteux), we used numerical treatments commonly employed to detect fire events from lacustrine deposits (e.g. Higuera *et al*. 2007; Ali *et al*. 2009). As *in situ* fires generally produce both large and small charcoal particles (Ohlson & Tryterud 2000), we considered that the detected fire events had affected the patches (*in situ* fire events) only if small (0.25–2 mm) and large

Table 2. Radiocarbon dates obtained from organic matter profiles from the 13 sampled post-fire residual stands.

Site	Sample depth (cm)	Dated material	Age (a BP)	Age (cal. a BP median probability)	Sample number
Limite					
	7–8	Charcoal	190±30	180	Beta321200
Jennifer					
	13–14	Charcoal	350±30	395	Beta321198
Mosquito2					
	18–19	Charcoal	1880±30	1830	Beta321199
Expérience					
	5–6	Charcoal	680±30	650	Beta326011
Mosquito1					
	5–6	Charcoal	190±30	180	Beta326012
Surprise					
	5–6	Charcoal	190±30	180	Beta326013
Falaise					
	6–7	Charcoal	750±30	685	Beta326008
Lauriane					
	8–9	Charcoal	250±30	295	Beta326012
Monsabrais					
	24.5–25	Macro-remains	810±30	720	SacA 25579
	50–50.5	Macro-remains	4975±45	5695	SacA 25578
	75–75.5	Macro-remains	5790±45	6590	SacA 25577
	100–100.5	Macro-remains	6090±45	6960	SacA 25576
	124.5–125.5	Macro-remains	6275±45	7210	SacA 25575
	148–149	Macro-remains	7265±50	8090	SacA 25574
Cadeau					
	10–10.5	Macro-remains	530±30	540	Beta318903
	25.5–26	Macro-remains	2160±35	2180	Poz43088
	50–50.5	Macro-remains	2820±35	2925	Poz43087
	75–75.5	Macro-remains	3695±35	4035	Poz43086
	97–98	Macro-remains	5470±40	6275	Poz43085
Georges					
	14–14.5	Macro-remains	140±30	140	Beta318904
	30–30.5	Macro-remains	1240±30	1185	Beta318905
	47–47.5	Macro-remains	4325±35	4890	Poz43091
Barrage					
	29–29.5	Macro-remains	260±30	305	Beta321197
	57–57.5	Macro-remains	900±30	825	Poz43090
Venteux					
	50–50.5	Macro-remains	800±30	715	Poz43089

(>2 mm) charcoal particles were simultaneously associated to the detected fire event. In other words, detected fire events based only on small charcoal particles were interpreted as extra-local (Clark 1988), i.e. fires that burned outside the residual patches.

The extra-local fire history was reconstructed using the CharAnalysis software (http://code.google.com/p/charanalysis/). Total charcoal concentrations (# cm^{-3}; sum of small and large particles), were converted into charcoal accumulation rates (CHAR; # cm^{-2} $year^{-1}$) using sediment accumulation rates as determined by radiocarbon dating. The CHAR series were decomposed into peak (C_{peak}) and background ($C_{background}$) components in order to identify fire events. C_{peak} represents the inferred fire events (a charcoal peak can correspond to one or more fires; Long *et al.* 1998), whereas $C_{background}$ represents the slowly varying charcoal trend attributed to various factors, including long-term changes in fuel biomass and area burned. To separate fire-related (i.e. signal) from non-fire related variability (i.e. noise) in the C_{peak} component, a locally determined threshold value was set as the 99th percentile of a Gaussian distribution model of the noise in the C_{peak} time series. C_{peak} was screened and peaks were eliminated if the maximum charcoal count from a peak had a >1% chance of coming from the same Poisson-distributed population as the minimum count within the preceding 75 years (Gavin *et al.* 2006).

To optimize the identification of *in situ* fire events we used an approach based on large charcoal particles. However, high variability in the record prevented us from using the CharAnalysis procedure. Instead we followed the method developed by Higuera *et al.* (2005). Total large charcoal concentrations (# cm^{-3}) were converted into charcoal accumulation rates (CHAR; # cm^{-2} $year^{-1}$) using sediment accumulation rates as determined by radiocarbon dating. Median CHAR (hereafter mCHAR) was used to fix the threshold to separate peaks from background noise and thus identify potential fire events. Using mCHAR allows minimization of the effect of extreme CHAR values (Gavin *et al.* 2003). As the peak component still encloses noise, varying multiples of the mCHAR have to be tested to identify the value that minimizes the detection of peaks not associated with known *in situ* fires (as recorded using historical records and dendrochronology (see Dansereau & Bergeron 1993; Bergeron 2000)). In other words, peaks more recent than AD 1717/1760 were interpreted as 'false positive'. Still following the Higuera *et al.* (2005) method, to be identified as a fire event, a CHAR peak had to exceed the threshold for three consecutive samples representing more than 10 consecutive years. Similarly, CHAR had to drop below the threshold for three samples and more than 10 consecutive years before one peak was considered finished and another could begin.

For the eight sites having less organic matter accumulation (<30 cm: Limite, Jennifer, Mosquito1, Mosquito2, Falaise, Expérience, Surprise, Lauriane), statistical analysis as described above was not possible and we only aimed to identify the most recent fire event by dating the topmost charcoal layer (including both small and large fragments) detected by visual inspection of the sequences.

Results

Chronological setting and accumulation rates

Organic matter accumulation began at least 8090 cal. a BP at the Monsabrais site, although most sequences covered shorter periods (Table 2). Core lengths were variable and in some cases did not appear to be correlated with the date of organic matter inception. For example, Mosquito2 (25-cm accumulation) had an older basal date than Barrage (60-cm accumulation). Age-depth models showed variable shapes and the mean sedimentation rate was 55 a cm^{-1} (range 10–218 a cm^{-1}). Lower accumulation rates were noted at Monsabrais between 720 and 5695 cal. a BP, at Georges between 1185 and 4890 cal. a BP and at Cadeau between 540 and 2180 cal. a BP (Fig. 2). These sudden leaps in ^{14}C ages were interpreted as potential sedimentary hiatuses, probably caused by consumption of organic matter during severe fire events (see Discussion). The linear interpolation for site Venteux (only two points: 50 cm and surface) yielded a sedimentation rate of 15.5 a cm^{-1} in the lower part of the observed range, comparable to rates of sites Barrage (15.5) and George (14.4).

Fire history reconstruction

The presence of charcoal layers at all sites indicates that all residual patches sampled in this study experienced fire at least once in the past (Figs 3, 4). For the patches with thicker organic matter accumulation (Monsabrais, Cadeau, Georges, Barrage, Venteux), and using small charcoal particles, C_{fire} was effectively separated from C_{noise}, as median SNIs were >4.3 (Table 3; Kelly *et al.* 2011). The resulting total number of fire events detected per core was 5 at Barrage and Monsabrais, 9 at Georges, 18 at Cadeau and 3 at Venteux (Fig. 3). The mean fire-free interval was 144 years at Barrage (range 42–239 years), 222 years at Venteux (range 171–256 years), 291 years at Cadeau (range 44–924 years), 362 years at Monsabrais (range 48–1152 years) and 455 years at Georges (range 5–1980 years). The 1717/1760 fire was detected at all patches except Monsabrais, but the 1923/1944 fire was only detected at Georges.

From the above-mentioned fire events detected in the charcoal records, only one (Monsabrais and Venteux)

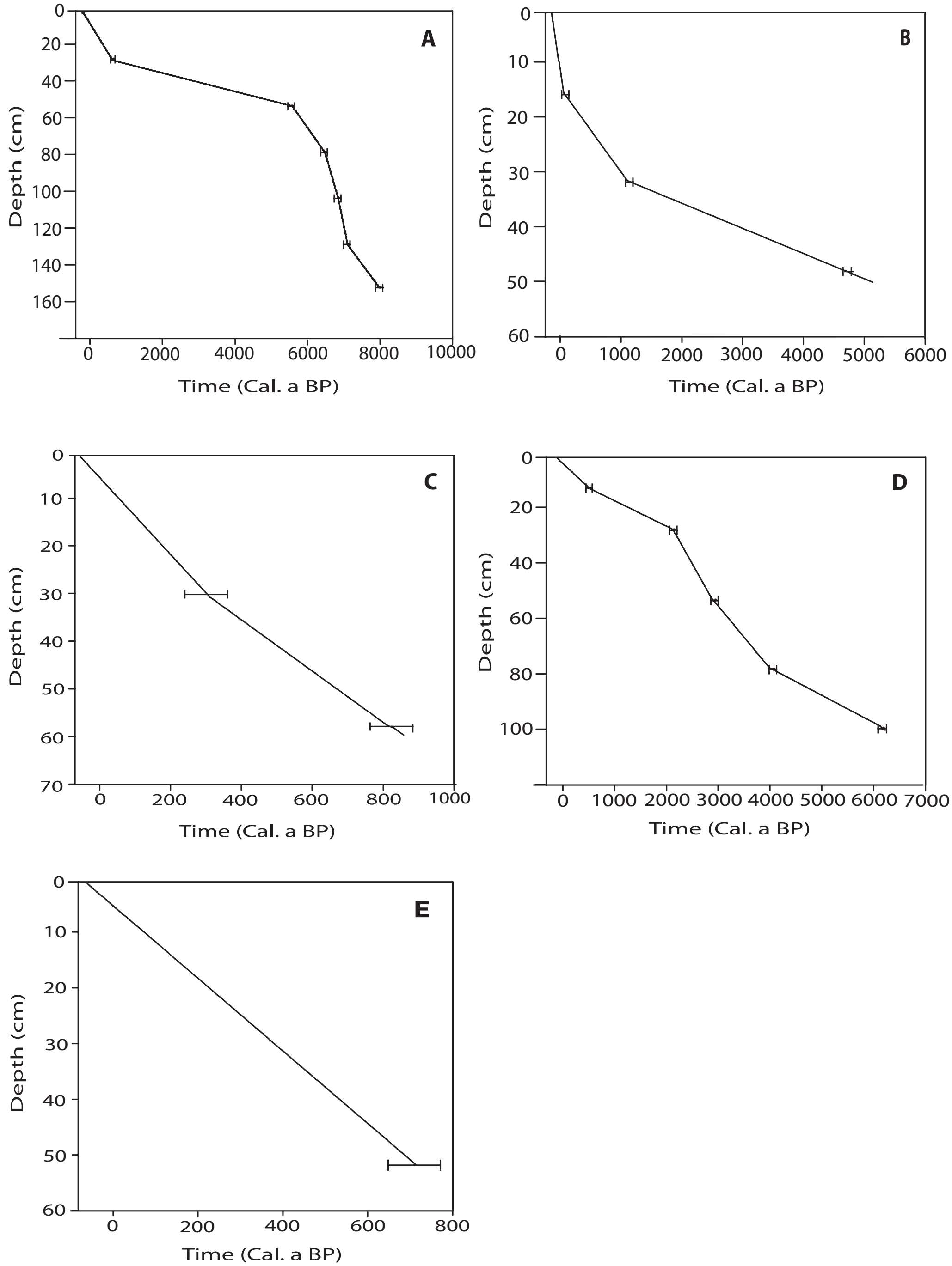

Fig. 2. Age-depth models for the five sites with >50 cm organic matter accumulation. A. Monsabrais. B. Georges. C. Barrage. D. Cadeau. E. Venteux.

or two (Cadeau, Georges, Barrage) fires were also detected using large charcoal particles, and could thus be qualified as *in situ* fires (Fig. 3). The remaining fire events were thus extra-local and probably did not burn the sampled patches.

Taking into account all 13 sites, the time since the last *in situ* fire ranged from 160 to 1830 years (Figs 3, 4). Eight sites burned during the AD 1717/1760 fire (i.e. between ~160 and 395 cal. a BP) (Figs 3, 4). The remaining sites burned for the last time before AD 1717/1760 and thus escaped at least two consecutive fires (Figs 3, 4).

The long-term fire history reconstructed at the five sites with thicker organic matter accumulation

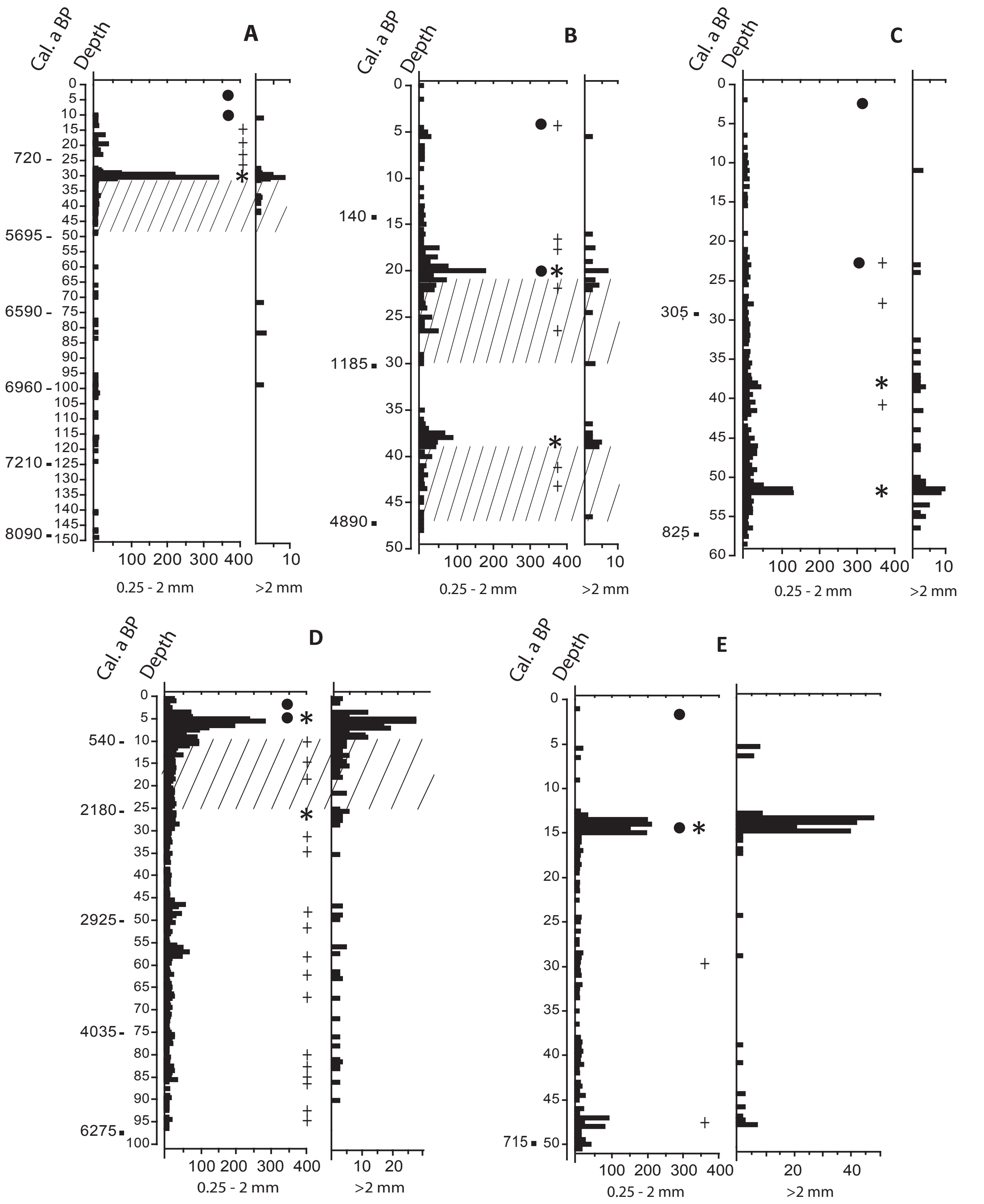

Fig. 3. Holocene charcoal accumulation records (# fragments cm^{-3}) according to depth in the organic matter profile for the five sites with >50 cm organic matter accumulation. A. Monsabrais. B. Georges. C. Barrage. D. Cadeau. E. Venteux. Small (>0.25 mm) and large (>2 mm) charcoal particles are shown separately. *In situ* fire events are indicated by an asterisk and extra-local fire events are indicated by a cross. Black dots indicate the 1923/1944 and 1717/1760 fires. Hatched areas represent sedimentary hiatuses. Calibrated ages (radiocarbon dates) are indicated beside corresponding depths.

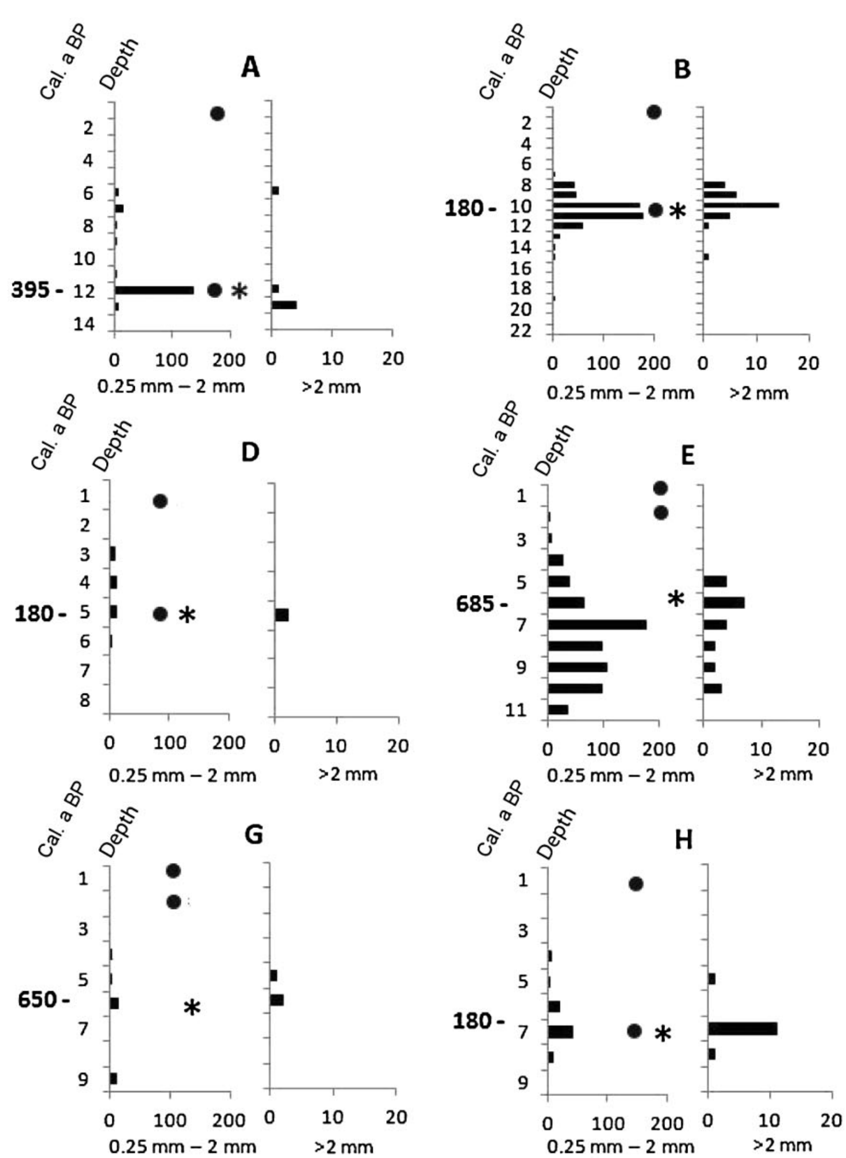

Fig. 4. Charcoal concentration (# fragments cm^{-3}) according to depth in the organic matter profile for the eight sites with <30 cm organic matter accumulation. A. Jennifer. B. Limite. C. Mosquito2. D. Mosquito1. E. Falaise. F. Lauriane. G. Experience. H. Surprise. Asterisks represent *in situ* fire events, and black dots indicate the 1923/1944 and 1717/1760 fires. Calibrated ages (radiocarbon dates) are indicated beside corresponding depths.

Table 3. Output from CharAnalysis for the five sites with thick organic matter accumulation.

Site	Median sample resolution (year sample^{-1})	C_{back} smoothing windows (years)	Median SNI	Mean FRI	Fires (#)
Monsabrais	16	700	41.30	362	5
Cadeau	22	900	5.81	291	18
Georges	33	900	4.37	455	9
Barrage	6	300	4.74	144	5
Venteux	8	300	18.76	222	3

(>50 cm) revealed that site Cadeau remained fire-free for at least 4095 years during the middle Holocene (6275–2180 cal. a BP). Long fire-free periods were also recorded at site Monsabrais during the early to middle Holocene (2395 years, between 8090 and 5695 cal. a BP) and at site Venteux during the late Holocene (520 years, between 715 and 195 cal. a BP). Site Georges, with two sedimentary hiatuses, shows a more complicated history, but at least 1470 years elapsed between the two recorded fire events (excluding hiatuses). Site Barrage was affected by two fire events separated by 250 years, but nevertheless escaped the last two fires.

Discussion

The long-term regional fire history based on fire events recorded from the longest sequences shows fire-free intervals similar to mean or median fire-free intervals recorded in lacustrine sediments in the same area (Carcaillet *et al*. 2001; Cyr *et al*. 2009), i.e. between 144 and 455 years for this study (Table 3) compared to ~100–500 years for lacustrine studies.

The reconstruction of the *in situ* fire events showed that five of the 13 sampled post-fire residual patches escaped at least two consecutive fires (the 1923/1944 fire and the 1717/1760 fire; Barrage, Expérience, Falaise, Monsabrais, Mosquito2) and thus displayed long ecological continuity and could be considered fire refuges. Their low susceptibility to fire could be due to particular microsite characteristics. Previous studies have indeed shown that topography, soil moisture, vegetation structure and fuel characteristics may contribute to decrease fire severity (Eberhart & Woodard 1987; Román-Cuesta *et al*. 2009; Madoui *et al*. 2010). Peatlands, rock outcrops, lakes and rivers have also previously been shown to act as barriers to fire propagation (Eberhart & Woodard 1987; Madoui *et al*. 2010). The other eight sites (Cadeau, Georges, Jennifer, Lauriane, Limite, Mosquito1, Surprise and Venteux) burned in the 1717/1760 fire and only escaped the most recent fire (1923/1944). These patches could have escaped fire because of stochastic processes, possibly involving the presence of fire breaks (e.g. peatlands, rock outcrops, lakes, rivers) or changes in meteorological conditions (e.g. sudden rain, change in wind speed or direction) that limited fire spread (Shroeder & Buck 1970). They can thus be considered random residual patches.

The long-term fire history reconstructed from the five sites with thicker organic matter accumulation (>50 cm) revealed that four of them (Cadeau, Georges, Monsabrais, Venteux) remained fire-free for very long periods during the Holocene (520–4095 years) and only burned during what appeared to have been exceptionally severe fires, as deduced by dendrochronological studies (Dansereau & Bergeron 1993; Bergeron 2000) or according to the sedimentary hiatuses created by the fire consumption of some part of the organic matter layer (Pitkänen *et al*. 1999; Ali *et al*. 2008). Such low fire susceptibility and long ecological continuity is comparable to that of fire refuges in Fennoscandian and Russian boreal forests, where fire-free periods were shown to be as long as 3600 years (Hörnberg *et al*. 1998; Wallenius *et al*. 2004, 2005). Hence, three of the patches that burned in 1717/1760, first leading us to classify them as random residual patches (Cadeau, Georgees and Venteux; see above), have been fire refuges in the past.

Conclusion

Identifying fire events from charcoal particles embedded in soil deposits is not an easy task, and the combination of several methods was necessary to obtain a satisfactory reconstruction of *in situ* fire history of the sampled post-fire residual forest patches. Although the presence of fire refuges had already been documented in Fennoscandian and Russian boreal forests, this study is the first to describe their occurrence in the eastern Canadian boreal mixedwood forest. Furthermore, post-fire residual patches with longer ecological continuity (either recently or in the past), having escaped at least two consecutive fires, were differentiated from other sites having escaped only one fire, probably by chance. Fire refuges can persist in the landscape for several centuries, up to a few millennia, and could serve as refuges for plant and animal species associated with ancient forests and key structural factors dependent on ecological continuity. Special conservation efforts could thus target fire refuges owing to their old age, long ecological continuity and potential specific biological diversity associated to different microhabitats.

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