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Long-term fire history of maple (*Acer*) forest sites in the central St. Lawrence Lowland, Quebec

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1 **Long-term fire history of maple (*Acer*) forest sites in the central St.**
2 **Lawrence Lowland, Quebec**

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Abstract: In the St-Lawrence lowlands, sugar maple (*Acer saccharum*) is considered the dominant species of old-growth deciduous forests while red maple (*Acer rubrum*) tends to dominate sites recently disturbed by logging and agricultural practices. Considering that the long-term influence of fire is not documented for such stands, we reconstructed the postglacial tree composition (as deduced from charcoal species) and fire history of a sugar maple (Ste-Françoise area) and a red maple (Villeroy area) stand located southwest of Quebec City (Canada). The sites are 10 km apart and show contrasting soil and landform features. Using botanical identification and ^{14}C dating of soil macrocharcoal, we found that fire struck both maple stands 14-20 times since deglaciation. Most fires occurred in the early Holocene and during the last 2000 years, the mid Holocene being a low frequency or fire-free period. During the last 1600 years, the Villeroy stand shifted from a *Tsuga canadensis*/conifer forest to a mixed forest and, most recently, to a red maple stand as fire became more frequent, possibly due to human activities of the last 400 years. This study confirms the influence of fire on the development of maple forests. Fire should be considered as an important disturbance factor in the dynamics of temperate deciduous/mixed forests.

Résumé : L'érable à sucre (*Acer saccharum*) est considéré comme une espèce dominante des vieilles forêts à feuillage décidu des basses terres de la vallée du Saint-Laurent, alors que l'érable rouge (*Acer rubrum*) a tendance à occuper les stations récemment perturbées par l'activité forestière et l'activité agricole. Étant donné que l'influence à long terme des feux n'est pas documentée chez les érablières, nous avons procédé à la reconstitution de l'histoire des feux et de la composition botanique (en partie, à l'aide des charbons de bois) de deux stations actuellement occupées par une érablière à érable à sucre (localité de Ste-Françoise) et une érablière à érable rouge (localité de Villeroy) situées au sud-ouest de la ville de Québec. Les deux stations sont situées à 10 km l'une de l'autre et diffèrent quant aux caractéristiques géomorphologiques et pédologiques. D'après les données radiométriques et botaniques des macrorestes de charbons de bois échantillonnés, 14 à 20 feux ont affecté les deux stations d'érable depuis la déglaciation de la région. La plupart des feux sont apparus au début de l'Holocène et au cours des derniers 2000 ans, alors que l'Holocène moyen a été une période sans feu ou de faible fréquence de feu. Au cours des derniers 1600 ans à Villeroy, une forêt de conifères dominée par la pruche du Canada (*Tsuga canadensis*) s'est transformée en forêt mixte et, plus récemment, en érablière à érable rouge alors que le feu est devenu plus fréquent au cours des 400 dernières années possiblement à cause de l'activité humaine. Notre étude confirme l'influence déterminante du feu sur le développement des érablières. Nous en concluons que le feu constitue un facteur de perturbation d'importance jouant un rôle dans la dynamique des forêts mixtes et décidues des régions tempérées froides.

58 Introduction

59 Maple (*Acer*) forests are among the main hardwood forest types of eastern North
60 America (Grandtner 1966; Rowe 1972; Bouchard and Maycock 1978; Brisson et al.
61 1988; Barbour and Billings 1999). Of the several maple species of southern Quebec and
62 New England, sugar maple (*Acer saccharum*) stands as a dominant canopy tree of mature
63 and old-growth deciduous forests (Grandtner 1966; Girardin 1969; Brown 1981; Foster et
64 al. 1998; Cogbill 2000), whereas red maple (*Acer rubrum*) dominates disturbed,
65 secondary forests under mesic and wet soil conditions (Bergeron et al. 1988; St-Jacques
66 and Gagnon 1988; Gauthier and Gagnon 1990; Abrams 1998). The two maple species are
67 in a constant flux of population changes across their natural range limit since the early
68 times of European settlement in close association with stand disturbances (Whitney 1994;
69 Abrams 1998; Foster et al. 1998). Sugar maple has lost terrain in New England because
70 of extensive agricultural settlement and logging (Foster et al. 1998). In contrast, red
71 maple increased significantly its ecological range over the last centuries from wetlands to
72 well-drained forest lands because of repetitive disturbance events caused by logging and
73 land clearing (Abrams 1998).

74 Fire as a stand disturbance in deciduous and mixed forests of the temperate zone
75 of eastern North America was often considered of secondary importance and occasional,
76 mostly man-made, and caused by early colonist campfires and aboriginal fires (Lorimer
77 1977; Oliver and Stephens 1977). Fire disturbance is also viewed as a successional factor
78 in the dynamics of several hardwood and mixed forests of New England (Henry and
79 Swan 1974; Foster et al. 1998) and southern Quebec, although logging and land clearing
80 remain the principal disturbances reported for forest ecosystems of the St. Lawrence

valley (Grandtner 1966; Bergeron et al. 1988; St-Jacques and Gagnon 1988). In contrast, sugar maple forests at their northern distribution limit have been influenced by fire at least over the last two millennia (Pilon and Payette 2015). Fire was identified as a developmental factor in the dynamics of northern sugar maple forests in the Témiscamingue and Saguenay areas. The paleoecological record of soil charcoal from maple forest sites also shows the tolerance and resilience of sugar maple to recurrent fires during the Holocene (Talon et al. 2005; Pilon and Payette 2015).

Maple forests are a major component of the diversified forest mosaic of the St. Lawrence Lowland, which is dominated by early-successional and secondary forest stands. The influence of fire on the composition and stability of these ecosystems at the site scale and at different temporal scales is still largely unknown despite the numerous stand surveys done over the past decades. This lack of knowledge on the dynamics of maple sites prompted this study whose main objective is to reconstruct the postglacial fire history and, to some extent, the plant composition of two representative sites presently occupied by sugar maple and red maple in the central St. Lawrence lowland, near Quebec City. To do so, macrocharcoal analysis of forest soils was used for this reconstruction. The analysis is based on the botanical identification and radiocarbon dating of charcoal fragments retrieved from the soil surface and the mineral solum of two maple forest sites dominated by sugar maple and red maple, respectively.

100

Study sites

The two maple sites are located southwest of Quebec City (Canada), in the central St. Lawrence Lowland (Table 1). The Villeroy site is part of a large parabolic-dune field - peatland complex formed at the Pleistocene-Holocene transition (Filion 1987). Plants of the Villeroy forest are colonizing well-drained, acidic podzolized soils composed of medium to fine sands. The Ste-Françoise site is situated about 10 km from the Villeroy site and extends on a relatively flat fluvio-marine terrace composed of reworked till. The loamy soil of this site is an acidic and moderately drained podzol.

The Ste-Françoise stand is dominated by sugar maple and yellow birch (*Betula alleghaniensis*). A small number of mature red maple, basswood (*Tilia americana*) trees and American beech (*Fagus grandifolia*), and juvenile balsam fir (*Abies balsamea*), white ash (*Fraxinus americana*) and striped maple (*Acer pensylvanicum*) (Table 2) are distributed as companion species. Red maple is the dominant canopy species of the Villeroy stand with several other tree species as companions, including sugar maple, American beech, yellow birch, large-toothed aspen (*Populus grandidentata*) and balsam fir (Table 2).

Methods

Sampling of size structure and charcoal

In order to reconstruct the fire history of the two maple sites, a description of the structure and composition of the two stands was most indicated. The size structure (diameter at breast height, dbh) of all tree stems distributed in each maple stand was

123 recorded systematically in 1000-m² sample plot. Stems < 2 cm dbh were counted in
124 subplots totalling 50 m² at the Ste-Françoise site and 300 m² at the Villeroy site. The total
125 number of seedlings and saplings in each stand was extrapolated based on the surface of
126 the subplots.

127 The Ste-Françoise site was sampled in June 2013. A rectangular plot (20 m x 50
128 m) was positioned at about 30 m from the border forest. Charcoal sampling included 25
129 microsites with 22 microsites distributed along the upper and lower lines and the other
130 microsites at the center of the plot. At the Villeroy site, the first field survey was executed
131 in 2012 and included the sampling of 10 microsites positioned every 5 m along a line at
132 the center of the stand. In 2013, 15 supplementary microsites were added and were
133 distributed every 5 m along a 75-m long line for a total of 25 sampled microsites.

134 A 20 cm x 20 cm sample of the organic horizon, from the soil surface to topmost
135 part of the mineral soil, was used for charcoal extraction at each microsite. The thickness
136 of each organic sample was measured before being sampled. In 2012, a mineral soil
137 sample beneath the organic horizon was taken at each microsite of the Villeroy site with a
138 soil corer allowing the recovery of 750 cm³ of soil. Two superposed mineral soil samples
139 (solum A and solum B) were taken in the other 15 microsites sampled at the Villeroy site
140 in 2013 as in the Ste-Françoise site except for three of them because of sampling
141 problems. Solum A and B samples are from soil cores taken at 0-15 cm and 15-30 cm
142 depth, respectively. Charcoal fragments were also extracted from buried organic horizons
143 along a nearby forest road and also in the Villeroy peatland adjoining the sand dunes.

Each sample of the organic horizon (surface compartment) and the mineral soil (mineral compartment) was placed for 12 hours in a solution of 2-5% NaOH to disperse the soil aggregates and to eliminate the organic matter during screening. The samples were cleaned using running water over 2 mm and 4 mm mesh screens. All charcoal fragments were extracted manually under a binocular microscope and dried at room temperature before being weighed. The charcoal fragments are >2mm, which indicates that they were formed and deposited in the sampled sites and that they were not transported over long distances (Ohlson and Tryterud 2000). The fragments were sectioned to analyze the three anatomical planes under an incident light microscope at magnifications of 200x and 500x. The identification criteria described by Hoadley (1990), Inside Wood (2004) and Panshin and de Zeeuw (1980), as well as the charcoal collection of the Centre d'Études Nordiques (Université Laval, Québec), were used for the botanical identification of all the charcoal fragments at the genus level, and the species level when possible. The preservation state of the fragments (vitrification, reaction wood, physical decay), their small size as well as the orange deposits filling the wood cells were the main factors reducing our ability to identify the charcoal fragments.

Charcoal dating and fire history

The fragments were selected for ^{14}C dating (AMS method: accelerator mass spectrometry) according to charcoal species/genus present in the sites and to position in the two plots. Charcoal fragments selected were pretreated to CO_2 in the ^{14}C laboratory of the Centre d'Études Nordiques and dated at the *Keck Carbon Cycle AMS* facility (University of California, Irvine, California, USA) or at the *Center for Applied Isotope Studies* (University of Georgia, Athens, Georgia, USA). The software Calib7.02 (Stuiver

et al. 2013) and the database IntCal13.14C (Reimer et al. 2013) and UWSingleYEAR98 (for dates < 71 years BP) (Stuiver et al. 1998) were used for the calibration of the ^{14}C dates in calendar years. For each ^{14}C date (± 2 standard deviations), we have considered the distribution of the calendar ages according to their associated probabilities given by the software. The distribution of the calendar ages is generally divided in probabilistic states because of the variable content of atmospheric ^{14}C through time closely associated with solar activity (Solanki et al. 2004). The mean of the interval having the highest probability was used for the determination of the calendar age of each dated sample plus 65 years added to the standard 0 year BP (1950 AD). The charcoal dates with overlapping calendar years were considered as originating from the same fire. (see supplementary material for details) The dated charcoal fragments were used to calculate fire intervals corresponding to the number of non-overlapping calendar years that separates fire events. Based on all the fire events identified, a long term fire-frequency history was constructed for the two sites. All the calibrated radiocarbon dates were pooled in a cumulative probability analysis using the sum-probabilities option in CALIB 7.02 (Stuiver et al. 2013) 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 (Lafortune et al. 2006; Payette et al. 2012). This method sums the probabilities of all dates and therefore takes into account the uncertainties inherent to radiocarbon dating.

Forest stands are continuously affected by disturbance events, so the distribution of charcoal fragments in the surface compartment and the soil compartment is not stratified (Carcaillet 2001) as it is in the sedimentary environments of dunes, peatlands and lakes (Filion 1984; Tolonen 1985; Bradbury 1996). Given that the distribution of charcoal in the forest environment is continuously affected by blowdowns and other soil

disturbances modifying the original soil horization, it is necessary to date the greatest number of charcoal fragments to record all the fire events that occurred at the site. Because one cannot date all the charcoal fragments, and the fire events, accumulated in the soil since the initial establishment of the forest after deglaciation, it is now common practice to use an indirect method to evaluate the total number of fires that occurred at a site (de Lafontaine and Payette 2012). The random sampling of charcoal fragments does not assure that all fires will be detected, thus justifying the construction of an accumulation curve to know whether the number of detected fires corresponds to the number of all the fires that occurred in the maple sites. The accumulation curve relates the number of fires detected according to the number of charcoal pieces dated. When the curve forms an asymptote, it suggests that most of the fires that occurred at the site have been theoretically detected. The accumulation curve of each site was calculated with `accumresult()` function using the random method of the BiodiversityR package in the R software (Kindt and Coe 2005; R Development Core Team 2011). This function plots 100 accumulation curves by randomly resampling from the radiocarbon dates of a given site. The mean accumulation curve is then calculated from these 100 curves and plotted. An indicator of the number of estimated fires was calculated from the mean accumulation curve of each site. An index was produced based on a nonlinear regression of the mean number of fires detected in relation to the number of dated charcoal pieces. The nonlinear regression $F(n) = F(\text{max}) (1 - e^{-Kn})$ corresponds to the number of fires detected, n the number of charcoal pieces dated, K the constant controlling the shape of the curve, and F_{max} the index of the number of fires. The F_{max} index and the constant K were calculated using the `nls()` function of R (R Development Core Team 2011). The F_{max} index corresponds to the factor controlling the flattening of the exponential negative

curve that is considered here as an estimator of the actual number of fires (Soberon and Llorente 1993; Payette et al. 2012; Frégeau et al. 2015).

Results

Structure of the Ste-Françoise sugar maple forest

The size structure includes about 4400 stems distributed among 7 tree species present in the stand. Sugar maple is the dominant species and includes the largest and tallest stems of the canopy and the lower tree strata in the form of a flattened bell-shape curve (Figure 1). Yellow birch is mostly distributed in the medium and small size classes. The regeneration layer (< 2 cm dbh) is composed of several sugar maple, red maple and yellow birch, with occasional American beech, white ash and balsam fir seedlings.

The forest floor is covered by a leaf litter and a thick organic horizon accumulated above a thin horizon composed of charcoal pieces. A small number of dead tree stems and branches are distributed on the soil surface. These features indicate that the maple forest originated recently from a fire. The oldest stem out of 18 trees cored at 30 cm above ground established in the 1880s, which suggests an age of 130-140 years for the last fire to have occurred at the site.

Structure of the Villeroy red maple forest

The size structure of the stand includes more than 2250 individuals distributed among 6 tree species with the largest trees being red maples (Figure 1). The latter species dominates most size classes > 6 cm, although sugar maple is also well distributed in these

classes but without reaching the largest sizes. The advanced generation is equally shared by sugar maple (50%) and red maple (48%). A small number of Amercian beech (1.3%), balsam fir (<1%) and large-toothed aspen (<1%) are also part of the advanced regeneration layer. Balsam fir occupies only this layer whereas the other tree species are present in the upper layers.

The forest floor is covered by a thick litter accumulated above an horizon of charcoal pieces. Whereas the forest is composed of several layers with the upper tree layer (> 15-20 m height) and the shrub layer (< 2 m height) as the most important, no tree stems nor branches lay on the ground except for a limited number of small stems recently fallen on the ground. The soil surface of the forest is largely open in contrast to that of forests which have not been disturbed for a long time, which indicates that the stand originated from a relatively recent fire. The oldest stem out of 12 trees cored at 30 cm above ground established in the 1920s or the early 1930s probably after man-made bush fires (Bureau 1968; Payette et al. 2013).

Charcoal species of the Ste-Françoise site

Both soil compartments contain several charcoal pieces, the latter being more abundant at the soil surface than in the mineral soil (Table 3). Charcoal from the soil surface are composed of angiosperms, including maple and undetermined species. Carbonized fungi also are common on the ground as in other sugar maple stands of Quebec (Pilon and Payette 2015). Only a small amount of charcoal pieces were recovered from the mineral soil, about 4 times more in the upper part than in the lower part of the mineral solum. Half of the charcoal pieces are of unknown identity, whereas the majority of the other pieces are angiosperms. Three charcoal pieces are conifers, including a *Picea/Larix*

261 fragment. Two birch, 22 broadleaf (including several thin pieces showing only one
262 longitudinal axis) and 24 other charcoal pieces corresponding to bark were recovered.
263 Broadleaf charcoals with spiral thickenings, a structure present in the vessel elements,
264 correspond possibly to maple species. The latter fragments break down as lamellar
265 structures showing only one plane and, therefore, could not be properly identified.
266 Several wood sections possess parenchyma rays of 3 to 4 cells wide possibly
267 corresponding to soft maples (either red maple or shrub maple). Other pieces of similar
268 structures display larger parenchyma rays (5-6 cells) which may be indicative of sugar
269 maple wood. One charcoal piece containing rays of 7 cells large was identified as sugar
270 maple. All the charcoal pieces with a lamellar structure originated from dead wood on the
271 forest floor and are dominating the charcoal assemblage of the surface compartment.
272 Given the neat structure of the dead wood population, it is assumed that the age of the fire
273 is rather close to the age of the wood that produced the charcoal. The saprophytic fungus
274 *Annulohypoxylon multifforme* is also part of the charcoal assemblage of the surface
275 compartment, which testifies that the last fire burned woody debris (stems and branches)
276 of the forest floor.

277

278 **The Ste-Françoise fires**

279 Fourteen fire events were identified at the site over the last 9900 years (Table 4).
280 Fires that occurred since 2500 cal yr BP are represented by charcoal pieces derived from
281 broadleaf species (including one sugar maple charcoal) and bark. Several charcoal
282 fragments are of the lamellar type as described earlier, i.e., thin sections showing only
283 one longitudinal axis. Fires occurring prior to 7400 cal yr BP are represented by
284 broadleaf (including birch), vitrified and conifer (including *Picea/Larix laricina*) charcoal

pieces. The oldest fire has been recorded by a conifer charcoal likely originating from a small stem or a branch. The most frequent fires occurred during the last 2500 years, particularly the last 1000 years, with a mean fire interval of 340 ± 275 years and 185 ± 80 years, respectively. A long quiescent, fire-free period ranged between 7400 and 2500 cal yr BP, whereas the early Holocene between 9900 and 7400 cal yr BP featured several fires succeeding at a mean interval of 495 ± 245 years. According to the accumulation curve of all the charcoal dates, 18 fire events (standard error = 0.11) could have occurred at the site during the Holocene, i.e., 4 fire events more than the number of fire events recorded by all the dated charcoal pieces (Figure 2).

Charcoal species of the Villeroy site

The organic horizon of 18 out of the 25 microsites contain several charcoal pieces (Table 5). Charcoal was also found in 14 out of the 25 cores corresponding to the first 15 cm of mineral soil (samples of solum A) and 6 out of the 15 cores of samples of solum B. The number of charcoal pieces is 20 times greater in solum A cores than in solum B cores. Paleosols associated with eolian activities were not found in the sampling area except along a nearby forest road.

Broadleaf charcoal pieces of the surface compartment correspond to small stem and branch fragments as well as bark and pith. It was not possible to check for the presence of xylem structure because of the small size of the charcoal pieces. Soft maple charcoal pieces are distributed in several microsites including 5 pieces showing a lamellar structure similar to that of charcoal pieces dominating the assemblage of the surface compartment of the Ste-Françoise site. Charcoals of the surface compartment display an

308 anatomical structure similar to that of soft maple (e.g., *Acer rubrum*, *Acer pensylvanicum*
309 or *Acer spicatum*), species of the *Rosaceae* family, basswood (*Tilia Americana*) and
310 sugar maple. Several *Populus* charcoal pieces were found in one microsite only, and they
311 probably originated from one tree individual. The 29 birch charcoal pieces of the surface
312 compartment also occurred in one microsite probably originated from one tree individual.
313 Eastern hemlock (*Tsuga canadensis*) charcoal pieces were found in one microsite of the
314 mineral compartment and in several microsities of the surface compartment. Several
315 charcoal pieces identified to *Tsuga-Larix*, *Tsuga-Abies*, *Tsuga-Abies-Thuja* are
316 probably eastern hemlock charcoal, but their small size or degree of decay were such that
317 the presence of the other conifer species could not be discarded. In contrast, charcoal
318 pieces of balsam fir were identified and it is probable that charcoal of this species is
319 represented in the latter groups of charcoal pieces. Eastern hemlock and balsam fir are
320 conifer species showing similar anatomical characters. A large part of the sampled
321 charcoal pieces do not show secondary xylem structures (tracheids, parenchyma rays,
322 vessel elements, etc.) and it is presumed that these fragments were formed after the
323 burning of bark and stem (or branch) cortex or another structure.

324 White pine (*Pinus strobus*) and aspen stems were found buried in the sandy road
325 bordering the maple stand. The pine stem was dated 1320 cal yr BP (UCIAMS-129791,
326 UL-4217: 1350 $\pm$ 15 yr BP). Fifty seven charcoal pieces were recovered from the organic
327 horizon buried beneath the forest road. All the charcoal pieces $\geq$ 2.5 mg were analyzed
328 under the microscope: 8 pieces were vitrified and 8 other pieces were bark, parenchyma
329 and cortex fragments. Six pieces are soft maples or other broadleaf samples that contain
330 spiral thickenings in the vessel elements. Finally, 8 pieces are conifers, including at least
331 one spruce (*Picea*) charcoal.

The Villeroy fires

Sixteen fire events were recorded at the Villeroy site over the last 9700 years (Table 6). Two long fire-free periods occurred between 8400 and 5000 cal yr BP and 4100 and 1600 cal yr BP, respectively. Most dated charcoal fragments refer to the 3 most recent fires (85, ~ 150 and 250 cal yr BP). These fires were recorded from charcoal of the forest stand, the organic horizons beneath the forest road and in peat layers located nearby. The charcoal pieces from these fire events are forming a diversified botanical assemblage with *Tsuga*, *Acer* and *Populus*. The 150-yr fire event also is represented by spruce, balsam fir and American yew (*Taxus canadensis*). The dating of 5 charcoal pieces of the organic horizon buried beneath the forest road refers to 3 different fire events including a 550 cal yr BP fire which was not detected along the sampling transect. Four superposed organic horizons buried in the peat deposits near the maple stand (Table 6) contained several conifer (*Picea* sp. - *Larix laricina*) fragments. The radiocarbon dates of charcoal fragments contained in these stratigraphically distinct organic horizons resulted from 3 different fire events dated to 150, 250 and 1570 cal yr BP. Fires dated between 500 and 9700 cal yr BP are less represented in the global charcoal assemblage. The oldest fires (> 4000 cal yr BP) are represented by altered (vitrified, mineralized, etc.) charcoal pieces of broadleaf and conifer species. The most frequent fires occurred over the last 1600 years with a mean fire interval of 215 ± 190 years. However, the mean fire interval of the last 600 years was 120 ± 55 years. The number of estimated fires by the accumulation curve is 20 (standard error = 0.71), i.e. 4 fire events more than the number of fire events recorded by all the dated charcoal pieces (Figure 3).

356 Discussion

357 Our data show that the two maple forest sites have burned repetitively over the
358 years. The two maple sites have recorded about the same number of fires during the
359 Holocene, i.e., 14 and 16 fires. It is probable that a greater number of fires may have
360 struck both sites during this period, but not more than 18 to 20 fires according to the
361 accumulation curves.

362 The fire history of both maple sites is relatively similar. Two main periods of fire
363 activity were recorded at the Ste-Françoise site, the oldest period ranging from 9900 to
364 7500 years before present and the second period from 2500 years ago to present time. A
365 period of 5000 years of quiescent conditions on both sides of the mid-Holocene separated
366 the two periods. It is possible that sporadic fires affected the site during the mid-
367 Holocene, but there is no evidence to confirm this. Fire frequency at the Villeroy site is
368 much alike that of the Ste-Françoise site. Two periods of fire activity occurred between
369 9700 and 8500 cal yr BP and 1600 cal yr BP to present, respectively. The main difference
370 with the Ste-Françoise site is the incidence of 3 fire events between 5000 and 4150 cal yr
371 BP. The several thousand years that have passed on both sides of the mid-Holocene were
372 thus characterized by a period of relative low fire activity. The mid-Holocene coincides
373 with the decline of eastern hemlock in the St-Flavien area, near the Villeroy site, between
374 5700 and 4250 cal yr BP (Bhiry and Filion 1996a,b). The oldest charcoal pieces of the
375 Villeroy site (9900 years old) are buried into the upper podzolic solum of the dune soils,
376 confirming the old age of the parabolic dunes in this region which were formed at the
377 transition between the Pleistocene and the Holocene, about 11 500 - 10 000 cal yr BP
378 (Filion 1987).

At the scale of the southwestern part of the Quebec City region, fires were frequent during the early Holocene in the study sites, in the lac Yamaska region located less than 100 km south of the Villeroy site (Carcaillet and Richard 2000) and in early Holocene forest sites now fossilized beneath peat layers of the Grande-Tourbière-de-Villeroy and the Grande Plée bleue bog near the vicinity of St-Louis-de-Pintendre (Lavoie et al. 2012; Lavoie and Colpron-Tremblay 2013). Beneath the peat deposits of these bogs, macrocharcoal layers confirm the past development of forests which were progressively paludified and transformed into the extensive ombrotrophic peatlands as they occur today. Fire activity was probably associated with dry climatic conditions which prevailed during the deglaciation of the St. Lawrence valley (Filion et al. 2009). The deciduous forest of the Tantaré site north of Quebec City also recorded a high fire frequency from the early to mid-Holocene, between 10500 and 6500 cal yr BP (Talon et al. 2005; figure 4).

The drier climate of the early Holocene is also responsible for the edification of the extensive sand dune complex distributed across the St. Lawrence Lowland (Filion 1987), including the Villeroy dunes on which the study maple forest and the bordering peatland were established (Lavoie and Colpron-Tremblay 2013; Payette et al. 2013). Eolian activity in the region declined around 9000-8600 cal yr BP, and stabilization of the regional sand dune complex occurred around 8200 cal yr BP which coincided with the disintegration of the Laurentide Ice above Hudson Bay and its correlative loss of control on the dry climate which was previously generated by its enormous mass (Filion 1987; Barber et al. 1999). The charcoal fragments of the 5 oldest fires of the Villeroy site correspond to an early establishment of woody species on stabilized dunes. Because these

402 charcoal fragments were found in the uppermost 15 cm of the podzol soil, it is probable
403 that dune stabilization occurred before 9700 cal yr BP in our study site.

404 The mid-Holocene does not seem to have been a fire-prone period when one
405 considers the fire records of the Ste-Françoise and the Villeroy sites, similar to the fire
406 activities that prevailed at the Tantaré site, the Rivière-Éternité site (Saguenay area)
407 (Figure 4), and the lac Yamaska region (Carcaillet and Richard 2000). The climate during
408 this period was possibly more humid, at least during the summer season, which reduces
409 fire ignition and propagation. Fire frequency increased after 3000-2000 cal yr BP in the
410 studied sites and the Rivière-Éternité site, except at the Tantaré site which has not been
411 impacted by fire since 6000 cal yr BP (Talon et al. 2005; figure 4). To our knowledge,
412 there exists no empirical evidence, climatic and archeological, to explain the increased
413 fire frequency at this time. On the other hand, the higher fire frequency of the last 400
414 years in all the study sites may have been caused, at least in part, by human activities.
415 The central St. Lawrence lowland was among the first pristine forest land areas to be
416 cleared for agricultural purposes during the French regime (Courville 1996). The areas
417 surrounding the Ste-Françoise and the Villeroy settlements were burned repetitively over
418 the last centuries, particularly during the period of agricultural settlement which generally
419 followed logging and other man-made activities in the region (Bureau 1968).

420 Besides the recent anthropogenic influence which cannot be overlooked, the early
421 Holocene and the late Holocene were periods of high fire frequency before and after the
422 quiescent period of the mid-Holocene. Long fire intervals during the last 10 000 years
423 suggests the edification of stable forest landscape during several thousand years, a
424 situation which reduces the establishment of post-fire pioneer species. It is only when

425 repetitive fires are occurring that such species are able to invade disturbed sites such as is
426 the case presently in our two sites.

427 It is possible that most fires having struck the Ste-Françoise and the Villeroy
428 sites were limited spatially. As a result, we suggest that the regional vegetation
429 surrounding our maple sites was possibly forming a mosaic of small, old-aged forest
430 stands regenerated after fire until the onset of the French regime or later during the period
431 of extensive settlement (Bureau, 1968).

432 Only limited information was gained on the botanical composition of the plant
433 cover affected by fire at the Ste-Françoise site because of the lamellar structure (one
434 plane instead of the 3 planes usually visible on 3D charcoal pieces) of most charcoal
435 pieces. However, according to the relatively small set of charcoal pieces identified, it is
436 possible that a mixed-conifer and broadleaf forest, including birch, prevailed between
437 9900 and 7500 cal yr BP. Pollen data of the St-Flavien-de-Lotbinière site, near the
438 Villeroy site, suggest that mid-Holocene forests were represented by mixed stands
439 dominated by angiosperm and gymnosperm species, including sugar maple, yellow birch
440 and elm (*Ulmus*), along with a maximum representation of white pine and eastern
441 hemlock (Filion and Quinty 1993; Filion et al. 2009). A second development of broadleaf
442 or mixed forests, including the arrival of sugar maple at least 700-800 years ago,
443 dominated the Ste-Françoise site during the last 2500 years. Similar to the Ste-Françoise
444 site, a mixed-conifer and broadleaf forest has occupied the dune sands of the Villeroy site
445 between 9700 and 4500 cal yr BP. A conifer forest occupied in part by eastern hemlock
446 and balsam fir established around 1600 cal yr BP. Owing to the occurrence of two fires
447 250 and 150 years ago, this stand was replaced by a mixed forest composed of eastern

448 hemlock, sugar maple, soft maples, balsam fir, birch and aspen. During the last fire of the
449 1920-1930s, however, most conifer species, particularly eastern hemlock, disappeared
450 and were replaced by broadleaf species like red maple, sugar maple and large-toothed
451 aspen. Although red maple is described as intolerant to fire (Abrams 1998), it is the
452 dominant canopy tree of the present Villeroy post-fire stand. Red maple and sugar maple
453 appear well-adapted to fire as they now form the core of the Villeroy forest. Sugar maple
454 is able to produce a large seed crop (Houle 1992) and to resprout after fire (Bilodeau,
455 1992) as it is currently the case for red maple at the Villeroy site. The proximity of the
456 Villeroy bog where mixed red maple-black spruce (*Picea mariana*)-eastern larch (*Larix*
457 *laricina*) wetland stands are widespread is certainly a factor explaining the abundance
458 and expansion of red maple on fire-disturbed well-drained sites.

459 The most important compositional changes that occurred at the sites recently were
460 associated with a suite of logging and fires separated by short intervals during the last
461 centuries. Pioneer species tolerant to fire disturbance are now dominating the forest
462 landscape, including the red maple stand of Villeroy which has replaced former mixed
463 stands dominated by eastern hemlock. Although sugar maple does not seem to produce a
464 large quantity of charcoal, it is possible that the forest stand of the Ste-Françoise site is of
465 relatively recent origin as it has been shown for other sugar maple stands in Quebec
466 (Pilon and Payette 2015). Contrary to previous expectations about its successional status,
467 sugar maple is a forest tree adapted to conditions prevailing in all the stages of ecological
468 succession. The maple forests of the central St. Lawrence Lowland, including the Ste-
469 Françoise forest and the Tantaré forest are such good examples.

470

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Tables

Table 1. Stand characteristics of the Villeroy and Ste-Françoise maple forests.

Characteristics	Ste-Françoise	Villeroy
Coordinates	46° 27' N 71° 53' W	46°22' N 71°48' W
Altitude	128 m	132 m
Slope	0-1%	1-10%
Thickness (cm) of organic matter	10.4 ± 4.7 ^a	3.2 ± 1.2 ^b
pH F horizon	3.5	4.2
pH B horizon	3.8	4.6
Texture of B horizon	Sandy clay loam	Medium-fine sand

^a n = 25 (includes dead wood). F and H horizons are little differentiated.

^b n =15 (2013 data), L and F horizons. Organic matter often buried in mineral soil.

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Table 2. Principal species of the Villeroy and Ste-Françoise maple forests.

Layer	Species	Ste-Françoise	Villeroy
Tree	<i>Acer saccharum</i>	X	X
	<i>Acer rubrum</i>	X	X
	<i>Betula alleghaniensis</i>	X	X
	<i>Fagus grandifolia</i>	X	X
	<i>Fraxinus americana</i>	X	
	<i>Populus grandidentata</i>		X
	<i>Tilia americana</i>	X	
	<i>Abies balsamea</i>	X	X
Shrub	<i>Acer pensylvanicum</i>	X	X
	<i>Acer spicatum</i>	X	
	<i>Cornus alternifolia</i>	X	
	<i>Cornus canadensis</i>		X
	<i>Viburnum lantanoïdes</i>	X	
	<i>Lonicera canadensis</i>	X	
	<i>Vaccinium myrtilloides</i>		X
	<i>Diervilla lonicera</i>	X	
Herb	<i>Medeola virginiana</i>	X	X
	<i>Trillium erectum</i>	X	
	<i>Clintonia borealis</i>	X	
	<i>Maianthemum canadense</i>	X	
	<i>Oxalis montana</i>	X	
	<i>Polygonatum pubescens</i>	X	
	<i>Arisaema triphyllum</i>	X	
	<i>Poaceae</i>		X
	<i>Chimaphila umbellata</i>		X
	<i>Aralia nudicaulis</i>	X	
	<i>Epifagus virginiana</i>		X
	<i>Aster</i> sp.		X
	<i>Dryopteris carthusiana</i>	X	X
	<i>Pteridium aquilinum</i>		X
	<i>Huperzia lucidulum</i>	X	X
	<i>Lycopodium dendroideum</i>		X

Table 3. Number, mass and identification of charcoal pieces of the Ste-Françoise site.

Features	Surface	Solum A	Solum B
<i>n</i>	> 740	44	11
Mean mass (±σ) (mg)	4.0 ± 8.4 ^a	3.3 ± 4.3	6.2 ± 8.4
<i>Picea / Larix laricina</i>			1
Unidentified conifer		1	1
<i>Betula</i> sp.			2
Broadleaf with spiral thickenings	35	12	1
Unidentified broadleaf	24	7	2
cf. <i>Acer saccharum</i>	1		
Unidentified (bark, pith, parenchyma cells)	25	20	4
Unidentified (vitrified, mineralized, altered)	5	4	
Fungi	30		

^a 565 samples weighed.

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Table 4. ^{14}C yr BP, calibrated age (cal yr before 2015), botanical identification of charcoal pieces and number of fire events recorded in the Ste-Françoise site.

Laboratory no. ^a	Subplot no.	Compartment ^b	^{14}C Age (yr BP)	Identification	Age interval with highest probability (cal yr BP)	Probability	Average age (cal yr BP)	n cumulated fires
C145371	2	S	Modern	Broadleaf with spiral thickenings			≥65	
G18890	2	A	80±20	Unidentified broadleaf	97-148	0.49	125	14
C145375	1	A	180±30	Broadleaf with spiral thickenings	201-289	0.57	245	
C145592	8	S	185±25	Broadleaf with spiral thickenings	205-286	0.61	245	
C145594	2	S	145±20	Broadleaf with spiral thickenings	235-296	0.34	265	13
C145374	2	A	145±30	Broadleaf with spiral thickenings	234-298	0.30	265	
C145372	5	S	475±30	Broadleaf with spiral thickenings	562-606	1.00	585	12
C145369	7	S	770±30	cf. <i>Acer saccharum</i>	734-798	1.00	765	
C145370	1	S	790±30	Unidentified broadleaf	737-812	0.98	775	11
G18895	1 9	A	950±20	Unidentified (bark, stem pith, parenchyma cells)	861-940	0.71	900	
C145373	1	A	910±35	Unidentified broadleaf	821-983	0.97	900	10
C145368	5	S	920±30	Unidentified broadleaf	845-986	0.98	915	
G18892	1 0	A	930±20	Unidentified (bark, stem pith, parenchyma cells)	859-979	1.00	920	
G18893	1 0	B	1085±20	Unidentified (bark, stem pith, parenchyma cells)	1002-1074	1.00	1040	9
C145573	1	B	1120±20	Unidentified broadleaf	1035-1127	1.00	1080	
G18889	5	B	1710±20	Unidentified (bark, stem pith, parenchyma cells)	1623-1697	0.73	1660	
G18891	5	A	1720±20	Unidentified (bark, stem pith, parenchyma cells)	1628-1703	0.59	1665	8
C145593	2	S	2435±20	Broadleaf with spiral thickenings	2423-2564	0.74	2495	7
G18896	2	B	6450±25	<i>Betula</i> sp.	7385-7490	1.00	7440	6
C145596	2	B	6710±25	<i>Betula</i> sp.	7625-7682	0.86	7655	
G18897	4	B	6755±25	Unidentified conifer	7642-7725	1.00	7685	5
C145571	2	A	7015±25	Unidentified broadleaf	7858-7947	0.63	7905	4
G18894	2	A	7645±25	Unidentified (vitrified)	8454-8528	0.92	8490	
C145570	1	A	7655±30	Unidentified (vitrified)	8458-8549	0.84	8505	3
C145588	4	B	8225±30	<i>Picea</i> sp.- <i>Larix laricina</i>	9150-9361	0.98	9255	2
C145595	1	A	8825±30	Unidentified conifer (small stem)	9791-10018	0.77	9905	1

^aC = UCIAMS, G = UGAMS

^bS = surface, A = mineral A, B = mineral B

Table 5. Number, mass and identification of charcoal pieces of the Villeroy site.

	Surface	Solum A ^a	Solum B ^b
<i>n</i>	>267	242	9
Mean mass (±σ) (mg)	7.0 (±20.2)	26.4 (±13.8)	3.0 (±2.0)
Unidentified (bark, stem pith, parenchyma cells)	12	11	
Unidentified (vitrified, mineralized, altered)	10	26	3
Unidentified conifer	21	58	2
<i>Taxus canadensis</i>	1	1	
<i>Picea</i> sp. - <i>Larix laricina</i>	4	2	
<i>Abies balsamea</i>	1	1	
<i>Tsuga canadensis</i>	10	14	
<i>Tsuga canadensis</i> - <i>Abies balsamea</i>	11	7	
<i>Tsuga canadensis</i> - <i>Larix laricina</i>		8	
<i>Tsuga</i> - <i>Abies</i> - <i>Thuja</i>	6	4	
Unidentified broadleaf ^c	18	21	2
Unidentified broadleaf, shrub ^d	6	4	
Soft maple (or <i>Rosaceae</i> , <i>Tilia</i>)	10	1	
<i>Acer saccharum</i>	2	0	
<i>Acer</i> sp.	2	4	
<i>Populus</i> sp.	3	49	
<i>Salicaceae</i>		31	
<i>Betula</i> sp.	29		2

^a25 soil cores

^b15 soil cores

^cIncludes several small stems or branches

^dIn the surface compartment: *Cornus*, *Viburnum* or *Ericaceae*

Table 6. ^{14}C yr BP, calibrated age (cal yr before 2015), botanical identification of charcoal pieces and number of fire events recorded in the Villeroy site.

Laboratory no. (UCIAMS)	Subplot no. ^a	Compartment	^{14}C age (yr BP)	Identification	Age interval with highest probability (cal yr BP)	Probability	Average age (cal yr BP)	<i>n</i> cumulated fires
131936	19	S	modern	<i>Tsuga -Picea - Larix</i>			~85	16
123829	(10)	S	modern	Unidentified broadleaf			~85	
124475	(4)	S	modern	cf. <i>Tsuga canadensis</i>			~85	
131937	25	S	45±20	Broadleaf with spiral thickenings ^b	99-127	0.59	115	15
140576	11	S	80±15	cf. <i>Tsuga canadensis</i>	98-139	0.54	120	
123828	(10)	S	25±30	<i>Acer</i> sp.	98-140	0.56	120	
133265	25	A	70±20	cf. <i>Picea</i> sp.	97-141	0.48	120	
131011	Horizon	30-40 cm	75±20	<i>Picea</i> sp. – <i>Larix laricina</i> .	97-148	0.53	125	
133267	25	A	80±20	<i>Taxus canadensis</i>	97-148	0.49	125	
131932	Road		135±20	<i>Picea</i> sp. - <i>Larix laricina</i>	125-185	0.31	155	
124480	(7)	S	135±20	<i>Populus</i> sp.	125-185	0.31	155	
131945	19	S	105±20	<i>Tsuga canadensis</i>	117-206	0.59	160	
140588	16	S	110±15	<i>Tsuga canadensis</i>	122-206	0.61	165	
131025	Horizon	≈15cm	115±15	<i>Picea</i> sp. – <i>Larix laricina</i> .	123-207	0.61	165	
133270	16	A	115±20	cf. <i>Abies balsamea</i>	120-210	0.57	165	
131935	11	S	115±20	<i>Abies -Tsuga</i>	120-210	0.57	165	
140580	24	A	120±15	Unidentified conifer	124-209	0.60	165	
140589	16	A	120±15	Unidentified (vitrified)	124-209	0.60	165	
140591	15	A	120±15	cf. <i>Abies-Tsuga</i>	124-209	0.60	165	
140586		S	125±20	<i>Tsuga canadensis</i>	122-213	0.53	170	
131933	Road		130±20	cf. <i>Acer</i> «soft»	124-214	0.49	170	
131022	Horizon	≈50 cm	190±15	<i>Picea</i> sp. – <i>Larix laricina</i> .	211-254	0.47	235	14
133264	22	B	200±20	<i>Betula</i> sp.	211-254	0.49	235	
131931	Road		215±20	<i>Abies - Thuja - Tsuga</i>	214-252	0.51	235	
122736	(10)	A	190±20	<i>Acer</i> sp.	209-280	0.61	245	
122733	(10)	A	195±20	<i>Acer</i> sp.	210-279	0.60	245	
122734	(10)	A	180±20	<i>Acer</i> sp.	207-284	0.62	245	
131944	19	S	180±20	<i>Betula</i> sp.	207-284	0.62	245	
131947	Road		170±20	cf. <i>Acer</i> «soft»	230-287	0.51	260	
133269	25	A	170±20	<i>Populus</i> sp.	230-287	0.51	260	
124482	(9)	S	165±20	<i>Abies-Tsuga</i> cf. <i>Tsuga</i>	231-289	0.50	260	
131946	21	S	160±20	Shrub broadleaf ^c	232-289	0.47	260	
140587	(8)	S	160±15	<i>Tsuga canadensis</i>	234-287	0.53	260	

131943	16	S	155±20	Broadleaf with spiral thickenings ^b	233-290	0.43	260	
124481	(7)	S	145±15	<i>Acer</i> sp.	237-290	0.36	265	
124484	(6)	S	150±20	cf. <i>Tsuga canadensis</i>	234-293	0.39	265	
122732	(6)	A	150±25	Betulaceae	233-296	0.36	265	
124483	(7)	S	305±15	<i>Abies balsamea</i>	423-495	0.76	460	13
131934	Road		420±20	Conifer (except <i>Pinus</i>)	529-579	1.00	555	12
140577	15	B	1170±20	Unidentified (vitrified)	1118-1241	0.93	1180	11
140578	20	A	1305±15	Shrub (small altered stem)	1300-1352	0.73	1325	10
131015	Horizon 30-50cm		1545±20	<i>Picea</i> sp. – <i>Larix laricina</i> .	1516-1587	0.61	1550	9
134712	20	A	1540±20	<i>Tsuga canadensis</i>	1517-1587	0.55	1550	
140590	22	A	1625±20	<i>Abies</i> - <i>Tsuga</i>	1581-1631	0.73	1605	
133268	19	A	3675±20	Unidentified (vitrified)	4028-4150	0.93	4090	8
140581	19	A	3685±15	Unidentified (vitrified)	4042-4149	1.00	4095	
140585	16	B	3945±20	Unidentified conifer	4445-4506	0.68	4475	7
122735	(2)	A	4315±30	Unidentified broadleaf	4903-4959	0.72	4930	6
133266	21	A	7465±25	Unidentified (vitrified)	8340-8425	0.55	8385	5
140579	11	A	7675±25	Unidentified conifer	8476-8587	0.96	8530	4
140575	22	A	8230±25	Unidentified (vitrified)	9180-9358	0.98	9270	3
122731	(2)	A	8365±25	Unidentified broadleaf	9436-9532	0.67	9485	2
131936	(6)	A	8650±25	Unidentified broadleaf	9607-9732	1.00	9670	1

Shaded lines: Charcoal beneath the road bordering the Villeroy stand and charcoal buried in nearby dune sands and peat deposits.

^aSubplots in parenthesis were sampled in 2012.

^b*Acer* «soft» – *Tilia* – *Rosaceae*

^c*Cornus*-*Viburnum*-*Ericaceae*

Figure captions

Figure 1. Tree size structure of the Ste-Françoise (upper panel) and the Villeroy (lower panel) stands.

Figure 2. Distribution of the sum of cumulated probabilities of calibrated ^{14}C charcoal dates. Grey shadings correspond to probability areas showing the time intervals of fire dates based on the greatest probability distribution. Each sign x indicates the occurrence of a fire event centered on the mean of the greatest probability interval of one or several radiocarbon dates (A) and average accumulation curve of number of charcoals dated and fires detected (B) in the Ste-Françoise site. The accumulation curve $F(n) = F(\text{max}) (1 - e^{-kn})$, is the average of a 100 iterations where $F(n)$ is the number of fires detected, n is the number of charcoal fragments dated, $F(\text{max}) \pm 1\sigma$ is the estimated number of fires (asymptote) and k is the constant.

Figure 3. Distribution of the sum of cumulated probabilities of calibrated ^{14}C charcoal dates. Grey shadings correspond to probability areas showing the time intervals of fire dates based on the greatest probability distribution. Each sign x indicates the occurrence of a fire event centered on the mean of the greatest probability interval of one or several radiocarbon dates (A) and average accumulation curve of number of charcoals dated and fires detected (B) in the Villeroy site. The accumulation curve $F(n) = F(\text{max}) (1 - e^{-kn})$, is the average of a 100 iterations where $F(n)$ is the number of fires detected, n is the number of charcoal fragments dated, $F(\text{max}) \pm 1\sigma$ is the estimated number of fires (asymptote) and k is the constant.

Figure 4. Number of dated charcoal fragments per 250 cal years BP class in the Villeroy (this study, 46°22'N, 71°48'W), Ste-Françoise (this study, 46°27'N, 71°53'W), Rivière-Éternité (48°16'N, 70°28'W) and Tantaré (Talon et al. 2005; 47°04'N, 71°32'W) sites.

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■ *Acer saccharum*

□ *Acer rubrum*

▨ *Betula alleghaniensis*

■ *Fagus grandifolia*

Supplementary material

Long-term fire history of maple (*Acer*) forest sites in the central St. Lawrence Lowland, Québec

S. Payette, V. Pilon, P.-L. Couillard and M. Frégeau

Figure 1. Calibrated age distributions (2-sigma) of individual ^{14}C dates (full lines) and sum of probabilities of all samples (dotted line) of the Ste-Françoise site. The cal. age ranges with the highest probabilities are shaded in color. ^{14}C dates belonging to a single fire event are represented by the same color and are highlighted by a gray bar. The associated numbers refer to the column « n cumulated fires » of table 4.

Figure 2. Calibrated age distributions (2-sigma) of individual ^{14}C dates (full lines) and sum of probabilities of all samples (dotted line) of the Villeroy site. The cal. age ranges with the highest probabilities are shaded in color. ^{14}C dates belonging to a single fire event are represented by the same color and are highlighted by a gray bar. The associated numbers refer to the column « n cumulated fires » of table 6. Some dates were obtained two to three years before the present.