# Fires in temperate peatlands (southern Quebec): past and recent trends

**Claude Lavoie and Stéphanie Pellerin**

**Abstract:** In this study, we reconstructed the long-term fire history of a set of ombrotrophic peatlands (bogs) located in a temperate region of southern Quebec (Bas-Saint-Laurent). Past and recent fire-free intervals (time interval between two consecutive fires) were compared using macrofossil analyses. During most of the Holocene epoch, fires were relatively rare events in bogs of the Bas-Saint-Laurent region. The fire-free intervals were approximately ten times longer (all sites considered) before the beginning of agricultural activities in the region (1800 AD) than after. This strongly suggests an anthropogenic influence on the fire regime prevailing in the bogs over the last 200 years. However, the shortening of the fire-free intervals was mainly the result of the ignition of one or two fires in almost every site during a relatively short period (200 years), rather than a higher fire frequency in each of the bogs. In some cases, fires had an influence on the vegetation structure of bogs, but it is more likely that a combination of several disturbances (fire, drainage, and drier than average summers) favoured the establishment of dense stands of pine and spruce, a forest expansion phenomenon that is now widespread in temperate bogs.

*Key words:* agriculture, bog, fire, forest expansion, Holocene, Quebec.

**Résumé :** Nous avons reconstitué l'histoire des feux qui ont brûlé un ensemble de tourbières ombrotrophes d'une région tempérée du sud du Québec (Bas-Saint-Laurent). Les intervalles de temps écoulés entre deux feux consécutifs ont été comparés (périodes précédant ou suivant les débuts de l'agriculture dans la région) à l'aide de l'analyse macrofossile. Pendant la majeure partie de l'époque Holocène, les feux ont été relativement rares dans les tourbières du Bas-Saint-Laurent. Si on considère toutes les tourbières comme formant un seul et même ensemble, on constate que l'intervalle de temps écoulé entre deux feux consécutifs a été environ dix fois plus long avant le début des activités agricoles dans la région (vers 1800 AD) qu'après. Cela indique qu'il y a eu une influence anthropique sur le régime de feux des tourbières au cours des 200 dernières années. Toutefois, le raccourcissement de l'intervalle de temps écoulé entre deux feux consécutifs est davantage le résultat de l'allumage d'un ou deux feux dans presque tous les sites pendant une période de temps relativement courte (200 ans) que d'une fréquence de feux beaucoup plus élevée dans chaque tourbière. Les feux ont parfois une influence sur la structure de végétation des tourbières. Cela dit, il est plus probable que ce soit une combinaison de plusieurs perturbations (feu, drainage, sécheresse) qui ait favorisé l'établissement de boisés de pin et d'épinette dans les tourbières, un phénomène maintenant très répandu dans les sites tourbeux des régions tempérées.

*Mots-clés :* agriculture, boisement, feu, Holocène, Québec, tourbière ombrotrophe.

## Introduction

Fires are, along with insect outbreaks, the main natural disturbances of boreal ecosystems (Payette 1992). Wetlands, and more particularly peatlands, which are very common at boreal latitudes, do not escape this kind of disturbance. For instance, 23 000 to 110 000 ha of peatlands across western Canada burned annually from 1980 to 1999 (Turetsky et al. 2004). Mean fire-free intervals (time interval between two consecutive fires) of about 30 to 1150 years have been estimated for boreal peatlands in Canada (Alberta, Manitoba, Northwest Territories, Saskatchewan), Finland, Russia (Siberia), and Sweden (Kuhry 1994; Hörnberg et al. 1995; Yefremova and Yefremov 1996; Pitkänen et al. 1999, 2001, 2002; Robinson and Moore 2000). Fire usually has few long-term impacts on the vegetation structure of ombrotrophic peatlands (bogs). It helps to maintain a treeless environment by killing trees, which results in a higher water table that favours the growth of *Sphagnum* mosses (Damman 1977; Chambers 1997). Some shrubs (*Rhododendron groenlandicum* (Oeder) Kron and Judd, *Vaccinium* spp.), lichens (*Cladonia* spp.) and mosses (*Pohlia nutans* (Hedw.) Lindb., *Polytrichum* spp.) may be favoured by fire, but only for a very brief (20–40 years) period (Jasieniuk and Johnson 1982; Foster 1984; Foster and Glaser 1986; Kuhry 1994; Benscoter et al. 2005; Benscoter 2006).

According to paleoecological studies, the postfire vegetation succession in bogs located at temperate latitudes is similar to that observed in boreal sites (Robichaud 2000; Lavoie et al. 2001; Pellerin and Lavoie 2003*a*). Nevertheless, bogs at temperate latitudes are probably less frequently burned than those located in boreal forests. Although temperate

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bogs can easily be ignited during dry summers, they are often surrounded by deciduous forests that are not fire prone; fire-free intervals in these forests may be as long as 900–1000 years (Wein and Moore 1977; Fahey and Reiners 1981). On the other hand, the surrounding environment of temperate bogs has been severely disturbed by logging and farming activities during the last 200 years (Tolonen 1985; Yefremova and Yefremov 1996; Lachance and Lavoie 2004). Consequently, most of them are today completely isolated in a matrix of cultivated fields and dissected by ditches evacuating large amounts of water (Bouchard and Jean 2001; Van Seters and Price 2001; Pellerin and Lavoie 2003*b*; Lachance and Lavoie 2004). Several sites have also been mined for the production of horticultural peat (Robichaud 2000; Girard et al. 2002; Pellerin and Lavoie 2003*b*). These bogs are consequently drier, and particularly susceptible to accidental fire events that still occur on a regular basis because of negligence or industrial activities.

Vegetation communities of many bogs in temperate regions of Germany, Quebec, Sweden, and Switzerland have undergone important changes during the last 50–70 years (Frankl and Schmeidl 2000; Freléchoux et al. 2000; Pellerin and Lavoie 2003*b*; Linderholm and Leine 2004). For instance, in southern Quebec, several open bogs dominated by *Sphagnum* species were rapidly replaced by forest stands dominated by black spruce (*Picea mariana* (Mill.) BSP) and jack pine (*Pinus banksiana* Lamb.) (Pellerin and Lavoie 2003*b*). The forest expansion process has progressively reduced the richness of typical bog species (plants and birds) and the diversity of habitats found in the peatlands (Lachance et al. 2005). Pellerin and Lavoie (2003*a*, 2003*b*) hypothesized that anthropogenic drainage and drier than average summers were the main causal factors of tree establishment. However, this phenomenon was probably strongly accelerated by accidental fire events that spread thousands of spruce and pine seeds over burned areas, and eliminated the *Sphagnum* mat, which was preventing the successful establishment of tree seedlings. Fires were not necessarily more frequent during the 20th century than in the past, but their impacts were very different because the environmental conditions prevailing in bogs have changed. There are, however, no historical or paleoecological data allowing the comparison of past and recent (before and after the development of agriculture) fire regimes in bogs to support this assertion. In this study, we reconstructed the long-term fire history of a set of bogs located in a temperate region of southern Quebec. Past and recent fire-free intervals were compared using macrofossil analyses. We hypothesized that fire-free intervals prevailing during the last 200 years were shorter than those during the rest of the Holocene epoch, but that fires were not frequent enough to have a strong influence on the vegetation structure of the bogs. We hypothesized that instead a combination of several disturbances favoured the establishment of dense pine and spruce stands, i.e., trees that are well adapted to fire and drier conditions.

## Study area and sampling sites

The study area is a narrow strip (176 km$^2$) of agricultural lands located between the towns of Rivière-du-Loup and L'Isle-Verte, in the Bas-Saint-Laurent region, southern Quebec (Fig. 1). This region offers a good opportunity to study past and recent trends of the fire regime of peatlands located at temperate latitudes because bogs with thick and old (6000–9000 years) peat deposits are abundant. Recent studies (Lavoie et al. 2001; Pellerin and Lavoie 2003*a*) have also shown that charcoal layers found in peat cores extracted from these bogs are easily distinguishable, which facilitates the reconstruction of fire events.

The region was deglaciated about 12 000 years BP, but was then submerged by the Goldthwait Sea (Dionne 1977). Vegetation cover became established about 9500 years BP, shortly after marine regression, and the modern vegetation developed around 8000 years BP (Richard et al. 1992). On mesic and xeric sites, forests are dominated by sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betula alleghaniensis* Britt.), and balsam fir (*Abies balsamea* (L.) Mill.). Large ombrotrophic peatlands, dominated by black spruce, ericaceous shrubs and *Sphagnum* species, are common in wet depressions (Gauthier and Grandtner 1975; Grondin 1996). The regional climate is continental and wet, with a mean annual precipitation of 962 mm, 29% of which falls as snow (Environment Canada 2002). The mean temperatures in January (coldest month) and July (warmest month) are –13 and 18 °C, respectively. The mean annual temperature is about 3 °C.

Native Americans were probably present in the region as early as 9000–8000 years BP, but their presence is better documented after 7000 years BP. Archaeological evidence suggests that the region was occupied by scattered nomadic groups, belonging to Algonquin tribes (Maliseet, Micmac, Montagnais), composed of a few individuals. No evidence of agriculture dating from the prehistoric period has been found (Lechasseur 1993). The European colonization of the region began at the end of the 17th century. Colonization was slow before 1800, but the population expanded rapidly in the first half of the 19th century (Morin 1993). Around 1830, half of the land bordering the St. Lawrence River was cleared for cultivation near Cacouna (Fig. 1; Bouchette 1832). Almost all forests of the plain bordering the St. Lawrence River were transformed into agricultural lands at the end of the 19th century (Fortin 1993). Today, the region is mainly covered by agricultural fields, although woodlots on mesic and xeric sites still occupy about 15% of the total area (Lachance et al. 2005).

Seventeen bogs are present in the study area (Fig. 1). Among those, seven are currently used for the extraction of horticultural peat or are abandoned after decades of mining. Nevertheless, 10 unmined bogs and six unmined fragments of large bogs were still present at the beginning of this study (1999), and occupied a total area of 516 ha. These bogs or bog fragments had never been subjected to peat mining, large-scale logging or farming activities. They ranged in size from 2 to 189 ha and have an organic soil deposit ≥30 cm thick. Four of these bogs were dissected by or located very close to a railway built in 1876 (Girard et al. 2002). A mosaic of open and forested patches usually characterized their vegetation. Dominant tree species include black spruce, jack pine, and tamarack (*Larix laricina* (Du Roi) K. Koch). Ericaceous shrubs, mainly *Chamaedaphne calyculata* (L.) Moench, *Kalmia angustifolia* L., *R. groenlandicum*, and *Vaccinium angustifolium* Ait. are widespread in all sites. In open habitats, *Sphagnum* mosses, mainly *S. capillifolium*

(Ehrh.) Hedw., *S. fuscum* (Schimp.) Klinggr., *S. magellanicum* Brid. and *S. rubellum* Wils., cover the ground layer, whereas *Pleurozium schreberi* (Brid.) Mitt. dominates the ground layer of forested sites (Lachance and Lavoie 2004; Lachance et al. 2005).

A combination of large (original area > 100 ha) and small (original area < 100 ha) bogs were used to obtain a record of the fire events that occurred during the Holocene. Four of the five largest bogs (BDB, CAC, PAR, SAW) and five of the eleven smallest sites (N4, N10, N19, N22, TUF) with at least one unmined fragment were randomly selected for sampling (Fig. 1). Other data (plant and charcoal macrofossils, tree population structures, interviews with landowners) from Pellerin (2003) and Pellerin and Lavoie (2003*b*) were also used to reconstruct recent (1800–2001) fires that occurred in the other bogs (N1, N3, N6, N9, N13, MIC, OUE, SAE).

## Materials and methods

### Sampling and macrofossil analyses

During the summer of 1999, the peat deposit thickness of all selected bogs was mapped using a systematic sampling design, based on a grid of equidistant sampling stations. The distance between sampling stations was set at 50 m to obtain at least 20 stations per peatland. At each station, the thickness of the peat deposit was measured using an iron rod driven into the soil (Pellerin 2003). In 1999 or 2001, one peat core was extracted in each selected bog at the approximate location of the thickest peat deposit, i.e., in most cases, near the centre of the bog. The cores were extracted with a 4.5 cm diameter side-wall peat corer (Jowsey 1966). In the field, peat subsamples of 25–100 $cm^3$ were taken by cutting adjacent 2.5 cm thick slices along each core, except at the BDB site where 5-cm thick slices were cut. Subsamples were put in plastic bags for their transport to the laboratory, where they were kept frozen before processing.

All peat subsamples were wet-sieved through 2 mm, 1 mm, and 0.5 mm mesh screens, and the remaining fractions were air-dried. Macroscopic remains (vascular plants, bryophytes, charcoal pieces) were sorted from air-dried fractions under a low-power (50×) stereomicroscope. When macrofossil remains of a particular taxon were too numerous to be easily counted ($n > 1000$), 0.5 g of the subsample was extracted, fossil pieces were counted and the number of pieces was estimated for the total dry weight of the subsample (Lavoie and Payette 1995). All charcoal pieces were counted (no estimation). Charcoal particles were considered as such when they were black and opaque with angular edges. Macrofossil counts were expressed as numbers per 100 $cm^3$ of sediment. Nomenclature follows Anderson et al. (1990) for mosses (except *Sphagnum* spp.), Anderson (1990) for *Sphagnum* species, and Hinds (2000) for vascular plants.

### Sediment dating

All macrofossil diagrams were constructed before selecting peat samples for radiocarbon dating. Wood or charcoal remains were then extracted from basal peat samples and from samples located just above the fen (minerotrophic)–bog transition for dating (Table 1). The fen–bog transition zone was mainly characterized by a decrease in the abundance of sedges (Cyperaceae spp.) and brown mosses, and by an increase in the abundance of *Sphagnum* remains. Two additional peat samples were also dated from the BDB core for the purposes of a previous study (Lavoie et al. 2001).

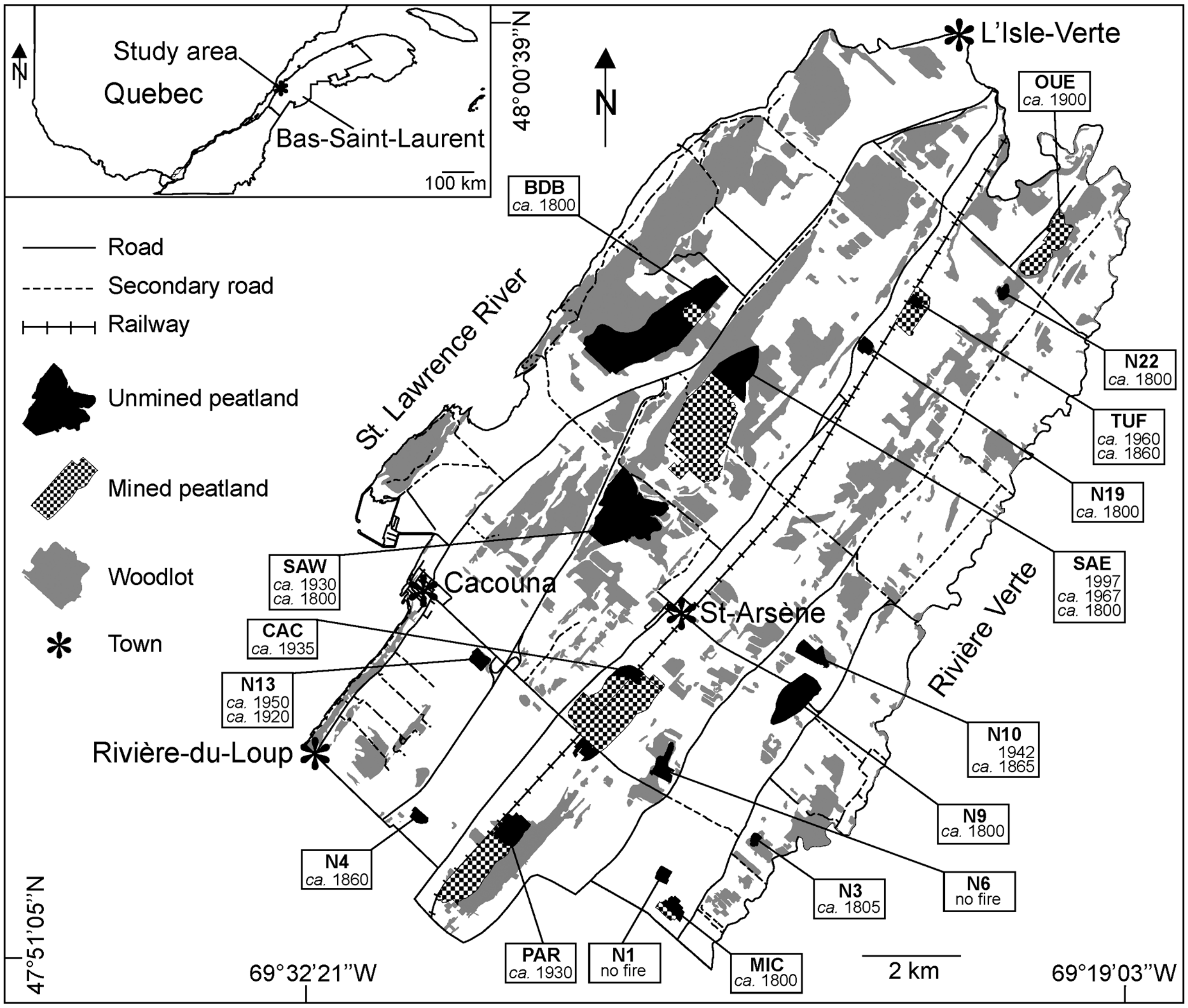
Pollen diagrams from bogs of the study area (Pellerin 2003; Pellerin and Lavoie 2003*b*) were used to determine which sample in each peat core corresponded to the beginning of noticeable human activities (farming) in the area, i.e., ca. 1800 AD (Bouchette 1832; Morin 1993). In diagrams, this event is characterized by an abrupt increase in the percentage of pollen of ruderal and cultivated taxa such as ragweeds (*Ambrosia* spp.), sorrels (*Rumex* spp.) and grasses (Poaceae spp.; Foster et al. 1992; Pellerin and Lavoie 2003*b*). This increase occurred at approximately 15 cm depth in peat cores extracted from forested sites (CAC, N19, PAR), and between 20 cm and 35 cm depths in peat cores extracted from open sites (BDB, N4, N10, N22, SAW, TUF). Methodological details about pollen analyses and the use of pollen as chronological marker can be found in Pellerin and Lavoie (2003*b*).

### Paleoecological reconstruction of fires

Recent studies have shown that the presence of macroscopic charcoal pieces ≥0.5 mm in soils is solid evidence for a local fire (Clark et al. 1998; Ohlson and Tryterud 2000). Consequently, each peat sample containing such macroscopic charcoal pieces was considered indicative of a local fire event. A single fire event may, of course, have been recorded in several adjacent peat samples; in this case, charcoal pieces were usually normally distributed around a sample in which they were particularly abundant. It was, however, impossible to distinguish two consecutive fires that were registered in the same subsample.

Few fire events were detected in the peat cores, and it was consequently difficult to calculate a fire-free interval for a single site. Thus, all sites were pooled for calculation. For each stratigraphic sequence, we calculated the number of fires that occurred during two periods, that is, before (pre-agriculture) and after (post-agriculture) the beginning of farming in the study area (ca. 1800 AD). The period during which peatlands were minerotrophic (fen) was not considered for the comparison of fire-free intervals because the different vegetation structure of fens may have had a strong influence on the fire regime. We totaled the number of fires recorded in each period (all sites considered), and the number of years corresponding to the duration of each period (all sites considered). To obtain the fire-free interval for each period, we divided the cumulative number of years (duration) of a specific period by the cumulative number of fires that have been recorded during that period, all sites considered. When a specific fire occurred at the transition between the two periods, we first included the fire in the pre-agriculture period, and, in a second calculation, in the post-agriculture period. For the calculation of the post-agriculture period, we also included the fire-free interval data from the eight other peatlands (N1, N3, N6, N9, N13, MIC, OUE, SAE) for which only macrofossil analyses conducted on surface (30–60 cm) peat deposits were available (Pellerin 2003; Pellerin and Lavoie 2003*b*). Peat samples from those sites were treated and analyzed with the same methods used in this study. In summary, the

**Fig. 1.** Study area, Bas-Saint-Laurent region, southern Quebec, Canada, and spatial distribution of bogs and woodlots on well-drained sites. Data on woodlots are from Environment Canada (1999). Fires that burned during the 19th and 20th centuries are indicated (years) for each bog.




fire-free intervals that were calculated are pooled maximum estimates, and as such, means across sites.

## Results

Radiocarbon dates from basal peat samples (Table 1) indicate that peat accumulation in most bogs began between 8900 and 8000 years BP. The basal peat sample from the CAC site is more recent because the peat core was extracted near the margin of the bog, that is, where the peat deposit was thinner and younger. The younger age of the basal peat deposit in the BDB bog can be explained by the low elevation of the site (15 m above sea level); this site was probably submerged under the Goldthwait Sea as late as 7000 years BP (Dionne 1977). The fen–bog transition did not occur simultaneously at all sites, but occurred in general between 7600 and 6600 years BP or between 4600 and 3100 years BP, except at the N4 site where the transition was very late (230 years BP).

Thirty-one charcoal layers were clearly distinguished (Fig. 2) in the peat cores (bog developmental stage only). Charcoal fragments generally consisted of charred wood, needle or seed remains of spruce or tamarack, and of charred moss fragments of *Sphagnum* and *Polytrichum* species. Fire-free intervals (Table 2) were approximately ten times longer before the beginning of agricultural activities in the region (2000–2500 years) than after (150–280 years). In fact, a total of 21 fires have been recorded in the 17 bogs of the study area during the 19th and 20th centuries, including all fires that occurred ca. 1800 AD (Fig. 1). However, only five sites (N10, N13, SAE, SAW, TUF) burned more than once during this period, and a short fire-free interval of less than 30 years (for a single site) was recorded only in the N13 and SAE sites. Bogs located close to the railway did not burn more frequently than the other sites.

Fires that occurred during the bog developmental stage had various impacts on vegetation (Fig. 1). In some cases, they opened the landscape (removal of trees), and favoured the proliferation of mosses (CAC: fire 2; N4: fire 1; N19: fire 2; N22: fire 1). In other cases, fires favoured the establishment of trees (BDB: fire 3; CAC: fire 3; N10: fire 1; PAR: fire 3; SAW: fire 5). However, in most cases, fires

**Table 1.** Radiocarbon dates from Bas-Saint-Laurent peatlands (Quebec, Canada).

| Laboratory no.[a] | Site | Core depth (cm) | Radiocarbon date (years BP ± $\sigma$) | 2 sigma age range (calibrated years) | Calibrated age[b] | Dated material |
|---|---|---|---|---|---|---|
| UL-2190 | BDB | 55.0–60.0 | 1500±90 | 381–688 AD | 534 AD | Charcoal |
| UL-2191 | BDB | 105.0–110.0 | 3010±90 | 1443–997 BC | 1220 BC | Wood |
| Beta-144854 | BDB | 155.0–160.0 | 5010±40 | 3940–3695 BC | 3818 BC | Wood |
| Beta-144855 | BDB | 205.0–210.0 | 5710±40 | 4675–4460 BC | 4568 BC | Wood |
| TO-11163 | CAC | 165.0–167.5 | 4000±50 | 2600–2430 BC | 2515 BC | Wood |
| TO-10460 | CAC | 227.5–232.5 | 6240±70 | 5320–4995 BC | 5158 BC | Wood |
| TO-10919 | N4 | 35.0–37.5 | 230±50 | 1625–1685 AD | 1655 AD | Charcoal |
| TO-10457 | N4 | 137.5–140.0 | 8070±80 | 7185–6745 BC | 6965 BC | Wood |
| TO-10920 | N10 | 60.0–62.5 | 3080±60 | 1450–1210 BC | 1330 BC | Wood |
| TO-10455 | N10 | 100.0–102.5 | 8550±80 | 7680–7515 BC | 7598 BC | Wood |
| TO-11161 | N19 | 57.5–60.0 | 7630±60 | 6530–6395 BC | 6463 BC | Wood |
| TO-10454 | N19 | 85.0–90.0 | 8420±80 | 7590–7315 BC | 7453 BC | Wood |
| TO-11162 | N22 | 102.5–105.0 | 6740±60 | 5730–5605 BC | 5668 BC | Wood |
| TO-10453 | N22 | 180.0–185.0 | 8530±80 | 7650–7510 BC | 7580 BC | Wood |
| Beta-167001 | PAR | 240.0–242.5 | 6610±60 | 5640–5470 BC | 5555 BC | Wood |
| Beta-167002 | PAR | 390.0–394.0 | 8890±80 | 8260–7750 BC | 8005 BC | Wood |
| Beta-185595 | SAW | 300.0–302.5 | 4570±40 | 3490–3110 BC | 3300 BC | Wood |
| TO-10459 | SAW | 440.0–443.0 | 8240±90 | 7520–7055 BC | 7288 BC | Wood |
| Beta-185596 | TUF | 142.5–147.5 | 7060±40 | 6000–5840 BC | 5920 BC | Wood |
| TO-10458 | TUF | 217.5–222.5 | 8020±80 | 7140–6675 BC | 6908 BC | Wood |

[a]Beta and TO samples were dated using the accelerator mass spectrometry technique; UL samples were dated using the conventional radiometric dating technique.

[b]Median value of 2σ calibrated age range.

had few impacts on the vegetation structure of bogs, at least at a local scale.

## Discussion

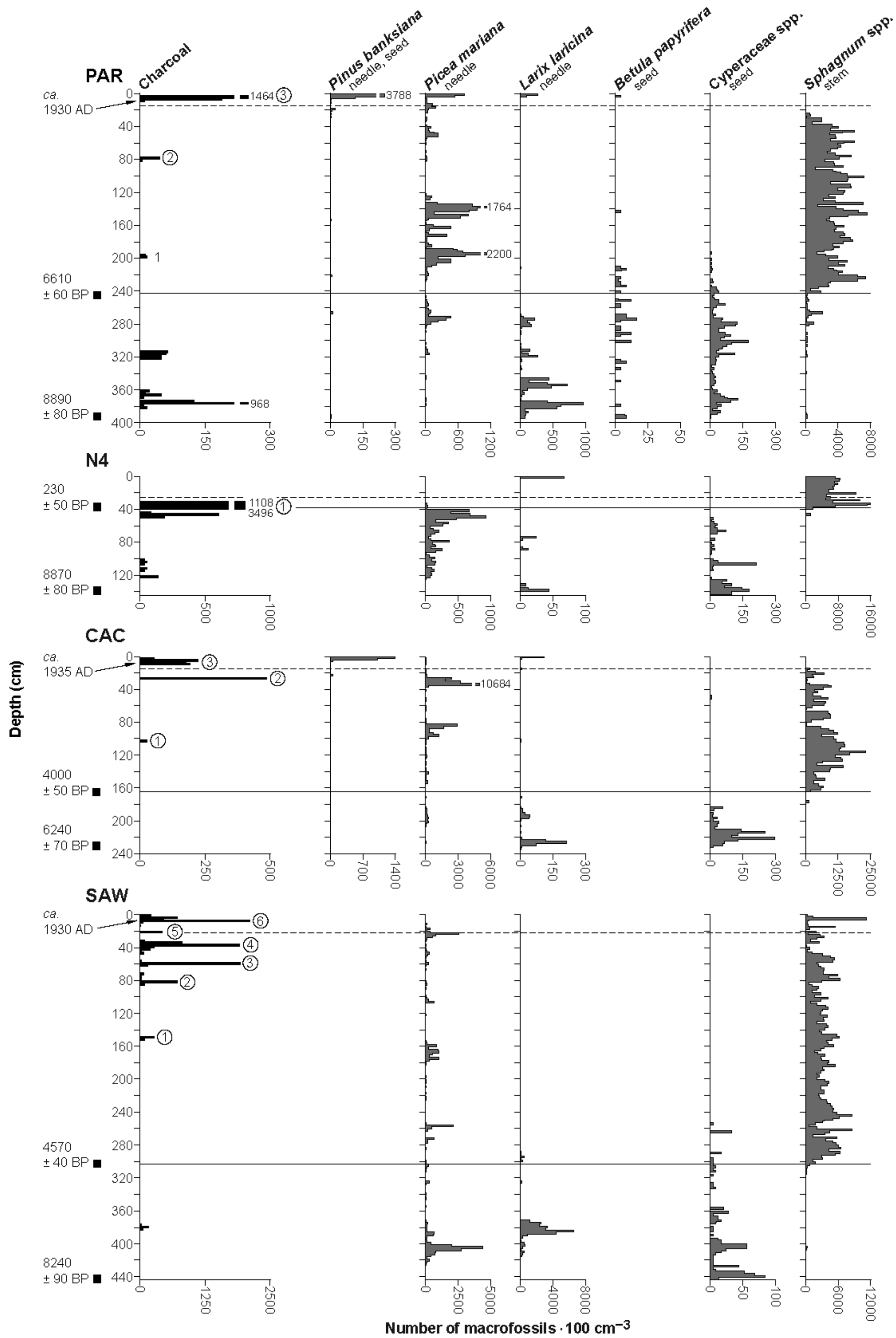
During most of the Holocene epoch, fires were relatively rare events in bogs of the Bas-Saint-Laurent region. Our data suggest that fire-free intervals of the bogs of the study area were 2000–2500 years long before the beginning of large-scale cultivation activities (ca. 1800 AD). Lightning was certainly the most important ignition source (Fahey and Reiners 1981). Native Americans also probably ignited fires (bogs are often blueberry-rich a few years following a fire), but it is unlikely that they had a major influence on the fire regime of the bogs. The nomadic groups present in the Bas-Saint-Laurent region were small and clustered mostly in river valleys and along major water bodies. Furthermore, there is no evidence for the use of fire by Native Americans for cultivation, probably because coastal resources were very abundant during summertime in this region (Lechasseur 1993; Clark and Royall 1996).

The fire-free intervals recorded in the bogs of the Bas-Saint-Laurent region were much shorter (10 times) during the 19th and 20th centuries than during the rest of the Holocene epoch, that is, during the last 5000–8500 years. This strongly suggests an anthropogenic influence on the fire regime prevailing in the bogs over the last 200 years. Until recently, farmers used fire to clear tree stumps before cultivation; fire could easily spread from clearings to adjacent bogs on dry summer days. Several fires have also been ignited by negligence of peat miners or blueberry pickers (Anonymous 1992; Larouche 1997, 2002). However, the shortening of the fire-free intervals was mainly the result of the ignition of one or two fires in almost every site during a relatively short period (200 years), rather than a higher fire frequency in each of the bogs. For instance, only two bogs (N13 and SAE) burned twice during the 20th century. The situation prevailing in the Bas-Saint-Laurent region is consequently very different from that of other agricultural regions (western Siberia, eastern Finland), where bogs burn every 30–50 years as a consequence of intensive cultivation or logging activities (Yefremova and Yefremov 1996; Pitkänen et al. 2001, 2002).

The fact that bogs located close to the railway did not burn more frequently than the other sites indicates that cinders produced by steam locomotives did not have much influence on the fire regime of the peatlands of the study area from 1876 (construction of the railway) to 1950 (replacement of steam locomotives by diesel engines). Cinder-producing steam locomotives increased the fire frequency in Maine (USA) peatlands dissected by railways, but this situation has been observed only in rich fens with a very different vegetation structure from that of the Bas-Saint-Laurent bogs, that is, mainly dominated by sedges, forbs and shrubs (Jacobson et al. 1991).

In some cases, fires had an influence on the vegetation structure of bogs in the Bas-Saint-Laurent region, but it is more likely that a combination of several disturbances (fire, drainage, and drier than average summers) favoured the recent establishment in almost all bogs of dense stands of pine and spruce, trees that are well adapted to fire and drier conditions (Pellerin and Lavoie 2003*b*). A closer examination of the fire–forest expansion relationship suggests a link between the timing of the last fire occurring in a bog and the increase of its forest cover between 1948 and 1995 AD (Fig. 3). With one exception (N19), the forest expansion

**Fig. 2.** Macrofossil diagrams (selected taxa) of several bogs of the Bas-Saint-Laurent region, southern Quebec, Canada. The full line indicates the fen–bog transition zone. The dotted line indicates the peat sample depth corresponding to the beginning of large-scale agricultural activities in the study area (ca. 1800 AD). Fires that occurred during the bog developmental stage of each peatland are indicated by a number.



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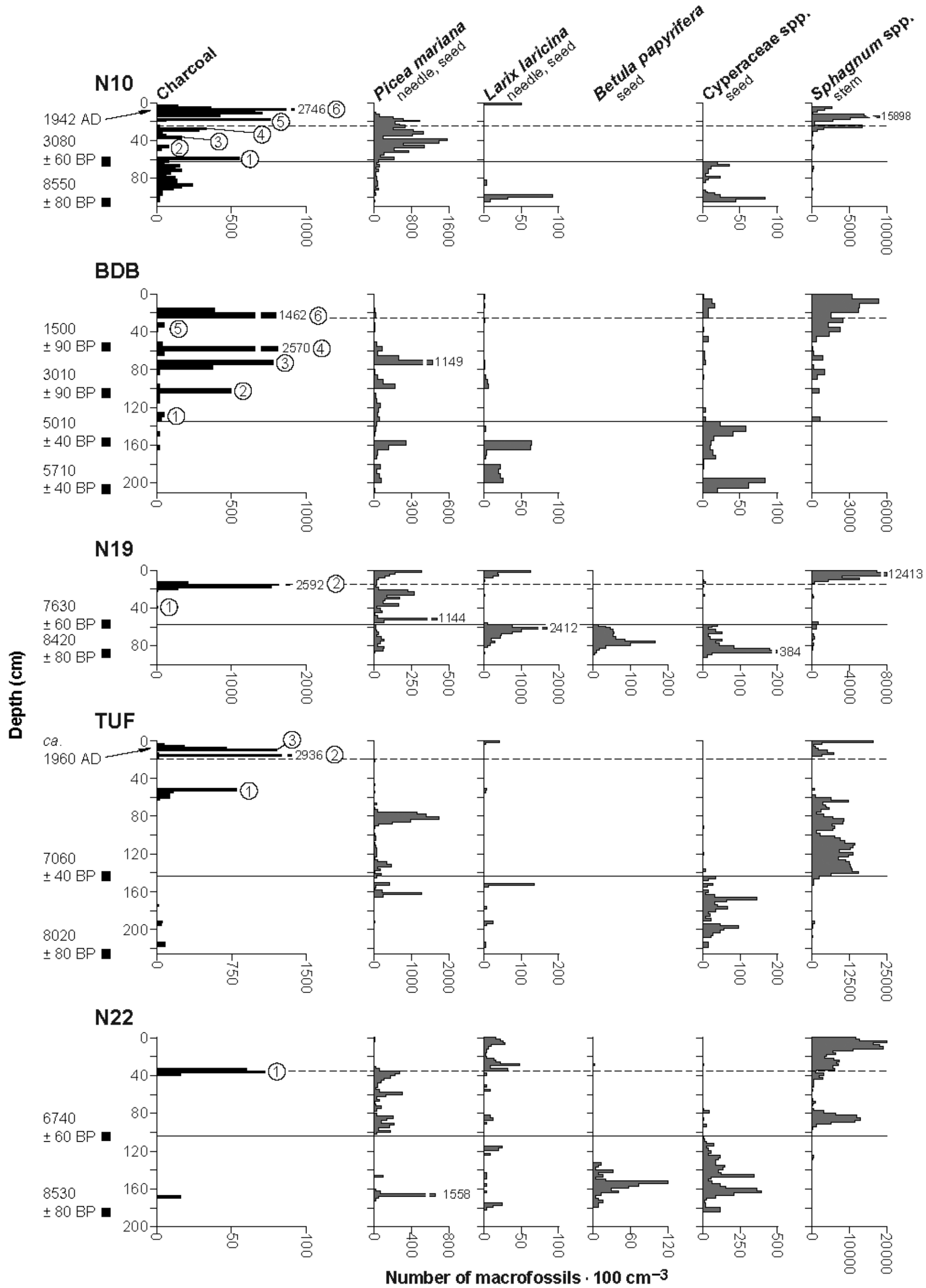



trend was stronger in sites that burned for the last time after 1930 AD than in bogs that burned for the last time before 1930 AD, or in sites that did not burn at all during the last 200 years. We hypothesize that the impact of accidental fire events on the vegetation structure of bogs (from open to forest sites) was larger after 1930 AD because, as reconstructed by Pellerin and Lavoie 2003*b*, they occurred during dry climatic periods (1913–1935 AD, 1960–1970 AD; PAR, SAE, SAW), or because bogs were disturbed by drainage from agriculture or peat mining either before they burned or a few years after the passage of the fire (CAC, N10, N13, TUF). Fires probably triggered the forest expansion by eliminating the *Sphagnum* mat and spreading thousands of pine and spruce seeds released by a few individuals. Dry soil conditions (drainage, low precipitation), prevented the rapid re-establishment of the *Sphagnum* mat, and favoured the rapid growth of tree seedlings and saplings, which in turn further contributed to decreasing the amount of water stored in the soil by intercepting rainfall, withdrawing water from the peat, and increasing evapotranspiration rates (Pellerin and Lavoie 2003*a*, 2003*b*).

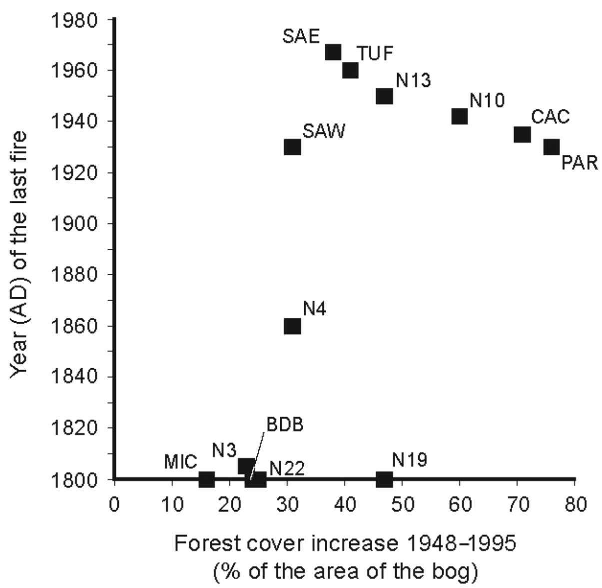
It is important to keep in mind that our reconstruction

**Table 2.** Fire-free intervals in bogs of the Bas-Saint-Laurent region (Quebec, Canada) before and after the beginning of large-scale agricultural activities in the region (ca. 1800 AD).

| Time period | Sum of time period covered by peat cores (calibrated years) | Sum of fire events reconstructed during this time period ($n$)[a] | Fire-free interval (years)[a] |
|---|---|---|---|
| Bog – before 1800 AD[b] | 47 796 | 19–24 | 1992–2516 |
| Bog – after 1800 AD[b] | 1 807 | 7–12 | 151–258 |
| Bog – after 1800 AD[c] | 3 399 | 12–21 | 162–283 |

[a]Minimum – maximum estimates, that is, including or excluding all fires that occurred ca. 1800 AD.
[b]Only bogs with a peat core covering the total thickness of the peat deposit (BDB, CAC, N4, N10, N19, N22, PAR, SAW, TUF) considered.
[c]All bogs of the study region considered.

**Fig. 3.** Relationship between the year of the last fire that occurred in a bog (for the 1800–1995 AD period) and the afforestation trend recorded between 1948 and 1995 AD in the same bog. The forest cover increase is expressed as the percentage of the bog area covered by forest in 1995 minus the percentage of the bog area covered by forest in 1948. Only two bogs in the study area, N1 and N6, did not burn during the last 200 years, and their forest cover increase from 1948 to 1995 AD was 5% and 20%, respectively. Data on forest cover are from Pellerin and Lavoie (2003*b*).




gives only a maximal estimation of the fire-free interval, since it is impossible to record all fires that occurred in a site using only one peat core (Turetsky et al. 2004). In fact, few fires spread over an entire site. A peat core extracted from a single location may not record several fires ignited in other parts of the peatland (Simmons and Innes 1996; Pitkänen et al. 2001). The best strategy for reconstructing the history of fire events is to extract several peat cores in different locations and date all charcoal layers with radiocarbon dating. Such a strategy is, however, extremely expensive and time consuming. An alternative would be to distinguish charcoal layers in peat cores by visual examination only (Pitkänen et al. 1999, 2001, 2002). Unfortunately, it was not possible to easily identify charcoal layers by visual examination of peat samples extracted from the Bas-Saint-Laurent bogs. Furthermore, it would have been impossible to use this method to identify fire events that left few traces of their passage. Considering that the aim of this study was not to calculate the exact fire-free interval in the Bas-Saint-Laurent bogs, but to compare fire-free intervals recorded in peat cores before and after the development of agriculture in the region, we assumed that our method, although imperfect, was appropriate to detect major changes in the fire regime of the bogs.

## Conclusion

Fires may have a strong impact on the vegetation structure of bogs located in landscapes strongly transformed by agricultural activities. However, this impact is probably much stronger in sites severely disturbed by drainage or during short climatic dry periods. In the Bas-Saint-Laurent region, almost all bogs burned at least once during the 19th and 20th centuries, which was very unusual considering the very long fire-free interval characterizing these bogs during the Holocene epoch. However, the fire-free interval was not short enough to impede the complete re-establishment of a *Sphagnum* mat and of other typical bog species. Other factors (drainage, periods of drought) must interact with fires to generate substantial change in the vegetation structure of bogs, such as a forest expansion process. Considering that the ecological integrity of most peatlands of the Bas-Saint-Laurent region has been severely disturbed by several anthropogenic activities (Lachance and Lavoie 2004), and that accidental fires still occur on a regular basis, it is likely that fire will contribute in the near future to accelerating the vegetation changes observed in bogs during the 20th century.

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