Fire and logging histories in southwestern Québec, Canada: a paleoecological perspective

James H. Speer[1], Raphaël D. Chavardès[2,3], Amélie Bergeron[2,4], Dorian M. Gaboriau[2,3,5], Ana Verhulst-Casanova[2,3], Marion Blache[2,3,6], Jonathan Lesven[2,3,7], Dagny Signorelli[8], Lucinda Kaye[9], Nicole Prehn[10], Alexandre F. Nolin[2,3,5,11], Martin P. Girardin[11,12], Yves Bergeron[2,3,5]

[1]Earth and Environmental Systems, Indiana State University, Indiana, USA

[2]International Research Laboratory on Cold Forests, Université du Québec en Abitibi-Témiscamingue, Québec, Canada

[3]Institut de recherche sur les forêts, Université du Québec en Abitibi-Témiscamingue, Québec, Canada

[4]Université de Sherbrooke, Québec, Canada

[5]Centre d'étude de la forêt, Université du Québec à Montréal, Québec, Canada

[6]ISEM, Univ Montpellier, CNRS, IRD, Montpellier, France

[7]Université de Franche-Comté, Besançon, France

[8]Western Colorado University, Colorado, USA

[9]State College, Pennsylvannia, USA

[10]University of Greifswald, Greifswald, Germany

[11]Centre for Forest Interdisciplinary Research, The University of Winnipeg, Manitoba, Canada

[12]Laurentian Forestry Centre, Canadian Forest Service, Québec, Canada

Introduction

Covering roughly one-third of the world's forested areas, boreal forests provide essential services for human activities (Gauthier et al., 2015) and are highly related with climate through their functions in the global carbon cycle (Kurz et al., 2013; Snyder et al., 2004). Since their establishment after the last glacial period and the retreat of the Laurentide Ice Sheet (Dyke, 2004), North American boreal forests have been shaped mainly by insolation-driven climate variability (Berger et al., 2016; Brooks et al., 1998; Yin & Berger, 2012). This climate variability influenced the spatial distribution and reproduction of tree and plant species. The historical variability within the species composition of boreal forests is also intrinsically linked to natural disturbance regimes driven by insect outbreaks, windthrow events, and fires (Johnson, 1996; Payette, 1992). Notably, complex fire regimes result in stand-replacing crown fires, although stand-maintaining surface fires are also evident in fire-scarred trees (Johnson et al., 2001; Weber & Flannigan, 1997). In eastern Canada, the natural variability of fires was additionally subjected to anthropogenic activities since the establishment of First Nations (Blarquez et al., 2018). Moreover, shifts in land uses occurred during and after European colonisation, particularly since the industrial era (around ca. 1900) when timber harvesting intensified (Boucher et al., 2009; Whitney, 1996).

In the Canadian province of Québec, boreal forests cover approximately 72 million hectares (Ministère des Forêts de la Faune et des Parcs, 2022; Natural Resources Canada, 2021) and have been increasingly managed for timber over the last century (Bergeron et al., 1999). Forests of Québec can be divided into three main zones composed of: 1) hardwood forests dominated by sugar maple (*Acer saccharum* Marsh.) and white ash (*Fraxinus americana* L.) (Ministère des Forêts de la Faune et des Parcs, 2003a) in southern Québec, 2) coniferous forests including balsam fir (*Abies balsamea* (L.) Mill.), spruces (*Picea* spp.), and pines (Pinus spp.) that progressively replace deciduous species dominated by paper birch (*Betula papyrifera*, Marsh.) and quaking aspen (Populus tremuloides, Michx.) further north, and 3) mixedwood forests between the hardwood and coniferous forests zones (Ministère des Forêts de la Faune et des Parcs, 2003b, 2020, 2022; Natural Resources Canada, 2021).

Boreal forests of eastern Canada, including Québec's forest, underwent major compositional changes as a result of human activities and climate change (Danneyrolles et al., 2016). For example, during the last century the fire exclusion policy of the government of Québec negatively affected numerous fire-dependent species (McRae et al., 1994; Parisien et al., 2020). Overexploitation is one of the major causes of forest composition changes in Québec (Danneyrolles et al., 2016) where white (*Pinus strobus* L.) and red pine (*Pinus resinosa* Ait.) in particular, have been harvested during the last few centuries (Anand et al., 2013; Uprety et al., 2013). In southwestern Québec, major exploitation of red and white pine in the Témiscamingue forests began in the 1840s and focused on cutting large trees (Danneyrolles et al., 2016). Trees were cut during winter before being pulled by horses near rivers or lakes for storage (Gourd, 1983). Flotation of the logs on rivers (*i.e.*, log driving), did not begin until the following spring where the wood piles (*i.e.* tied rafts) were transported to the provincial capital. In 1895, free floating of logs began on the rivers connected to Timiskaming Lake where human-made barriers/obstacles, called estracades, were erected to stop the logs. The logs were then divided according to their purchasers and hung in batches for delivery. Over the decades, this practice was modernised with the appearance of motorised boats for the transport of wood and people. Until the early 1900s, the wood was harvested for carpentry, and after 1917, was destined for the pulp and paper industry and sawmills. This practice ended in 1977 due to complaints about environmental pollution and nuisance (Vincent, 1995). However, the floating of the wood was not without loss, as some tree trunks sank to the bottom of the lake during the transport (Riopel, 2002). As cold water has allowed a proper preservation of the tree trunks, this timber is currently extracted from the bottom of some lakes as a lumber resource, which allows the reconstruction of fires and silvicultural practices over the last centuries.

Several methods can be used to reconstruct past fire histories including dendrochronological dating of fire scars on living or dead trees (Swetnam & Baisan, 1996), as well as chronologies of charcoal concentrations measures from radiocarbon-dated lacustrine sediments (Remy et al., 2018; Whitlock & Anderson, 2006). These methods differ in terms of fire chronology resolution and time window but both consist of assessing and understanding past disturbance dynamics in forest ecosystems. By dating tree rings, fire scars give feedback on the year or season in which a fire occurred (Brossier et al., 2014; Waito et al., 2018). After a non-lethal fire, tree cambium cells have been exposed to high temperatures and may partially die around the tree trunk. In the following years, a fire scar will appear on the tree as a result of the lack of growth in the burned area. Fire scars can be divided into five classes (Swetnam & Baisan, 1996): late earlywood (July/August), middle earlywood (June/July), early early wood (May/June), latewood (August), and dormant (Sept./April). Dormant season fire scars will be nestled between the latewood and earlywood. The year of fire needs to be determined from the greater frequency of earlywood or latewood scars based on the normal fire season.

While dendrochronological methods and fire scars provide decadal to secular fire histories by measuring annual tree rings, sedimentary charcoal are used to extend fire histories over several thousand years. Charcoal is produced by wood combustion during a fire and then transported by wind or runoff and deposited in soils, bogs, or in lake sediments (Oris et al., 2014). The amount of charcoal deposited in a sediment layer depends on fossilization processes that control the production, transport, and sequestration of sediments (Lynch et al., 2004; Whitlock & Larsen, 2001). Once the number or sum of the areas of charcoal particles quantified at regular intervals along the sediment core, fire occurrences or quantity of biomass burned may be reconstructed (Magne et al., 2020; Gaboriau et al., 2020). The relation between biomass burned and fire occurrence is used to estimate the size and/or severity of fires (Ali et al., 2012; Hennebelle et al., 2020). However, a fire regime reconstruction based on the extraction and identification of sediment charcoal does not necessarily detect each fire, as a unique charcoal peak can be linked to several fires (Higuera et al., 2010). Hence, dendrochronology can be used as a complementary method to validate the sediment-charcoal signal (Ali et al., 2012; Girardin et al., 2013).

Projections of future fire activity under climate change in North American boreal forests are uncertain as studies simulate opposing scenarios. Both an increase in fire size, severity, and occurrence (Walker et al., 2019; Whitman et al., 2019) and a decrease of annual burned area (Chaste et al., 2019) are projected during the next decades in Québec. There are thus concerns to improve the understanding of past fire dynamics in boreal forests of eastern Canada. Understanding the associations between fire and climate could also help assessing changes in fire occurrence over the last few centuries and enable more sustainable management of boreal forests.

Objectives

Within the framework of the 31st North American Dendroecological Fieldweek (NADEF) our Paleoecology Group aimed to understand fire and logging histories in southwestern Québec, Canada. We applied dendrochronological and dendropyrochronological methods to reconstruct the last two centuries of fire and timber harvesting occurrence. Charcoal records from lake sediments were also used as a proxy to reconstruct fire occurrences. Finally, we assessed associations between fire occurrences and climate.

Material and methods

Reconstructing fire histories in the Témiscamingue and Abitibi regions

Reconstructing fire history and forest structure using sunken raft logs recovered from Tee Lake in the Témiscamingue region

We reconstructed fire history and forest structure in the Témiscamingue region using white pine sunken logs. These logs were recovered by boat from Tee Lake (46°46’12’’ N, 79°01’40’’ W, 262 m a.s.l.) located 6 km south of the parc national d’Opémican (Figure 1), by the 'Bois de Drave' company (https://boisdedrave.com/). For this report, ~40-cm long cross-sections from 12 sunken logs were used for tree-ring analysis.

Fire history at the SAFE02 site in the Abitibi region

Fieldwork was conducted at the Ecosystemic Silviculture and Forest Management (SAFE02) site (48°29’05’’N, 79°25’14’’W, 301 m a.s.l.) of the Teaching and Research Forest of Lake Duparquet (Forêt d’enseignement et recherche du Lac Duparquet, hereafter ‘FERLD’) in southwestern Québec, Canada (Figure 2). The SAFE02 site is in the balsam fir – paper birch bioclimatic domain (Saucier et al. 2011). Sampling was conducted in a stand dominated by eastern-white cedar (*Thuja occidentalis* L.), paper birch, and white spruce (*Picea glauca* (Moench) Voss). Fifteen trees with fire scars were triple cored at approximately 120° around the stem at breast height (about 1.3 m above the ground) using a 5 mm diameter increment borer. Each core was packaged in a paper straw to prevent the loss of broken sections, and samples were referenced with plot number, tree identification, species, and date of extraction. Additionally, seven 10 cm-thick cross-sections and partial cross-sections were collected on living trees using a chainsaw. Cross-sections with internal rot were wrapped in a plastic film to prevent the loss of broken parts.

Lab processing

Core and cross-section preparation

Cores and cross-sections were air dried in their paper straws in a 60°C dryer for 12 hours. Cores were then tightly mounted on a prefabricated wooden support using white glue and re-writing the unique reference numbers and tree identification on the support. Once dry, the mounted cores were sanded using belt sanders starting from coarse 120 to thinner 220, 320 and 400 grit sandpaper. Tree cores were then manually sanded using 30- and 15-microns 3M abrasive film to expose the wood anatomical structure and facilitate ring width measures. Each core was checked with a hand lens or microscope to determine if the surface was sufficiently polished to see the individual cells without any scratches. Cross-sections were reconstituted and glued onto wooden planks and underwent the same treatment as tree cores using industrial belt sanders.

Tree-ring width measurements

Each core and cross-section were scanned at 1200 dpi resolution colour images using an Epson expression 10000 XL scanner. Tree-ring width (TRW) were measured in CooRecorder (v.9.3.1; Larsson 2017) before being compiled and crossdated to build a preliminary master chronology in the CDendro program (v.9.3.1; Larsson 2017). We also used the COFECHA program (Holmes, 1983) to verify the series' crossdating and each TRW series was compared to the master chronology to identify false or missing rings.

Correspondence between fire scars and charcoal records

We tested for the correspondence between years of fire scars dated in the seven eastern-white cedar cross-sections collected in SAFE02, and charcoal accumulation rates ($mm^2.cm^{-2}.yr^{-1}$) from lake sediments of the 302-cm long core extracted from Lake Francis (48°31′35″N, 79°28′20″W; 305 m a.s.l.), located 5 km north from sampled cedar trees (Carcaillet et al., 2001). The charcoal chronology from Lake Francis was downloaded from the Global Paleofire Database (Blarquez et al., 2014). To compare the charcoal chronology to the SAFE02 fire-scar records, we focused on the last 200 years including the innermost ring date of the oldest sampled tree, (*i.e.*, 1852). Five radioactive lead (^{210}Pb) dates from Lake Francis Kajak-Brinkurst (KB) core sediments were also used to construct an age/depth model (Carcaillet et al. 2001). To identify local fire events in charcoal accumulation rate series using the CharAnalysis software (v.1.1; Higuera, 2009), a 150-years-long smoothing window was used to differentiate charcoal peaks from the background noise. Fire events inferred from charcoal records were then associated with the fire years deduced from eastern white-cedar tree scars.

Climate conditions for two identified fires years at the SAFE02 site

We visually depicted climate conditions for 1760 and 1923, the two identified fire years at the SAFE02 site (Figure 3). For this purpose, we used reconstructions of the summer Palmer Drought Severity Index (PDSI;Palmer, 1965) at 286 grid points across North America (Cook et al., 2004). Higher or lower PDSI values indicate wetter or drier conditions, respectively (Palmer, 1965). To develop continuous maps depicting summer drought conditions during 1760 and 1923 at Lake Duparquet, we applied Inverse Distance Weighted (IDW) interpolation (Bivand et al., 2008) with the reconstructions for those two years.

Fire-history at the Lake Duparquet Islands

We downloaded all available fire-history data for Lake Duparquet islands (Bergeron, 1991) from the International Tree-Ring Data Bank (Zhao et al., 2019). However, data exploration revealed that most fire-scar years were recorded by one to two trees on different islands (Figure 2). Because fire is a spatial process and to reinforce associations between fire and climate conditions that favour ignition and combustion of forest fuels, specifically persistent warm and dry weather or drought, we applied the following criteria: fires recorded by at least two trees on an island during a given year were considered a 'fire year' (adapted from Heyerdahl et al., 2008).

Tree-ring and fire-scar records

We used the Fire History Analysis and Exploration System (Sutherland et al., 2017) and the 'burnr' package in R (Malevich et al., 2018) to develop tree-ring and fire-scar records for the cross-sections collected at Tee Lake and SAFE02 and for the data from the Lake Duparquet islands.

Climate data and fire-climate associations for the Lake Duparquet Islands

To represent seasonal and monthly climate for Lake Duparquet, we used reconstructions of mean spring temperature (Nolin et al., 2022) and mean spring streamflow (Nolin et al., 2021), and a July Monthly Drought Code reconstruction (Girardin et al., 2013). Higher or lower Drought Code values indicate drier or wetter conditions, respectively (van Wagner, 1987).

To test the associations between fire years and the three climate reconstructions (spring mean streamflow, spring mean temperature, July monthly Drought Code), we first used Superposed Epoch Analysis (SEA) in the R package 'burnr' (Malevich et al., 2018). To meet the assumptions of SEA, we used Autoregressive Integrated Moving Average (ARIMA) procedures to test for autocorrelation with up to six lags for each climate reconstruction (SAS Institute Inc. 2017). ARIMA procedures showed that all reconstructions had no significant temporal autocorrelation ($P \geq 0.418$). For each reconstruction, we calculated mean values during the year coinciding with fire years and the three preceding years and compared them to bootstrapped values derived from a Monte Carlo simulation of randomly selected years that provided 95%, 99% and 99.9% confidence intervals. To further test associations between fire years and climate reconstructions, we used Bivariate Event Analysis (BEA) using the K1D software (Gavin, 2010). BEA focuses on climate extremes, which were identified as years that exceeded ±1 standard deviation, based on the three climate reconstructions. To determine whether fire-years coincided with or lagged extremely warm or dry Spring conditions or dry July conditions, we conducted BEA from 1771 to 1984 with forward selection so that climate extremes preceded fire years. We generated 95% confidence intervals based on 1000 randomised Monte Carlo simulations to test if the two sets of events were temporally synchronous or independent.

Results & Discussion

Tree-ring chronologies using sunken raft logs retrieved from Tee Lake

We developed a new TRW mean-site chronology for the white pine sunken logs from Tee Lake. With 12 series, we managed to build a chronology ranging from 1721 to 1965. The outer-ring dates are consistent with the decline of the log-driving activities in 1970 and 1976 in the region of Temiscamingue. Series intercorrelations ranged from r = 0.331 to 0.492 (mean = 0.410) indicating moderately robust crossdating. Mean sensitivity was 0.257 and first order autocorrelation was 0.815 indicating moderate variations in widths between two consecutive rings.

Fire and logging histories using sunken raft logs retrieved from Tee Lake

Of the 12 subfossil cross-sections recovered from Tee Lake, four showed fire scars (Figure 4). Seven fire years were identified between 1842 and 1949. The composite chronology revealed that fire-to-fire intervals ranged from 2 to 44 years (mean = 18 years).

Tree-ring chronologies for SAFE02

We developed a new mean-site chronology for eastern-white cedar at SAFE02 (n = 23 series). Cedar series ranged from 1852 to 2021, and intercorrelations ranged from r = 0.354 to 0.758 (mean = 0.531) indicating moderately robust crossdating. Mean sensitivity was 0.225 and first order autocorrelation was 0.709 indicating moderate variations in widths between two consecutive rings.

Fire history and fire-climate associations at SAFE02

Fire history at SAFE02 and comparisons with charcoal records in Lake Francis

We found 14 fire years ranging from 1942 to 2011 on seven fire-scar samples collected at SAFE02 (Figure 5). Based on the composite chronology, fire-to-fire intervals ranged from 1 to 21 years (mean = 5 years). Most scars (71%) were formed between the early and late growing season (early earlywood to late earlywood scars). In parallel, two fire events (around 1885 and 2000) were identified in charcoal records from Lake Francis during the same period. Fire events obtained by lacustrine charcoal records matched with one fire scar date (around 2000s), possibly corresponding to a local fire (Figure 6). The charcoal peak observed in 1885 did not correspond to any fire scars but we did not have any fire scars that dated prior to 1942 probably because of preservation issues. Even if fire years did not coincide precisely between the dendrochronological and paleoecological data, there is a concordance in the recorded fire events. We need to consider the time for transport of charcoal particles by erosion in lake sediments (Oris et al., 2014). Hence, fires that occurred during the 1970s and 1980s could be attributed to the increase of charcoal particles in sediments from 1970 to 2000. But we also assumed that the small surface area of Lake Francis (*i.e.,* 1 ha), the distance between sampled trees and the lakeshores (around 5 km), and fire sizes if they were limited, may have reduced the detection of charcoals in lake sediments during the 1980s. Additionally, new ^{210}Pb dating on macro-remains or bulk sediment would refine the fire peaks chronology in the most recent period. In any case, paleofire reconstructions obtained from charcoal sediment records and independent fire scars from trees in the same area are complementary, improving the resolution of chronologies and constituting a possible validation tool for the detection of past fire events.

Fire-climate associations at SAFE02

For the two fire years previously identified using tree age and fire-scar records (1760 and 1923; Dansereau & Bergeron, 1993), the interpolated summer PDSI indicated 1760 as having dry conditions in central Ontario but wetter conditions in western Québec, whereas 1923 had dry conditions in western Québec (Figure 7). During 1760, it was more likely that a fire started in Ontario and spread eastward with regional prevailing winds until it reached Lake Duparquet forming a fire break, while during 1923, the fire was more likely localised (Dansereau & Bergeron, 1993).

Fire history and fire-climate associations at the Lake Duparquet Islands

Fire history at the Lake Duparquet Islands

Using a more conservative approach to define fire years (fires recorded by at least two trees on an island during a given year), we found 12 fire years between 1745 and 1947 that were recorded on 25 fire-scar samples distributed among seven islands of Lake Duparquet (Figure 8). Based on the composite chronology, fire-to-fire intervals ranged from 1 to 49 years (mean = 18 years). Finally, 83% of scars were formed during the early growing season (early earlywood scars).

Fire-climate associations for the Lake Duparquet Islands

From 1771 to 1984, the outcomes from Superposed Epoch Analysis (SEA) indicated the 11 fire years coincided with drier than average July conditions that followed lower spring flows, although the associations were not statistically significant ($\alpha = 0.05$) (Figure 9). Bivariate Event Analysis (BEA) indicated fire years were mostly synchronous with extremely dry July conditions (Figure 10).

The islands on Lake Duparquet and FERLD forest have relatively high lightning strike occurrence (from 0.48 to 0.63 lightning strikes/year/km^2; Drobyshev et al., 2010). On the islands in particular, high lightning strike density was associated with higher topography than the surrounding water (Drobyshev et al., 2010). However, rainfall is usually abundant during strikes over the lake and the FERLD forest (Environment Canada, 2022; Natural Resources Canada, 2022), which suggests that moisture conditions during such events limit fire ignition, combustion, and spread. With abundant rainfall, forest fuels tend to have high moisture content (van Wagner, 1987) and coinciding fires tend to be of lower severity and burn less spatially. These assumptions may be the reason why we found many distinct fire years with single fire-scars across the islands and the FERLD. To circumvent this problem for the fire-climate associations for the Lake Duparquet Islands, we focused on fire years recorded by two or more trees on a given island. Doing this strengthened associations between drier climate and fire years as fire ignition, combustion, and spread was more likely with drier weather and climate conditions (Macias Fauria et al., 2011) particularly during July.

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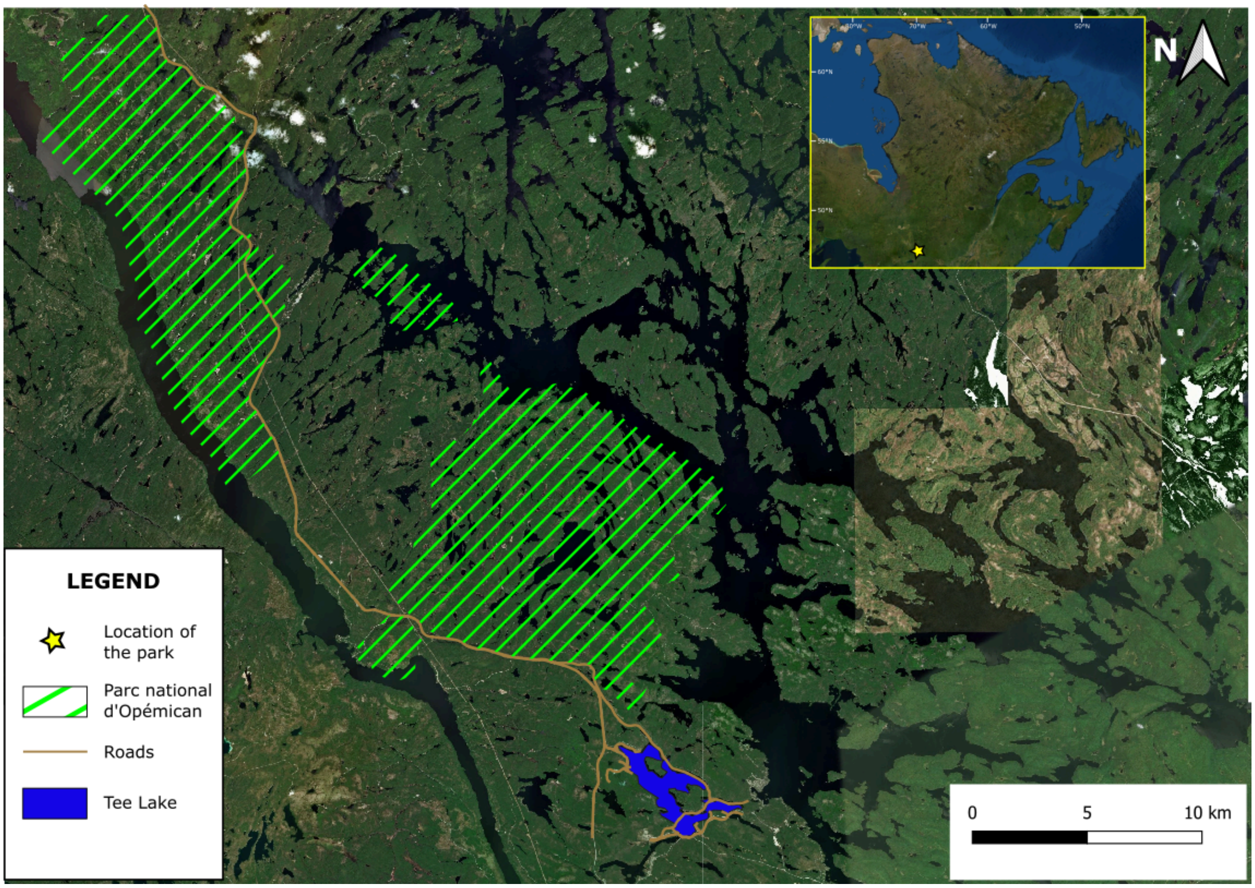

Figure 1. Location of the Parc National d’Opémican and Tee Lake where sunken logs were collected in Témiscamingue region, southwestern Québec, Canada

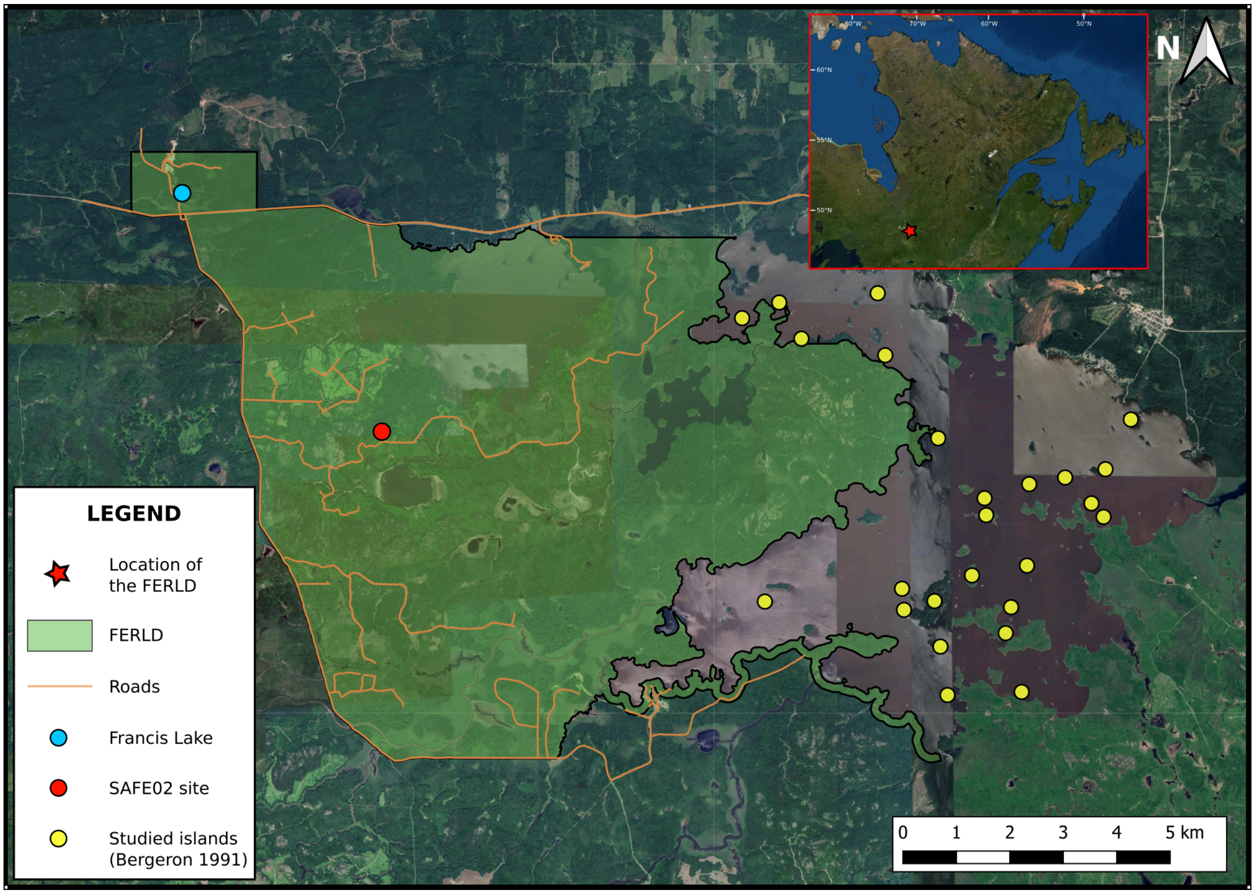

Figure 2. Location of SAFE02 and Lake Francis within the Teaching and Research Forest of Lake Duparquet (Forêt d'enseignement et de recherche du Lac Duparquet, FERLD) in southwestern Québec, Canada. Lake Duparquet is the largest lake on the eastern side of the image.

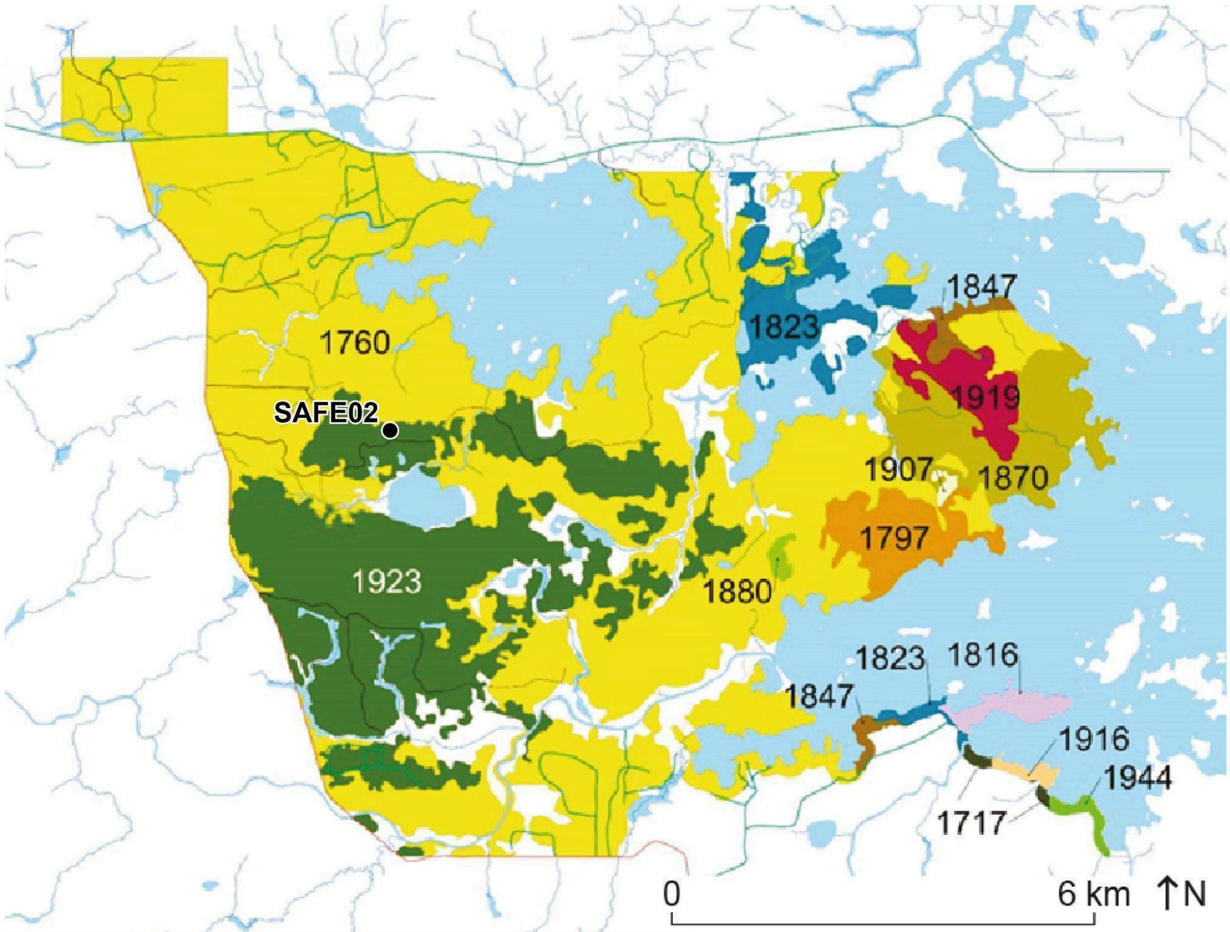

Figure 3. Reconstructed burned areas and corresponding fire years in the Teaching and Research Forest of Lake Duparquet (Forêt d'enseignement et de recherche du Lac Duparquet, FERLD; adapted from Dansereau & Bergeron, 1993; reproduced with permission from the International Research Laboratory on Cold Forests). Individual burned areas and fire years were reconstructed from tree age structure and fire-scar records (Dansereau & Bergeron, 1993). Lake Duparquet is the largest lake on the eastern side of the image.

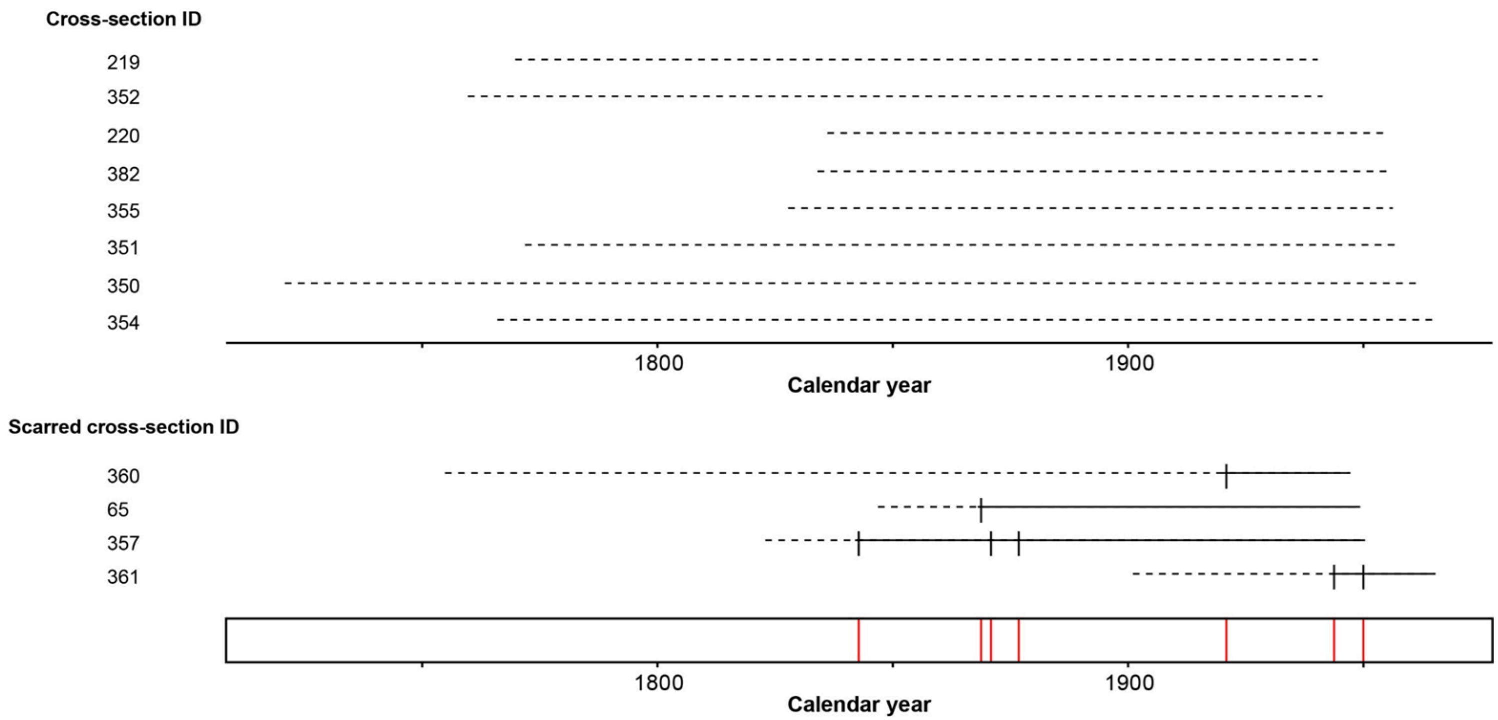

Figure 4. Length of series and fire records from 1721–1965 for the eight cross-sections (top panel) and four fire-scarred cross-sections (middle panel) recovered as sunken logs from Tee Lake. The top and middle panels show the temporal extent of the series not recording fire as a dashed horizontal black line, the fire recording extent as a black horizontal line, and each fire year as a black tick. The bottom panel shows the composite fire record across the four fire-scarred cross-sections with the seven fire years as red bars.

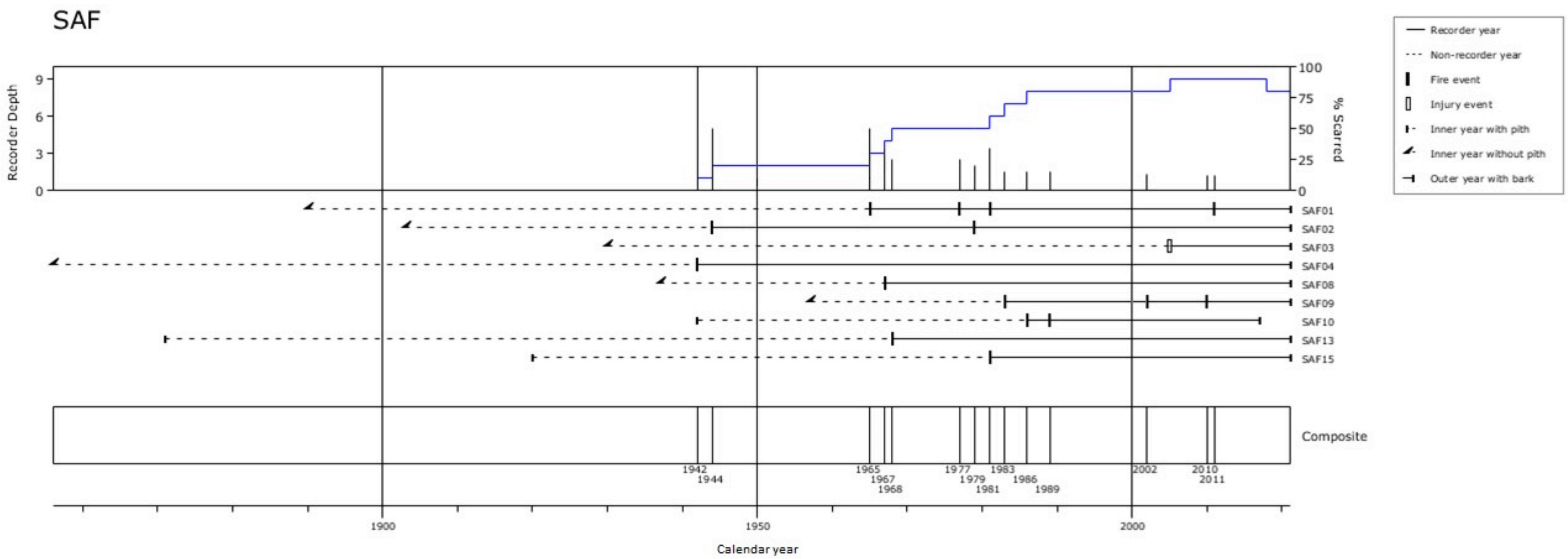

Figure 5. Length of fire records from 1852–2021 for the nine fire-scarred cross-sections collected from SAFE02 in the Teaching and Research Forest of Lake Duparquet (Forêt d'enseignement et de recherche du Lac Duparquet, FERLD). The top panel shows the sample depth curve (blue line) and percent scarred samples (black columns). The middle panel shows the temporal extent of non-recording years as dashed horizontal black lines and the fire recording extent as a black horizontal lines, with each fire year as a black tick or an injury event as an open tick. The bottom panel shows the composite fire record across the nine fire-scarred cross-sections with the 14 fire years as black bars.

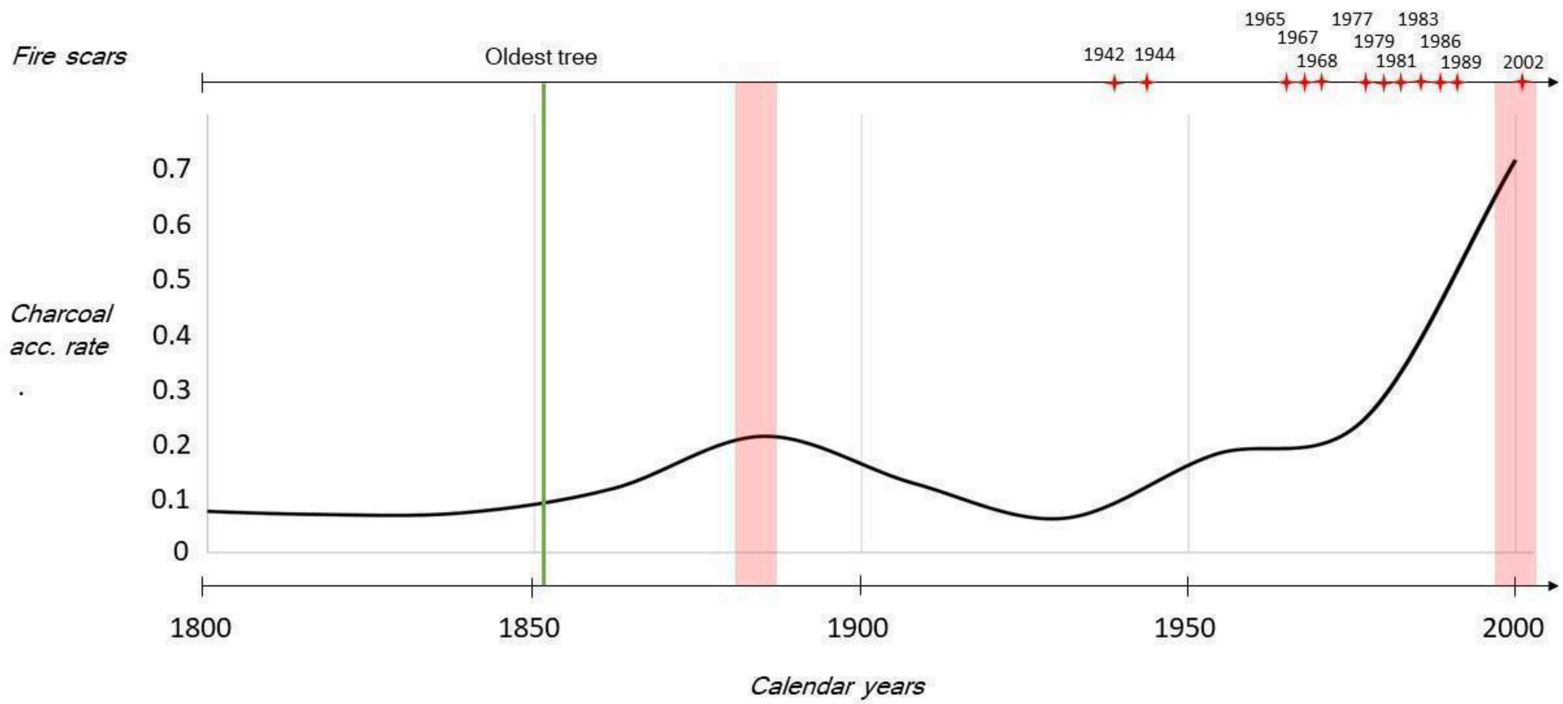

Figure 6. Summary of fire years obtained from 1800 to 2002 with 12 scars on seven cedar trees sampled at SAFE02 in the Teaching and Research Forest of Lake Duparquet (Forêt d'enseignement et de recherche du Lac Duparquet, FERLD), and charcoal accumulation rate (mm^2 cm^2 yr^{-1}) with significant charcoal peaks (light red areas) detected by CHARanalysis in Lake Francis. Note that a 150 years smoothing window was used to differentiate charcoal peaks from background noise.

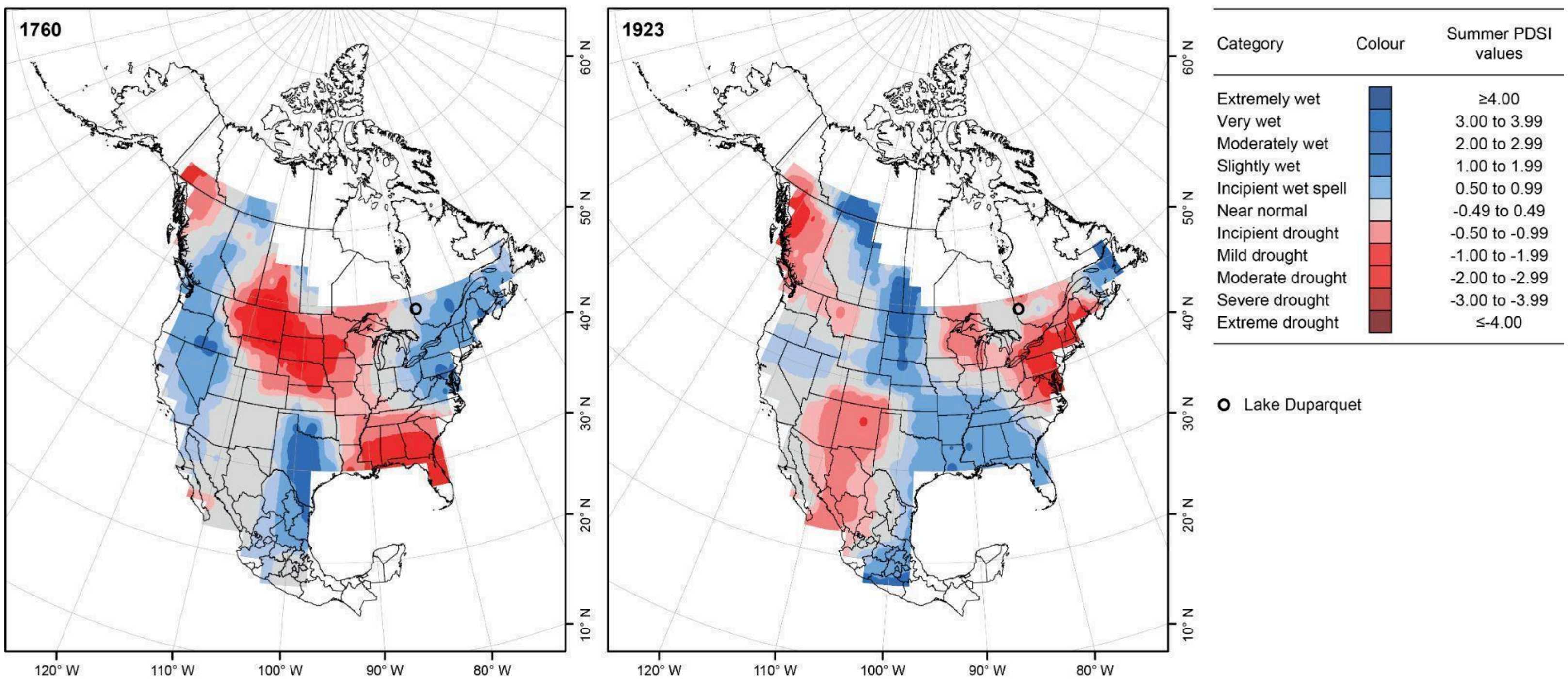

Figure 7. Reconstructions of mean summer Palmer Drought Severity Index (PDSI) values (Cook et al., 2004) interpolated across North America for the 1760 and 1923 calendar years. Categories and thresholds for summer PDSI (Palmer, 1965) and the location of Lake Duparquet in western Québec Canada are shown in the right panel.

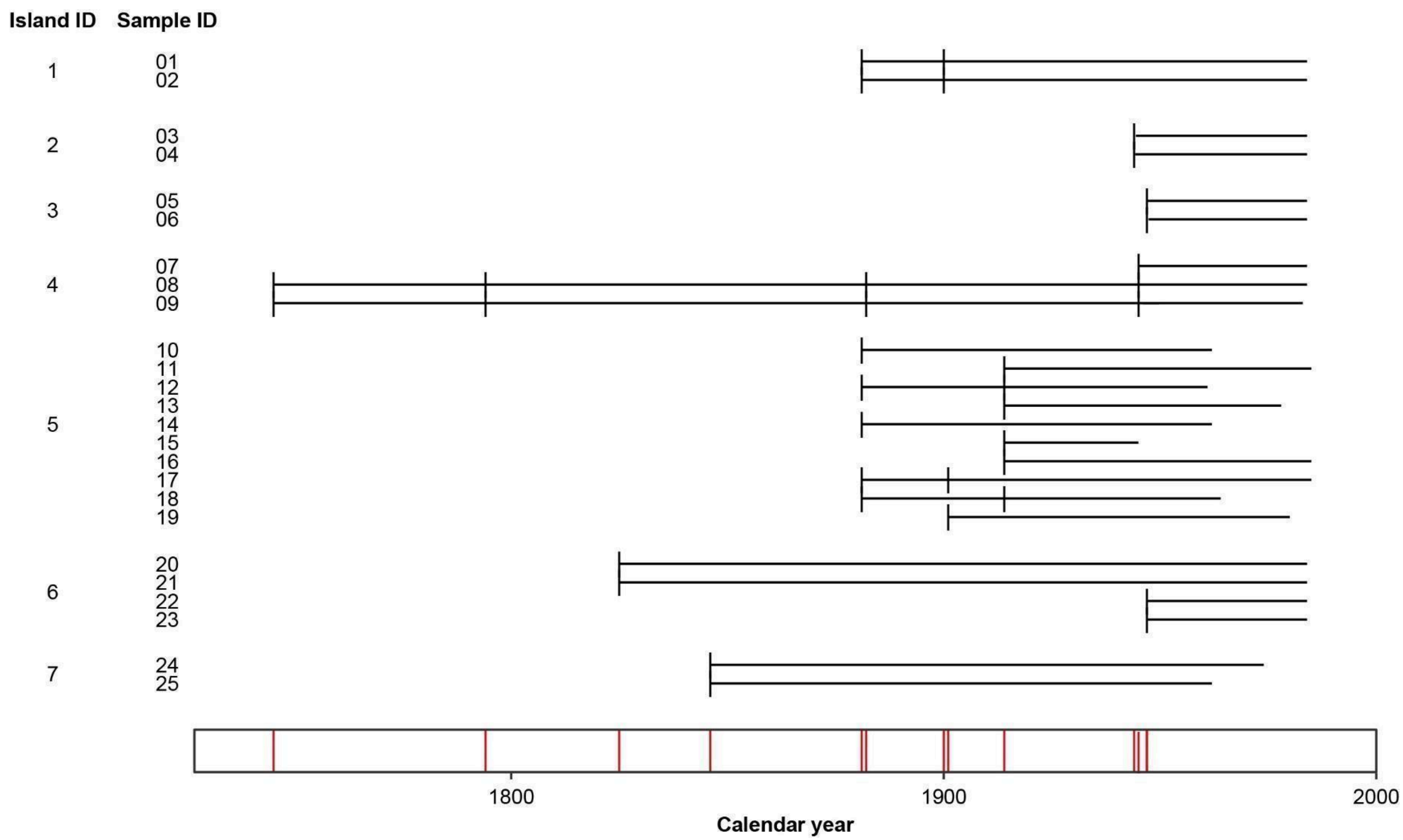

Figure 8. Fire records from 1745–1984 for the 25 fire-scar samples with fire years on seven islands of Lake Duparquet. The top panel shows the temporal extent of each fire record as a horizontal line and each fire year as a black tick. The bottom panel shows the composite fire record across islands with the 12 fire years as red bars.

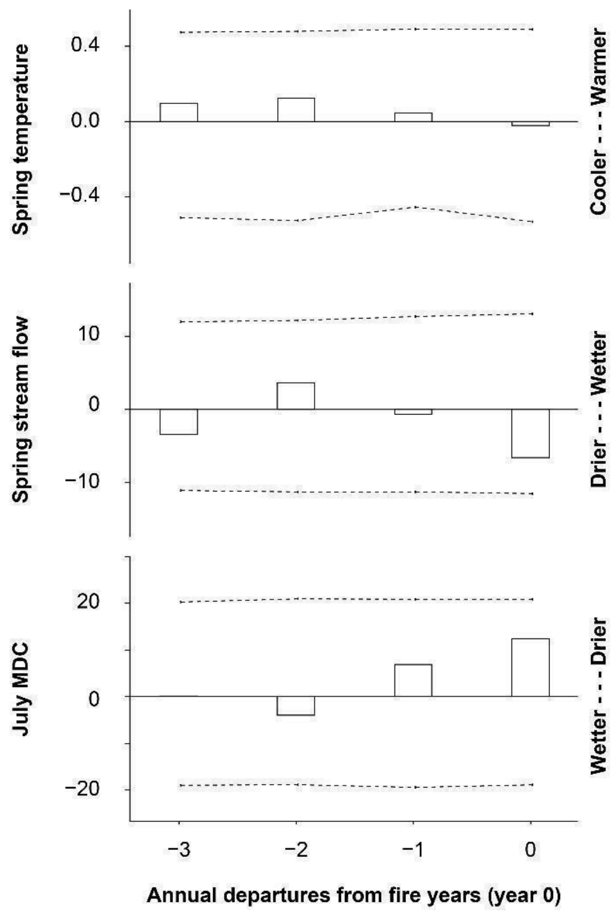

Figure 9. Superposed epoch analyses showing associations between reconstructions of climate during fire years from 1771–1984. Reconstructions of regional climate correspond to a reconstruction Spring temperature and Spring stream flow for Lake Duparquet (Nolin et al., 2022), and a reconstruction of the July Monthly Drought Code (MDC) for the eastern Abitibi-Plains (Girardin et al., 2013). Dashed lines represent confidence intervals of 95%. Bars indicate departures from the mean.

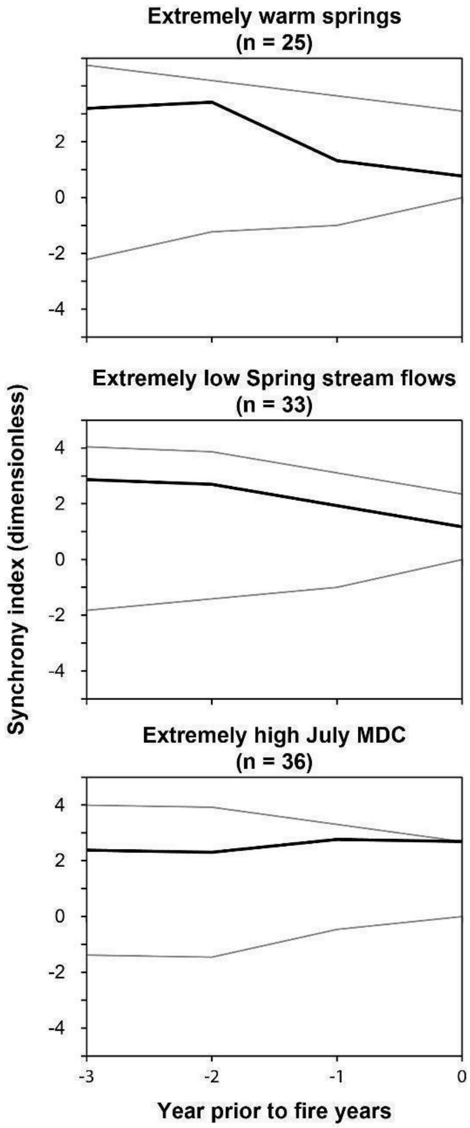

Figure 10. Bivariate event analyses showing associations for fire years during coinciding and preceding extremely warm springs or extremely low spring stream flows according to the reconstructions of Spring temperature or stream flow, respectively (Nolin et al., 2022), and extremely dry July's according to the reconstruction of the July Monthly Drought Code (MDC; Girardin et al., 2013). Solid black lines represent reconstruction indices and grey lines the 95% simulation envelopes, respectively. Reconstruction indices at or above the upper envelopes indicate synchrony with fire years whereas indices falling between envelopes are not statistically significant and indicate independence from fire years.