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Abstract. The North American boreal forest has been developing since the end of the last glaciation approximately 10,000 yr ago. With climate warming and human occupation, it is anticipated that fire danger, ignition, and activity will be increasing, compromising forests' benefits for generations to come. In this study, we show, however, that a century of rapid climate changes and human densification has had the opposite effect in the boreal eastern interior of the North American continent, reducing biomass burning to values below two millennia of historical levels. A multi-millennial fire history was reconstructed for eight forested landscapes from the Lake of the Woods Ecoregion (LWE) located at the boreal–prairie ecotone. Fire history was reconstructed using a combination of archival (period 1920–2010), tree-ring (stand initiations and fire scars: period 1690–2010), and lake sediment charcoal (2500 BP to present) records. The archival record revealed recent large fires (>200 ha) in 1948, 1980, and 1988. An additional 19 fires were identified by the fire-scar record. Fire events in 1805, 1840, 1863, and the 1890s were identified in numerous locations around multiple lakes suggesting that they were of large extents. In accordance with the tree-ring record, the charcoal accumulation rate (CHAR) peak record generally identified the major fires but tended to lag from the tree-ring records by several decades. Within LWE, the long-term charcoal record revealed that CHAR was higher for each lake in the earlier portion of the record including the warm Medieval Climate Anomaly (AD −900 to AD 1000), followed by a progressive decrease toward the cool Little Ice Age period. This decline was abruptly interrupted in the mid- to late 19th century with large synchronized fires, also reported over western and central North America, and resumed approximately four decades later. Fire disturbance level is today below the historical range, despite the accentuated climate warming. Aging of the forest landscape may create biodiversity loss notably in fire-adapted species while at the same time setting the tone for major fires in upcoming decades if no action is taken for managing fuels.

Key words: boreal–prairie ecotone; climate change; fire scars; lacustrine charcoal particles; millennial fire history; paleoecology; post-fire stand initiation; south-central Canada; tree-rings.

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Introduction

The boreal forest is a globally important biome that covers ~8% of the Earth's land surface (Pan et al. 2013). It provides critical services to local, regional, and global populations (Gauthier et al. 2015). Communities, including indigenous ones, benefit from ecosystem services provided by the forest for fishing, hunting, leisure, and spiritual activities. Forest resources further represent a vital part of the national economies of northern countries such as Canada, Finland, Sweden, and Russia by providing 60% of the harvested softwood timber worldwide (Gauthier et al. 2015). These forests are also estimated to store ~272 Pg of carbon or approximately 32% of terrestrial vegetation biomass, mostly in the form of necromass (Pan et al. 2013). The boreal forest is a dynamic system in which fire has always been a primary natural process, driving physical and biological attributes of the landscapes (Bowman et al. 2013). For instance, in Canada fire has been an important disturbance shaping the boreal forest since the end of the last glaciation about 11,700 yr ago, and much of the current forest is the legacy of these past disturbances (Larsen 1980, Engelmark et al. 1993, Stocks et al. 2003, Boulanger et al. 2017, Drobyshev et al. 2017).

There is increasing concern under climate change that a higher fire activity combined with long exposures of forest stands to fire risk will significantly compromise forests' benefits for generations to come (Gauthier et al. 2015). Evidence of increasing fire activity in northwestern and northeastern Canada initiated by climatic warming and atmospheric drying during the late 20th to early 21st centuries is already cumulating in analyses of agencies' fire statistics and other measurements (Gillett et al. 2004, Girardin et al. 2013, Mansuy et al. 2013). In contrast, areas of declining fire activity are reported in many southern boreal areas of eastern and western Canada, particularly in managed forests (Girardin et al. 2013). These regions have experienced significant increases in summer precipitation since ~1850 AD, likely brought by a strengthening of the Continental Polar Trough and jet stream displacement, which have contributed to increasing moisture content in deep-organic layers (St. George 2007, Meyn et al. 2010, Girardin et al. 2013, Drobyshev et al. 2017). Albeit climate is likely to be a primary driver of this decreasing fire activity during recent decades, other confounding effects from European settlement and passive and active fire suppression may also have played a key role in driving these trends (Lefort et al. 2003, Tardif 2004, Tardif et al. 2016). Heterogeneity in fire activity underscores the complexity of the above-mentioned ecosystem functioning. The relatively short fire records that currently exist for the boreal forest also add difficulties in interpreting fire activity trends; they were collected during a period of widespread landscape development and fire suppression that may not accurately represent naturally evolving conditions (Murphy et al. 2000). While at regional to sub-continental scales it is possible to assign causal factors to observed trends in fire activity (Gillett et al. 2004, Macias Fauria and Johnson 2006), at a local scale, the results may be bounded by major uncertainties and are subject to debate (Cumming 2005, Woolford et al. 2010).

The determination of past forest fire variability is an important area of research that enables placement of current fire observations into an historical context (Ali et al. 2012, Kelly et al. 2013), provides management guidelines (Cyr et al. 2009, Tardif et al. 2016, Bergeron et al. 2017), and further aids in the prediction and interpretation of future fire projections anticipated with climatic changes (Macias Fauria and Johnson 2006, Girardin et al. 2013). Fire history and vegetation assemblages can be reconstructed through ecological investigations using indicators such as exactly dated fire scars, stand initiations, and lake sediments, each providing a distinct proxy record of past conditions. Fire scars are typical of low severity surface fires or along the lower severity edges of high severity crown fires (Falk et al. 2011, Johnson and Kipfmueller 2016). Stand initiation in the boreal forest is typically related to stand-replacing crown fires, and dating of even-aged stands can be used as an indicator of past fire events given that a number of boreal species have developed specific adaptations to facilitate post-fire regeneration (Johnson 1992, Johnson and Gutsell 1994, Whitlock and Bartlein 2003). The regeneration, growth, and scarring traits of trees, combined with the persistence of successive cohorts within the forest, allow for the determination of the spatiotemporal trends in fire occurrence (Heinselman 1973, Clark 1990, Weir et al. 2000, Bergeron et al.

2004). Finally, paleoecological investigations are particularly suited to fire history reconstructions and can extend the record beyond that provided by archival and tree-ring records (Whitlock and Larsen 2002). Charcoal particles sequestered in lake sediments are commonly used to reconstruct fire histories at centennial to millennial time scale (Ali et al. 2009*a*, Higuera et al. 2010, Kelly et al. 2013).

The objective of this study was to reconstruct the fire history of the past two millennia in the boreal eastern interior of the North American continent using a multi-proxy approach. No long-term fire history reconstruction has been conducted therein. The study area is located at the transition between the Boreal Shield, Prairies, and Great Lakes–St. Lawrence Ecozones, where landscapes are subject to impacts from ongoing human-caused climate changes (Frelich and Reich 2010, Price et al. 2013). Eight kettle lakes and their surrounding forests were sampled focussing on the presence of fire scars, post-fire even-aged stands, and charcoal particles in lake sediments. Establishment of a fire history in the area was necessary to provide information on long-term changes in fire–climate associations (Harvey et al. 2017), on the potential effect that Indigenous and European land use have had on fire activity (Johnson and Kipfmueller 2016, Tardif et al. 2016), and to guide management targets for maintaining the long-term benefits provided by these forests (Gauthier et al. 2015, Cyr et al. 2009, Girardin and Terrier 2015, Tardif et al. 2016, Bergeron et al. 2017).

Materials and Methods

Study area

The study area is located in the southern boreal forest of central Canada, in the eastern interior of the North American continent, in the Lake of the Woods Ecoregion (hereafter LWE) along the border between the provinces of Manitoba and Ontario (Fig. 1). The LWE occupies the southern-most portion of the central Boreal Shield Ecozone (ESWG 1996). The LWE's actual burn rate approximates 0.2%/yr to 0.5%/yr with about 40% of the area burned resulting from human ignition, 58% from lightning ignition, and the remaining 2% being of an unidentified source (period 1959–1999; Stocks et al. 2003, Boulanger et al. 2017). As a response to climate change, it is expected that the prairie ecotone could move northeast, synchronous with an increase of disturbances like fire leading to a reduction in the extent of the boreal forest (Frelich and Reich 2010, Karmakar et al. 2015).

The geology of LWE is comprised mainly of massive crystalline Archean rocks and limestone (ESWG 1996, Smith et al. 1998, Crins et al. 2009). The entire LWE was extensively covered by glaciers during the last glaciation up until approximately 12,000 yr ago, followed by the transition to coverage by glacial Lake Agassiz, which ended around 8000 BP (Thorleifson 1996). Bedrock is overlain with thick to thin glacial till, fluvioglacial, and glacial Lake Agassiz deposits (ESWG 1996, Smith et al. 1998, Crins et al. 2009). The topography is comprised of undulating terrain alternating between upland bedrock outcrops and lowlands (ESWG 1996).

The climate of LWE is characterized by short, warm summers and long, cold winters (ESWG 1996, Smith et al. 1998, Crins et al. 2009). For Indian Bay (Manitoba: 49.63° N, 95.12° W) and Kenora (Ontario: 49.78° N, 94.45° W) communities, the highest mean July temperature ranged from 19.1° to 19.7°C and the lowest mean January temperature ranged from −17° to −16°C, respectively (GCCN 2016; period 1981–2010). Mean annual precipitation ranged between 630 mm at Indian Bay and 715 mm at Kenora, of which approximately 536 mm falls as rain (GCCN 2016).

Dominant tree-species include black spruce (*Picea mariana* (Mill.) BSP), jack pine (*Pinus banksiana* L.), white spruce (*Picea glauca* (Moench) Voss), northern white cedar (*Thuja occidentalis* L.), balsam fir (*Abies balsamea* (L.) Mill), trembling aspen (*Populus tremuloides* Michx.), paper birch (*Betula papyrifera* March), and other hardwoods (ESWG 1996, Smith et al. 1998, Crins et al. 2009). This area also represents the northwestern limit of the continuous distribution of red pine (*Pinus resinosa* Ait.) and eastern white pine (*Pinus strobus* L.).

Archaeological evidence traces human activities in the study area to approximately 8000 yr ago (Dickason 1992, McMillan 1995). At the time of European contact, the boreal forest region of central North America was occupied by Native Americans of Anishinaabe heritage (Dickason 1992). The Anishinaabe people practiced limited slash-and-burn agriculture and largely subsisted

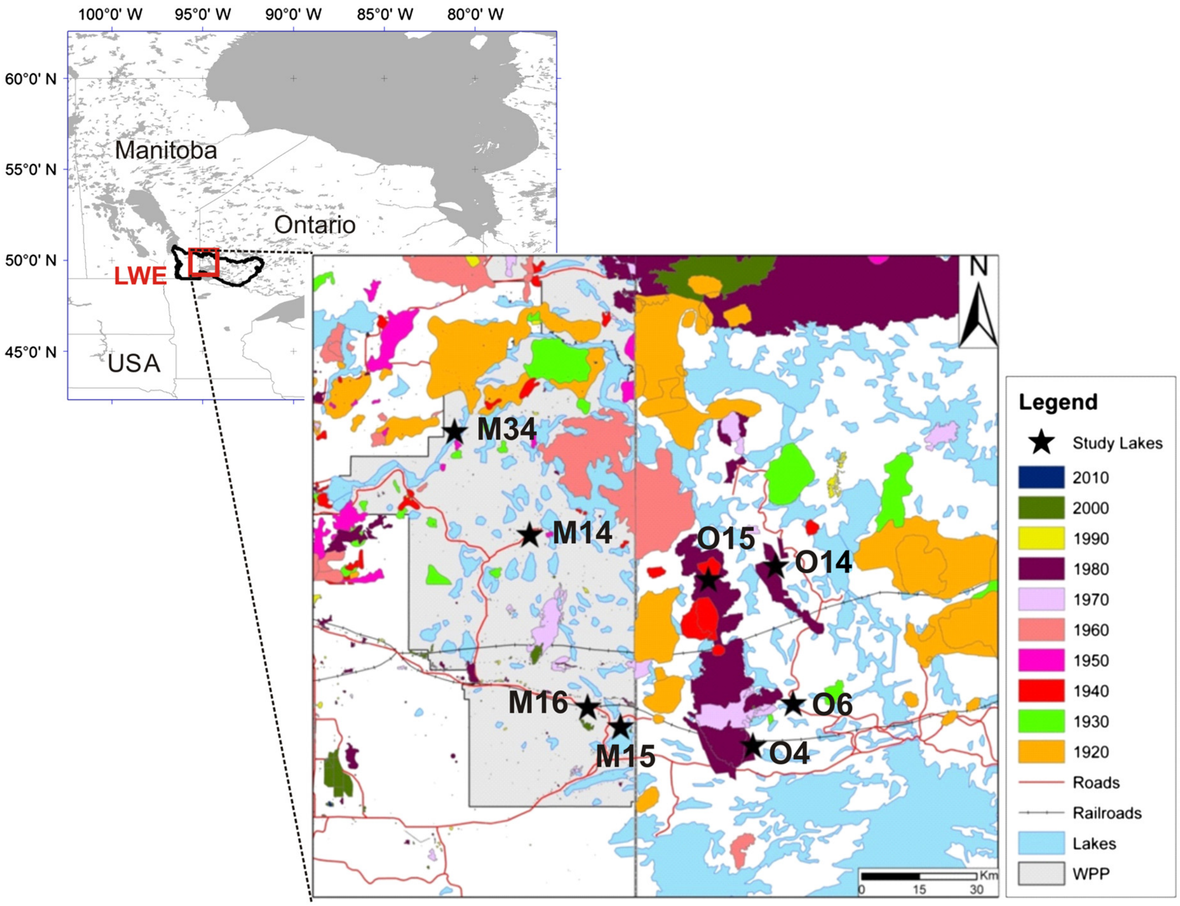

Fig. 1. Map of the study area in the Lake of the Woods Ecoregion (LWE; black line) and the archival record of fires that occurred since 1920. The Ontario record only contains fires >200 ha in size, whereas the Manitoba record contains all recorded fires regardless of size. Data were obtained from the Manitoba and Ontario provincial fire database. The study lakes are indicated by the black stars. The extent of Whiteshell Provincial Park (WPP) is shown by the gray shading.

on hunting and gathering activities. The arrival and expansion of European settlement into central North America began during the 17th century in relation to the fur trade (McMillan 1995). The earliest establishment of a modern transportation network through the area was in the 1860s (Wightman and Wightman 1997, Davidson-Hunt 2003). Railway construction through the area began in 1874. Large-scale logging began in the 1880s and was sustained until a sharp decline in the 1930s; from 1984 to 2015, the rate of harvesting in the study area ranged between 0.016%/yr and 0.037%/yr (Guindon et al. 2014; J. Barette, D. Paré, and F. Manka, *unpublished data*). A period of road construction occurred in the 1930s. A number of additional roads were constructed over time within the study area.

Fire statistics

Wildland fire statistics and forest resource inventory information were obtained from the Manitoba Land Initiative (http://mli2.gov.mb.ca) and Land Information Ontario (https://www.ontario.ca/page/land-information-ontario) data warehouses, each providing a record of fire activity from 1920 to present day. The Ontario record only contains fires >200 ha in size, whereas the Manitoba record contains all recorded fires regardless of size. Alexander (1981) and Murphy et al. (2000) provided an overview of the limitations of the Canadian archival fire record prior to satellite coverage in the mid-1970s.

Lake selection and sampling

Suitable lakes (n = 8; Table 1) were determined by initial field visits to ensure that they had no inflowing streams, a minimum water depth of 1 m, no evidence of aquatic plant growth at the center, and minimal evidence of beaver activity (Carcaillet et al. 2001*a*, Whitlock and Anderson 2003). Sediment cores were extracted from the deepest point in each lake from atop the frozen lake surface in late winter 2012. A Kajak-Brinkhurst (KB) gravity sediment corer (Glew et al. 2001) was used to collect the most recently deposited material at the water–sediment interface and was extruded on site in 1.0-cm sections. A single complete sequence of sediment was collected in the form of 1-m overlapping sediment cores using a Livingston piston sediment corer (Wright et al. 1984). Sediment was wrapped in polyurethane and aluminum foil for preservation and transported to the laboratory. Sediment was stored at a temperature of 4°C for optimum preservation. In the laboratory, sediment cores were sliced into disks at contiguous 1-cm intervals.

In the summer of 2012 and 2013, the eight lakes (Appendix S1: Figs. S1–S8) were visited to collect the tree-ring record for fire history reconstruction. There were three components to the tree-ring sampling: First, a systematic survey of the lake shore was done to obtain the tree-ring record immediately adjacent to the lake (100 m); second, a survey up to the 1 km limit from the shore was conducted to obtain the local tree-ring record; and third, a regional record of fire was obtained by sampling from between 1 and 20 km of the lake. To collect the local and regional record of fire, each lake was divided into six equal portions (hereafter sectors) by drawing lines 1 km in length from their shoreline (Appendix S1: Figs. S1–S8). Samples collected within the 1 km limit of the lake comprised the local record and samples collected beyond 1 km comprised the regional record. Tree-ring sampling locations were informally pre-selected on Google Earth based on archival fire information, but final sample locations were selected based on on-the-ground observations. Pre-selection of sample locations favored areas that were more likely to retain past fire information such as around fire breaks, areas with particular topographical characteristics, or vegetation transition areas.

The sampling of the tree-ring records followed standard methods with both tree cores and cross sections collected (Heinselman 1973, Johnson and Gutsell 1994). The collection of samples had the aim of (1) determining the time-since-last-fire date (stand-initiation age), (2) developing long reference tree-ring chronologies, and (3) developing an exactly dated fire-scar event chronology. Tree-ring sampling within a site required the collection of at least two tree cores from the base of at least 10 living trees to obtain the earliest growth rings of the tree (pith). Collection of fire

Table 1. The location and physical characteristics of the eight sampled lakes and the general condition of the surrounding landscape.

Lake	Latitude (N)	Longitude (W)	Elev. (m)	Max. depth (m)	Max. length (m)	Max. width (m)	Area (ha)	KB core length (cm)	LS core length (cm)	Relief	General moisture
M14	50°04′32″	95°24′08″	330	1.2	400	345	8.6	51	97	Low	Hydric
M15	49°47′09″	95°11′25″	337	5.7	513	125	5.3	41	96	Med	Xeric
M16	49°48′57″	95°15′56″	341	2.5	485	124	5.0	26	90	High	Xeric–mesic
M34	50°13′48″	95°34′40″	290	4.5	300	200	4.3	39	–	Low	Mesic
O4	49°45′27″	94°52′40″	366	7.2	710	230	14.6	37	98	High	Xeric
O6	49°49′17″	94°47′01″	361	3.3	436	208	6.3	44	93	Med	Xeric
O14	50°01′42″	94°49′28″	332	8.3	360	120	7.0	36	99	Med	Xeric
O15	50°00′29″	94°58′57″	339	3.9	461	192	6.2	22	97	High	Xeric–mesic

Notes: The relief column represents general topography ranging from low-lying areas surrounded by low elevation rock outcrops (Low) through to lakes bordered by steep outcrops and extensive undulating terrain (high). Elev., elevation (m); Max. dept, maximum water depth; Max. lengt; maximum length of the lake; Max. width, maximum width of the lake; KB, Kajak-Brinkhurst core length; LS, Livingstone core length. En dash indicates not applicable.

scars from living trees entailed removal of a wedge that contained the scar and the pith if possible, whereas the collection of material from snags, downed trees, and logs entailed removing a full cross section.

Multi-millennial fire history reconstruction

Age–depth models.—To obtain an age–depth model for surface sediments, ^{210}Pb measurements were performed from the uppermost 12–20 cm of the sediment cores. ^{210}Pb values (Appendix S2: Table S1) were inferred by measuring the activity of the daughter product, that is, ^{210}Po, by alpha spectrometry assuming an equal concentration between the two isotopes. The ^{210}Pb concentrations were interpreted using the constant rate of supply model of ^{210}Pb accumulation (Appleby and Oldfield 1978). As the difference between the unsupported ^{210}Pb concentration and the background (supported ^{210}Pb) concentration decreases with sample depth, the uncertainty of age estimation increases.

Radiocarbon dating of terrestrial plant macroremains and/or bulk gyttja samples allowed extending the chronologies downcore (Appendix S3: Table S1). Macroremains included needles, leaves, roots, seeds, wood, and bark. The ^{14}C dates were calibrated using the CALIB (Ver. 7.0; Stuiver and Reimer 1993) based on the IntCal13 dataset (Reimer et al. 2004). Age–depth models (Appendix S4: Fig. S1) were obtained using the MCAgeDepth program (Higuera 2008), which applies a Monte Carlo resampling technique to assess median ages and to generate confidence intervals (CI) around the fit, based on the probability distribution of each date.

From charcoal particles to biomass burning.—For charcoal analysis, a 1-cm^3 sub-sample was removed from each 1-cm sediment slice and soaked in a 3% ($NaPO_3$) solution before wet sieving through a 160-μm mesh. Typically, charcoal fragments larger than 160 μm are mostly produced by fire events within 1–30 km of the shore of the sampled lake, allowing fire events to be reconstructed at the local scale (Lynch et al. 2004, Higuera et al. 2007, Oris et al. 2014). For each 1 cm^3 of sediment processed, images of every charcoal particle on the sieve were captured at 20× magnification using a Nikon DS-FI1 digital camera attached to a Nikon Eclipse 200 dissecting microscope connected to a computer with the NIS Elements Basic Research Imaging Software 3.0 (Nikon Instruments, Melville, New York, USA). Charcoal measurements (count and area) were then made using the software NIS Elements and then merged to obtain the charcoal record per centimeter for each lake. Exploratory analysis of the charcoal data was then undertaken using charcoal count and area (Carcaillet et al. 2001*b*, Brossier et al. 2014; Appendix S5: Figs. S1–S2). Both parameters being highly correlated (Ali et al. 2009*b*) only charcoal area is presented and analyzed.

Charcoal series from the KB and Livingstone sediment cores were merged into one continuous record for each lake. This was undertaken by examining the pattern of charcoal area and number contained within the KB and Livingstone sediment cores and determining the best overlapping position (Ali et al. 2009*a*; Appendix S6: Fig. S1). Once it was established how much the data should be shifted, the entire length of the KB was kept (because KB had more robust dating by ^{210}Pb) and the Livingstone sediment core adjusted, with overlapping Livingstone data dropped, producing a continuous record from the two merged datasets. Note that it was often observed that the KB sediment core contained lower amounts of charcoal compared to the Livingstone sediment core (Appendix S6: Fig. S1). This phenomenon was attributed to differential sediment compaction resulting from natural processes and sampling effects that led to more charcoal per centimeter in Livingstone sediment cores due to lower sample resolution at greater depths (Glew et al. 2001, Courtney Mustaphi et al. 2015).

Raw charcoal data (e.g., mm^2/cm) were converted to charcoal accumulation rate (CHAR; $mm^2{\cdot}cm^{-2}{\cdot}yr^{-1}$) and interpolated ($C_{interpolated}$) using the median sample resolution obtained from the recent sediment (1670–2010). Each lake thus had a unique median age determined (Lake M14 = 9, M15 = 11, M13 = 9, O4 = 12, O6 = 8, O14 = 11, O15 = 10 yr). The median age was derived from the most recent period (last 300 yr) and applied to the entire sediment. A median age derived from the most recent period (i.e., the upper part of the sequence) generally optimizes the detection of recent fire events (Brossier et al. 2014). The CHAR series are hereafter used to infer past biomass burning (Ali et al. 2012, Kelly et al. 2013). Finally, fire event dates (peaks) were extracted from the CHAR series using the method described by Higuera et al. (2010) and Brossier et al. (2014; Appendix S7: Fig. S1, Data S1). All these procedures were conducted using the Char Analysis program (Ver 1.1; Higuera 2009).

Fire scar and stand-replacing fire histories

The preparation and analysis of the dendrochronological samples followed standard methods (Cook and Kairiukstis 1990). The tree cores were mounted on labeled wood molding and allowed to dry for several days. Once dry, samples were sanded using a progression of sandpaper grits from 80 to 600. A similar procedure was applied for cross sections. Next, the samples were visually cross-dated. Tree-ring width measurements were obtained to an accuracy of 0.001 mm using a Velmex measuring table attached to a computer containing the J2X measuring software (VoorTech Consulting, Holderness, New Hampshire, USA). Measured series were verified using the COFECHA program (Holmes 1983; Appendix S7: Fig. S1, Data S1).

The stand-initiation database was obtained by assessing the regeneration date of pioneer species in even-aged forest stands (cohort). To establish the date of post-fire cohorts, we dated the origin of the living trees and origin of the dead trees based on the age of the oldest sampled ring. For determination of the stand-initiation dates, the number of years to the tree center (pith) was estimated for samples missing the pith by measuring the distance to it using templates of embedded concentric circles that best fitted the curvature of the innermost ring (Tardif et al. 2016). The number of years to the circle center was then estimated using an age–radius regression derived from samples for which the pith was intercepted.

Of the 1592 trees dated in this study, 859 (54%) had their pith estimated. For the trees that required pith estimation, the average age adjustment was 7.6 yr. The stand-initiation age data were binned into 10-yr age classes to obtain initiation dates for a given stand. An exactly dated fire-scar database (Data S1) was constructed by recording the date of every scar within a sample and the approximate season (position in ring) of burn (dormant period, the earlywood, or the latewood). Scars of uncertain origin were excluded from the analysis. Fire scars recorded in the dormant period were attributed to a spring fire as opposed to the fall of the previous year because of the higher prevalence of early-season fires in the boreal forest (Stocks et al. 2003). Large-scale severe fire years were identified using location of fire scars in multiple sites and checkpoints.

Fire and drought/temperature relationships

Drought is the primary climatic driver of fire activity in many forests worldwide. Nonetheless, there are numerous indications of additive effects of temperature on biomass burning in boreal forests (Balshi et al. 2009, Ali et al. 2012, Flannigan et al. 2016). Notably, warmer temperatures can lead to anomalously high fire activity through longer snow-free periods and lengthening of the fire seasons (Hirsch 1989, Ali et al. 2012, Girardin and Terrier 2015, Flannigan et al. 2016). Such relationships between biomass burning and drought and temperature conditions were examined as follows. Gridded summer Palmer Drought Severity Index (PDSI) reconstructions extracted from the North American Drought Atlas (Cook et al. 2010) were used for fire climatology analyses. This Atlas consists of 286 annual PDSI reconstructions (2.5° × 2.5° resolution grid) extending several centuries into the past and was derived from 835 exactly dated, annual tree-ring chronologies. The PDSI is an estimate of relative dryness that takes into account effects of evapotranspiration and precipitation on cumulative moisture depletion in deep-organic layers, with values spanning −10 (dry) to +10 (wet). The PDSI reconstructions (n = 25) distributed with the Boreal Shield (west of 90° W) and Boreal Plain ecozones were extracted from the Atlas and then aggregated using the median statistic. The temporal coverage provided by this regional PDSI reconstruction is AD 750–2005. Additionally, we used PAGES2k's tree-ring temperature reconstructions for the North American continent (period AD 1204–1974; bounded by 30°–55° N, 95°–130° W) and the Arctic Circle (AD 1–2000; north of 60° N) (PAGES 2k Consortium 2013) to infer the associations between continental-scale temperature variability and fire activity in LWE. The rational for the inclusion of the Arctic temperature reconstruction lies in that variability over the polar region impacts the magnitude of the atmospheric long waves, and associated ridges and trough, and ultimately affects patterns of drought and fire activity in Canada's boreal forest (Macias Fauria and

Johnson 2006). A previous study indicated significant positive correlation among the 20th-century annual fire occurrence in the Boreal Shield ecozone, drought severity, and summer temperatures across a large area adjacent to the Arctic Circle bounded by 45°–60° N, 60°–110° W (Girardin and Mudelsee 2008).

Data analysis

The regional record of fire was examined by combining the fire history data of the eight lakes into a single LWE dataset for each of the following components: stand initiation, fire scar, and charcoal record. The stand-initiation distribution of each lake was normalized to the total number of initiation dates recorded on that lake, and then, the eight lake distributions were averaged so to yield a single LWE stand-initiation distribution. Fire-scar dates from all sites were combined to obtain the frequency across the study area. The lake CHAR records were transformed using the standard composite approach outlined in Power et al. (2008) and Blarquez et al. (2014) to examine CHAR regionally. Briefly, CHAR was rescaled using a minimax transformation, and variance was homogenized using the Box–Cox transformation followed by transformation into Z-scores, smoothed using a Lowess smoother, and averaged to form a composite CHAR index (Blarquez et al. 2014). The transformation was undertaken using the paleofire package in the RStudio (2014) application for R 3.0.2 (Blarquez et al. 2014). Tree-ring and lake sediment charcoal records were also examined at the lake level and in relation to the distance (<500 m, 500–1000 m, >1000 m) and aspect to the lake edge (west, east, north, south).

Survival analysis based on Cox proportional hazard models was used to estimate the fire cycle (i.e., time required to burn the entire study area) with associated 95% CIs obtained from bootstrap resampling (*coxph* function of the survival R package; Portier et al. 2016, Therneau 2016). The estimated fire cycle was defined as the time required for the cumulative hazard function (*cumhaz*) reaching a value of 1. In cases this value could not be reached, the ratio of the time corresponding to the maximum *cumhaz* and the maximum *cumhaz* was used instead. The dataset for the analysis included 443 time-since-last-fires. For a minority of these time-since-last-fires (14%), no accurate time could be attributed to the original fire because no tree cohort could be clearly identified. In these cases, a minimum time-since-last-fire based on the age of the oldest tree sampled at the site was used; these minimum time-since-last-fires were considered censored in the survival analysis (see Bergeron et al. 2004 and Portier et al. 2016 for complete details).

Additionally, a fire return interval (FRI) distribution was constructed using sampled sites where two precise fire dates were available from the fire-scar records. The distribution of the FRIs as a function of the calendar year was analyzed for temporal changes using a moving average across 30 FRI observations.

From fire event dates extracted from CHAR series, we computed the mean fire return interval (mFRI) using a kernel-density function (Mudelsee 2002) that allowed a detailed inspection of time-dependent event frequencies (Mudelsee et al. 2004). mFRI can be viewed as the inverse of an arithmetic average of all fire frequencies determined in a designated area during a specified time period and is herein expressed in n years/fire. We used a Gaussian kernel, K, to weigh observed fire event dates, $T_{(i)}$, $i,\ldots, N$ (where N is the total number of events) and calculated mFRI at each time t as:

$$\mathrm{mFRI}_{(t)} = 1/\left(\sum_i K((t - T_{(i)})/h)/h\right)/n_{(t)} \quad (1)$$

where $n_{(t)}$ equals the total number of sampled sediment cores at time t. Selection of the bandwidth (h = 200 yr) was guided by cross-validation aimed at finding a compromise between large variance and small bias (which occurs under shorter h bandwidth) and small variance and large bias (longer h). We assessed the significance of changes with the help of bootstrap CI computed from confidence bands (90%) around mFRI (Mudelsee et al. 2004). XTREND was used for analysis (Mudelsee 2002). Finally, the mFRIs were translated into their corresponding range of age classes at time t using the negative exponential model for the theoretical stand-initiation distribution described by Van Wagner (1978).

The composite CHAR index was correlated with the PDSI and the Arctic temperature reconstructions using non-parametric stationary bootstrapped correlations (Ólafsdóttir and Mudelsee 2014) and wavelet coherence (WTC) analyses (Grinsted et al. 2004). Both analyses account for the presence of serial autocorrelation in time series when testing for significance of relationships. For the purpose of the correlation and WTC analyses, the composite CHAR index was interpolated to an annual-time step, compatible with the PDSI and temperature records, using spline estimation. The WTC examines the significance and magnitude of coherence (i.e., correlation) between two time series and further reveals information about the phase relationship (delays) in a lag-period space (at a time and frequency localization). This analysis of phase relationships is relevant in a context in which the direct correlations between a CHAR index and climate variables may be made difficult due to the uncertainty of the fire record obtained from sediment cores. For each time series, the required frequency spectrum was constructed using continuous wavelet transform analysis. We used the Paul wavelet (order 4) as it is not very localized in frequency space and allows signals that are relatively aperiodic to be included in the analysis (Moore et al. 2007). The statistical significance level (90%) of the WTC against red noise backgrounds was estimated using Monte Carlo methods with $n = 1000$ iterations. Wavelet coherence was executed using the R package biwavelet version 0.20.11 (Gouhier et al. 2017).

Additionally, changes in the occurrence rate of extreme seasonal droughts were analyzed using the same kernel functions as used for mFRI computation. Drought events under analysis were those falling below the lowest 15% percentile threshold of the PDSI record and were identified using a running median smoothing ($2k + 1$ points) and the median of absolute distances to the median (factor z; Mudelsee 2006). Parameters k were fixed at 500 yr; z was set at 1.5. The bandwidth was set at 25 yr, based on cross-validation.

Finally, the average climatology for those years during which fire scars were recorded was compared to the average climatology during non-fire years using a bootstrap bias-corrected and accelerated method for comparison of two sample distributions (program 2Samples; Mudelsee and Alkio 2007).

Variability in mFRI, fire cycles, and climate over the last millennia was examined during three main periods: MCA, Medieval Climate Anomaly (AD 900–1200); LIA, Little Ice Age (AD 1500–1850); AE, Anthropocene Era (AD 1950 to present; Waters et al. 2016). The establishment of the three periods was justified based on the different climatologies that characterized those periods over central North America, particularly during the warm MCA (Laird et al. 2012) and the cool LIA (Laird et al. 2003).

Results

Recent fire history

The archival records for the recent period indicated that large fires (>200 ha) have occurred throughout LWE in almost every decade since systematic recording began in the 1920s (Fig. 1; Appendix S8: Table S1). The records also indicate spatial heterogeneity in fires among lakes. In the Manitoba portion of the study area, the archival record indicated no local (within 1 km) large fires for any of the four study lakes since 1920. Within Manitoba, the closest archival fire event to a lake occurred in 1952 for Lake M34 and in 1956 for Lake M14 (approximate distance of 2 and 5 km, respectively) and in 2002 for Lake M15 and Lake M16 (approximate distance of 2.5 and 3.5 km, respectively). The size of these fires was relatively small compared to other fires within the archival record (Fig. 1). In the Ontario portion of the study area, large fires in the archival record were recorded within 1 km of Lake O15 in 1948 and 1988, of Lake O14 in 1980, and of Lake O4 in 1988. In relation to the size of the fires that occurred around the lakes, the 1988 fire burned approximately 22,600 ha, the 1980 fire burned 3900 ha, and the 1948 fire burned about 900 ha. The closest recorded fire to Lake O6 was the 1988 fire located 4 km to the west. A large fire in 1976 also burned approximately 6 km and 5 km away from Lake O4 and O6, respectively (Fig. 1).

The regional tree-ring fire history of LWE was reconstructed by compositing the stand-initiation distribution (Fig. 2a) and fire-scar dates (Fig. 2b) for the eight lakes. In total, 1592 trees sampled from 469 sampling locations were used to develop the tree-ring fire history. Of the 469 sample locations, there was an average of 59 per lake with a minimum of 37 and a maximum of 105 (Appendix S9: Table S1). The fire history represented by stand-initiation dates was largely obtained from fire-adapted pioneer species with jack pine and trembling aspen accounting for 65% and 13% of all samples, respectively (Appendix S9:

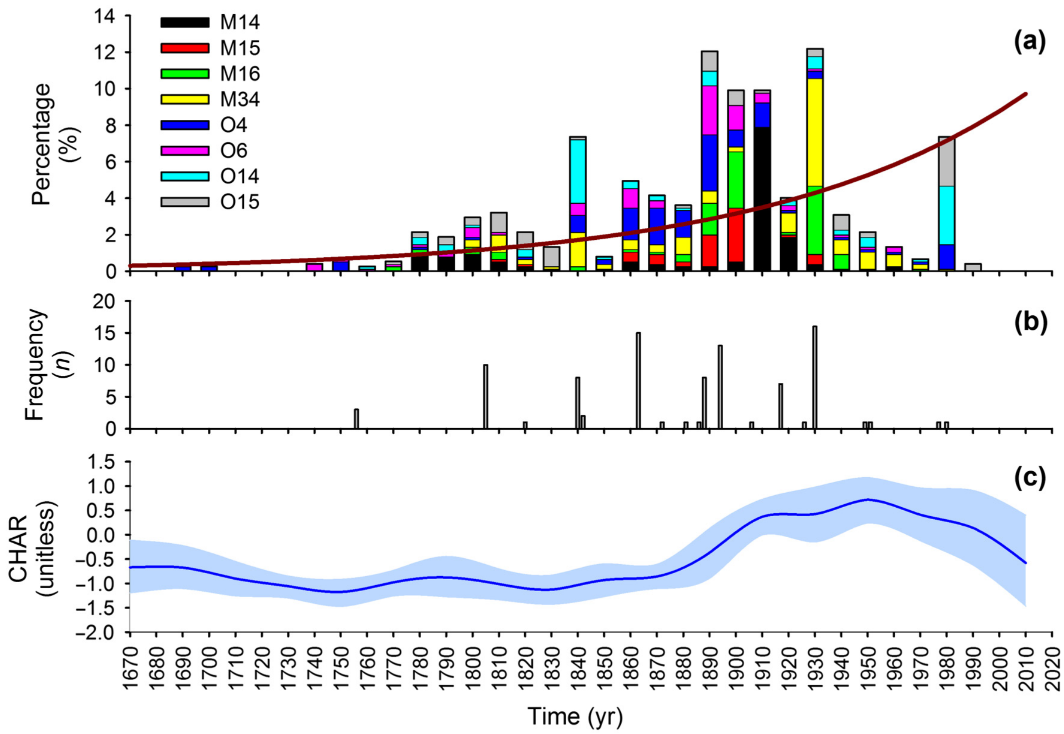

Fig. 2. Composite stand initiation (a), fire-scar frequency (b), and composite charcoal accumulation rate (CHAR) for the study region (c). The stand-initiation data (a) represent 10-yr classes (e.g., 1890 = 1890–1899) and were pooled after converting the number of trees in a given age class to percentage. The solid line is the theoretical global stand distribution assuming a constant fire cycle of 103 yr estimated using survival analysis. For (b), the distribution of fire scars between lakes is detailed in Appendix S8: Table S1). For the composite CHAR (c), the solid line represents the CHAR index based on 20-yr binning and the shaded area represents the 95% confidence intervals.

Table S1). Similarly, the fire history reconstruction from fire-scarred trees was largely from jack pine, red pine, or white pine samples collected from within 67 (15%) of the sample locations and for a total of 133 scars. From these 133 fire scars, 20 fire years were identified with 12 located within 1 km of the lakes (Appendix S8: Table S1).

The composite stand-initiation results revealed that tree recruitment occurred in almost every decade throughout the entire record (Fig. 2a). Major periods of stand initiation centered around AD 1800–10, 1840, 1860–70, 1890–1910, 1930, and 1980 were indicative of high severity fire events in the LWE. Compared to the 20th century, fires in the 19th century were also synchronous across numerous lakes from Manitoba and Ontario (Fig. 3). The 1805 fire was recorded around Lakes M14, and O6 and O15; the 1840 fire around M34, O4, O6, and O14; the 1863 at M14, M15, M16, O4, and O6; the 1894 fire at O4 and O6; the 1930 fire around M16 and O6; and 1980 around O14 and O15 had a corresponding period of stand initiation with trees also recording a fire scar. Among all lakes, Lake O4 recorded the most fire scars suggesting that a surface fire regime may have predominated. The decadal resolution of the stand-initiation records, compared to the annual resolution of the fire scar, often resulted in a delayed response between fire events and their identification within the stand-initiation data. Similarly, the 1980 archival record of fire around Lake O14 had a corresponding period of stand initiation in the 1980s and a corresponding fire scar dated to 1980. The 1988 fire around Lake O15 had a corresponding pulse of stand recruitment in the 1990s. Additional fire-scar events recorded around Lake O14 in 1951 and Lake M16 in 1977 were each located in only one sample site and did not contain an associated fire event in provincial databases (Appendix S8: Table S1).

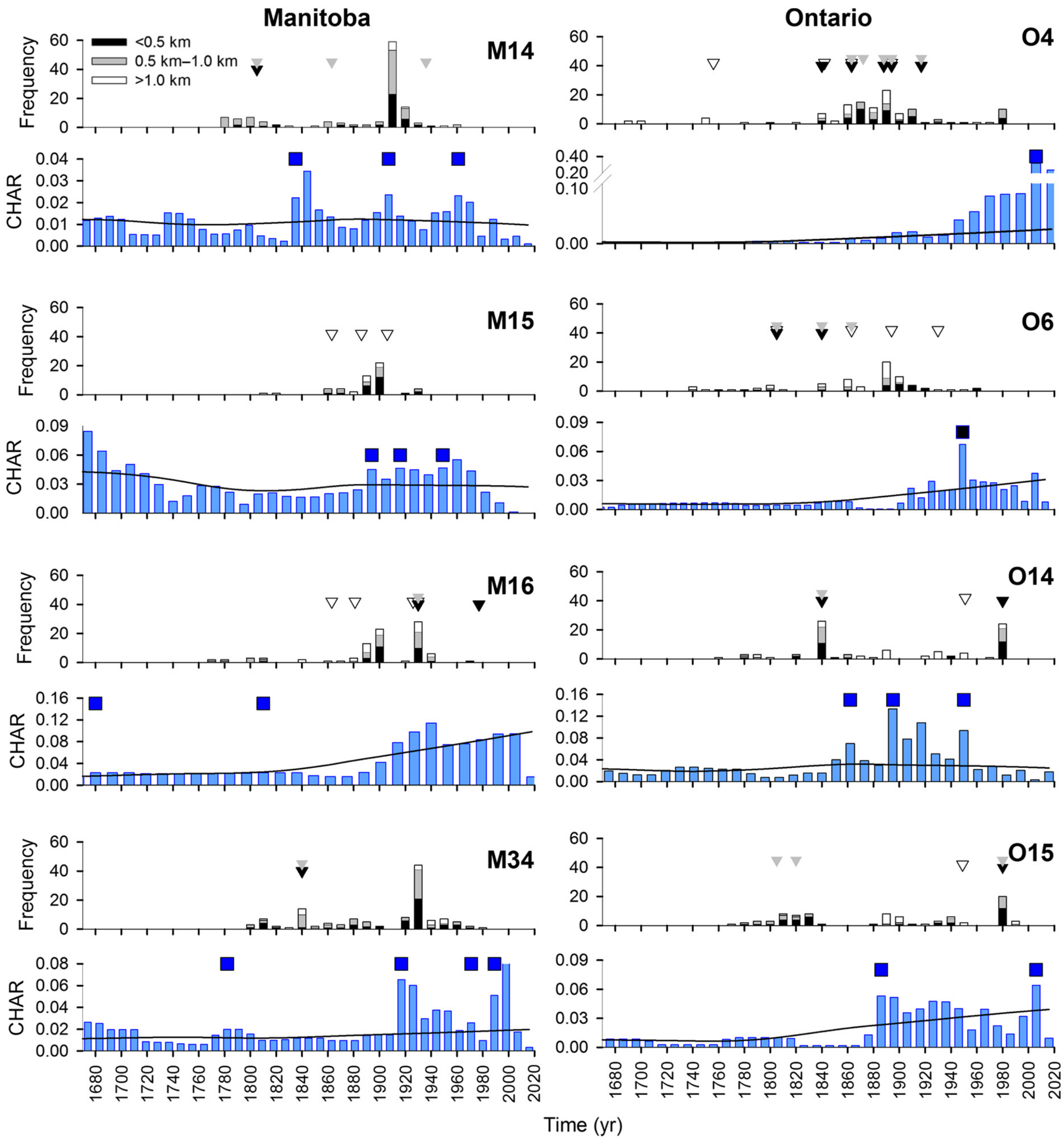

Fig. 3. Individual lake local fire record from Manitoba (left) and Ontario (right) with tree-ring (top) and charcoal accumulation rate (CHAR) (bottom) data indicated for their overlap period. In the top panel for each lake, the local (within 0.5 and 1.0 km, and >1.0 km) stand initiation is represented by bars (frequency, n), whereas fire-scar years are indicated by the triangles. In the bottom panel, the bars, line, and symbols represent CHAR, CHAR background, and CHAR peaks (blue squares), respectively (see Appendices S1–S10 for CHAR background computation). The CHAR for all lakes was calculated using the same parameters based on lake specific median ages. Note the different scale for the y-axes.

Multi-proxy fire data comparison

Lake-by-lake comparisons of CHAR records, stand initiations, and fire-scar events are illustrated in Fig. 3. At many lakes, the CHAR peaks often occurred 20–40 yr after the tree-ring dated fire events (Fig. 3). This is well illustrated at Lake M14 where the three separate fire events identified by fire scars had corresponding CHAR identified approximately 20 yr after the fire event (Fig. 3; Appendix S10: Table S1). More generally, an increase in the short-term CHAR composite from the mid-1800s to the mid- to late 1900s revealed a lagged response to the increased frequency of fire identified from the stand-initiation and fire-scar records between 1800 and 1940 (Fig. 2). This lag is within the expected margin of error resulting from the uncertainty of the age–depth models (Appendix S4: Fig. S1). Specifically, at the lake level, it appears that widespread fire years identified by the tree-ring stand-initiation data and/or fire-scar records contained a corresponding CHAR increase/peak associated with the 1840s (Lakes M34, O4, O14), 1863 (Lakes M14, M15, M16, O4, O6), and the 1890s (Lakes M14, M15, M16, M34, O4, O14) fire events (Fig. 3). Similarly, increased CHAR/peak identification corresponding to fire events localized around individual lakes was also observed for the 1805 (Lake M14), 1820 (Lake O15), 1930 (Lake O6), 1932 (Lake O6), and 1936 (Lake M14) fire events.

Proximity of fire to a lake had a limited effect on peak detection (i.e., <500 m or 500–1000 m; Fig. 3). As a general feature, CHAR peaks were associated with fires that occurred within 500 m of the lakes; however, not all fires occurring within 500 m of the lakes were identified as a CHAR peak (Fig. 3). Lake O14, for example, recorded no increase in CHAR despite a fire scar and recruitment corresponding to the 1980 fire (Fig. 3) being observed (Fig. 1). Further, the direction of a fire in relation to the lake also appeared to have a limited influence (not presented). Similarly, the distance between lakes had little explanatory effect as lakes in close proximity (e.g., Lakes M15 and M16; Lakes O14 and O15) often contained heterogeneous CHAR records and a unique record of fire events. Lake M15 generally contained higher CHAR values and more CHAR peaks compared to Lake M16, despite only being located 6 km apart.

The mFRI value estimated from the CHAR peaks and computed over AD 1680–2010 (i.e., 139 yr with 95% CI [107, 199]) was not statistically different from the fire cycle estimated using survival analysis applied to the 1680–2010 stand-initiation distribution (i.e., 103 yr with 95% CI [95, 108]). Therefore, although the CHAR records failed to identify some fire events and/or presented a lagged response to some fire events, the fire event dates extracted from the CHAR record can still provide reliable information on fire event recurrences at the regional scale.

Multi-millennial to decadal fire trajectories

The multi-millennial CHAR composite record revealed that charcoal accumulation has been variable over time (Fig. 4a). Between AD −500 and AD 100, the maximum CHAR within the record was observed, suggesting it was a period of maximum area or biomass burned, followed a steady CHAR into the MCA, which was followed by a continuous decline in CHAR from AD 1200 to 1600 (Fig. 4). This sustained decrease in CHAR was followed by a rapid increase around AD 1880, consistent with a lowering of the mFRIs deduced from CHAR (Fig. 5a), and synchronous with the end of the LIA. Both CHAR and mFRI leveled-off in the 1950s (Figs. 2c, 5), and CHAR declined again to reach values among the lowest in the 2500-yr CHAR record (Fig. 4a). The transition into the AE also marked a significant lengthening of the fire cycle estimated using survival analysis applied to the stand-initiation distribution, with values of 52 (95% CI [49, 55]) and 285 yr (95% CI [232, 354]) during periods AD 1680–1949 and 1950–2010, respectively. An important lengthening (threefold) of the FRI during the Anthropocene was also indicated by the distribution constructed from precisely dated tree fire scars (Fig. 5a, inset graph).

Fire history–climatology

Charcoal accumulation rate shows significant covariance with the Arctic Circle (north of 60° N) temperature reconstruction: $r = 0.57$ with 95% CI [0.38, 0.71] (Fig. 4). The WTC analysis between the Arctic temperature reconstruction and CHAR confirmed areas of significant in-phase correlation at periods of >256 yr, increasing in power since the MCA (Fig. 6). Upon visual examination, there were episodes of cool Arctic temperatures and low

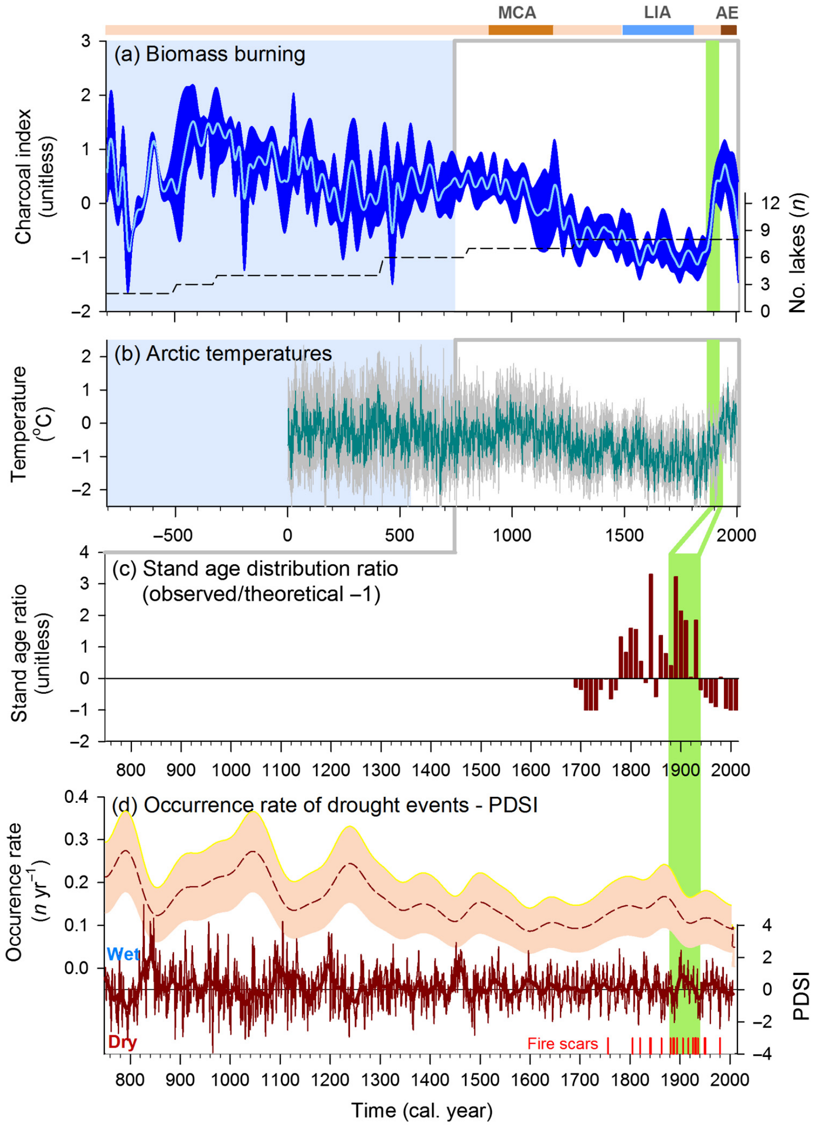

Fig. 4. Multi-millennial fire history reconstruction in Lake of the Wood Ecoregion (LWE) and associated climatology. (a) Composite charcoal accumulation rate (CHAR): The solid line represents the CHAR index based on 20-yr binning, and the shaded area represents the 95% confidence intervals (CI). Time-dependent variations in the number of sampled lakes are shown by the dashed line. (b) Arctic temperature reconstruction and uncertainty bands. (c) Ratio of the global observed stand-initiation distribution divided by the theoretical distributions (computed from Fig. 2). (d) Regional reconstruction of the Palmer Drought Severity Index (PDSI; thin-red curve) and occurrence rate of extreme drought years (dashed curve) in western boreal Canada, as inferred from tree-ring width records, and associated 90% CI (shaded area). A 10-yr second-order polynomial fitting across the PDSI is also shown, along with years during which fire scars were detected. Variability of fire activity and climatology over the last millennia was examined during three main periods: MCA, Medieval Climate Anomaly (900–1200 AD); LIA, Little Ice Age (1500–1850 AD); AE, Anthropocene Era (1950 to present). The vertical shading delineates the period of important fire activity in the LWE from the 1880s to 1930s. The Arctic temperature reconstructions and the PDSI showed no correlation over their overlapping period (r = 0.00 with 95% CIs [−0.08; 0.08]; AD 750–2000).

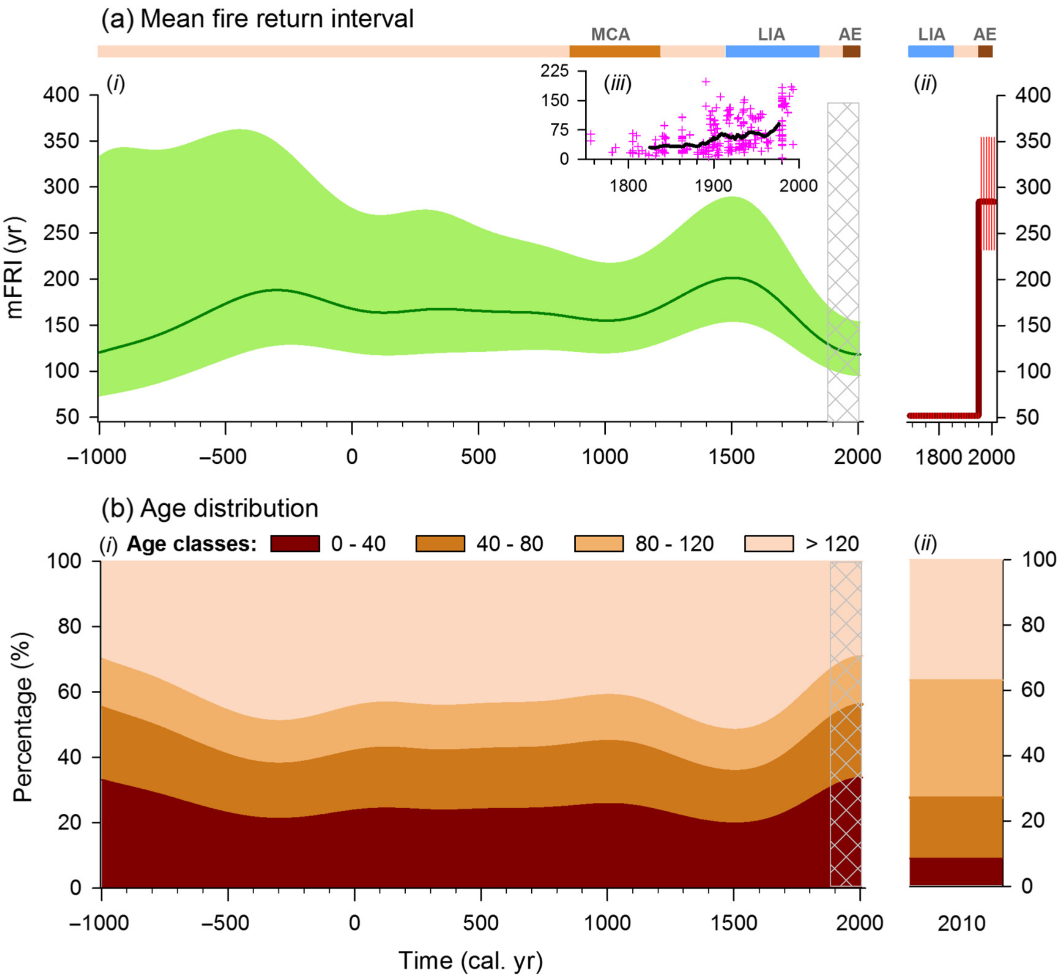

Fig. 5. (a) Multi-millennia mean fire return intervals (mFRI) and (b) evolving theoretical stand-age distribution deduced from (i) lake sediment records, (ii) reconstructed stand-initiation distribution, and (iii) tree fire-scar records. For the lake sediment records (i), time-dependent changes in the mFRI and theoretical stand-initiation distribution were computed from the PEAK analysis (solid line); 90% confidence bands are shown (shaded area). For the reconstructed stand-initiation distribution (ii), fire cycles (thick-red line) with 95% confidence intervals (error bars) were assessed using survival analysis applied to the stand-initiation distribution for periods of pre-1950 and 1950–2010; the stand-initiation distribution as of AD 2010 is shown on the right-side of panel b). In (a), the inset graph (iii) indicates the FRI distribution (n = 279) constructed using only those sampled sites where two precise fire dates obtained from sampling of fire scars were available (84% of these sites were *Pinus banksiana* stands; the black line is a running average across 50 FRI observations). Hatched areas: edge effect whereby a lag in the charred time series (see Fig. 2), and the 200-yr window bandwidth used for calculation of the mFRI with CHAR, prevent from detecting abrupt shifts in mFRI during the Anthropocene Era.

biomass burning in the proximity of the LIA period and sustained high temperatures and biomass burning during the MCA and earlier, and prior to the AE (Fig. 4). Similarly, episodes of important stand initiations during the late 1800s to early 1990s coincided with increasing Arctic temperature. Nevertheless, the relationship between temperature and biomass burned (CHAR and stand initiation) decoupled during the AE: Post-1950 high temperatures coincided with low burning activity. No significant association was found between the appearance of fire scars and Arctic temperatures.

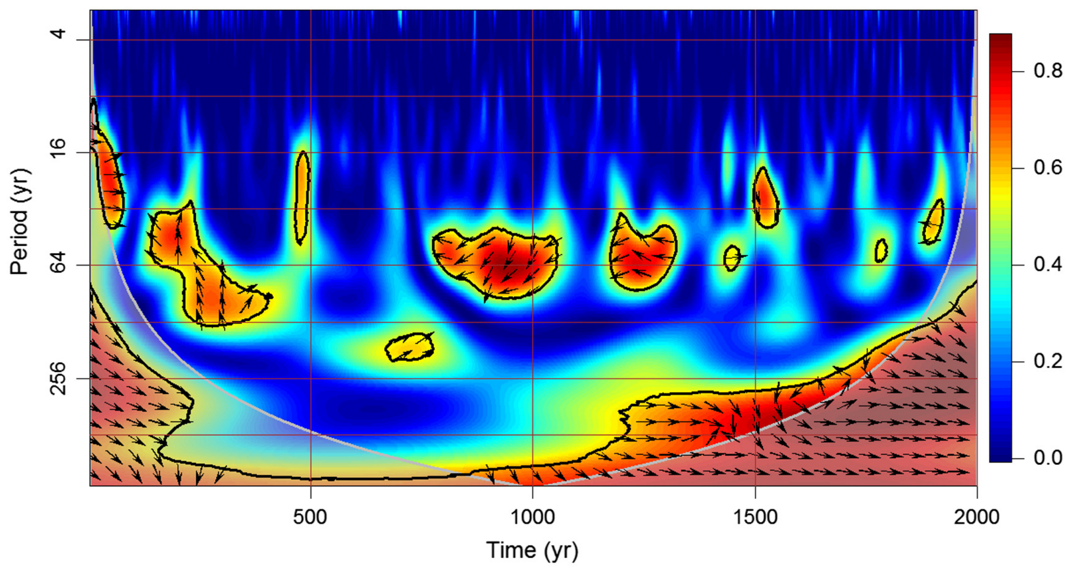

Fig. 6. Wavelet coherence between the composite charcoal accumulation rate (CHAR) index and the Arctic temperature reconstruction of PAGES 2k Consortium (2013). Areas of large common power in time and period scales between CHAR and temperature data are shown in red. The 90% significance level against red noise is shown as a thick contour. The lighter shade delineates the cone of influence where zero padding has reduced the variance. The relative phase relationship is shown by arrows, with in-phase pointing right, antiphase pointing left, temperature leading CHAR by 90° (1/4*k*) pointing up, and CHAR leading temperature by 90° (1/4*k*) pointing down. In-phase and antiphase relationships may be interpreted as positive and negative correlations, respectively, in time and period scales (Grinsted et al. 2004).

Furthermore, no relationship was found between CHAR and the North American continental temperature reconstruction (analyses not shown).

The CHAR record did not significantly correlate with the regional PDSI reconstruction (Fig. 4; WTC analyses not shown). However, episodes of stand initiations and pulses of biomass burned in CHAR visually coincided with periods of higher occurrence rate of extreme droughts. Notably, succeeding periods of high occurrence rate of extreme summer droughts from the 8th to the 16th centuries, and to some extent during the late-18th to the early-19th centuries, coincided with high biomass burned (CHAR and stand initiation). Today's occurrence rate of extreme droughts is low and similar to rates estimated during the LIA, which is again coherent with the decreasing biomass burned. Noteworthy, the average PDSI computed over years during which fire scars were detected ($\overline{\text{PDSI}} = -0.42$; $n = 20$) was significantly lower than the average PDSI during non-fire years ($\overline{\text{PDSI}} = 0.15$; $n = 237$; Student's t-test for difference in averages $= -0.58$ with 95% bootstrap CI [−0.95, −0.21]; 1750–2006 period).

Discussion

Climate and fire activity

The multi-proxy boreal fire history reconstruction presented for the prairie–boreal ecotone in the eastern interior of North America provides important insights into spatiotemporal variations in fire activity with each proxy (archival, tree-ring and charcoal) providing a unique perspective (resolution) extending back to more than two millennia. The CHAR record obtained from sediment cores likely captured low-frequency fire signals and/or the gradual changes occurring over a much longer time period. At the end of the spectrum, the tree-ring record captured the high-frequency component of the fire regime and making it possible to examine the fire–climate interactions on a factual basis. These complementary features constitute a major strength of multi-proxy approaches allowing as in this study to gain a comprehensive view of the fire regime of the region.

Within LWE, biomass burning was highest in the earlier portion of the studied period (AD −500 to 100) and lowest during the LIA (AD 1500–1850). This long-term variability in the composite CHAR record is broadly consistent with other results near our study area (Ali et al. 2009*a*, 2012, Moos and Cumming 2012) and with the North American CHAR composite results of Marlon et al. (2013). Nevertheless, it is inconsistent with regional fire records from southeastern and eastern boreal Canada and Alaska where biomass burning peaked around the MCA (Senici et al. 2010, Girardin et al. 2013, Kelly et al. 2013, Rémy et al. 2017). High CHAR values in the early portion of the record are synchronous with the high temperatures prevailing in the Arctic and North American continent during that time (PAGES 2k Consortium 2013; Fig. 4). The maximum CHAR around AD −200 is also timely with a period of decreased moisture availability in central North America. For example, Haig et al. (2013) examined diatom species assemblages within their sediment cores from Gall Lake in northwestern Ontario (west from LWE) and estimated that lake water levels around 2000 yr BP were over a meter below the Holocene average. The CHAR record suggests that fire activity during the MCA was also generally higher than that observed for the post-MCA period. This observation is also consistent with Haig et al. (2013) indicating that MCA conditions resulted in lower water levels within northwestern Ontario. Following the MCA, the CHAR resumed its progressive decrease where the composite record revealed the lowest CHAR values for the entire record occurred during the LIA around AD 1600–1850 (the exact period being uncertain owing to the lagged response of CHAR behind the fire events; discussed in next paragraph). Haig et al. (2013) indicated that, following the MCA, lake water levels in northwestern Ontario returned to their higher, pre-MCA, levels around the beginning of the LIA. Therefore, the cooler wetter conditions responsible for this lake level change may also have contributed to the decrease in fire occurrence during the LIA. This transition from drought to moist conditions, and high to low biomass burning from post-MCA to LIA, is apparent in the examination of occurrence rates of extreme droughts deduced from the tree-ring-based PDSI reconstruction. However, we advise readers that PDSI estimates have a reduced ability to track low-frequency secular changes (consequence of the detrending of the predictor tree-ring data) and are affected by a substantial reduction in the number of site PDSI predictor tree-ring chronologies prior to the 1800s (Cook et al. 2010). Caution is thus warranted when interpreting the PDSI-CHAR relationship.

In our study, the mid-LIA marked the onset of the overlapping period between the different fire-proxy records. For fire events that were identified through both tree-ring and CHAR records, many of the CHAR peaks appeared to lag behind tree-ring records by several decades and this is a common occurrence related to the timing of charcoal transport and deposition (Higuera et al. 2005, Conedera et al. 2009, Brossier et al. 2014). Higuera et al. (2005) observed that a CHAR peak associated with a severe 1890 fire identified within tree-rings occurred 36 yr after the actual fire event. Within LWE, the lagged response is well illustrated by Lake M14 where CHAR peaks in the 1830s, 1900s, and 1960s may be associated with fire events that occurred several decades before. The lagged effect is particularly evident for the CHAR composite record where a CHAR increase beginning near the end of the 19th century is contrary to tree-ring records showing a decrease in widespread fire beginning in the 1900s and can only be reconciled if related to a lag between actual fire events and the transport and deposition of charcoal. Sampling sediment cores at 0.5-cm intervals instead of at 1 cm would likely have provided a better estimation of fire peak dates in the CHAR record (see Carcaillet et al. 2001*a*). Differences between fire records would still, however, be observed given that in non-varved (laminated) lake sediments, some uncertainties will always remain due to ^{210}PB and ^{14}C dating, the merging of upper and lower sediment cores, and the processes leading to determine CHARs. Despite some incongruities, the relative agreement between archival, tree-ring, and CHAR records provides an opportunity to assess the modern fire history in relation to climatic changes and human activities.

The regional LWE tree-ring fire history reconstruction revealed that widespread fires occurred in AD 1805, 1840, 1863, and 1894, with the 1890s marking the last period of widespread stand-replacing fires around the lakes until those recently observed in the 1980s. These years correspond to known fire-prone years and major drought periods within western boreal Canada and adjacent areas. Within LWE, the fire activity in the 19th century occurred in association with periods of widespread drought throughout western and central North America (Sauchyn and Skinner 2001). Similar conditions were reported in adjacent areas of Ontario (Alexander 1981, Fritz et al. 1993), northern Minnesota (Frissell 1973, Heinselman 1973, Alexander 1981, Clark 1990), Manitoba (Tardif 2004), and western Canada (Sauchyn et al. 2015). The 1805 fire year also occurred during a period of increased fire activity recorded within Hudson Bay Company (hereafter HBC) archival records of northwestern Ontario between 1790 and 1805 (Fritz et al. 1993). Within the Boreal Shield of North America, Girardin et al. (2006) identified 1804 as the year with the most fire-prone condition for the period 1781–1982. Rannie (2001) also indicated that HBC records reported severe drought and late-season fire activity in 1804 south of modern-day Winnipeg and so the 1805 fire year may be a late-season 1804 fire or represent a multiyear drought event within central North America. Within LWE, the 1840 fire year occurred during a period between the 1830s and 1860s that the HBC archival records reported as containing lower fire activity (Fritz et al. 1993). However, reports of increased drought during the 1840s, identified through decreased ring widths (St. George and Nielsen 2002, Tardif 2004, St. George et al. 2008) and increased annual area burned (AAB) (Girardin and Sauchyn 2008) throughout central and western North America, suggested that the 1840 fire event in LWE may have been more widespread than the HBC archival records implied.

The 1863 fire event within LWE occurred during a period of particularly severe drought in the 1860s identified across North America (Alexander 1981, Sauchyn and Skinner 2001, Herweijer et al. 2006, St. George et al. 2008, 2009). Allsopp (1977) reported both year 1863 and 1864 being dominated by drought and grasshoppers. This drought period was also associated with widespread fires in 1863/1864 reported throughout northern Minnesota (Frissell 1973, Heinselman 1973, Clark 1989, 1990), northwestern Ontario (Alexander 1981, Fritz et al. 1993, Girardin et al. 2006, Scoular 2008), and Manitoba (Girardin et al. 2006). Within central North America, Fritz et al. (1993) indicated HBC archival records reported the 1860s as a transition toward increasing fires up to the end of the 19th century. Allsopp (1977) also reported 1886, 1889, and 1894 to be very dry with the growing season precipitation reaching, respectively, 37%, 56%, and 44% of the long-term average. Widespread fires in the 1880s and 1890s were reported in northern Minnesota (Frissell 1973, Heinselman 1973, Clark 1989, 1990), Manitoba (Tardif 2004, Tardif et al. 2016), northwestern Ontario (Alexander 1981, Fritz et al. 1993, Scoular 2008), and western North America (Rowe 1955, Tande 1979, Johnson et al. 1998). Similar to the other widespread fires, the conditions responsible for fires in the 1880s and the widespread 1894 fire event appear to be related to prolonged drought over a large area of central and western North America (Sauchyn and Skinner 2001, Herweijer et al. 2006, St. George et al. 2008, Sauchyn et al. 2015). This period is also timely with the onset of warming conditions across vast areas of North America, including LWE (Price et al. 2013, Jaume-Santero et al. 2016, their Fig. 8). Following the 1890's fires, HBC archival records revealed that fire activity declined into the 1900s (Fritz et al. 1993), which is consistent with information from the multi-proxy fire history. The advent of the 20th century marks a sharp transition toward a reduction of widespread synchronous fire years among large regions, likely brought by increases in the amount of precipitation associated with a strengthening of the Continental Polar Trough and jet stream displacement (St. George 2007, Girardin et al. 2009, Drobyshev et al. 2017). The 1988 fire, man-made, was the last large fire having hit the study area. Its occurrence was favored by warm, dry, and windy weather, brought with a blocking atmospheric ridge positioned over the fire area, and conducive to the rapid spread of the fire (Hirsch 1989).

Human and environmental impacts

As discussed above, climate variability from the MCA to the LIA and AE has likely played a key role in triggering changes in conditions suitable for synchronous large-scale biomass burning

(Girardin et al. 2013, Kelly et al. 2013, Marlon et al. 2013). However, human activities may also have influenced fire behavior and this point requires further examination (Johnson and Kipfmueller 2016). The archaeological evidence suggests Indigenous populations have been present in North America for at least 9000 yr (Johnson and Miyanishi 2012). During this time, fire has routinely been applied across North America for a variety of purposes, for example, maintenance of berry patches (Anderton 1999, Davidson-Hunt 2003, Ferguson 2011), improvement of grazing for hunting purposes (Day 1953, Boyd 2002, Davidson-Hunt 2003, Ferguson 2011, Johnson and Miyanishi 2012), and inter-tribal warfare (Davidson-Hunt 2003). Modern burning practices of the Anishinaabe people of central North America (north of LWE; Miller and Davidson-Hunt 2010) and the Slave people of northern Alberta (Ferguson 2011) indicate that traditional methods of lighting fires during periods of low fire risk allowed the extent of purposefully set fires to be limited. Ferguson (2011) revealed that the burning practices of the Slave people were to leave campfires burning in the fall when vacating an area with the expectation that sufficient fall snow cover would limit the extent and severity of the burn. Davidson-Hunt (2003) revealed that written reports of these fire events indicated that the intention of purposely set fires was to occasionally burn an extensive area. Although traditional burning practices may have been effective at limiting area burned in the majority of cases, there would have existed the possibility of a particular fire becoming much larger than intended or of fires occurring accidentally. Rannie (2001) referenced documentation from HBC records of a severe prairie fire that was accidentally set on 1 December 1800 and revealed that a fire could become very large despite ignition so late in the fire season. However, situations like this may have been limited to the prairies as forested areas burned less easily because of a better ability of preventing snowfall from blowing away (Ferguson 2011).

The factors contributing to the emergence of important biomass burning during the late 19th to early 20th centuries are likely including both climate and human influences. The archaeological evidence for central North America suggested that permanent settlement had not occurred within LWE until the arrival of the fur trade around AD 1600 (Fritz et al. 1993, Davidson-Hunt 2003). During the period 1786–1830, Fritz et al. (1993) identified at least 38% of the forests fire reported near the HBC trading post in northwest Ontario (north of our study area) were of human origin. A subsequent increase in settlement throughout North America beginning in the 17th century brought an increase in fire occurrence (Bowman et al. 2013) and corresponded with a CHAR increase in LWE beginning in the late LIA (AD ~1850). From then, there is possibility of confounding influences of climate and human ignition in the pulse of biomass burning observed from the late 19th to early 20th centuries: Major drought conditions associated with continued settlement expansion (Davidson-Hunt 2003, Johnson and Miyanishi 2012, Bowman et al. 2013) and increasing fire events identified in the tree-ring (Fig. 2b) and CHAR (Fig. 5a) records may have been favored by increased ignition sources associated with agricultural, forestry, and transportation-related activities. This thesis is reinforced by the fact that the end of the pulse took place despite the continuing warming (Jaume-Santero et al. 2016) and in the absence of a clear shift in drought regime in LWE (Fig. 4; also see Girardin et al. 2013). Several authors have reported that European settlement was associated with a lengthening of the 20th-century fire cycle in western Manitoba and eastern Saskatchewan, respectively (Weir et al. 2000, Tardif 2004, Tardif et al. 2016). Therefore, changes in settlement and its relation to fire may have contributed to a decrease in widespread LWE fire events during the AE identified within the tree-ring and CHAR records. Davidson-Hunt (2003) further suggested that the reduction may also have been related to the adoption of policies aimed to both discourage/penalize human activities responsible for fire occurrences, combined with a move toward active fire suppression.

Landscape fragmentation and changes in vegetation cover, composition, and structure may also have contributed to the decrease of biomass burning. Harvesting, industrialization, and fire activity since the early-20th century contributed to an increase in the proportion of broadleaf species in western, central, and eastern Canada (Laquerre et al. 2011, Boucher et al. 2016, Searle and Chen 2017). Because broadleaf stands are characterized by higher leaf moisture and lower flammability and rate of fire ignition than coniferous stands, their densification may have contributed to a decrease of the intensity (i.e., energy output) and rate of spread of fires through the AE. This biotic effect may provide an additional explanation for the recent decoupling between warming and biomass burning. Such explanation remains speculative and requires to be tested through investigations of recent changes in forest cover, perhaps through detailed reconstructions of forest composition with high-resolution pollen records (Blarquez and Aleman 2016), permanent forest inventories (Searle and Chen 2017), and statistical modeling (Girardin and Terrier 2015).

The multi-proxy fire records highlighted a rapid transition toward an exceptionally low biomass burning activity during the AE. While this may be perceived as encouraging for human well-being (e.g., infrastructure, allowable cuts), this situation may not be without ecological consequences. For instance, a reduction of fire activity has important implications on the age distribution of forest stands: Maintenance of a low fire activity in LWE will shift the age distribution is such a way that the proportions of young age classes (0–40 yr) will become lower than encountered during the historical past, and the proportion of old forests overly abundant (Fig. 5b). This may imply an excessive accumulation of fuels (which increases the fire hazard risks), loss of habitats for wildlife, and reduction of biodiversity as aging of forests tends to promote succession into needleleaf species. In many regions, harvesting rates surpass the historical fire disturbances and maintenance of old forest is a larger concern than lack of young age classes (Bergeron et al. 2017). But this is obviously not the case in the study area: The cumulated rates of harvesting (<0.05%/yr, see *Study area*) and fire disturbances (0.35%/yr) approximate 0.40%/yr (return interval of 250 yr), which is well below the long-term historical disturbance rates of 0.66%/yr (return interval of 150 yr; Fig. 5) estimated from CHAR or from the stand-initiation distribution (1.91%/yr; return interval of 52 yr; Fig. 5). The anticipated increase of fire activity with climate change may contribute to restore the age distribution to conditions encountered during the Holocene, but such potentially destructive phenomena may be not socially acceptable and are not foreseen during the next 40 yr or so (Girardin and Mudelsee 2008). Meanwhile, there are opportunities for management that would contribute to maintain natural features (Gauthier et al. 2009). Management for restoring the proportion of younger age classes could bring additional benefits by promoting species and populations that are better adapted to the anticipated future climate conditions.

Conclusion

The focus of this research was to reconstruct a (1) recent fire history (last 300 yr) for a portion of the LWE using archival, tree-ring, and lake sediment charcoal records and (2) a multi-millennial fire history using the long-term charcoal record. The analysis of the multi-millennial charcoal record revealed that biomass burning was higher in the earlier portion of the record followed by a progressive decrease toward the more recent record, until the late 1890s marked by a sharp pulse of biomass burning lasting about 4 decades. Large fire events in LWE during the 18th and 19th centuries were synchronous to other widespread western North American fires. These spatially synchronous fires strongly suggest that they were driven by climate. The potential northward displacement of the jet stream after the LIA may have set a marked decline of fire activity followed with a reduction in fire synchrony with other regions. This may highlight the increasing control (or impact) of humans on fire via passive or active fire suppression. Alternatively, pulse in fire activity may be reflecting climate less conductive to fire (LIA) allowing for fuel and old-growth forest to develop. The overall disturbance rate is now at such a low level that the forest may well be out of the range of variability in which it has evolved over the past two millennia. As the forest landscape is getting older, it may be setting the tone for major fires in upcoming decades with the anticipated warming (Price et al. 2013) and may create issues with biodiversity loss notably in fire-adapted species.

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