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To cite this article: Niina Kuosmanen *et al* 2023 *Environ. Res. Lett.* **18** 094051

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ENVIRONMENTAL RESEARCH
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OPEN ACCESS

RECEIVED
11 March 2023

REVISED
26 June 2023

ACCEPTED FOR PUBLICATION
15 August 2023

PUBLISHED
14 September 2023

LETTER

Repeated fires in forested peatlands in sporadic permafrost zone in Western Canada

Niina Kuosmanen[1,*], Minna Väliranta[2], Sanna Piilo[2], Eeva-Stiina Tuittila[3], Pirita Oksanen[4] and Tuomo Wallenius[2]

[1] Department of Geosciences and Geography, Faculty of Science, University of Helsinki, PO Box 64 (Gustaf Hällströmin katu 2), FI-00014 Helsinki, Finland

[2] Environmental Change Research Unit (ECRU), Ecosystems and Environment Research Programme, University of Helsinki, PO Box 65, FI-00014 Helsinki, Finland

[3] School of Forest Sciences, University of Eastern Finland, PO Box 111, FI-80101 Joensuu, Finland

[4] Centre for Economic Development, Transport and the Environment (ELY-keskus), North Ostrobothnia, PO Box 86, FI-90101 Oulu, Finland

[*] Author to whom any correspondence should be addressed.

E-mail: niina.kuosmanen@helsinki.fi

Keywords: forested peatland, wildfire history, peat accumulation, carbon storage capacity, post-fire succession

Abstract

Wildfires play a crucial role in northern boreal peatland ecosystems, influencing the functioning of these ecosystems by affecting vegetation composition and biomass, peat accumulation patterns, and soil carbon stocks. Northern peatland ecosystems are under pressure due to climate warming and increasing anthropogenic stress. The frequency and severity of wildfires is predicted to increase in the coming years. Therefore, understanding long-term natural fire dynamics and their effect on peatland functionality will provide crucial information for peatland management and preservation policies. To investigate the long-term fire history of Western Canada and its effect on peat accumulation and vegetation succession, we analyzed macroscopic plant remains and charcoal within peat cores taken from five peatlands in the region. Records of the most recent fire events were derived from fire scars and documented fires in the study area. Regional long-term peatland fire patterns were examined by pooling together macroscopic charcoal records and calculating 100 year moving averages. All studied sites, except the northernmost one, demonstrated repeated fires throughout the past 1500 years, suggesting that fires have been an integral part of the peatland ecosystem in Western Canada. Compiled charcoal records indicated a peak in fire activity, with the highest abundance of charcoal for the period from the 1300s to the 1550s and decreasing fire activity during recent centuries. The clear and consistent post-fire increase in the abundance of *Sphagnum* mosses suggests a relatively rapid recovery of peatland ecosystems after burning. The regeneration pattern, where pre-fire vegetation repeatedly re-establishes, suggests that from a long-term perspective, fires do not necessarily have a negative effect on peatland functioning and peat accumulation. In conclusion, peatlands could remain as effective carbon sinks if their natural state is secured.

1. Introduction

Northern peat-accumulating wetlands and peatlands play a crucial role in the global carbon cycle. These ecosystems cover ca. 4 million km^2 and, based on different estimates, store 400–600 Pg of carbon (C) (e.g. Loisel *et al* 2014, Hugelius *et al* 2020). Predicted and ongoing warming is placing high-latitude boreal peatlands under increasing pressure by accelerating permafrost thaw (e.g. Hugelius *et al* 2020, Treat *et al* 2021), altering hydrological balance (e.g. Zhang *et al* 2018a, 2022, Swindles *et al* 2019) affecting peat and carbon accumulation dynamics (e.g., Garneau *et al* 2014, Gallego-Sala *et al* 2018, Zhang *et al* 2018b, Piilo et al 2022), and increasing wildfire risk (e.g. Turetsky et al 2015, Holloway et al 2020). In boreal North America, forested peatlands are commonly forested by black spruce (*Picea mariana*) and the high above-ground biomass on the top of peat layers makes them particularly susceptible to intense fires (Johnston et al 2015, Beaulne et al 2021).

Fire is a key ecological and environmental factor influencing the functioning of ecosystems in the boreal zone. Changes in the fire regime (e.g., frequency, size and severity) thus alter the functioning of the boreal ecosystem (Zoltai et al 1998, Turetsky et al 2015). In the short term, fires can reduce C stocks and directly release CO_2 into the atmosphere (Wieder et al 2009). However, in the long term, fires may potentially have a profound effect on forested permafrost peatland carbon storage by altering the hydrology (Holloway et al 2020 and references therein, Ackley et al 2021), vegetation composition and successional pathways (Magnan et al 2012), peat accumulation (Turetsky et al 2015), and by promoting permafrost thawing (Gibson et al 2018). Centennial dendrochronological records demonstrate a decrease in fire activity from the nineteenth century to the twentieth century in Western Canada (Wallenius 2011). However, in turn, during recent years, fire frequency and severity have increased in boreal Canada (Hanes et al 2019, Ali et al 2020) and this increase is predicted to continue (Flannigan et al 2005). An increase in fire frequency may have significant implications for soil C stocks; for example, through the release of preserved old soil carbon (Mack et al 2011, Turetsky et al 2015, Walker et al 2019).

Previous estimates of the effects of wildfires on peatland carbon stocks in Alaska (Turetsky et al 2011) and Western Canada (Turetsky et al 2002) have shown increased carbon losses due to increased fire frequency, ultimately decreasing the peatland carbon stock. However, these estimates are limited to the past decades or to the past few centuries at the most, while wildfires have occurred repeatedly throughout the Holocene in Canadian boreal peatlands (Zoltai 1998). So far, the length of the temporal scale used for estimating the fire frequency and impact has been limited by available data sources, which have mainly been based on satellite data (Giglio et al 2013), historical records (Turetsky et al 2004, 2015, Kasischke and Turetsky 2006) and dendrochronological records (Larsen 1996, Heyerdahl et al 2007, Wallenius et al 2011). Dendrochronological methods, such as mapping of forest stand ages and fire-scarred trees (e.g. Lageard et al 2000, Wallenius 2011, Aakala et al 2018), have extended fire frequency records up to several hundreds of years beyond the range of historical records and satellite images. However, extending records of fire frequency even further back in time requires the use of paleological archives of sedimentary charcoal from lake and peat deposits (Whitlock and Larsen 2002). Furthermore, combining dendrochronological and sedimentary records allows more comprehensive reconstructions of the long-term fire history (Stivrins et al 2019, Kuosmanen et al 2020, Edvardsson et al 2022). It is particularly important to understand the interlinked historical fire and vegetation dynamics and the subsequent effect on the long-term carbon storage in forested peatlands under the changing climate and predicted increase in fire frequency.

Although Holocene wildfire history patterns in the boreal zone are to some extent already extensively studied and well understood (Holloway et al 2020), dendrochronological studies have mainly concentrated on Northern Europe and Southern and Eastern Canada (Margolis et al 2022). However, there are relatively few long-term fire records, covering several centuries or millennia, from boreal peatlands in Western Canada. As long-term records could enhance the understanding of the potential effects of fires on the forested peatlands in a region that is currently experiencing increasing fire activity in Western Canada, we aim to fill this data gap by (1) reconstructing the fire history of five forested peatlands located in the sporadic permafrost zone based on macroscopic charcoal records and local dendrochronological fire reconstructions, (2) calculating the peat accumulation rates (PeatAR), and (3) assessing the effect of fires on post-fire regeneration and vegetation succession.

2. Methods and materials

2.1. Study area and sites

The study area in Western Canada belongs to the discontinuous permafrost zone (figure 1). Of the five studied peatlands, three are located in British Columbia, namely BC1 (N57°08′52′′, W120°39′5′′), BC2 (N25°25′55′′, W120°7′10′′) and BC3 (N58°51′8′′, W122°25′22′′), and one site is in the Northwest Territories (NWT) (N61°50′45′′, W122°24′0′′). These four sites are located in the southern part of the Taiga Plains ecozone, while one study site in Alberta (ALB) (N57°17′46′′, W115°20′45′′) is located in the northwestern part of the Boreal Plains ecozone (Ecological Framework of Canada 2014). The mean annual temperature is approximately −0.2 °C (Environment Canada 2014). In the study region, 35%–55% of the land area is covered by wetlands, which makes it one of the densest wetland areas in Canada (Environment and Climate Change Canada 2016). Studied peatlands are forested bogs with black spruce as the main tree species, with ericaceous vegetation (e.g., *Rhododendron groenlandicum*, *Vaccinium vitis-idaea* and *Vaccinium oxycoccos*) forming the field layer of the dry habitats. *Sphagnum* mosses form the ground layer with

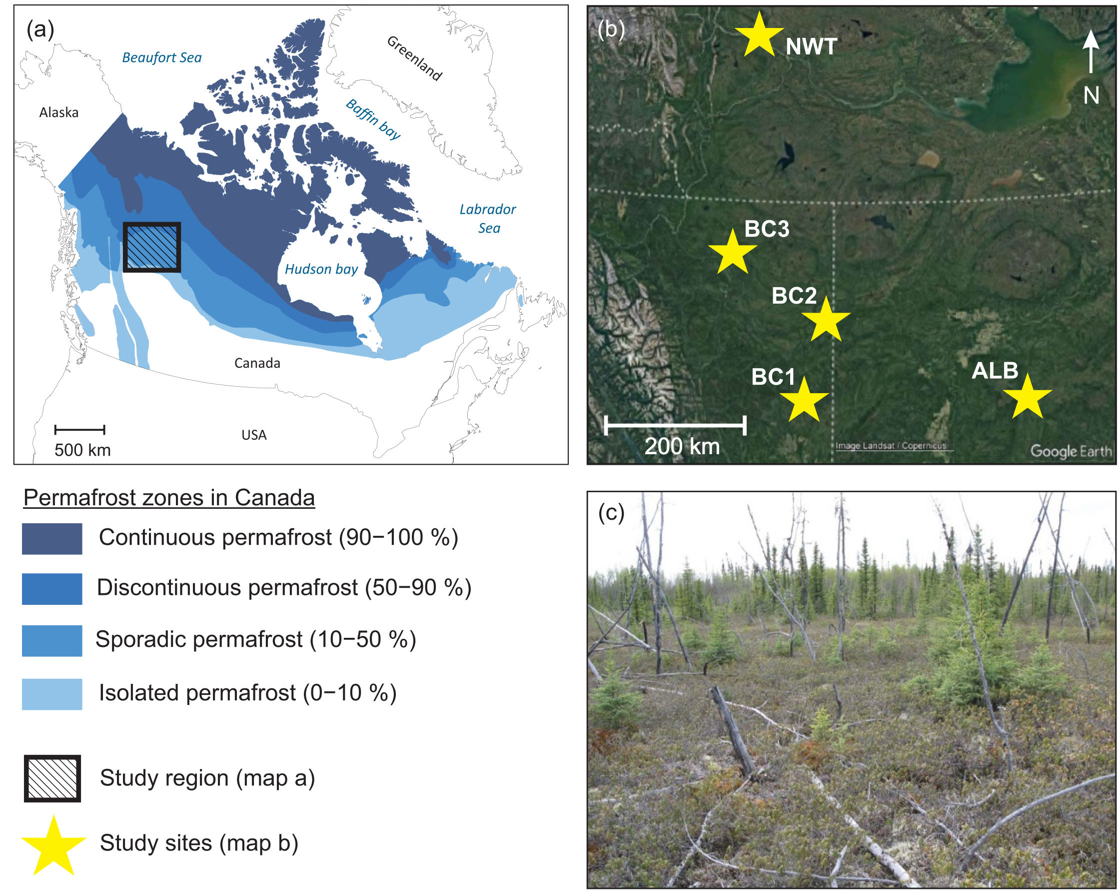

Figure 1. (a) Permafrost distribution showing permafrost zones in Canada (data source: Natural Resources Canada 2022), (b) map of the study area with study sites marked with yellow stars (map data: Google Earth © 2022, Image Landsat/Copernicus), (c) study site BC2 showing typical vegetation on the studied peatlands (photo: Tuomo Wallenius).

Sphagnum fuscum as the dominant taxon. The microtopography consists of low-relief hummocks and lawns.

2.2. Dendrochronological fire records and fire statistics

The latest fire events at the study sites were determined using fire scars on trees, forest stand ages and snags killed and charred by fire. Disks and wedges, including fire scars, were sawn from up to seven living and dead trees per site. For a more detailed description of the methods used see Wallenius *et al* (2011). In addition, fire statistics including mapped fire polygons were derived from Boulanger *et al* (2014).

2.3. Collection of the peat cores

The peat profiles were collected in summer 2009. Two replicate peat profiles (A and B) were cored from each site in British Columbia coded as: BC1A (53 cm) and BC1B (50 cm), BC2A (51 cm) and BC2B (48 cm), and BC3A (107 cm) and BC3B (99 cm). In addition, a peat profile was collected from the sites in ALB (109 cm) and NWT (49 cm), respectively. Coring was conducted with a Russian peat corer, with a cylinder of 50 cm long and 5 cm in diameter. Coring points represent dry hummock habitats.

2.4. Core chronology and peat accumulation

Core chronologies were secured by AMS ^{14}C dates with a minimum of three dates per peat profile. Plant macrofossil samples were dated by the Poznań Radiocarbon Laboratory (Poland), and one sample by the Finnish Museum of Natural History (LUOMUS, Helsinki, Finland). Some peat records appeared to be young (younger than 1950 CE) and the ^{14}C calibration procedure did not always yield robust-enough results for the top peat sections. Therefore, in those cases, we applied local/regional dendrochronological data as a supportive element. The age of the latest known fire on the study site in question, determined from dendrochronological data and fire statistics, was used as a chronological control point for the top part of each peat record. The age of this latest known fire event was treated as the assumed age of the most recent charcoal peak in the peat record. In other words, the dendrochronologically determined youngest fire age was adapted to date the youngest charcoal peak. This depth and age, which linked the tree and peat records, were then included in the age–depth models created for all cores using Bayesian age–depth modeling (BACON) (Blaauw and Christensen 2011) with IntCal20 curve in R programming software (R Core Team 2019).

PeatAR (mm yr^{-1}) for each core was calculated based on the constructed age–depth models. As young incompletely decomposed *Sphagnum* growth affects the PeatAR, the average PeatAR (mm yr^{-1}) was calculated separately for the period of 1000–1900 CE, for the last 100 years (1900–2009 CE), for the whole core up to 1900 CE and for the whole length of each core.

2.5. Macroscopic charcoal analysis

Macroscopic charcoal analysis was performed from 5 cm^3 samples in 1–2 cm intervals to reconstruct past fire events. In a few cases where less material was available, a smaller subsample size was used. Samples were gently cleaned under running water using a 140 μm mesh and analyzed on a Petri dish under a stereomicroscope. A maximum of 50 particles >1 mm in size were counted from each sample and then counting was stopped. To assess the long-term changes in regional fire activity, charcoal records from all cores were pooled together and the number of charcoal particles was divided by the number of samples in each period. This method is similar to the method used in dendrochronological fire history reconstructions; instead of fire scars on tree trunks (either present or not present in each year and sample, see Niklasson and Granström 2000), we used the macroscopical charcoal particle count (varying between 0 and 50) as an indicator of the occurrence of fires. A running 100 year mean of this fire activity index was compared to annually burned area reconstruction by using dendrochronological methods from the same area (Wallenius *et al* 2011). This allowed us to compare the pattern of the different fire history reconstructions for the latest two centuries (the common period) and relate the fire activity index values to annually burned areas in the region.

2.6. Plant macrofossil analysis

To reconstruct vegetation succession related to fires, plant macrofossil analysis was performed using the same samples as the macroscopic charcoals. The analysis method followed Väliranta *et al* (2007). Macrofossil plant identification followed the literature; Eurola *et al* (1992), Piippo (1996), Bastien and Garneau (1997), Mauquoy and Van Geel (2007), Flora of North America (2014) and Laine *et al* (2009). The percentage share of each component estimated under a Petri dish represents the relative abundance of the compound or taxon from the sample volume; all main components adding up to 100% per subsample. The main identified components were Cyperaceae vegetative remains, Ericales vegetative remains, *Sphagnum* moss and other bryophytes; liverworts, wood matter and unidentified organic matter were also found. Taxonomic identification and determination of relative abundances of bryophytes were conducted under a high-power microscope.

Table 1. Fire history for sites BC1, BC2, BC3, ALB and NWT sites from Western Canada based on dendrochronological (Wallenius *et al* 2011) and fire statistics data (Boulanger *et al* 2014). Time since the last fire is counted to the sampling year of year 2009.

Site	Known fires	Time since last known fire (years)	Source
BC1 A	1950	59	Fire statistics
BC1 B	1950	59	Fire statistics
BC2 A	1980	29	Fire scars and statistics
BC2 B	1980	29	Fire scars and statistics
BC3 A	1895	114	Tree ages
BC3 B	1895	114	Tree ages,
ALB	1844, 1863, 1982[a]	27	Tree ages, fire statistics
NWT	1975	34	Death years of trees killed by fire

[a] This fire was located 1.1 km from the coring site according to mapped fire areas in the Canadian Large Fire Data Base (Bosch *et al* 2004).

3. Results

3.1. Fire history from tree-ring records and fire statistics

Based on the dendrochronological and fire statistic data, sites BC1, BC2, BC3 and NWT have burned only once during the last 200 years and site ALB three times with earliest fire in 1845 CE and the latest fire in 1982 CE in the study region (table 1).

3.2. Peat profile chronologies

The time period covered by the analyzed peat cores varied notably from 660 cal yr BP (BC1B) to 7500 cal yr BP (BC3B) (table 2, figure 2). All but one core covered more than the last millennia, providing information on the long-term development of the peatland fire history in the study area. The ^{14}C ages of the top samples that resulted in modern ages were inconsistent with the control point ages determined by the last known fire event at the study site in question based on dendrochronological data and fire statistics. Therefore, modern radiocarbon ages were excluded from the age–depth models and the respective chronologies were constructed by using a combination of the chronological control ages derived from the last known fire (table 2) and the radiocarbon dates below this control horizon. In this study, we present the results covering the last 1500 years.

3.3. PeatAR

The PeatAR values vary notably during the last millennia and between the studied cores (table 3 and figure 3). Common in all records is a relatively stable PeatAR until an increase during the last century (table 3), reflecting the incomplete peat decomposition process. For the BC1 site, the PeatAR

Table 2. Radiocarbon dating results and the chronological control age determined from dendrochronological and fire statistics data.

Site	Depth (cm)	Laboratory ID	^{14}C age BP ± error and *calendar ages (CE)*	Remark
BC1A	21	—	*1950*	Control age
BC1A	28	Poz-119268	163.35 ± 0.43	pMC (modern)[a]
BC1A	39	Poz-122604	106.59 ± 0.33	pMC (modern)[a]
BC1A	53	Poz-36335	2425 ± 35 BP	
BC1B	19	Poz-122605	117.01 ± 0.35	pMC (modern)[a]
BC1B	21	—	*1950*	Control age
BC1B	28	Poz-119269	137.26 ± 0.39	pMC (modern)[a]
BC1B	50	Poz-36334	660 ± 30 BP	
BC2A	18	—	*1980*	Control age
BC2A	23	Poz-119270	106.78 ± 0.33	pMC (modern)[a]
BC2A	37	Poz-122606	5 ± 30 BP	
BC2A	47	Poz-119271	625 ± 30 BP	
BC2A	52	Poz-36332	1805 ± 30 BP	
BC2B	19	Poz-122608	101.08 ± 0.33	pMC (modern)[a]
BC2B	21	—	*1980*	Control age
BC2B	24	Poz-119275	100.59 ± 0.34	pMC (modern)[a]
BC2B	39	Poz-119276	360 ± 30 BP	
BC2B	49	Poz-36333	1425 ± 30 BP	
BC3A	53	Poz-119278	100.14 ± 0.35	pMC (modern)[a]
BC3A	57	—	*1895*	Control age
BC3A	88	Poz-122607	800 ± 30 BP	
BC3A	107	Poz-36330	2820 ± 30 BP	
BC3B	26	Poz-119279	102.01 ± 0.32	pMC (modern)[a]
BC3B	31	—	*1895*	Control age
BC3B	71	Poz-122609	1660 ± 30 BP	
BC3B	94	Hela-2569	4874 ± 42 BP	
BC3B	100	Poz-36329	7000 ± 40 BP	
ALB	27	Poz-122610	125.05 ± 0.37	pMC (modern)[a]
ALB	42	—	*1982*	Control age
ALB	45	Poz-122611	101.09 ± 0.33	pMC (modern)[a]
ALB	65	Poz-122612	80 ± 30 BP	
ALB	87	Poz-122614	405 ± 30 BP	
ALB	105	Poz-122615	1330 ± 30 BP	
NWT	1	—	*1975*	Control age
NWT	9	Poz-77236	280 ± 30 BP	
NWT	32	Poz-77239	670 ± 30 BP	
NWT	35	Poz-91297	810 ± 30 BP	
NWT	38	Poz-91298	865 ± 30 BP	
NWT	50	Poz-77240	1130 ± 30 BP	

[a] Modern ages were excluded from the age–depth models.
Note: pMC: percent Modern Carbon.

remains stable around 0.11 mm yr^{-1} in BC1A and around 0.46 mm yr^{-1} in BC1B until 1800 CE, after which it increases in both cores first to 1 mm yr^{-1} around the 1950s and then to 5 mm yr^{-1} during the last century. The BC2 site peat cores demonstrate differing PeatAR. The BC2A core shows a stable PeatAR (<0.1 mm yr^{-1}) until 1600 CE, after which the PeatAR varies between 0.45 mm yr^{-1} and 0.83 mm yr^{-1} until an increase up to 5–10 mm yr^{-1} during recent decades. The BC2B core shows a stable PeatAR around 0.22 mm yr^{-1} until 1400 CE, with a decrease to 0.10 mm yr^{-1} and then an increase up to 5–10 mm yr^{-1} during recent decades. In site BC3, the PeatAR in core BC3A stays <0.1 mm yr^{-1} until 1000 CE, after which there is increase and stable PeatAR around 0.43 mm yr^{-1} until an increase to 2–5 mm yr^{-1} the last century. The BC3B core shows a stable PeatAR of around 0.25 mm yr^{-1} until 1800 CE, after which there is an increase up to 3 mm yr^{-1} during the last two centuries. For the ALB core, the peat accumulation rate varies between 0.21 mm yr^{-1} and 0.43 mm yr^{-1} until 1500 CE, with an increase to 1.0 mm yr^{-1} and a further increase up to 10 mm yr^{-1} from 1940 CE. At site NWT, PeatAR stays relatively low, varying between 0.29 mm yr^{-1} and 0.59 mm yr^{-1}.

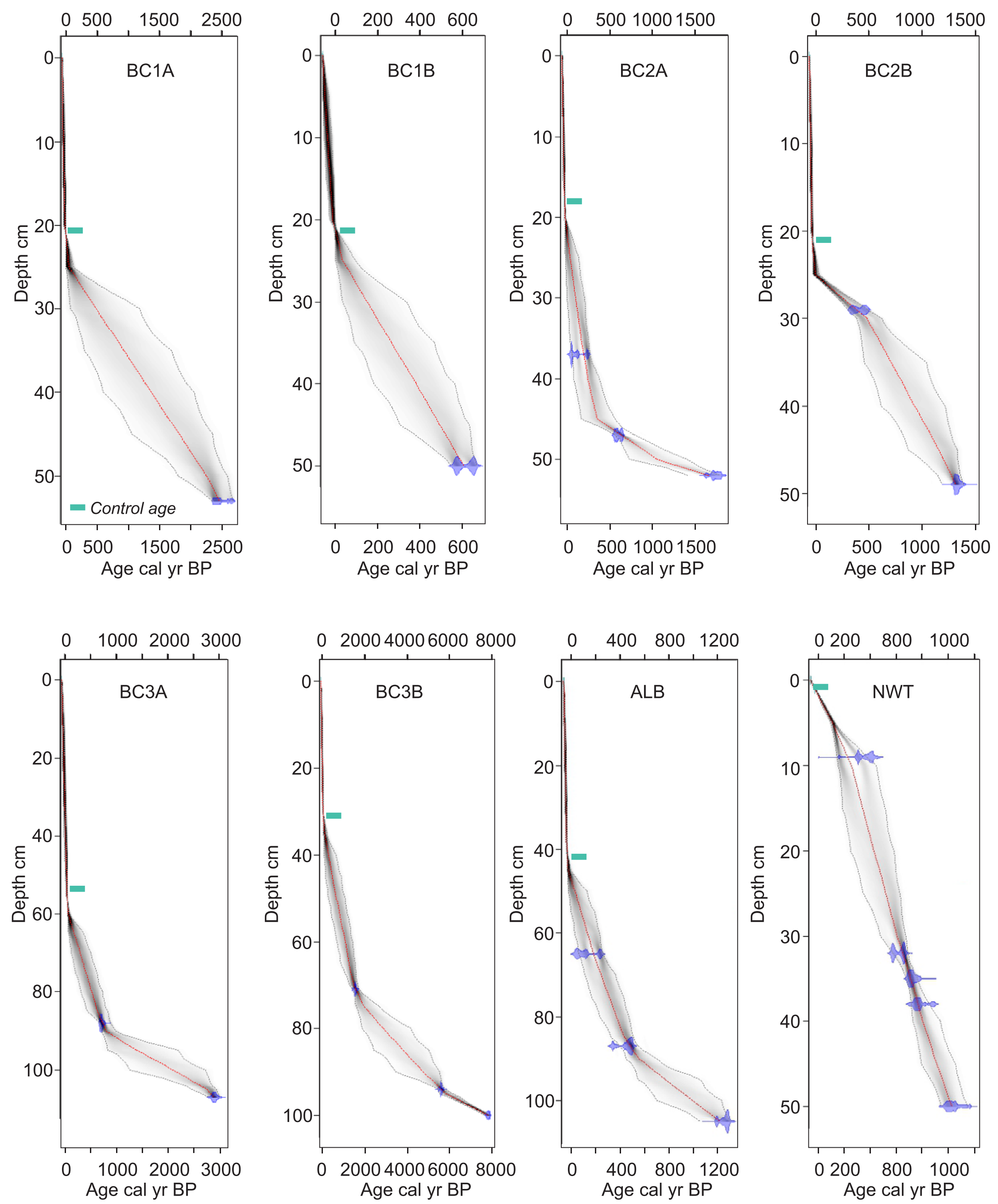

Figure 2. Age–depth models for all eight peat cores based on ^{14}C dating and control age from dendrochronological and fire statistic data (light green marks) created with the Bayesian 'rbacon' -modeling tool in R using the IntCal20 calibration curve. Purple marks show the range of the calibrated radiocarbon ages.

Table 3. Average peat accumulation rates (mm yr^{-1}) for all study sites for selected time periods (CE).

Site	1900–2009 CE	1000–1900 CE	Whole core up to 1900 CE	Whole core (basal age cal yr BP)
ALB	9.02	0.70	0.66	5.27 (1230)
NWT	0.29	0.50	0.50	0.48 (2530)
BC1A	4.05	3.03	0.11	1.99 (1063)
BC1B	3.74	0.42	0.42	0.42 (668)
BC2A	5.83	0.49	0.44	3.37 (1422)
BC2B	7.71	0.20	0.20	4.14 (1335)
BC3A	5.35	0.66	0.48	2.89 (2970)
BC3B	2.79	0.34	0.22	0.20 (7470)

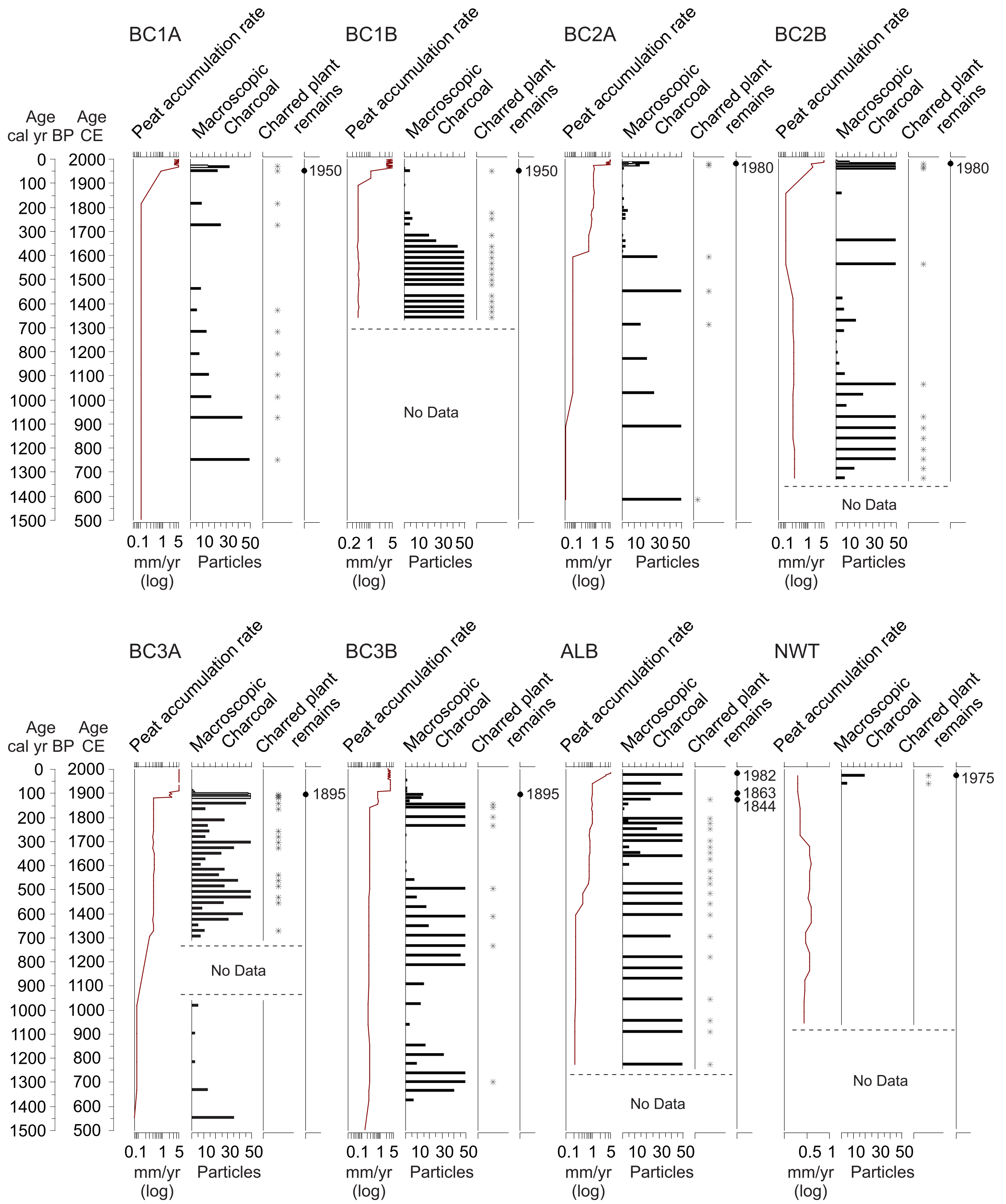

Figure 3. Diagrams for all eight cores showing peat accumulation rate (note the logarithmic scale), macroscopic charcoal record, presence of charred plant remains and fires reconstructed from dendrochronological records and fire statistics (marked by calendar years).

3.4. Macroscopic charcoal and plant macrofossil record

All British Columbia records (BC1, BC2, BC3) demonstrate that during the last 1500 years, fires have occurred regularly on these sites (figures 3–6). However, there is notable variability in the fire records between the sites and the cores coming from one individual site. Records from BC1 show a decrease in charcoal abundance towards the present. The BC1A record shows a high charcoal abundance (>50 particles per samples) until 1000 CE, around 1700–1800 CE and at 1950–1970 CE. The BC1B charcoal values are high until 1600 CE, followed by a decrease with a low charcoal abundance (<10 particles per sample). In both records, the increase in the proportion of *Sphagnum* mosses, accompanied by a decline in vascular plant remains, coincides with a decrease in charcoal abundance (figure 4).

The BC2 records show a decrease in macroscopic charcoal abundance from 1000 CE onwards coinciding with the increase in *Sphagnum* abundance and a decrease in woody material (figures 3 and 5). In the BC2A record, a peak with >50 particles per sample occurs at 1450 CE and there is an increase in

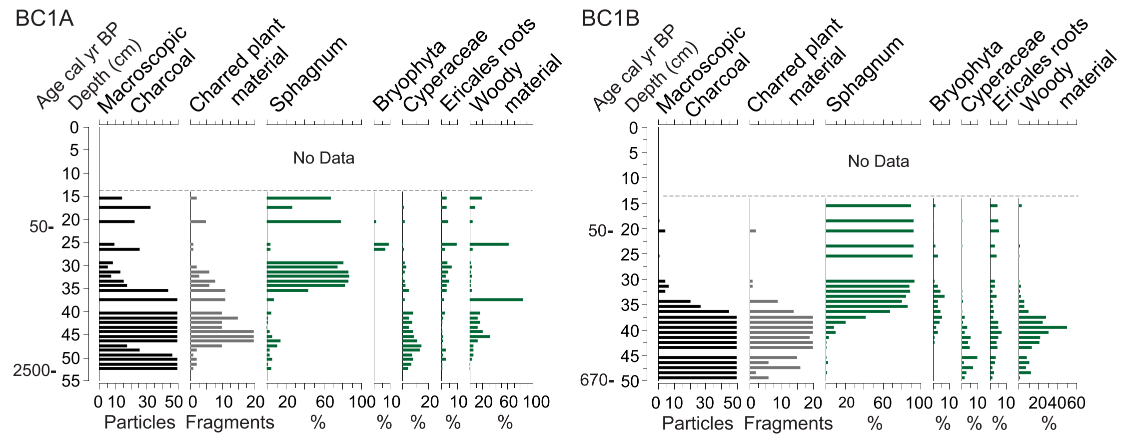

Figure 4. Diagrams for site BC1 in British Columbia showing the macroscopic charcoal record and selected plant macrofossils plotted against depth (cm) for two different peat cores, BC1A and BC1B.

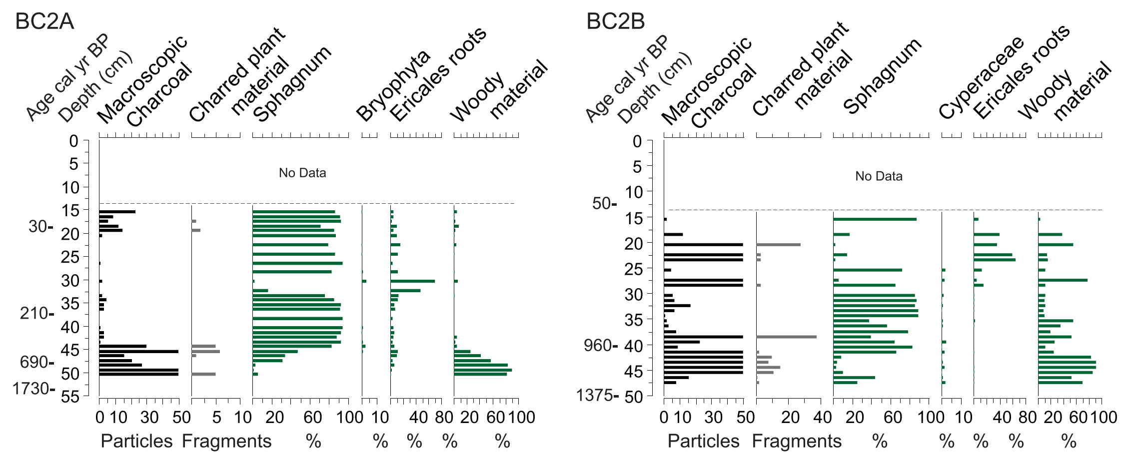

Figure 5. Diagrams for site BC2 in British Columbia showing the macroscopic charcoal record and selected plant macrofossils plotted against depth (cm) for two different peat cores, BC2A and BC2B.

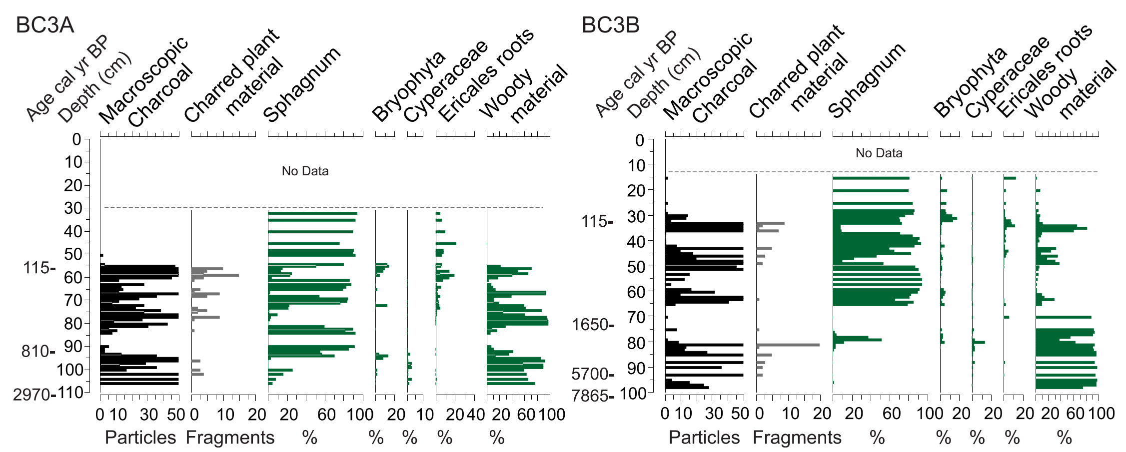

Figure 6. Diagrams for site BC3 in British Columbia showing the macroscopic charcoal record and selected plant macrofossils plotted against depth (cm) for two different peat cores, BC3A and BC3B.

charcoal abundance from 1970 CE. The proportion of *Sphagnum* remains high regardless of the increase in charcoal abundance. In the BC2B record, high charcoal abundances (>50 particles per sample) occur between 1550 CE and 1650 CE, after which the values remain low until 1960 CE, when there is an increase in charcoal abundance. As charcoal abundance rises, there is a corresponding decline in *Sphagnum*

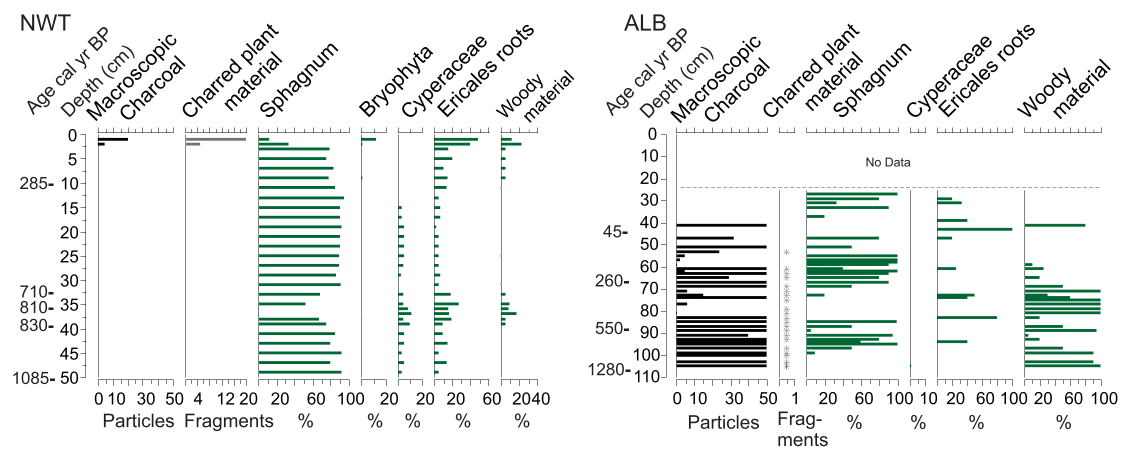

Figure 7. Diagrams for sites in the North Western Territories and Alberta showing the macroscopic charcoal record and selected plant macrofossils plotted against depth (cm).

proportions; however, following a peak in charcoal levels, there is an immediate increase in the proportion of *Sphagnum*.

The BC3 records demonstrate different fire histories when compared to the BC1 and BC2 records. In general, the BC3A record shows low charcoal values with a few exceptions with peak values (>50 charcoal particles per sample) at 1460–1490 CE, at 1700 CE and at 1850–1900 CE. The *Sphagnum* proportion decreases (<20%) with higher charcoal abundances. However, there is a clear increase in *Sphagnum* proportions (>80%) between the charcoal-rich periods (figures 3 and 6). The BC3B charcoal record shows three periods of higher charcoal abundances (>50 particles per sample) at 700–750 CE, at 1200–1400 CE and at 1750–1850 CE. There is no notable decrease in *Sphagnum* proportions around the charcoal peak at 700–750 CE, but a clear decrease is seen during the two latter periods of high charcoal abundances.

At the ALB site, macroscopic charcoal abundances are high (>50 particles per sample), with the exception of lower abundances (<10 particles per sample) between 1550–1600 CE, at 1670 CE and at 1800–1860 CE (figures 3 and 7). In general, the *Sphagnum* proportion remains relatively high during the high charcoal abundances. Exceptions for this are periods of low *Sphagnum* proportions that coincide with a high proportion of woody material during 1500–1700 CE and 1860–1980 CE. After 1980 CE, the proportion of *Sphagnum* increases and the charcoal abundance decreases.

At the NWT site, only the top-most samples had relatively low amounts of macroscopic charcoal (5–20 particles per sample) between 1940 CE and 1975 CE (figures 3 and 7). Charred plant material is found in the same samples with simultaneous decline in *Sphagnum* proportion and increase in other bryophytes, dwarf shrub roots and woody material.

3.5. Regional fire history

The regional fire history from all peat records pooled together with 100 year moving averages shows three different phases during the last millennia. During the first 300 years, charcoal abundances are relatively stable varying mainly between 16 and 22 charcoal particles per sample (figure 8). The second period between 1300 CE and 1550 CE shows the highest charcoal abundances, indicating increasing fire activity. The third period from 1550 CE to the present demonstrates decreasing fire activity with an exceptional peak in charcoal abundances at 1850 CE. After this, charcoal abundances decrease rapidly from 1900 CE onwards.

4. Discussion

4.1. Fire history in Western Canada

Records from five forested peatlands demonstrate that reoccurring fires have been part of the permafrost peatland ecosystems in Western Canada in the past. Although fire patterns vary between individual sites, the overall regional trend demonstrates similar fire activity during 1000–1300 CE corresponding to the medieval warm period (MWP) and the later part of the little ice age (LIA) 1600–1800 CE (figure 8) (Hughes and Diaz 1994, Luckman and Wilson 2005). The MWP is globally connected to increased biomass burning due to warmer and drier conditions (Marlon *et al* 2012). However, some studies suggest that regardless of warmer temperatures during the MWP, the growing season conditions may not have been notably dry; for instance, around the Rocky Mountains area due to the precipitation patterns under La Niña conditions (Edwards *et al* 2008, Holmquist *et al* 2016 and references therein). This could partly explain the lower fire activity in our study region. Furthermore, in the BC1 and BC3

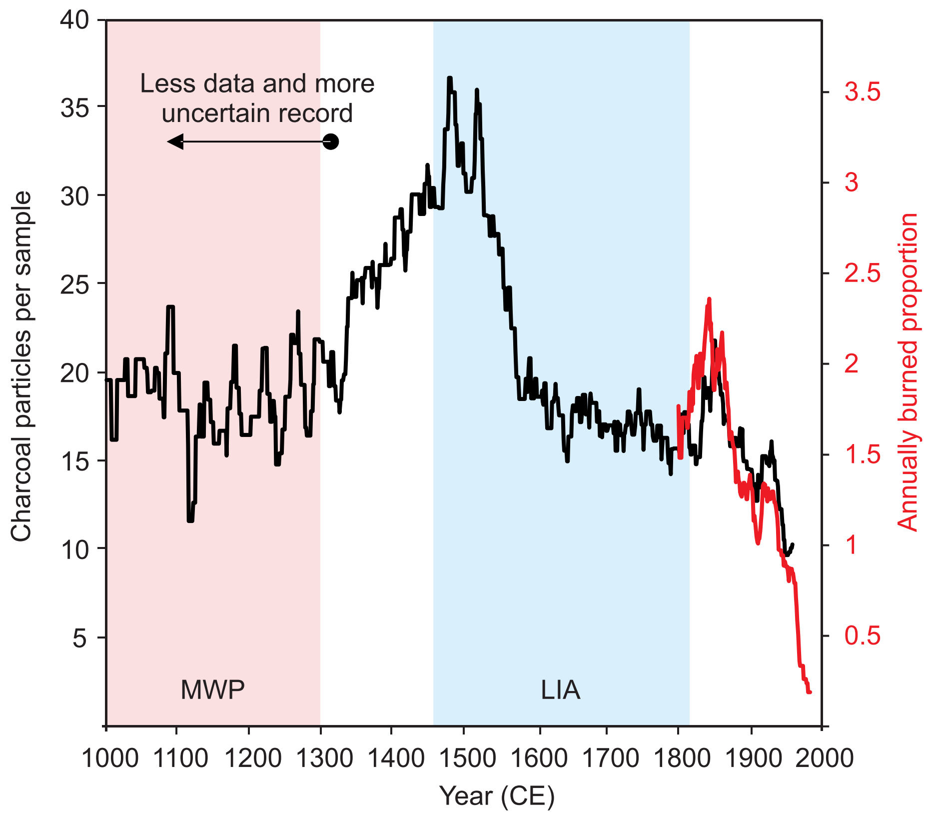

Figure 8. Reconstruction of the general trend in fire activity in the study region derived from all eight charcoal records pooled together and compared with the annually burned proportion based on fire scar analysis (Wallenius 2011). MWP: medieval warm period; LIA: little ice age.

sites, the studied two records from each site demonstrate varying fire histories indicating that local site-specific factors such as vegetation composition (fuel load) and hydrological conditions (water table level) may have played crucial roles in controlling the peatland fire occurrence by creating divergent fire-prone conditions (Flannigan *et al* 2009, Magnan *et al* 2012, Ronkainen *et al* 2013, Kuosmanen *et al* 2014, Feurdean *et al* 2022).

The more intense period of fires during 1300–1550 CE corresponds to climate reconstructions based on oxygen isotopes (Edwards *et al* 2008) and tree-ring records (Luckman and Wilson 2005) that have suggested drier climatic conditions at that time. These known drier hydrological conditions overlap with the expansion of *Sphagnum* mosses (*S. fuscum* as the main taxon) and declining Cyperaceae abundances suggesting development towards drier peat surface conditions. Recent studies have shown similar ecohydrological shifts in northern peatlands towards drier hummock-type habitats where fen-sedge communities are replaced by *Sphagnum* communities as a response to changes in climate (e.g. Swindles *et al* 2019, Zhang *et al* 2020, Magnan *et al* 2022, Piilo *et al* 2022). Furthermore, charred *Picea mariana* needles indicate the presence of forest cover, which may have increased the available fuel load and accelerated the spread of fires (Flannigan *et al* 2009, Magnan *et al* 2012, Ronkainen *et al* 2013, Johnston *et al* 2015). It is noteworthy that the fire activity is fairly similar during the relatively different climate periods, i.e. MWP and LIA. Due to this apparent similarity in fire patterns, it could be speculated that in addition to climatic factors, other drivers such as vegetation composition (fuel load), site-specific ecohydrology and human impact may have affected the fire regimes.

Although it is clear that boreal forest can burn only when the weather conditions are favorable for the spread of fires, it is plausible that increasing human impact and changes in land-use practices of indigenous communities may have altered regional vegetation structure and fire-ignition patterns (Larson *et al* 2021). Fire has been an important management tool for indigenous people in manipulating vegetation and forest structure for wild game, food resources (berries, fruits, etc.) and clearing the land for settlement purposes already existed in pre-cultivation cultures (Dey and Guyette 2000, Carter *et al* 2021). The larger populations over the area of the northeastern plains of Manitoba during medieval times, combined with lower food resources due to drought during the MWP, have been documented to result in a northward migration during 1200–1400 CE pushing human activities towards the boreal regions (Flynn 2002). It is also estimated that the indigenous population peaked between 1100 cal yr BP and 500 cal yr BP in the Pacific Northwest, where higher levels of biomass burning were observed in inland areas (Walsh *et al* 2015). Therefore, it is possible that increased population size may have caused migration towards the northern boreal regions resulting in a period of more intense fires in our study region through burning around campsites and for hunting purposes.

A notable feature is the detected declined regional fire trend during the last 400–500 years with exceptions of short-term increases in mid-nineteenth century. A similar declining trend in regional biomass burning was recorded by Gaboriau *et al* (2020) from the MWP. In addition, a regional fire history reconstruction from the same study region based on dendrochronological data demonstrates a declining trend in annually burned areas during the last 200 years (Wallenius *et al* 2011). A recent work that combined several dendrochronological studies showed that, spatially, the same phenomenon has occurred over most of boreal Canada (Chavardes *et al* 2022). Gaboriau *et al* (2020) connects the decline partly with a change in forest composition with more mixed conifer-broadleaf forest where deciduous tree taxa are less prone to fires. However, the decline in fire activity also coincides with the cooling temperatures of the LIA and might be partly explained by less favorable climate conditions (Edwards *et al* 2008). One possible explanation for the decrease in fire activity could be a decline in indigenous populations in the Americas, soon after the first contact with European settlers in 1492 (Decker 1991, Carlos and Lewis 2012, Koch *et al* 2019). Conclusively, it is plausible that the general decrease in fire activity is not caused by any individual driver but several simultaneous factors influencing the fire regime, i.e. the cooler and moister climate creating less fire-prone conditions, the less fire-prone forest composition and the lower human impact that initiated fewer fires.

During the declining trend in fire activity, two notable peaks emerged from the regional fire record, namely around mid-nineteenth century and around the 1930s. The population of European settlers started to grow at the beginning of the nineteenth century as the Hudson Bay Company and missionaries established several settlements in the region, e.g. Fort Vermilion in 1788, Fort Nelson in 1805 and Fort Providence in the 1860s. It is possible that the increasing movement of trappers, tradesmen, missionaries and settlers in the region contributed to the mid-nineteenth century peak in fire activity. According to early ecologists, the use of fire by European immigrants was careless and extensive in North American forests during the nineteenth century (Sargent 1884, Bell 1888).

In the early twentieth century, the peak in the fire record corresponds with the recorded historical fires. These fires could be connected to the severe drought periods over North America (Stahle *et al* 2007). Regardless of the general declining trend in fire activity during the last two centuries, the Canadian fire regime has been suggested to have shifted towards increasing fire activity during recent decades. This may also make forested peatlands more susceptible to burning.

4.2. Regeneration of peatland ecosystem after fires

The increase in the abundance of *Sphagnum* after the fire periods suggests the effective recovery of the peatland ecosystems after a fire disturbance. Similar post-fire recovery of *Sphagnum*-dominated dry hummock communities has been recorded from boreal peatlands in Northern Europe (Sillasoo *et al* 2011, Marcisz *et al* 2019) and in ALB (Lukenbach *et al* 2015, Kettridge *et al* 2017). The relatively quick regeneration of hummock vegetation communities to pre-fire conditions is in line with the notion that in Canadian bogs the microtopography affects the burning patterns and hummocks, which can retain more moisture due to their dense structure, are actually less severely burned (Benscoter *et al* 2005a, 2005b). The relatively quick recovery of *Sphagnum*-dominated hummock communities seen at all studied sites suggests low-intensity fires in the studied peatlands, similarly to the findings of Benscoter *et al* (2005b).

Rather stable peat accumulation regardless of the reoccurring fires suggests that in the long-term, low-intensity fires do not strongly affect the net peat accumulation. Fire events also release nutrients and it is possible that the re-establishing vegetation after a fire event boosts peat accumulation and hence maintains the carbon storage capacity (Mathijssen *et al* 2016, Marcisz *et al* 2019). Turunen *et al* (2002) reported similar results from boreal peatlands in Western Siberia, where they did not record any significant net losses in peat accumulation and carbon storage due to fires. However, human-induced climate change can have multiple effects on these ecosystems, threatening their role as carbon sinks (Loisel *et al* 2021). Increasing fire frequency together with a warming climate can promote drying of peatlands, creating more fire-prone conditions and resulting in more severe or more frequently occurring fires (Kettridge *et al* 2019, Walker *et al* 2019), which can accelerate the release of carbon from permafrost soils in particular (Post and Mack 2022). Furthermore, frequent fires may initiate peatland regime shifts towards plant communities that less effectively accumulate carbon, such as shrub-grass ecosystems, that may also increase the flammability of boreal ecosystems (Kettridge *et al* 2015, Jones *et al* 2022).

5. Conclusions

We demonstrate here that reoccurring fires have been a natural part of the sporadic permafrost zone peatland ecosystems in Western Canada over the last 1500 years. The most intense period of fire activity took place from the 1300s to the 1550s, with decreasing fire activity over recent centuries.

The variability of the fire records between the sites and even between the cores from the same site demonstrates that fires can be very localized and certain parts of large peatlands might have experienced burning, while other portions remained untouched by fire. This information is important in understanding the recovery processes and the significance of peatland carbon sink capacity. The unburned parts of the peatland ecosystem may act as small refuges and starting points for recovery and vegetation succession. The evident variation in nearby fire records, coupled with our findings indicating comparable regional fire occurrences during both the MWP and the LIA, marked by distinct temperature conditions, suggest that in addition to climate, site-specific factors such as vegetation succession and ecohydrological conditions may play crucial role in fire regulation in boreal forested peatlands. Thus, to predict the future fate of peatland dynamics under changing environmental conditions, it is important to acknowledge not only temperature, but also changes in precipitation and the effect of peatland microtopography and hydrological conditions.

The detection of a clear and consistent post-fire increase in the abundance of *Sphagnum* mosses implies the rapid recovery potential of peatland ecosystems after low-intensity fires. The regeneration pattern where pre-fire vegetation repeatedly re-establishes suggests that fires do not necessarily have a negative effect on long-term peat accumulation, which may remain relatively stable in a natural fire regime with low-severity fires. In conclusion, forested peatlands play a valuable role as carbon sinks and storage, and it appears that low-severity fires do not notably affect these key ecosystems if peatlands are allowed to undergo natural succession after fire.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

We would like to thank Ullastiina Mahlamäki, for the help during the fieldwork, and Laura Sandholm for peat analyses. N K was supported by the Academy of Finland (Project 323065), M V was supported by the Academy of Finland (Projects 123503, 296519 and DisPeat Project 1338631), T W was supported by Academy of Finland (Project 121919). This work has received funding under the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 869471 (CHARTER) and T W, M V, S P and N K acknowledge this support. E S T acknowledge support from the Academy of Finland Flagship funding for ACCC (Grant No. 337550) and for the BorPeat Project (330840).

ORCID iDs

Niina Kuosmanen https://orcid.org/0000-0002-9688-3797
Minna Väliranta https://orcid.org/0000-0003-0129-7240
Sanna Piilo https://orcid.org/0000-0002-9054-1542

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