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Converging and diverging burn rates in North American boreal forests from the Little Ice Age to the present

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ABSTRACT

Warning. *This article contains terms, descriptions, and opinions used for historical context that may be culturally sensitive for some readers.*

Background. Understanding drivers of boreal forest dynamics supports adaptation strategies in the context of climate change. **Aims.** We aimed to understand how burn rates varied since the early 1700s in North American boreal forests. **Methods.** We used 16 fire-history study sites distributed across such forests and investigated variation in burn rates for the historical period spanning 1700–1990. These were benchmarked against recent burn rates estimated for the modern period spanning 1980–2020 using various data sources. **Key results.** Burn rates during the historical period for most sites showed a declining trend, particularly during the early to mid 1900s. Compared to the historical period, the modern period showed less variable and lower burn rates across sites. Mean burn rates during the modern period presented divergent trends among eastern versus northwestern sites, with increasing trends in mean burn rates in most northwestern North American sites. **Conclusions.** The synchronicity of trends suggests that large spatial patterns of atmospheric conditions drove burn rates in addition to regional changes in land use like fire exclusion and suppression. **Implications.** Low burn rates in eastern Canadian boreal forests may continue unless climate change overrides the capacity to suppress fire.

Keywords: boreal forests, breakpoints, burn rates, Cox models, fire-history study sites, meta-analysis, survival analysis, tree cohort records.

Introduction

Fire activity in North American boreal forests varies substantially over space and time (Gavin *et al.* 2007; Girardin *et al.* 2019; Erni *et al.* 2020). Some of its variation has been associated with shifts in historical climate, such as the Holocene Thermal Maximum (Marlon *et al.* 2013; Hoecker *et al.* 2020), the Little Ice Age (LIA) (Drobyshev *et al.* 2017), or more recently with anthropogenic climate change (Ellis *et al.* 2022; Jain *et al.* 2022). Moreover, prolonged fire exclusion (Davidson-Hunt 2003; Miller *et al.* 2010; Ryan *et al.* 2013) and the introduction of organised and mechanised fire suppression in the mid to late 20th century influenced to varying levels climate-driven fire activity in many North American boreal forests (Parisien *et al.* 2020; Tymstra *et al.* 2020). Given the growing costs of wildfire suppression and risks towards life and property worldwide (McWethy *et al.* 2019), there is a need to better understand the spatial and temporal dimensions of fires and their associated fire regimes. This is especially true in North American boreal forests because these sustain fundamental ecosystem services including crucial freshwater and carbon reservoirs (Gauthier *et al.* 2015).

Although there is evidence of surface fires in North American boreal forests, high-severity stand-replacing fires dominate in these forests (Brassard and Chen 2006;

Erni *et al.* 2020; Margolis *et al.* 2022). Analysing the age structure of forest stands and dating fire scars have proven instrumental in exposing historical dynamics of fires (Heinselman 1973; Johnson 1992). Tree cohort records are particularly useful for this work, providing information on long-term historical variability in burn rates for boreal forests where stand-replacing fires dominate (Cyr *et al.* 2016; Drobyshev *et al.* 2017). Assessing how burn rates varied over time in North American boreal forests supports research on the drivers of burn rates (Danneyrolles *et al.* 2021) and provides a benchmark with other burn rate metrics derived from satellite imagery (Guindon *et al.* 2014), multi-century lake sediment paleofire records (Waito *et al.* 2018), and terrestrial biosphere or earth system models (Chaste *et al.* 2018).

Here, we conducted a meta-analysis including 16 fire-history study sites distributed across boreal North America to estimate how burn rates shifted between 1700 and 1990. We used tree cohort records to which we applied Cox regression models to estimate historical burn rates (1700–1990) on a decadal scale. We then used Canadian and U.S. national fire databases to estimate modern burn rates (1980–2020) at each site and compared mean burn rates across historical and modern periods. Based on our results, we discuss likely drivers behind temporal shifts in burn rates during the historical period and compare temporal trends with those derived from lake sediment paleofire records. We also discuss likely drivers behind distinct spatial patterns in burn rates for the modern period. Finally, we briefly discuss the potential implication of climate change on future burn rates in North American boreal forests.

Methods

Study area

We analysed tree cohort records from 16 published fire-history studies in North American boreal forests (Fig. 1, Table 1). We selected all available studies with such records that spanned multiple centuries. The 16 studies comprise sites spanning a bioclimatic gradient from subarctic to temperate forests (Baldwin *et al.* 2020). Boreal forests at the sites are mostly dominated by conifers including black spruce (*Picea mariana* (Mill.) BSP), white spruce (*Picea glauca* (Moench) Voss), balsam fir (*Abies balsamea* (L.) Mill.), and jack pine (*Pinus banksiana* Lamb.), and to a lesser extent deciduous tree species including trembling aspen (*Populus tremuloides* Michx.), paper birch (*Betula papyrifera* Marshall), and balsam poplar (*Populus balsamifera* L.) (Baldwin *et al.* 2020). In these forests, most fires are of high-severity and stand replacing (Erni *et al.* 2020; Margolis *et al.* 2022).

Burn rate estimation

For the 16 fire-history study sites, we reconstructed burn rates from tree cohort records (Table 1). Tree cohorts were identified with dendrochronological dating of initial stand establishment, considered as the time since last stand-replacing fire. In the case in which no trace of past fire events could be detected or precisely dated, for instance in uneven-aged stands where trees do not represent the first post-fire cohort, a minimum time since fire was estimated as the age of the oldest trees sampled. This estimate was considered as censored data for the subsequent survival

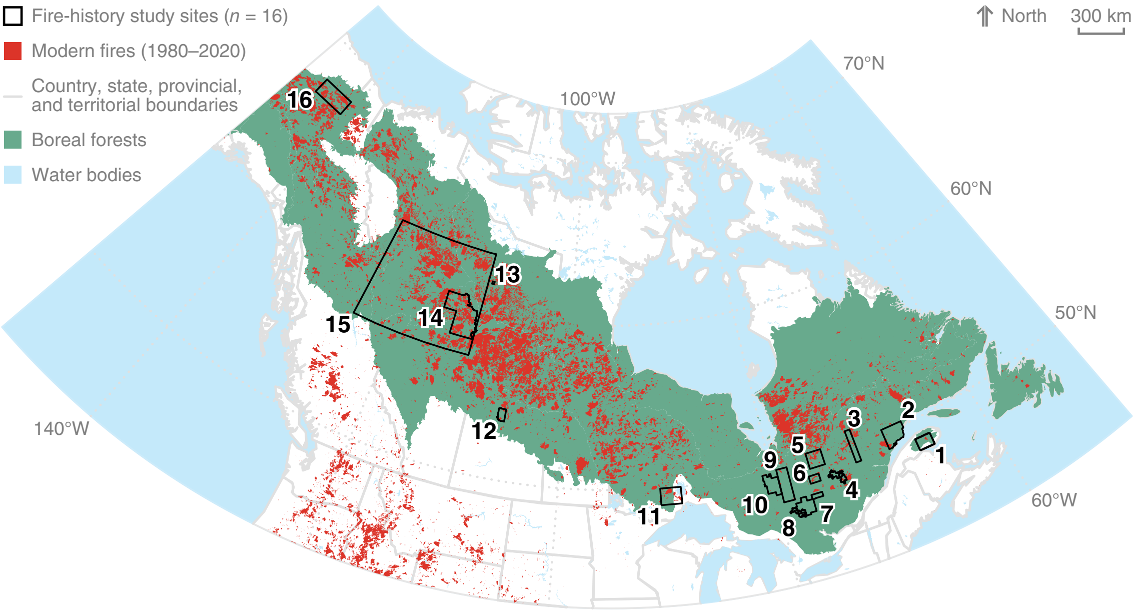

Fig. 1. Location of the 16 fire-history study sites in North American boreal forests and modern fires (1980–2020).

Table 1. Characteristics for the 16 fire-history study sites in North American boreal forests including mean burn rate (BR; % of study site area burned per year) estimates during the historical and modern periods.

Fire-history study site	Province, territory, or state	Area surveyed (km^2)	Source	Historical period (1700–1990)				Modern period (1980–2020)
				Censored data	Record (calendar years)		Mean BR estimate (% per year)	Mean BR estimate (% per year)
					Start	End		
1: Gaspésie	QC	8669	Lauzon *et al.* (2007)	Y	1790	1990	1.06	0.09
2: Côte Nord	QC	15 515	Cyr *et al.* (2007)	Y	1720	1990	0.48	0.14
3: Lac-Saint-Jean	QC	7915	Bélisle *et al.* (2011)	Y	1700	1990	0.37	0.20
4: Central Québec	QC	3629	Lesieur *et al.* (2002)	Y	1720	1990	0.98	0.53
5: Waswanipi	QC	10 628	Le Goff *et al.* (2007)	Y	1720	1990	0.74	0.56
6: Eastern Abitibi	QC	3505	Kafka *et al.* (2001)	Y	1770	1990	0.77	0.49
7: Southeastern Abitibi	QC	13 319	Drobyshev *et al.* (2017)	Y	1800	1990	1.02	0.00
8: Northern Témiscamingue	QC	2943	Grenier *et al.* (2005)	Y	1740	1990	0.48	0.00
9: Western Abitibi	QC	16 051	Bergeron *et al.* (2004)	Y	1700	1990	0.85	0.06
10: Lake Abitibi	ON	10 182	Lefort *et al.* (2003)	Y	1730	1990	0.69	0.02
11: Central Ontario	ON	13 795	Senici *et al.* (2010)	Y	1750	1990	0.46	0.60
12: Prince Albert	SK	3827	Weir *et al.* (2000)	N	1760	1990	3.78	0.40
13: Rutledge Lake	NT	10	Johnson (1979)	N	1770	1970	5.54	0.00
14: Wood Buffalo	AB	41 231	Larsen (1997)	N	1700	1990	1.90	1.47
15: Northwestern Canada	AB, BC, NT	487 633	Wallenius *et al.* (2011)	N	1770	1990	2.37	0.77
16: Porcupine River	AK	36 000	Yarie (1981)	N	1790	1970	5.91	1.13

analyses (Cyr *et al.* 2016). Conversely, precisely dated time since fire information represented uncensored data for these analyses (Cyr *et al.* 2016). Information about censored and uncensored data was available for the eastern Canadian sites (sites 1–11 in Table 1, Fig. 1) and is consistent with the region's long fire cycles, which often exceed the longevity of the oldest trees (Drobyshev *et al.* 2017). From the tree cohort records, we thus obtained for each fire-history study site a time series of burn rate censored or uncensored values at a 10-year resolution, except for Rutledge Lake and Porcupine River (sites 13 and 16, respectively), which had a 20-year resolution.

We used Cox regression (Cox 1972), a semi-parametric survival model, to estimate shifts in historical burn rates independently for each of the 16 sites between 1700 and 1990. Cox models are well suited for our data compared to other types of survival analysis because no assumption about the shape of the baseline hazard function is necessary (Cyr *et al.* 2016). Cox models allow the fitting of a baseline hazard curve. This curve corresponds to the probability of the landscape to have burned each decade (or each 20-year window for Rutledge Lake and Porcupine River), which in our study was the estimated historical burn rate of the landscape. For each of the 16 sites, we computed bootstrapped confidence intervals in burn rates from 1000 random samples with replacement in the original datasets (i.e. 1000 bootstrapped burn rate curves). Cox models were fitted using the 'survival' package (Therneau 2020) in R version 4.0.2 (R Core Team 2020).

To detect shifts in historical burn rates, we applied a breakpoint analysis on the bootstrapped burn rate curves. Homogeneous periods in terms of mean and variance in decadal burn rates were identified with the 'cpt.meanvar' function from the 'changepoint' package in R (Killick *et al.* 2016). This function computes the optimal positioning for shifts in burn rates with the Pruned Exact Linear Time method (Killick *et al.* 2016) and applies a modified Bayes information criterion as a penalty method (Zhang and Siegmund 2007). We applied the breakpoint analysis to the bootstrapped burn rate curves of each site to obtain probabilities of finding breakpoints that were more robust than when computed from one single observed curve. For each bootstrapped curve of each site, we limited the maximum number of breakpoints to five and the minimum number of time-steps to three between two breakpoints. The significance of breakpoint probabilities at each time-step (decade or 20-year window) was determined with a Monte-Carlo permutation method. For each site, we created 1000 randomised burn rates curves (i.e. random permutation of time since last stand-replacing fire and decade or 20-year window) and computed for each time-step a probability of finding a positive or negative breakpoint by chance. Positive and negative breakpoints corresponded to shifts of higher and lower burn rates, respectively. A breakpoint was deemed significant if its bootstrapped probability was greater than expected by chance. Non-significant breakpoints were removed from subsequent analyses. We also summarised these results across the 16 sites in the meta-analysis. For this, we calculated the proportion of sites recording a positive or negative breakpoint for each decade between 1700 and 1990. We calculated 90% confidence intervals using a Bayesian approach with an uninformative prior distribution (Gelman *et al.* 1997). The Bayesian approach employing the Jeffreys prior distribution for the parameter space, with Beta (1/2, 1/2), has been shown to be particularly robust under small sample sizes while also being well suited for uncertainty estimation under large ones (Brown *et al.* 2001).

To compare mean burn rates during historical versus modern periods at each site, we estimated modern burn rates using observational records. For all sites in Canada, we used the 1980–2020 National Fire Database polygon data (Natural Resources Canada 2021), whereas for the site in Alaska, we used the 1980–2020 combined wildland fire datasets for the U.S. (Welty and Jeffries 2021). For all sites, we calculated and compared mean burn rate estimates during the historical and modern periods.

Results

The 16 fire-history study sites comprised a total area of 662 814 km^2, individual areas spanning 10–487 633 km^2 (median = 9426 km^2) and records spanning 181–291 years (median = 246 years) (Table 1). Mean burn rate estimates varied across sites during the historical period (1700–1990), ranging from 0.37% per year at Lac-Saint-Jean to 5.91% per year at Porcupine River. Similarly, mean burn rate estimates varied across sites during the modern period (1980–2020) but were overall lower than their historical counterparts. No fires were recorded at Rutledge Lake, while the highest mean burn rate was estimated in Wood Buffalo at 1.47% per year. Central Ontario was the only exception for which the mean burn rate estimate was higher during the modern period (0.60% per year) relative to the historical period (0.46% per year).

Burn rates varied through time at all sites (Figs 2, 3). In particular, the period prior to the 1800s was denoted by high variability, with little distinction between sites experiencing positive and negative breakpoints in burn rates (i.e. breakpoints toward higher or lower burn rates, respectively). A large proportion of negative breakpoints in 1790, 1810, and 1820 highlighted shifting conditions towards lower burn rates for many of the fire-history study sites. A clear demarcation also occurred in 1940, with 44% of sites experiencing a negative breakpoint (90% CI [23%, 67%]) and no site recording a positive breakpoint. Among the 16 fire-history study sites, 11 (or 69% [48%, 83%]) recorded at least one negative breakpoint between 1940 and 1970, while none recorded a positive breakpoint (90% CI 0% [0%, 13%]).

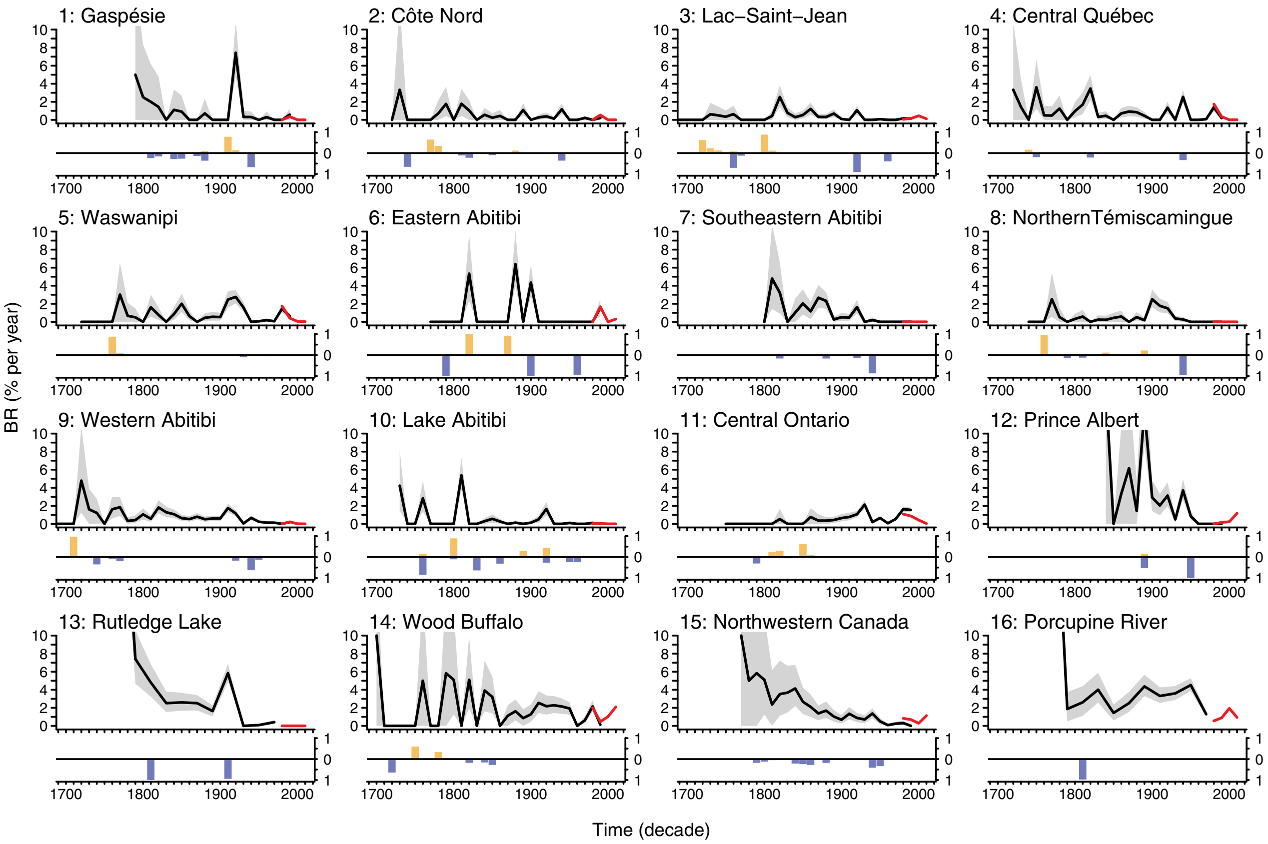

Fig. 2. Burn rates and their standardised breakpoint probabilities over time for the 16 fire-history study sites in North American boreal forests. Black curves are burn rates for the historical period (1700–1990), whereas light grey areas correspond to 90% confidence intervals derived from 1000 bootstrapped samples. Red curves are burn rates estimated for the modern period (1980–2020). Columns beneath curves are standardised probabilities of burn rate breakpoints during a given decade (or 20-year period for sites 13 and 16) calculated as the proportion of 1000 bootstraps indicating a breakpoint. Orange (blue) columns above (below) the horizontal line indicate a shift towards a higher (lower) burn rate.

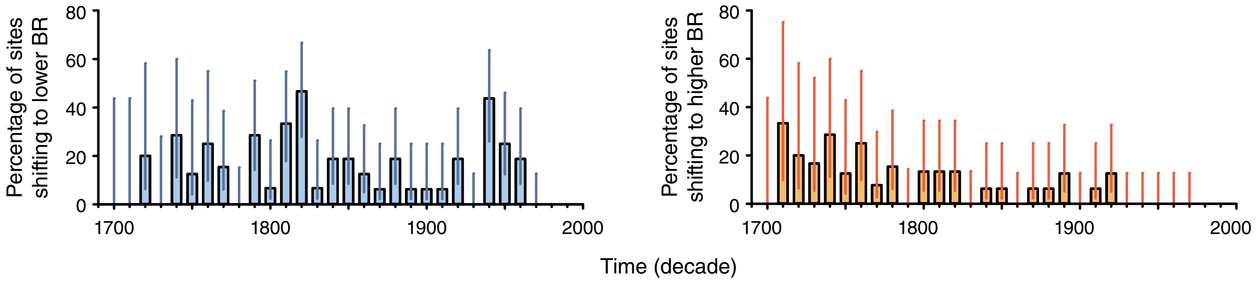

Fig. 3. Percentage of sites shifting to lower or higher burn rates (BR) over the historical period (1700–1990). Columns represent percentages whereas bars 90% confidence intervals.

Discussion

For most of the 16 fire-history study sites, burn rates between 1700 and 1990 showed a particularly strong declining trend during the early- to mid-1900s, corroborating research that compiled fire-history studies in eastern Canadian boreal forests (Drobyshev *et al.* 2017). The synchronicity of this decreasing trend across most sites suggests that large spatial patterns of atmospheric conditions drove a decline in fire activity across boreal forests of North America. In these forests, persistent (≥10 days) blocking high pressure ridges are related with greater area burned (Macias Fauria and Johnson 2008). Such ridges generate warm and dry weather that decreases fuel moisture content and makes fuels more susceptible to ignite and combust (Skinner *et al.* 2002). As the ridge breaks down, lightning with little rain and strong surface winds can be generated and lead to higher chances of fire ignition and spread (Flannigan and Harrington 1988). Girardin *et al.* (2006) suggest that a weakened western Canadian continental ridge and eastern Canadian polar trough during most of the 1750s–1850s was associated in central and eastern boreal forests of North America with drier climate, which would have lowered fuel moisture content and facilitated fires. However, this period was also characterised by strong volcanic eruptions that limited incoming solar radiation and lowered global temperatures between 1790 and 1830 (Wagner and Zorita 2005; Gennaretti *et al.* 2014). During these decades, we found that many sites shifted towards lower burn rates possibly associated with the eruptions, which may have decreased the risk of wildfires at least over multiple years following the eruptions.

At the end of the LIA ~150 years ago and into the 20th century, the eastern Canadian polar trough likely strengthened, limiting the inflow of dry Artic air, and increasing the amount of precipitation in central and eastern Canada (Macias Fauria and Johnson 2008; Drobyshev *et al.* 2017). During this period, we found generally fewer sites with shifts towards higher burn rates relative to earlier decades (e.g. 1710–1820), and a strong synchronous shift towards lower burn rates starting in 1940 and persisting until 1960. The strength of this shift towards lower burn rates across sites could have resulted from a cooler phase of northeastern Pacific Ocean sea-surface temperatures lasting between 1947 and 1976 and that brought moist and cool air masses towards North American boreal forests (Macias Fauria and Johnson 2006, 2008).

Apart from unfavourable atmospheric conditions towards fire, the exclusion of fire followed by the modernisation of fire suppression efforts also restricted fire activity in North American boreal forests. Prior to the 1900s, archive records reveal the application of fire as a land and resource management tool in some boreal forests by Indigenous peoples (Anderton 1999; Davidson-Hunt 2003; Ferguson 2011; Johnson and Miyanishi 2012). Population declines in many Indigenous communities during the last centuries (Waldram *et al.* 2006; Herring and Sattenspiel 2007) likely reduced cultural burns including prescribed fires. Moreover, policy shifts towards protecting communities and timber from fire during the 20th century likely also resulted in lowering fire ignitions and spread in some boreal forests (Hessburg *et al.* 2019; Bowman *et al.* 2020). Later in the mid to late 20th century, modernisation of fire suppression efforts in North America principally via organisation and mechanisation were shown to limit fire activity in some boreal forests of Canada (Cumming 2005; Martell and Sun 2008) and Alaska (Chapin *et al.* 2008). These counter-indications lead us to suggest that management and suppression policies are not the primary factor leading to declining fire activity because they are regionally variable and governed by individual agencies and provinces (Tymstra *et al.* 2020) while declining changes are relatively synchronous.

Our findings of declining trends in boreal forest burn rates over the last centuries in North America align with similar conclusions reached from analyses of sediment-inferred biomass burning in other North American boreal forests. Paleofire records are complementary to dendrochronological datasets for the reconstruction of past fire dynamics at different scales from secular to millennial temporal windows (Higuera *et al.* 2011; Brossier *et al.* 2014). Most paleofire research in North American boreal forests finds decreasing biomass burning since the 1700s. In eastern boreal forests, paleofire reconstructions showed a decrease of regional fire frequency towards the modern period with a minimum at present compared to the past 7000 years (Hély *et al.* 2010). In northern Québec, reconstructions for these forests revealed decreases in biomass burned and fire size between 3000 years BP (before present) and the present (Ali *et al.* 2009, 2012; Remy *et al.* 2018) concomitant with an opening dynamic towards forest tundra over the same period (Asselin and Payette 2005). Multi-millennial charcoal records from southern boreal forests of Ontario and Manitoba revealed that biomass burning declined during the past 2000 years (Waito *et al.* 2015, 2018). In the central Northwest Territories, a composite paleorecord from four lakes indicated a decrease in biomass burned following the end of the LIA (Gaboriau *et al.* 2020), although extreme wildfire years with large fires were more recurrent in the last two decades (Gaboriau *et al.* 2022). In the southwestern Yukon, a postglacial reconstruction of fire history inferred from sediment charcoal records showed a significant increase in fire frequency at ~1000 years BP, before a large decrease until the present (Prince *et al.* 2018). In eastern Alaska, Kelly *et al.* (2013) suggested a peak of fire activity around 1000–500 years BP during the Medieval Climate Anomaly, a warm and drought-prone period, followed by a large decrease in biomass burning until recent decades when fire frequency and biomass burning increased sharply.

Compared to the historical period (1700–1990), the modern period (1980–2020) showed less variability in mean burn rates across fire-history study sites and lower mean burn rates at all sites except in Central Ontario, indicating that fire activity in North American boreal forests has predominantly decreased over the combined windows of analysis, and that burn rates during the modern period are broadly within the historical range of variability. We also found that mean burn rates during the modern period presented different trends among eastern Canadian versus northwestern North American sites (sites 1–11 vs 12–16). Low mean burn rates ($\leq$0.20% per year) over the modern period for most sites in Québec and eastern Ontario (sites 1–3 and 7–10) were consistent with commonly high summer moisture that limited wildfire risks during the 20th and early 21st centuries in eastern Canada (Girardin and Wotton 2009). Empirical data and modelling notably highlighted the limitation on ignition imposed by the regionally wet and cool climate, although mild increases in fire activity were also reported in the latter half of the 20th century with drier climate (Chaste *et al.* 2018). In comparison, most of the sites in northwestern North America (sites 12 and 14–16) revealed increasing trends in mean burn rates over the modern period, corroborating findings of increasing area burned and number of large fires in western Canada over the last half-century (Hanes *et al.* 2019). Similar findings were also reported in Alaska, with the 2000s showing greater burned areas than the preceding six decades (Kasischke *et al.* 2010). These increases in burned areas were attributed to significantly warmer and drier climate over the later half of the 20th and early 21st centuries in western Canada (Whitman *et al.* 2022) and Alaska (Kelly *et al.* 2013). As warmer and possibly drier climate may well override the capacity to suppress fire (Flannigan *et al.* 2009) it remains uncertain if the observed decrease of burn rates in eastern Canadian boreal forests will continue in the future. Temperature increases in the order of +4 to +6°C would be unprecedented and could very well reverse these trends, to the point where irreversible changes in forest composition and loss of forest cover could occur (Chaste *et al.* 2019; Augustin *et al.* 2022; Boulanger *et al.* 2022). Projections of future fire activity in the region indicate statistically significant increases by 2061–2100 (Girardin and Mudelsee 2008). Such projections suggest that we can expect reconvergence of burned area patterns between sites in eastern Canada and those in northwestern North America by mid to late 21st century.

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