Canadian Journal of Forest Research

OPEN ACCESS | Research Article

Contextualizing recent increases in Canadian boreal wildfire activity: decadal burn rates still within historical variability of the two past centuries

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Abstract

With approximately 15 million ha burned, the 2023 wildfire season in Canada was exceptional. However, it remains unclear whether such recent increases in burned areas exceed the range of variability observed over past centuries. The objective of this study was to leverage available dendrochronological reconstructions of decadal burn rates to contextualize their recent increase within their historical variability over the past two centuries. We compared decadal burn rate reconstructions based on dendrochronological data (1800–2023) for five large eastern and western Canadian boreal forest zones to those of recent decades up to 2023. The area burned in 2023 ranged from 0.76% to 32.5% among the five zones, which is unprecedented compared to the proportion recorded since 1972 for four of the five zones analyzed. In contrast, the burn rates of the decade ending in 2023 (i.e., 2014–2023) generally remained within the natural range of variability of the last two centuries. However, burn rates in two zones were close to the highest decadal burn rates observed since the 1800s and exceeded historical variability in one zone in western Canada. We discuss the historical and current trends in burn rates, their drivers and implications.

Key words: environmental history, fire history, paleoecology, climate change, Pyrocene

Résumé

Avec environ 15 millions d'hectares brûlés, la saison des feux de forêt de 2023 au Canada a été exceptionnelle. Cependant, il reste à déterminer si cette récente augmentation des superficies brûlées dépasse les limites de variabilité historiques des deux derniers siècles. L'objectif de cette étude était de s'appuyer sur des reconstitutions dendrochronologiques des taux de brûlage décennaux afin de contextualiser leur récente augmentation, en tenant compte de la variabilité historique des derniers siècles. Nous avons comparé les reconstructions des taux de brûlage décennaux, basés sur des données dendrochronologiques couvrant la période 1800–2023, à celles des dernières décennies jusqu'en 2023 pour cinq vastes régions de la forêt boréale situées dans l'est et l'ouest du Canada. Les superficies brûlées en 2023 ont varié de 0,76% à 32,5% parmi les cinq zones, ce qui apparaît clairement sans précédent depuis 1970 pour quatre des cinq zones analysées. En revanche, les taux de brûlage de la décennie se terminant en 2023 (2014–2023) sont généralement restés dans la plage de variabilité historique depuis le XIXe siècle. Cependant, les taux de brûlage 2014–2023 dans deux zones étaient proches des taux de brûlage décennaux les plus élevés observés depuis les années 1800 et n'ont dépassé la variabilité historique que dans une seule zone de l'Ouest canadien. Nous discutons les tendances historiques et actuelles des taux de brûlage, leurs facteurs déterminants et leurs implications. [*Ceci est une traduction fournie par l'auteur du résumé en anglais*.]

Mots-clés : histoire environnementale, histoire des feux, paléoécologie, changement climatique, Pyrocène

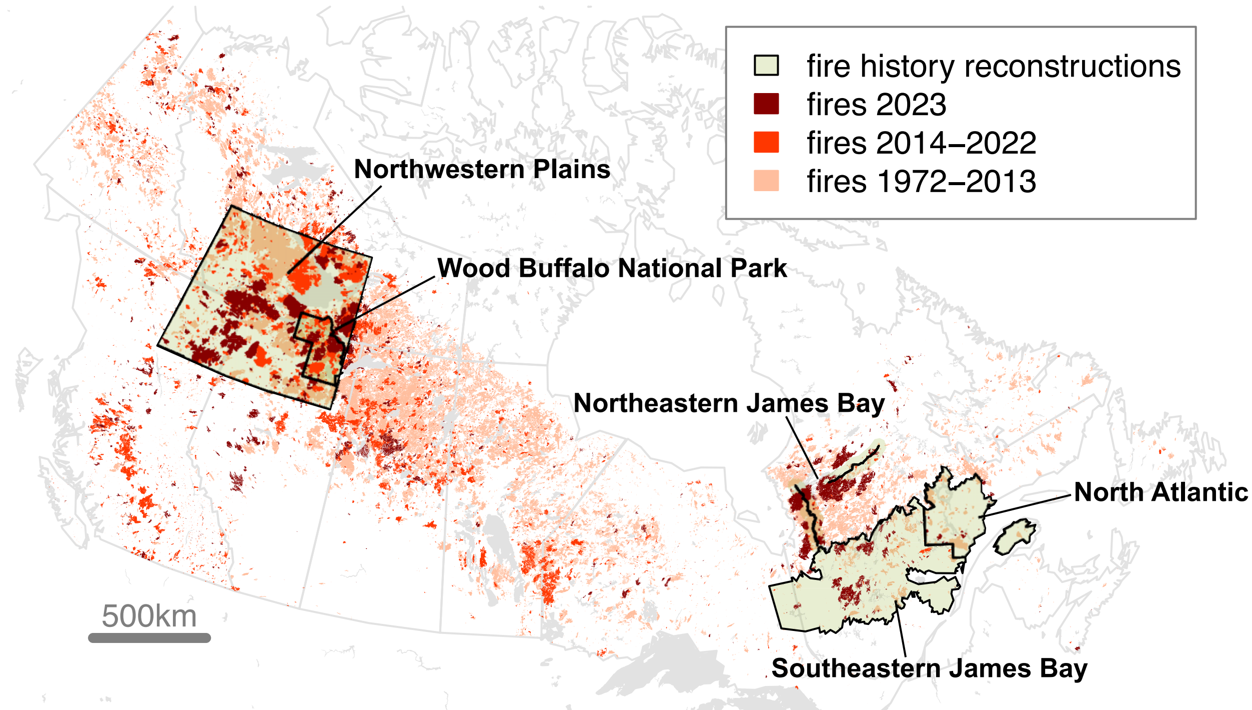
Introduction

With approximately 15 million ha of area burned in Canada, the 2023 wildfire was unprecedented since the start of comprehensive national reporting in the 1970s (Jain et al. 2024). The spatial extent of uncontrolled fires confirmed the recent decadal trend of increasing area burned, likely associated with a warming climate (Coogan et al. 2019; Hanes et al. 2019; Kirchmeier-Young et al. 2024) and related decrease in relative humidity at northern latitudes (Parisien et al. 2023; Jain et al. 2024). Yet, it remains unclear whether such recent increases in burned areas exceed the range of variability observed over past centuries (i.e., the range of decadal area burned observed historically; Keane et al. 2009). The answer to this question has important ecological implications, given that the historical range of variability represents the variability of fire regimes to which ecosystems were exposed over centuries, thereby implicitly reflecting the ecological boundaries within which forest ecosystems are resilient to wildfire disturbances. Indeed, landscape mosaics—their structure, composition, ecosystem functions, and service provisioning—are largely the legacy of several centuries of fire disturbances and subsequent successional processes (McLauchlan et al. 2020).

The bounds of the historical range of variability depend on the period under analysis. The Canadian National Fire Database (CNFDB) and the National Burned Area Composite (NBAC) are robust forest and grassland fire mapping and monitoring systems that provide data on modern fires. Canada-wide quasi-exhaustive data started being recorded in the 1960s for the CNFDB (Hanes et al. 2019) and accurate mapping started in 1972 with the advent of the Landsat satellite missions for NBAC (Hall et al. 2020; Skakun et al. 2021, 2022). Although those datasets are among the most comprehensive worldwide regarding accuracy and temporal depth (∼50–60 years), the period covered remains limited in characterizing the variability of a temporally fluctuating phenomenon like wildfires (Girardin and Sauchyn 2008). Data sources enabling the estimation of longer-term changes in boreal fire regimes include palaeoecological and dendrochronological records (Conedera et al. 2009; Aakala et al. 2023). Paleoecological fire studies therein are generally based on sediment charcoal accumulation rates from which components of fire regimes like biomass burned, fire size, and severity, and fire return intervals can be estimated over centennial to millennial time scales (e.g., Ali et al. 2012; Blarquez et al. 2013; Kelly et al. 2013; Gaboriau et al. 2020; Hennebelle et al. 2020; Girardin et al. 2024). However, these reconstructions are of a semi-qualitative nature because the indicator of the burning rate is most often based on charcoal influx per time unit. This poses a significant challenge since this metric is not directly comparable with modern measurements of burned areas. Additionally, these reconstructions' relatively low temporal resolution (most often >15 years) further complicates comparisons with current fire regime estimates.

Dendrochronology offers two main approaches for reconstructing historical fire regimes. First, collecting and dating samples of fire scars (i.e., wounds resulting from partial cambium mortality on trees affected by high temperatures during fires, observed on living trees and deadwood) allows the dating of fire events at annual to seasonal resolutions (Daniels et al. 2017). In North America, this method was widely applied to seasonally dry forest ecosystems exposed to frequent low- to moderate-intensity fires because it relies on trees that are scarred but not killed by fires (Margolis et al. 2022). In the North American boreal biome, wildfire regimes primarily consist of very large crown fires driven by high soil organic matter and fuel continuity (Hanes et al. 2019; Guindon et al. 2020; Wang et al. 2025), which contrasts with surface fire regimes in the Eurasian boreal zone (de Groot et al. 2013; Rogers et al. 2015; Magne et al. 2020). Paleoecological evidence indicates that large and severe fires have accounted for the majority of biomass burned in the North American boreal biome over the past millennia (e.g., Ali et al. 2012; Gaboriau et al. 2020; Girardin et al. 2024). However, the burn rates reconstructions based on fire scars have also proven to be reliable in North American boreal forests (Héon et al. 2014; Erni et al. 2017) since abundant fire scars can still be found within small low-severity burn patches or at the periphery of large wildfires as they gradually die down. Moreover, many researchers working in the boreal forest have used dendrochronology and interpretation of historical aerial photography to map the time-since-last-fire across the landscape by estimating the age of post-fire tree cohorts at the stand level (e.g., Johnson and Gutsell 1994; Larsen 1997; Bergeron et al. 2004). Time-since-last-fire datasets can be statistically analyzed to reconstruct spatiotemporal changes in fire regimes (Cyr et al. 2016). Whether based on tree-ring fire scars, time-since-last-fire mapping, or both, dendrochronology-based studies can estimate burn rates (i.e., the proportion of a landscape burned by fire over a fixed period) over the last centuries with a temporal resolution varying from annual to decadal.

Fig. 1. Location of the five long-term fire history reconstructions presented in this study. Fires that occurred during the periods 1972–2013, 2014–2022, and 2023 are represented in varying shades of red. All fire history reconstructions are based on the time-since-last-fire method, except for Northeastern James Bay, which is based on fire scars inventoried along two transects (see the "Materials and methods" section for references for more details). The figure was created using R version 4.4.2 and assembled from the following data sources: fire perimeters from the National Burned Area Composite database (Hall et al. 2020; https://cwfis.cfs.nrcan.gc.ca/datamart/metadata/nbac), administrative boundaries from the Government of Canada Open Data portal (https://open.canada.ca/), and fire history reconstruction shapefiles provided courtesy of co-authors holding the rights.



These methodological approaches may support more reliable comparisons between long-term reconstructions and modern spatial wildfire atlases (i.e., CNFDB or NBAC; Chavardès et al. 2022).

The objective of this study was to leverage available dendrochronological reconstructions of decadal burn rates in Canadian boreal forests to contextualize the recent reported increase in fire activity, including the 2023 fire season, within their historical variability over the past two centuries. All paleoecological, dendrochronological, and historical studies highlight complex and nonstationary long-term trends in burn rates and other fire regime characteristics (e.g., Ali et al. 2012; Hanes et al. 2019; Chavardès et al. 2022; Girardin et al. 2024). For example, recent regional meta-analyses have suggested that the burn rates were generally high during the Little Ice Age (LIA; roughly AD 1300–1850) and the early 20th century in most North American boreal forests (Drobyshev et al. 2017; Chavardès et al. 2022). The burn rates subsequently declined during the second half of the 20th century (i.e., the period partly covered by the modern Canadian fire mapping and monitoring datasets). This reinforces the necessity of comparing recent burn rates to long-term trends to assess whether recent climate-driven increases are currently pushing ecosystems beyond their historical variability. We thus compared the reconstructed historical burn rates (1800–2020) to those of the decade ending in 2023 (i.e., 2014–2023). Based on these analyses, we discuss the drivers of historical and current trends in burn rates and discuss to what extent future burn rates could exceed the historical range of variability.

Materials and methods

Spatial zones corresponding to historical reconstructions of burn rates

Historical burn rates were reconstructed with dendrochronological data for five large zones representative of the Canadian boreal biome (Fig. 1). Four zones rely on 11 previously published time-since-last-fire data, which were reanalyzed by Chavardès et al. (2022), and the fifth zone relies on published and unpublished fire-scar data (Héon et al. 2014; Erni et al. 2017; Shakeri 2024).

Our analyses of time-since-fire data build on over 50 years of methodological development (see, for ex.: Arno and Sneck 1977; Wagner 1978; Johnson 1979; Yarie 1981; Bergeron 1991; Johnson and Larsen 1991; Johnson and Gutsell 1994). Johnson and Gutsell (1994) established the mathematical principles and associated rigorous sampling methods crucial for applying the time-since-last-fire approach, which was carefully followed during data acquisition of the studies compiled for this manuscript. The time-since-last-fire data come in their raw form as randomly or regularly sampled plots across a given landscape. During data collection, the dates of the last fires were determined using historical archives for recent fires (when available, typically covering fires from 1930 to 1950) and dendrochronological dating of initial stand establishment for older fires. For cases where no traces of past fire events were detected or precisely dated (i.e., uneven-aged stands where the oldest trees do not necessarily represent the first post-fire cohort), a minimum time-since-last-fire was estimated as the age of the oldest trees sampled; such estimates were considered censored data for the subsequent survival analyses (Cyr et al. 2016). For all plots sampled across the different studies, we obtained time-since-last-fire (censored or uncensored) values at a 10-year resolution (i.e., minimum temporal accuracy allowed by dendrochronological dating).

Time-since-last-fire data from eastern Canada were compiled from nine independent studies (Kafka et al. 2001; Lesieur et al. 2002; Lefort et al. 2003; Bergeron et al. 2004; Cyr et al. 2007; Lauzon et al. 2007; Le Goff et al. 2007; Bélisle et al. 2011; Portier et al. 2016). To simplify the analysis, we aggregated those data within two large zones: Southeastern James Bay (1057 plots) and North Atlantic (185 plots). These two distinct zones were defined based on (1) the managed boreal forests of eastern Canada and (2) the homogeneous fire regime zonation defined by Boulanger et al. (2014). We separated data by managed or unmanaged boreal forests because they experience significant differences in fire risk management and disturbance dynamics (Tymstra et al. 2020). In the managed boreal forests to the south, fires systematically generate a suppression response by fire protection agencies, whereas, in unmanaged forests to the north, fires are mostly left to burn unless they threaten communities or infrastructures.

The time-since-last-fire data from the two zones in western Canada are from two independent studies: the Northwestern Plains (Wallenius et al. 2011) and Wood Buffalo National Park (Larsen 1997). Although their extents overlap (Fig. 1), these two zones were analyzed independently because they have substantial differences in sample density and distribution (85 plots randomly distributed within 1 km of the road network for the Northwestern Plains, and 167 plots randomly distributed across the whole area for the Wood Buffalo National Park). In those two studies, no data were considered censored (sensus Cyr et al. 2016) during data acquisition, as the short fire cycles in these areas make it highly unlikely that clear evidence of tree recruitment after the last fires would be absent.

In addition to the above-described time-since-last-fire data compiled by Chavardès et al. (2022), we included a burn rate reconstruction based on fire scars for the Northeastern James Bay zone (Fig. 1; Héon et al. 2014; Erni et al. 2017; Shakeri 2024). This region is predominantly shaped by stand-replacing fires, which typically leave few fire scar (Carcaillet et al. 2001). However, a meticulous search for fire scars on living and dead trees along natural fire breaks such as streams, lake shores, peatlands, and rocky outcrops combined with jack pine establishment dates, can provide a reliable record of past events (Héon et al. 2014). These data represent a quasi-exhaustive inventory of fire events that occurred along two transects extending over 300 and 340 km (640 km in total). Each transect consists of a linear sequence of 1 km × 2 km cells, within which multiple trees were sampled for fire-scar analysis. Each cell that recorded a fire event (i.e., based on at least two fire scars) for a given year was considered burned, thus making it possible to compute the number of kilometers burned each year since 1800.

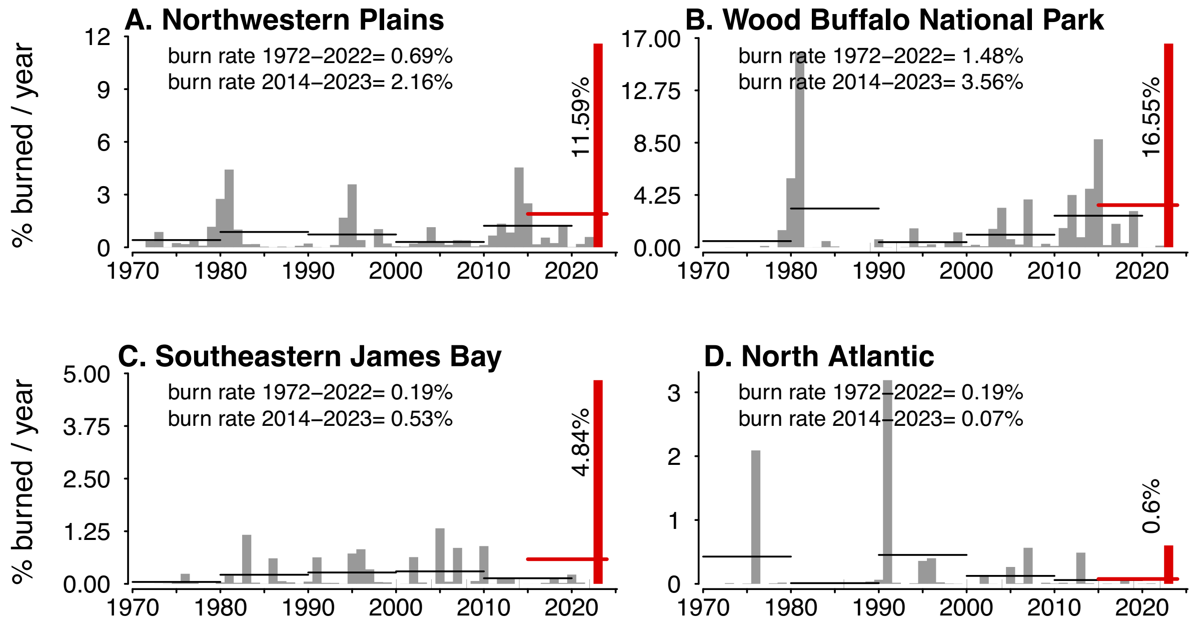
Data analyses

Historical burn rates were reconstructed for the first four large zones (Northwestern Plains, Wood Buffalo National Park, Southeastern James Bay, and North Atlantic) with time-since-last-fire data using the method described in Chavardès et al. (2022). Specifically, we used Cox regression (Cox 1972), a semi-parametric survival model, to estimate decadal mean burn rates for each of the four landscapes. 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). Moreover, Cyr et al. (2016) showed through simulations (i.e., fully known theoretical fire history) that time-since-last-fire data analyzed using Cox models offer an accurate and reliable estimate of burn rates, with the benefit of being minimally influenced by temporal variations in fire activity. Cox models fit a baseline hazard curve corresponding to the probability (or proportion) of area burned per decade, which is thus an exact equivalent of burn rates. Cox models were fitted using R's "survival" package (Therneau 2020). We computed bootstrapped confidence intervals (CIs) in burn rates from 1000 random samples with replacement in the original datasets (i.e., 1000 bootstrapped burn rate curves). For the fifth zone (Northeastern James Bay), the reconstructed proportions of territory burned each year were calculated as the number of cells burned each year divided by the total number of cells sampled.

We calculated the recent annual proportion of burned territories with the NBAC dataset (1972–2023; https://cwfis.cfs.nrcan.gc.ca/datamart/metadata/nbac), which contains high-resolution maps of wildland fires derived from 30 m resolution Landsat data (Hall et al. 2020; Skakun et al. 2021, 2022). The proportion of the area burned each year was determined by dividing the annual burned area for each zone by the fuel-covered area (e.g., excluding water and bare rock). Fuel cover areas were derived from the Canadian Fire Behaviour Prediction Fuel Type Description map in 2019 (https://cwfis.cfs.nrcan.gc.ca/downloads/fuels), which was derived from 250 m Moderate Resolution Imaging Spectroradiometer imagery (MODIS; Beaudoin et al. 2014). Modern annual burn proportions were averaged into decadal burn rates from 1980 to 2023 and then compared with reconstructed historical rates.

For the five zones, we defined two distinct historical ranges of variability: conservative and extended. The baseline periods used to encompass historical ranges of variability were 1800–2020 for the eastern zones, 1860–2020 for the Wood

Fig. 2. Proportions of area burned yearly since 1972 for four zones with fire history reconstructions from the National Burned Area Composite database. The proportions for 2023 are shown as red bars with exact values on the left. Thin black lines show decadal burn rates (1972–2020), and the red lines show burn rates over the decade ending in 2023 (2014–2023). The 1972–2022 burn rate values are displayed at the top left corner of each plot.



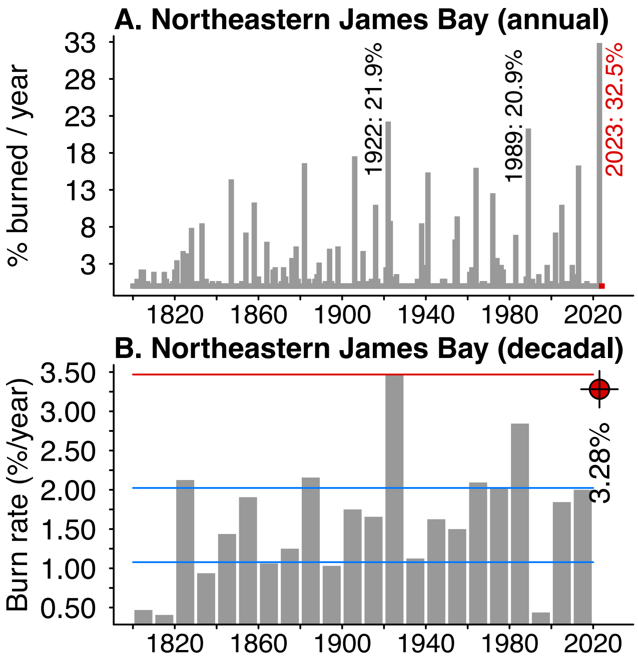
Buffalo National Park, and 1870–2020 for the Northeastern Plains. We started the baseline periods in 1860 and 1870 for the western zones because, generally, higher burn rates resulted in fewer old stand samples, making decadal burn rate estimations before 1860–1870 too imprecise (Chavardès et al. 2022). As most reconstructions are limited to a decadal resolution, we compared them with the mean annual burn rates over the decade ending in 2023 (i.e., 2014–2023) to evaluate whether it remained within or beyond the historical ranges of variability. Considering this last point and the high inter-annual variability in burned areas, we considered that comparing burn rates over 10 years rather than a single year is more suitable for tracking recent against historical trends. The boundaries of the conservative range of variability were defined as the mean of decadal 5% and 95% bootstrapped CIs, corresponding to a 90% CI of the long-term mean burn rate for each zone. Because no bootstrapped CIs were computed for the Northeastern James Bay reconstruction (i.e., fire-scar data), we simply defined the conservative historical ranges of variability as the 25th and 75th percentiles of the mean decadal burn rate distribution (1800–2020). For all reconstructions, the boundary of the extended historical range of variability was defined as the upper limit of the estimated decadal mean burn rates, thus corresponding to the highest mean decadal burn rates in each reconstruction.

We performed a straightforward nonspatial simulation exercise to illustrate how many equivalents of the 2023 fire season area burned would be needed to exceed the historical range of variability observed since the 1800s. For each fire-reconstruction zone, we generated eight sets of independent theoretical periods of 10 years, assigning the burn rate that would result from a recurrence every n years of the area that burned during the 2023 fire season. Each of the eight sets of independent 10-year periods corresponded to one of eight simulated recurrence levels: $n = 100$, 50, 30, 20, 15, 10, 5, and 3 years (e.g., $n = 5$, the area burned during the 2023 fire season would happen twice in 10 years). Between the years with 2023-equivalent extreme fire seasons, we attributed the annual proportions of area burned randomly sampled within the 1972–2022 period (Fig. 2) to the other years of the theoretical 10-year period. For each fire history reconstruction zone, we repeated the process 1000 times. We computed the median and 95% CI of theoretical burn rates obtained with a theoretical fire return period of n 2023 fire season area burned per 10-year period.

Results

For the five zones analyzed, the proportion of area burned in 2023 ranged from 0.6% to 32.5% (Figs. 2 and 3). Except for the North Atlantic, these annual proportions surpassed those recorded since 1972, which did not exceed 10%–20% (Figs. 2 and 3). Burn rates of the decade ending in 2023 (2014–2023) ranged from 0.07%·year^{-1} (North Atlantic) to 3.56%·year^{-1} (Wood Buffalo National Park). In two of the five zones, burn rates over 2014–2023 were below or within the conservative historical range of variability (North Atlantic: 0.15–0.82%·year^{-1}, Southeastern James Bay: 0.39–0.85%·year^{-1}; Fig. 4). The 2014–2023 mean burn rates for the remaining three zones were above the conservative historical range of variability (Northeastern James Bay: 1.07–

Fig. 3. Long-term burn rate reconstructions based on Northeastern James Bay area fire scars. (A) Annual burn rates with exceptional years highlighted (2023 is in red). (B) Mean annual burn rate per decade and historical range of variability. The conservative range is in blue (25th and 75th percentiles of mean decadal burn rates distribution), and the extended range is in red (maximum recorded mean decadal burn rates). The red point with a crosshair and value indicates the burn rate of the decade ending in 2023 (2014–2023).



2.02%·year^{-1}, Northwestern Plains: 1.02–1.78%·year^{-1}, and Wood Buffalo National Park: 0.83–1.82%·year^{-1}; Fig. 4). However, the 2014–2023 burn rates did not exceed the highest 10-year average burn rates recorded over the last two centuries in two of those zones (i.e., highest decadal mean burn rates since the 1800s in Northeastern James Bay: 3.47%·year^{-1}, Northwestern Plains: 2.40%·year^{-1}; Fig. 4), and thus remained within the extended historical range of variability. The 2014–2023 burn rates slightly exceeded the extended range of variability only in the Wood Buffalo National Park zone (3.56%·year^{-1} against 3.14%·year^{-1}; Fig. 4).

Simulations of future burn rates showed the frequency of 2023-like fire seasons required to surpass each zone's conservative or extended estimates of natural variability (Fig. 5). For example, in Northeastern James Bay, the equivalent of one 2023 fire season area burned every 50 years or less in the future would remain within its conservative range, whereas one 2023 fire season area burned every 15 years or less would exceed the extended range. In the Northwestern Plains, one 2023 fire season area burned every 15–10 years or more would remain within the conservative range, whereas one every 5 years or less would exceed the extended range. In Southeastern James Bay, one 2023 fire season area burned every 10 years or more would remain within the conservative range, and every 5 or 3 years would still remain within the extended range.

Discussion

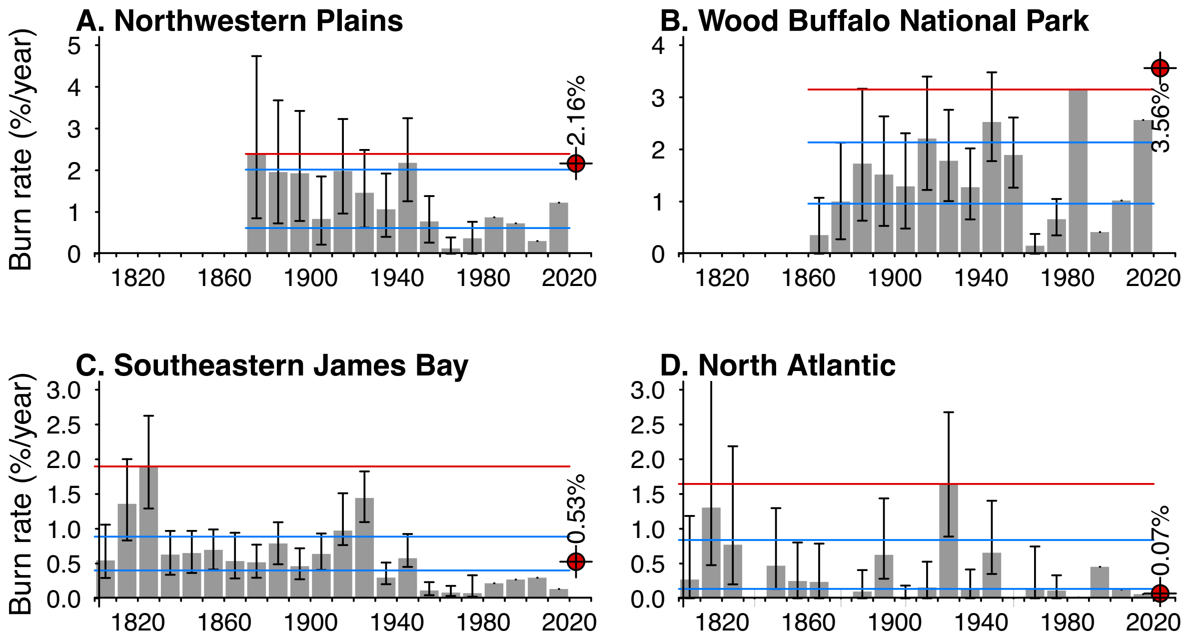
Our findings confirm that the area burned during 2023 in four of the five studied zones was unprecedented since 1972 (Jain et al. 2024). In contrast, the burn rates over the decade ending in 2023 (i.e., 2014–2023) generally remained within the natural range of variability observed since the 1800s, though some were close to the highest decadal burn rates observed over the last two centuries (i.e., Northeastern James Bay, Northwestern Plains). The 2014–2023 burn rates slightly exceeded historical variability only in the Wood Buffalo National Park zone. These results underscore the significant variability in fire regimes across Canadian boreal forests, both in their spatial patterns (Boulanger et al. 2013, 2014) and nonstationary temporal trends (Chavardès et al. 2022), which we briefly discuss below.

Historical and current trends in burn rates and their drivers

A large number of studies report high burn rates in North American boreal forests over the last centuries, followed by a subsequent decline throughout the 20th century (e.g., Johnson 1979; Yarie 1981; Larsen 1997; Bergeron et al. 2004; Wallenius et al. 2011; Drobyshev et al. 2017). Although the drivers of such changes have been discussed (e.g., Macias Fauria and Johnson 2007; Chavardès et al. 2022), they remain insufficiently understood. The main hypothesis is that despite the generally low average temperatures characterizing the LIA and the early 20th century (Gennaretti et al. 2014; Wang et al. 2022), periods of particularly high climatic dryness during fire seasons may have triggered large burned areas (Girardin et al. 2006, 2009; Macias Fauria and Johnson 2007; Drobyshev et al. 2017). During the ∼1950–2000 period, summer climate moisture generally increased with more precipitation, presumably explaining relatively low burn rates over this period (Macias Fauria and Johnson 2007; Girardin et al. 2009; Drobyshev et al. 2017). Other likely drivers are the effects of human land use, including changes to pre-colonial Indigenous uses of fire (Lewis and Ferguson 1988; Christianson et al. 2022), European colonization in the early 20th century, and the subsequent era of fire suppression (Danneyrolles et al. 2021; Chavardès et al. 2022). Disentangling the relative and interactive roles of drivers of long-term past changes in burn rates was beyond the scope of this study but should be investigated in follow-up research.

Over recent decades, anthropogenic climate change and its influence over increasing global fire activity have received growing attention (e.g., Flannigan et al. 2000; Moritz et al. 2012; Bakhshaii et al. 2020; Jones et al. 2022; Jain et al. 2024). Numerous studies projected future increases in area burned in Canada due to climate change (Flannigan and Wagner 1991; Flannigan et al. 2005, 2009; Boulanger et al. 2013, 2014; Coogan et al. 2019), whereas some more recent studies partly quantified the influence of climate change on observed area burned of the last decades (Hanes et al. 2019; Kirchmeier-

Fig. 4. Long-term historical range of variability reconstructed with time-since-last-fire data for four zones. Mean annual burn rates per decade are shown with bootstrapped 90% confidence intervals (CIs). Blue lines show the conservative historical range of variability (bootstrapped 90% CIs' long-term mean), and red lines show the extended range (higher decadal burn rates observed). Red points with a crosshair and their values indicate the burn rate of the decade ending in 2023 (2014–2023).



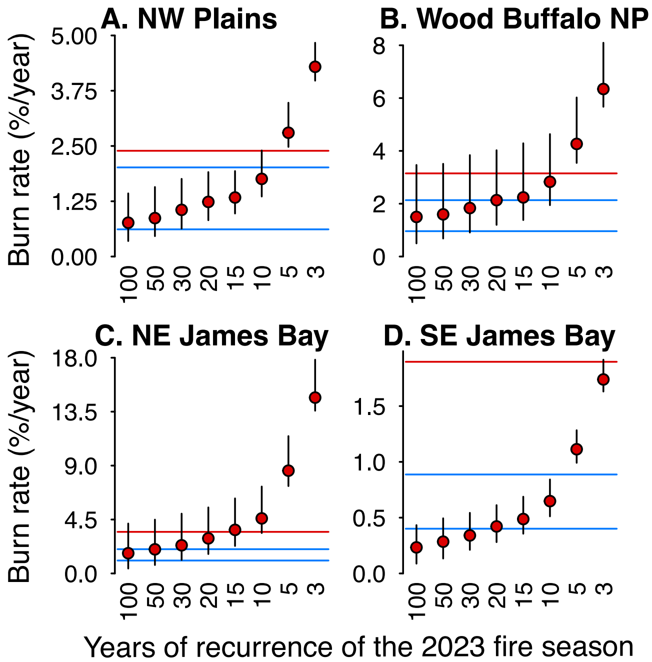
Young et al. 2019, 2024; Parisien et al. 2023). Until 2023, these increasing trends were more apparent in the western part of Canada's boreal forests (Coops et al. 2018; Kirchmeier-Young et al. 2019; Whitman et al. 2022; Parisien et al. 2023). Our study showed that the area burned over the 2023 fire season was larger by far than what had been experienced since the 1970s for both the western and eastern zones analyzed in this study, confirming these increasing trends may be spreading eastward (Jain et al. 2024). In eastern Canada, anthropogenic climate change has increased the likelihood of extreme fire weather conditions such as those experienced in 2023 by more than seven times (Barnes et al. 2023).

We argue that the period of low fire activity during the second half of the 20th century in several regions (e.g., Northwestern Plains, Southeastern James Bay) may have promoted fuel accumulation and continuity, making landscapes more susceptible to large wildfires (Héon et al. 2014; Parks et al. 2015; Erni et al. 2017) and thus may have played a role in fueling the exceptional 2023 fire season. Yet, it is noteworthy that fuel loads have also been reduced due to wood harvesting in some managed areas since the second half of the 20th century (e.g., Boucher et al. 2017; Wulder et al. 2020). Studies in the United States highlighted that the transition from widespread Indigenous cultural burns (e.g., Stephens et al. 2007; Roos 2020; Roos et al. 2022) to the current era of active suppression has also largely contributed to a fire deficit and increased current fire risks (e.g., Parks et al. 2015, 2025; McClure et al. 2024). However, we argue that the human-induced fire deficit may be less pronounced in Canadian boreal forests than in forests more to the south in the United States. A recent comprehensive review emphasized that, although the extent of pre-colonial Indigenous cultural burnings in North American boreal forests has not been accurately estimated, they likely primarily consisted of small localized burns (Christianson et al. 2022). Despite having important implications in shaping boreal landscapes, such cultural burns likely had less influence on the total burned area compared to recurring, very large (>10 000 ha), and uncontrolled lightning-caused fires (Hanes et al. 2019). Furthermore, the impacts of the subsequent active fire suppression era are likely strongly limited, as more than half of the areas analyzed are outside the active wildfire management zones (i.e., fires are left to burn without any management response; Tymstra et al. 2020).

Analytical limitations

Our study has some limitations originating mainly from the data used in the analyses. First, most of our dendrochronological data have a coarse temporal resolution. Apart from the Northeastern James Bay reconstruction based on fire scars, the burn rate reconstructions are at the decadal scale (i.e., mean burn rates over a given decade) because the precise dating of post-fire recruitment is almost impossible, particularly for older fires (Cyr et al. 2016). The decadal resolution of our dendrochronological reconstructions limits comparisons of burn rates between historical decades and the most recent decade (2014–2023). This precludes direct comparisons with any individual year. It is, therefore, possible that 2023 is unprecedented in terms of annual area burned within a single fire season, as suggested by the Northeastern James Bay reconstruction. Still, due to the decadal resolution, we cannot determine if extensive areas burned in both west-

Fig. 5. Comparison of theoretical future burn rates with the natural range of variability of four zones. For each fire-reconstruction zone, computed burn rates are equivalent to a recurrence of the 2023 fire season area burned every *n* years ($n = 100$, 50, 30, 20, 15, 10, 5, and 3 years, *x*-axis; see the "Materials and methods" section for more details). Blue and red lines represent the conservative and extended ranges of variability, respectively (see the "Materials and methods" section for more details). Northwestern (NW) Plains, Wood Buffalo National Park (NP), Northeastern (NE) James Bay, Southeastern (SE) James Bay. Results obtained for the North Atlantic zone are not shown due to the considerably lower burn rates during 2023 than the four zones presented here.



ern and eastern Canada during the same years before 1970. Therefore, 2023 may also be unprecedented regarding the large burned area recorded simultaneously (i.e., in the same year) in western and eastern Canada.

A second limitation is the higher uncertainty in burn rate estimates for the earliest decades analyzed due to the decreasing sample size as reconstructions extend further back (i.e., fewer old stands). However, Cyr et al. (2016) showed through simulations (i.e., fully known theoretical fire history) that while uncertainty in estimating burn rates with time-since-last-fire data and Cox models increase with decreasing sample size, the central tendency remains unbiased and accurate. The sample size issue is particularly pronounced in western Canada, where higher burn rates limit the availability of old stand samples. To reduce this uncertainty, we confined reference periods to the 1860s–1870s in western zones, even though pre-1860s estimates indicate burn rates may have been as high as—or even exceeding—those of the 2014–2023 decade (Larsen 1997; Wallenius et al. 2011; Andison 2019). Thus, we remain confident in our estimates of the historical range of variability in burn rates.

A third limitation is that our historical and modern rates estimates do not consider other key aspects of fire regimes, such as fire size or burn severity (i.e., the degree to which fires affect vegetation and soils; Keeley 2009). The fire regime since the 1960s in boreal North American forests has been dominated by large fires, with those >10 000 ha and 500–10 000 ha each accounting for ~50% of the burned area, while smaller fires are frequent but negligible in their contribution to total burned areas (Hanes et al. 2019). Large fires are typically severe crown fires, fueled by abundant soil organic matter, highly flammable and relatively short conifers, and dense vertical and horizontal fuel connectivity (de Groot et al. 2013; Rogers et al. 2015; Whitman et al. 2018; Guindon et al. 2020). Paleoecological evidence suggests that even though variations in fire size and severity have occurred during the last two millennia, large severe crown fires have accounted for most of the biomass burned (e.g., Ali et al. 2012; Girardin et al. 2024; Nesbitt et al. 2025). We argue that large, severe crown fires mainly drove the high burn rates in recent centuries, though we cannot rule out the possibility that smaller fires, including Indigenous cultural burns (Christianson et al. 2022), played a more significant role in the past. Nevertheless, recent trends in fire size and burn severity vary across Canada (Hanes et al. 2019; Guindon et al. 2020) and extreme fire weather is known to increase fire size and severity (Whitman et al. 2018; Parks and Abatzoglou 2020; Jain et al. 2024; Wang et al. 2025). Excessive climate-driven increases in fire size and severity may erode significant landscape elements such as fire refugia (Ouarmim et al. 2016), even if burn rates remain within their range of variability (Erni et al. 2017).

Finally, we would like to point out that the estimates presented in our work have been aggregated over extensive areas, within which significant spatial heterogeneity may exist regarding their fire regime (e.g., Larsen 1997; Girardin et al. 2006; Drobyshev et al. 2017; Andison 2019). Therefore, we caution against applying the estimates described in this article for forest management recommendations, which should rely on more locally specific studies.

Assessing future trends against the historical range of variability

While the resurgence in current and future burned areas due to climate change is undeniable (Boulanger et al. 2013, 2014; Kirchmeier-Young et al. 2019, 2024; Parisien et al. 2023; Jain et al. 2024), whether future burning rates will surpass historical variability is not a straightforward question. Indeed, even if fire regimes are nonstationary over time, notably with climate-driven increases in mean burn rates, such increases may be strongly nonlinear due to potential negative ecosystem feedback (Erni et al. 2017, 2018; Chaste et al. 2019). Increasing mean burn rates will naturally reduce fuel biomass over short- to medium-term periods (Héon et al. 2014; Portier et al. 2018; Wulder et al. 2020; Gaboriau et al. 2023). In some areas, increased mean burn rates could also induce long-term transitions from highly fire-prone conifer stands to more fire-resistant mixed or deciduous stands (Baltzer et al. 2021; Mack et al. 2021) or even quasi-permanent nonforested states due to regeneration failure (Splawinski et al. 2019; Coop et al. 2020; Baltzer et al. 2021; Augustin et al. 2022). In some managed forests, such negative feedback is amplified by forest management (e.g., Splawinski et al. 2019; Marchais et al. 2022). This implies that increases in the climatological fire hazard would likely be constrained by fuel composition and availability (Girardin et al. 2013; Terrier et al. 2013; Héon et al. 2014; Girardin and Terrier 2015; Boulanger et al. 2017), which should prevent burn rates from rising indefinitely. In any event, tracking future changes in burn rates against the historical range of variability will remain essential for understanding the impacts of climate change and ecological feedback on fire regimes.

Acknowledgements

We thank all researchers, students, and field and laboratory assistants who contributed to the data used in this paper and are not included in the list of authors. This long list includes (but not exhaustively) D. Lesieur, D. Charron, J. Héon, H. Le Goff, V. Kafka, P. Lefort, È. Lauzon, D.J. Grenier, R.C. Drever, C. Heathcott, M. Heathcott, L. Keary, C. Laferty, B. MacDonald, A. Masters, J. Mercer, C. Whyte, M. Wynn, S. Haughian, U. Mahlamäki, P. Oksanen, P.-P. Dion, S. Williams, P.-Y. l'Héreault, É. Tremblay, B. Dy, C. Gilbert, R. Terrail, Y. Neveu, A.-M. Labrecque, and V. Hébert-Gentile.

Article information

History dates

Received: 16 August 2024
Accepted: 26 June 2025
Accepted manuscript online: 23 July 2025
Version of record online: 11 September 2025

Data availability

Modern burn rates were estimated using publicly available data from the Canadian government (https://cwfis.cfs.nrcan.gc.ca/datamart). The dendrochronological data employed in this study were compiled from multiple sources, each governed by distinct usage rights established by the original authors. Reasonable requests for access to these data will be forwarded to the respective co-authors who hold the rights.

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Sylvie Gauthier served as Consulting Editor at the time of manuscript review and acceptance; peer review and editorial decisions regarding this manuscript were handled by another editorial board member.

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Competing interests

The authors declare no competing interests.

Funding information

Many institutions participated in financing the research synthesized in this study: the Natural Sciences and Engineering Research Council of Canada, the provincial governments of Québec, Alberta, and British Columbia, the Canadian Forest Service, Parks Canada, the Academy of Finland, and the European Research Council.

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