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PDO Dynamics Shape the Fire Regime of Boreal Subarctic Landscapes in the Northwest Territories, Canada

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Key Points:

- We developed the longest annual reconstruction of forest fire activity in the boreal subarctic of North America
- The Pacific Decadal Oscillation (PDO) exercised a major effect upon fire activity in the Northwest Territories (Canada) since the 1300s
- A trend toward a more positive PDO suggests a future increase in fire activity in the Northwest Territories

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Spatially explicit reconstructions of fire activity in northwestern boreal Canada are rare, despite their importance for modeling current and future disturbance regimes and forest dynamics. We provide a dendrochronological reconstruction of historical fire activity along Highway 3 in the Northwest Territories (NWT), Canada, within the boreal subarctic zone. We dated 129 fires that occurred between 1202 and 2015 CE, using samples from 479 fire-scarred living and dead jack pine trees (*Pinus banksiana* Lamb.). Three distinct periods can be distinguished in terms of historical fire cycle (FC) and fire occurrence. Initially (1340–1440 CE), fire activity was low (FC = 572 years; 1 fire/decade), before increasing notably between 1460 and 1840 (FC = 171 years; 4.45 fires/decade), and even more in recent times (1860–2015 CE; FC = 95 years; 7.63 fires/decade). Climate has been an important factor controlling changes in fire frequency and FC in the NWT since the 1300s. The 1440s and 1850s correspond with periods of increased fire activity synchronized with shifts from negative to positive Pacific Decadal Oscillation (PDO) phases. Since the mid-1800s, human activities may have contributed to the increase in fire activity, but climate remained the leading factor. During the 20th century, years with increased area burned corresponded to periods with drier-than-average conditions associated with positive PDO, suggesting fire activity in the study region is still influenced by climate. Spatial teleconnection patterns among PDO, drought, and large fire years (LFYs) in the NWT reveal persistent relationships between ocean-atmosphere circulation patterns and fire activity. PDO dynamics hold strong potential for predicting regional fire hazards across northwestern North America.

Plain Language Summary

We studied the history of forest fires along Highway 3 in the Northwest Territories, Canada, using growth rings from jack pine trees. We examined age structure and dated fire scars using a data set of 479 jack pine trees. We identified 129 fires that occurred between the years 1202 and 2015. Our findings show three main periods of fire activity. From 1340 to 1440, fires were rare, happening about once per decade. Between 1460 and 1840, fires became more frequent, with about 4.45 fires each decade. Since 1860, fires have occurred even more often, that is, 7.63 times per decade. We discovered that climate, especially changes in the Pacific Decadal Oscillation (PDO), played a significant role in increasing fire frequency over the years. In recent centuries, human activities may also have contributed to more frequent fires. During the 20th century, dry conditions linked to the PDO led to more fires. Our study suggests that the PDO and other climate factors continue to influence wildfire activity, making it possible to predict future fire risk in northwestern North America.

1. Introduction

Fire is a primary disturbance agent in forests of the Northern Hemisphere (Flannigan et al., 2005; McLauchlan et al., 2020; Stocks et al., 2003). In the boreal forests of northwestern Canada, the area burned by wildfires has increased over the past 50 years, primarily due to an increase in the occurrence of large fire years (LFYs) that have contributed disproportionally to areas burned over decadal and century scales (Hanes et al., 2019; Kasischke & Turetsky, 2006). In the Northwest Territories (NWT), Canada, the year 2014 stands out with 3.4 million ha burned, an event that was almost six times larger than the average annual area burned during 2009–2019

(600,000 ha, NTENR, 2015). Recent data from the 2023 wildfire season reveals that the area burned across Canada was approximately 22% larger than in 2014, highlighting high fire activity across the whole country (Natural Resources Canada, 2019).

LFYs and single large wildfires correlate with persistent (>10 days) positive height anomalies in the mid-troposphere (500 hPa), which block zonal atmospheric circulation (Johnson & Wowchuk, 1993; Justino et al., 2022; Skinner et al., 2002). During such events, the lack of rainfall and the warmer air rapidly dry out forest fuels over large areas, increasing the climatological fire hazards and extending the fire season (Gedalof et al., 2005; Hessl et al., 2004; Heyerdahl et al., 2002). These anomalies are, in turn, often driven by teleconnection patterns such as the Pacific Decadal Oscillation (PDO), the El Niño Southern Oscillation (ENSO), and the Pacific North American pattern (PNA) (Bonsal & Shabbar, 2011; Macias Fauria & Johnson, 2006). Large-scale atmospheric circulation patterns, therefore, determine the spatiotemporal extent of fire-prone periods (Bonsal & Shabbar, 2011; Heyerdahl et al., 2008; Yasunari et al., 2021).

Human activities have influenced fire regimes in western Canada over several thousand years. Fire has historically been used to manage pastures, aid in hunting, maintain berry crops, and assist in communication and ceremonial activities (Anonymous, 1970; Needlay et al., 2012; Turner, 1999). Although fire has been used as a tool by Indigenous peoples of western North America (Holman, 1944; Johnson & Miyanishi, 2012), the contribution of human-mediated fires to total area burned in this region remains a subject of debate, with some studies arguing that human activities played a leading role (Wallenius et al., 2011), while others suggesting a stronger climate control (Hanes et al., 2019; Macias Fauria & Johnson, 2006).

Annually resolved reconstructions of fire history allow us to quantify the factors that shaped historical fire regimes and, in particular, to decipher the relative contributions of climate variability and human land use. While a few dendrochronological (Larsen, 1997; Wallenius et al., 2011; Weir et al., 2000) and paleoecological (Gaboriau et al., 2020; Kuosmanen et al., 2023; Sulphur et al., 2016) reconstructions have been conducted in northwestern Canada, long-term fire dynamics remain poorly understood.

We developed a 680-year spatially explicit reconstruction of the fire activity in the area along Highway 3 in the vicinity of Yellowknife, the capital of NWT, based on the dating of fire-scarred living and dead jack pine trees (*Pinus banksiana*). The reconstructed period included the Little Ice Age (LIA, ~1300s–1850s, MacDonald et al., 2008), and the subsequent warming period, including the onset of the industrial era and fire suppression (1920s and 1930s). We hypothesized that (H1) climate variability would be the dominant force controlling regional fire activity in the NWT, with historical Indigenous land use being of marginal importance. Specifically, we suggested that periods of increased fire activity in the NWT would be associated with changes in atmospheric and ocean circulation patterns. We further hypothesized (H2) that the study region would exhibit higher fire activity during the LIA, as shown across the boreal zone (Chavardès et al., 2022; Drobyshev et al., 2016). We tested H1 using an annual fire reconstruction spanning 1340–2015 CE supplemented with modern observational records of climate and fire (1959–2019 CE). We tested H2 by comparing fire cycle values between periods. We used documentary information on Indigenous land use, European settlement, and census data, as the historical background necessary to interpret the results.

2. Material and Methods

2.1. Study Region

The study area is located in the Taiga Shield High Boreal (HB) Ecoregion (Ecosystem Classification Group, 2008) of the Taiga Shield Ecological Region within the NWT (62.4575°N, 114.3776°W; Figure 1). The climate of the NWT is continental with short, cool summers and very cold winters with persistent snow cover. The mean annual temperature ranges from −3°C to −6°C, with January being the coldest month (−26 to −28°C) and July the warmest (15–16°C). Annual precipitation averages 280–360 mm, with the wettest period from June through November, evenly distributed between rain and snow. Snow covers the ground from October to April–May, reaching a depth of 40 cm in late winter (Ecosystem Classification Group, 2008).

The Taiga Shield HB Ecoregion is characterized by plains and hills on Precambrian bedrock. The landscape features numerous small lakes and bogs, and two very large lakes, Great Bear Lake and Great Slave Lake. The region is underlain by discontinuous permafrost (Ecosystem Classification Group, 2008).

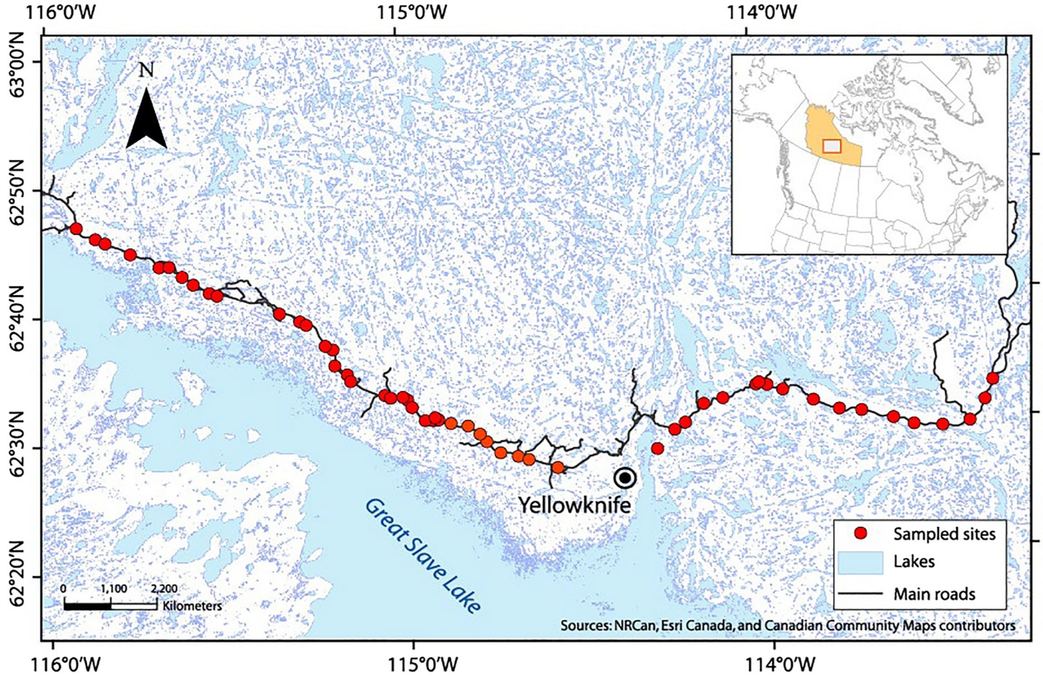

Figure 1. Location of the study area and sampled sites in the Northwest Territories, Canada.

Forests cover 18% of the NWT and are typical of open subarctic forests (Rowe, 1972). The most common coniferous species are white and black spruce (*Picea glauca* and *P. mariana*), jack pine, and eastern larch or tamarack (*Larix laricina*). The main deciduous tree species in the region are paper birch (*Betula papyrifera*) and trembling aspen (*Populus tremuloides*) (Ecosystem Classification Group, 2008; Rowe, 1972). Ground vegetation is dominated by dwarf shrubs (*Vaccinium* spp., *Ledum* spp. and *Empetrum nigrum*), lichens (*Flavocetraria nivalis, Cladina mitis, Umbilicaria hyperborea,* and *Cladonia* spp.), and mosses (*Pleurozium schreberi, Hylocomium splendens, Tomentypnum nitens*) (Rowe, 1972).

Forest fires are widespread in the subarctic region of the central NWT (Gaboriau et al., 2020; Sulphur et al., 2016). Cloud-to-ground lightning associated with summer thunderstorms cause the majority of forest fires (Epp & Lanoville, 1996; Kochtubajda et al., 2006). Severe drought has been linked to the occurrence of recent forest fires in the central NWT (Whitman et al., 2018). Modern observational data indicate that the fire season typically begins in late May and usually ends in early September (Forster, 1995). Paleoecological studies have documented a decline in the frequency of forest fires in the central NWT during periods of wetter and cooler conditions throughout the Holocene, along with an increase in the 20th century suggested to have been driven by warmer and drier climate conditions (Gaboriau et al., 2020; Sulphur et al., 2016).

2.2. Human Population and Land Use

In the NWT, the earliest known human settlements date to about 7 000 BP and are attributed to the Dene people (Ridington, 2012). The Dene were nomadic people who lived in the boreal forest and followed the rhythm of the seasons and the migration routes of animals (Helm, 1981; June & Andrews, 2009; Ridington, 2012). In addition to hunting, the Dene subsisted by fishing, trapping, and gathering wild plants (Anonymous, 1970). Farming and slash-and-burn agriculture were not practiced by the Dene people due to the harsh climate and their nomadic lifestyle. Crops which are successfully grown in the study region today were introduced only after contact with the Europeans (Ridington, 2012).

The Dene people traditionally used fire in various ways to manage landscapes, for example, to promote habitat diversity, prevent wildfires by clearing understory vegetation, enhance berry production, and support spiritual and cultural activities (Needlay et al., 2012; Turner, 1999). They carefully controlled fires to minimize the risk of them spreading (Turner, 1999). For example, to boost berry yields, they would burn a patch after harvest, timing the burn just before rainfall. They also used natural and human-made firebreaks, backfires, and water-soaked conifer boughs to control the fires (Turner, 1999). Although these practices are documented in regions south of the study area, they reflect a broader tradition of Indigenous fire use in similar environments. However, it is uncertain how much these practices influenced the larger fire patterns in the boreal subarctic region. Due to the small population sizes and likely strategic use of fire, it is improbable that Indigenous activities significantly affected the overall fire history observed in the study area.

The first European explorer to reach the NWT is believed to have been the English navigator Martin Frobisher in 1576 CE (Anonymous, 1970; Coates, 1985; Zaslow, 1971), but his visit apparently had no effect on the traditional lifestyle of the Dene (Anonymous, 1970). The first European settlement in the study region, Old Fort Providence, was established in 1789 CE as a center for the fur trade (Watt, 2013). Fur trading had major consequences on Dene lifestyle and livelihood (Anonymous, 1970; Watt, 2013).

Yellowknife was founded following the discovery of gold deposits in the 1930s (Price, 1967; Watt, 2013). Since the beginning of the 20th century, many Dene people have been employed by gold and diamond mines, as well as associated industries (GNWT, 2008).

2.3. Field Sampling

Sampling sites were located in proximity to Yellowknife, NWT (Figure 1). We carried out sampling in 2018. We randomly located sampling points along NWT Highway 3 every 2–5 km to ensure sufficient sampling density for the reconstruction of individual fire sizes. During field sampling, we inventoried each site and paid particular attention to the presence of old living black spruce or jack pine trees, and old deadwood. Rocky substrates were carefully inventoried, as their dry conditions would have facilitated wood preservation.

To provide an even distribution of the sampling effort, we surveyed a 2–3 ha area around each site for 2 hrs. The sampling was carried out by two experienced teams in parallel with partially overlapping "zones of responsibility", that is, the areas to search for the presence of live and deadwood with fire scars. While surveying the areas, the teams aimed to maximize the chance of locating fire-scarred trees by always inventorying dry areas and "interfaces", that is, areas located at the transition between dry and wet portions of the surveyed zone. We used chainsaws to cut wedges from live trees and snags and cross-sections from stumps. Between five and 20 samples were taken from each site. In total, we collected 483 samples of jack pine: 190 living and 293 dead.

2.4. Development of Fire Chronologies

The cross-sections and tree cores were sanded with progressively finer grits up to 400 grit to secure a clear view of the annual growth rings and fire scars under a binocular microscope at 40x magnification. We cross-dated cross-sections using the visual pointer year method (Stokes & Smiley, 1968), capitalizing on the pointer year chronology developed for that area. Information on the most useful pointer years is provided in Text S1 of Supporting Information S1. To measure tree rings, we obtained high-resolution (2,400–4,800 dpi) digital images of the samples using a flatbed scanner and measured the rings using Cybis AB CooRecorder and CDendro 9.0 (Larsson, 2018). As a proxy for correlation strength, we relied on a *t*-test calculated with the programs COFECHA (Grissino-Mayer, 2001; Holmes, 1983, 1999) and CDendro (Larsson, 2018).

Dating helped us associate calendar years with (a) fire scars, (b) oldest and (c) youngest rings on each sample and to develop site-specific fire chronologies. We also attempted to locate the position of each scar within the dated ring to obtain information on the seasonal occurrence of the fire. We assigned fire scars to one of the following four categories: scar with no seasonal dating, earlywood scar, latewood scar, and dormant scar. Dormant scars were located at the interface between two rings, and for these scars, the exact determination of the fire year and season was not possible. In these cases, we assigned the year and season based on the dates obtained from other trees at the same site. This approach was supported by the observation that in parts of the boreal zone with extensive snow cover during winter, the persistence of forest fires in the soil beneath the snow cover is highly unlikely (although see Scholten et al., 2021).

2.5. Reconstruction of Historical Fire Cycle and Identification of Fire Regime Shifts

The spatial reconstruction of fires relied on fire dates independently identified across the network of sites. To convert point data (i.e., fire frequency estimates for a site) into areal estimates, we assumed that a site fire chronology represented the fire history of a certain area centered on the site center, hereafter referred to as *unit*. By summing the areas of these units for the years with dated fire events, we obtained an annual chronology of area burned.

Selection of the unit size for this analysis required knowledge of the local topography. The study area includes many lakes formed after glacial retreat ca. 10,000–9,000 years BP (Dyke, 2005; Latifovic et al., 2017) and large sphagnum-dominated peatlands established after 6,000 BP (MacDonald, 1995). The terrain surrounding Yellowknife predominantly consists of peatlands populated by *Picea mariana*, and upland bedrock outcrops colonized by *Pinus banksiana* (Beaudoin et al., 2014). Considering the dominant mosaic of habitats and distances among sites, we opted for a unit size of 78.5 ha (radius 500 m), which tends to place the units within one element of the landscape mosaic. We converted the reconstructed burned areas into FC estimates (Van Wagner, 1978), that is, the length of time required for an area equal to the total study area to burn:

$$FC = \frac{TSA}{TBA * TI} \tag{1}$$

where TI is the length of the period studied (in years) and TSA and TBA are the total study area and the total burned area over this time period (in ha), respectively. To account for the decline in the number of sites representing the oldest periods of the area-wide chronology, we adjusted the estimates of the area burned using a protocol similar to that developed by Ryzhkova et al. (2020). For periods with declining site replication, we assumed that the proportion of burned sites among non-recording sites was equal to that of recording sites. This approach simply extended the observed proportion of burned sites to non-recording sites and randomly assigned the "burned" status only to a corresponding proportion of non-recording sites.

We estimated fire occurrence as the number of fire years aggregated over 10-year periods in the whole area studied. To ensure the fire occurrence over the study period was not affected by the variability in the number of recording sites, we adjusted the number of fire years, capitalizing on the relationship between their number and the length of the period (Drobyshev et al., 2022). We assumed that over the period with declining site coverage (from 1800 CE to 1450 CE) the fire regime had remained constant throughout the LIA, and the observed changes in the number of reconstructed fire years were primarily due to declining site replication. This assumption was only to account for the variability in the number of "recording sites" in the early part of the reconstructed fire chronology. We avoided introducing any potential change in fire activity, which might be due to the adjustment itself. For the 50-year segments within this period, we obtained the number of fire years and the number of sites representing that segment. We then estimated the difference between the maximum number of sites over the whole period (i.e., the maximum number of sites representing a year) and the number of sites representing a focal segment in question. This difference (*deltaS*) entered as an argument in the regression with the number of fire years as the dependent variable:

$$\text{Number of fire years} = F\,(\text{deltaS}), \tag{2}$$

The regression provided us with an estimate of the number of missing fire years, which was the difference between expected and observed fire years (Figure S1 in Supporting Information S1). We added these years to random positions within that segment. This represented a conservative solution to the adjustment problem: it assumed the same "process density" and decreased the risk of Type I error but increased the risk of Type II error in the regime shift analysis.

We used a regime shift detection algorithm (Rodionov, 2004) to identify changes in FC and fire occurrence over the period covered by the fire reconstruction (1340–2015 CE, minimum number of sites = 5). The algorithm uses sequential *t*-tests to identify a regime change. Specifically, a regime shift is identified when the cumulative sum of normalized deviations from the mean value of a new regime is different from the mean of the current regime, calculated on a pre-defined moving timeframe. The time scale to be detected is controlled primarily by the cut-off length. Both cut-off length and probability level affect the statistically significant difference between regimes, and hence the magnitude of the shifts to be detected (Rodionov & Overland, 2005). The algorithm was run with the *L* parameter set to 20, the Hubert weight parameter set to 1, and the significance level for the *t*-test set to 0.05. To assess the sensitivity of the results to a particular combination of sites, we used bootstrapping to obtain 10% and

90% confidence limits for FC, resampling our pool of sites 1,000 times. Details of the algorithm used for the analysis of dendrochronological reconstruction of fire activity are provided in Ryzhkova et al. (2020).

2.6. Estimation of Ignition Rates

Quantifying historical ignition rates is critical to assessing potential human contribution to the total amount of ignitions. The ignition rate is a function of the number of fires, the area studied, and the time period considered:

$$\text{Ignition rate} = \frac{\text{number of fires}}{(\text{period\_considered} \times \text{area\_studied})}, \tag{3}$$

The definition of the area studied, and the spatial extent of a single fire event are significant contributors to the uncertainty in ignition rate estimates. We used an earlier developed protocol (Drobyshev et al., 2022), which attempts to encompass the range of variability in both metrics and involves the calculation of two estimates for each of the metrics. We used two alternative protocols to calculate the area studied: (a) the opportunistic protocol assumed that the study area equals the size of a single polygon covering the entirety of sampled locations within a studied landscape, and (b) the conservative protocol assumed the study area to be the sum of the areas of the inventoried sites (units). The opportunistic protocol likely leads to an underestimation of true ignition frequencies, as some smaller fires are likely to "escape" the existing network of sites, while the area where they occurred contributes to the area used for the calculation. Using this protocol, the study area was 301.3 km^2. The use of the conservative protocol, however, can potentially inflate ignition estimates since the sampled sites, which are often more xeric and, therefore, more fire-prone than the rest of the landscape, represent only a proportion of the area studied. According to this protocol, the study area was 40.04 km^2. Similarly, we used two protocols to estimate the number of fires, to account for uncertainty in defining the perimeters of historical fire events. The conservative approach was to count a single fire year as a single fire, and the opportunistic approach was to count each burned study site (unit) as a single fire. We assumed that the true value of ignition rate was constrained by two values: one obtained with the conservative estimate of the study area and opportunistic estimate of the number of fires, and one obtained with the opportunistic estimate of the study area and conservative estimate of the number of fires. We provide, therefore, two estimates for each period, determined from reconstructed burned areas (see previous subsection).

2.7. Climate Indices

We examined PNA, PDO and ENSO, all of which affect precipitation patterns in the Northern Hemisphere (Hall et al., 2015; Macias Fauria & Johnson, 2008; Trouet & Taylor, 2010), as potential controls of fire activity in NWT.

The PNA plays an important role in shaping the North American hydroclimate (Liu et al., 2017; Shabbar, Bonsal et al., 1997; van der Schrier & Barkmeijer, 2007). The PNA has four action centers: a cyclone around the Aleutian Islands called the Aleutian Low, an anticyclone near Hawaii, a high-pressure system (ridge) over western Canada, and a low-pressure system (trough) over the southeastern United States (Wallace & Gutzler, 1981). During a positive PNA pattern, a deeper Aleutian Low intensifies the meridional flow of the jet stream across the North American continent, resulting in a pronounced ridge-trough configuration. This leads to warming in northwestern North America and cooling in the southeastern United States (Liu et al., 2017). In comparison, a negative PNA pattern is consistent with a more zonal flow, with weather anomalies reversing those associated with the positive PNA (Liu et al., 2017, 2021). The typical periodicity for the PNA is 2–3 years (Liu et al., 2017). We used the tree-ring-based reconstruction of the winter PNA index developed by Liu et al. (2017).

The ENSO describes the cyclical warming (El Niño phase) and cooling (La Niña phase) of the sea surface temperature (SST) in the central and eastern tropical Pacific Ocean that then affects global atmospheric circulation and weather patterns (Hart et al., 2010). During the La Niña phase, the eastern equatorial winds strengthen, which leads to a shallow thermocline due to upwelling of cool subsurface waters in the eastern tropical Pacific Ocean and the piling up of warm surface waters in the western tropical Pacific (Larkin & Harrison, 2002; Siqueira et al., 2019). This east-to-west SST gradient reinforces an east-to-west air pressure gradient that, in turn, maintains the easterly winds. During the El Niño phase, the easterlies weaken and become westerlies. This westward shift of the trade wind leads to a low-pressure cell over the eastern part of the tropical Pacific that increases precipitation and lowers the thermocline, and a high-pressure cell over the western tropical Pacific that brings colder and drier conditions. These ENSO events have extratropical effects in North America as they affect the Aleutian Low and the formation of the PNA pattern. El Niño events are generally associated with the strengthening of the Aleutian Low and the PNA pattern (Taschetto et al., 2020). The typical periodicity for ENSO is 3–5 years (Fedorov et al., 2020). We used the tree-ring-based millennial reconstruction of interannual ENSO variability by Li et al. (2011).

The PDO describes the variability of the North Pacific Ocean-atmospheric system and is measured as the leading principal component of monthly sea-surface temperature (SST) anomalies poleward of 20°N in the Pacific basin (Mantua et al., 1997). The cool phase of the PDO features lower-than-normal SST along the coasts of North America and the equator, and warm SST in the western North Pacific, forming a horseshoe-shaped pattern (Jia & Ge, 2017). During the warm (or positive) phase of the PDO, the pattern is reversed. The warm phase of the PDO is associated with a deeper Aleutian Low, whereas the negative phase is associated with a shallow Aleutian Low (Larson et al., 2022; Newman et al., 2016). The typical periodicity for the PDO is between 15–25 and 50–70 years (Mantua et al., 1997).

There are numerous reconstructions of the PDO based on tree rings (Biondi, 2001; D'Arrigo et al., 2001; Gedalof et al., 2002; Gedalof & Smith, 2001; Lyu et al., 2019), corals (Felis et al., 2010; Ramos et al., 2019), and historical documents (Shen et al., 2006). Unfortunately, most of these records do not extend beyond 300–500 years, making it difficult to analyze the effect of this variability under different climate regimes, for example, prior, during and following the Little Ice Age. Here, we used a tree-ring-based reconstruction of the PDO based on limber pine (*Pinus flexilis* James) growing in California and Alberta, which spans over 1,000 years to cover periods with contrasting climate regimes (MacDonald & Case, 2005).

2.8. Association Between Climate and Historical Fire Activity

To test the association of the NWT fire activity with ocean-atmosphere circulation patterns at the annual scale, we used the output of regime shift analyses on chronologies of circulation indices in a contingency analysis framework. First, we ran regime shift analyses on PDO, ENSO and PNA chronologies to classify the studied period into sub-periods with high (above the long-term mean) altitude lower phases of the indices. For the regime shift analysis, we used a cut-off length (parameter *L*, see Rodionov, 2006) of 10 years because we were primarily interested in the interannual influence of circulation patterns, as represented by the climate indices, on the occurrence of LFYs. Second, we assessed the statistical significance of the differences between observed and expected climate values for each of the sub-periods by bootstrapping. To this end, we assumed the same "abundance" of the identified regimes but their random localization over the studied period.

We performed contingency analyses on the reconstructed (1400–1998 CE) and modern (1950–2019 CE) fire records. For the reconstructed record, we identified LFYs as years in which at least two sites had burned. Modern LFYs were obtained from the Canadian National Fire Database (CNFDB). We extracted annually burned areas for the region centered on the study area and limited by 60–65°N and 100–120°W over 1950–2019 CE.

2.9. Climate-Fire Associations in the Modern Record

We used superposed epoch analysis, SEA (Grissino-Mayer & Swetnam, 2000; Swetnam, 1993), to assess the role of drought forcing on fire activity. The analysis used seven modern LFYs (1971, 1979, 1980, 1981, 1994, 1995 and 2014) identified over 1959–2019 CE. For the SEA we used the June–August self-calibrated Palmer Drought Severity Index (scPDSI) (Wells et al., 2004) covering the grid cells across the northwestern portion of North America (30–80°N, 180–80°W). The analysis was conducted using the KNMI Climate Explorer tool (Trouet & van Oldenborgh, 2013). To investigate the relationship between ocean-atmospheric oscillations and drought conditions, we correlated the March–May and June–August mean values of the instrumental record of the PDO (Japan Meteorological Agency, 2024) with the scPDSI over the period 1901–1996 CE.

2.10. Population Data

To assess the relationship between fire activity and human presence, we developed a chronology of population density across the entire NWT area. We used modern census data (Statistics Canada, 2022) and historical population data dating back to 1861 CE (Canada Year Book, 2010). Since population data prior to 1991 included both

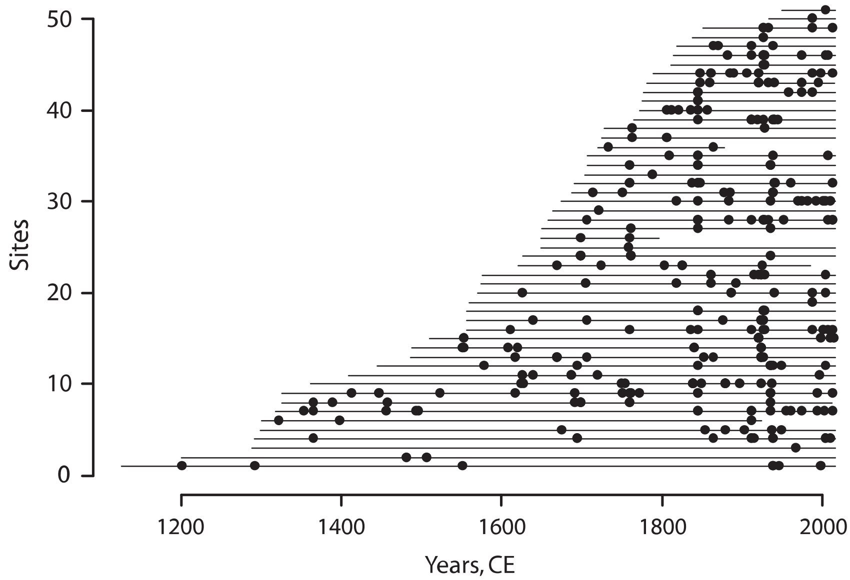

Figure 2. Dendrochronologically reconstructed annual fire history of the NWT over 1200–2018 CE. A single straight horizontal line represents a site, and a dark circle represents a fire event. Each line extends over the period covered by chronologies of at least five trees.

the NWT and Nunavut, we used combined NWT and Nunavut population data after 1991 to track population trends in the NWT.

3. Results

We dated 349 fire scars found on 479 samples, corresponding to a total of 129 unique fire years (Figure 2). The fire chronology for the study area covered 892 years, with the first fire dated to 1202 CE and the most recent fire dated to 2015 CE. To ensure a sufficient density of sites for spatial reconstruction of fire activity, we selected the period from 1340 to 2015 CE, for which each year was represented by at least 10 sites (Figure 2).

We assessed the regime shifts separately for the FC (Figure 3a) and for the decadal fire occurrence (Figure 3b). During the 1340–1440 CE, the mean FC was 572 years (95% confidence intervals, CI 400.4–1,000.9 years). It decreased to 171 (CI 150.6–195.0 years) between 1460 and 1840 CE, and then decreased again to 95 years (CI 82.4–109.9 years) over the 1860–2015 CE period (Table 1, Figure 3a). The dynamics of ignition frequencies reflected the changes in FC, with the lowest frequencies between 1340 and 1440 CE and the highest between 1860 and 2015 CE (Table 2).

We also identified three regimes in the historical dynamics of decadal fire occurrence since 1340 CE. During the first period, 1340–1440 CE, fire years occurred once per decade (Table 1 and Figure 3b). In the following period, 1460–1840 CE, fire occurrences increased to 4.45 fire years per decade. During 1840–2015 CE, the number of fire years had again increased to 7.63 per decade.

We examined the timing of tree regeneration using pith dates from our samples (Figure S6 in Supporting Information S1). Our data set included samples from all sites, covering both dry and wetter areas of the landscape, the latter predominantly dominated by black spruce. The analysis revealed several distinct regeneration waves, with the most noteworthy occurring in the mid-1800s, broadly coinciding with a regime shift toward increased fire activity as reconstructed from fire scar data (Figure 3a). The temporal resolution of the regeneration data remains limited, precluding further detailed conclusions on fire regime dynamics across the landscape.

The number of samples with at least two scars was 39.4%, and the number of samples with at least three scars was 12.2% of the total number of trees with scars. Fire seasonality estimated from the intra-annual scar position was successfully determined for 63% of the fires (Figure 4). Almost all (97%) of the fires occurred during the growing season, of which 72% were in the earlywood and 25% in the latewood. Only 7 fires, that is, 3% of all fires dated with seasonal resolution, occurred in the dormant season.

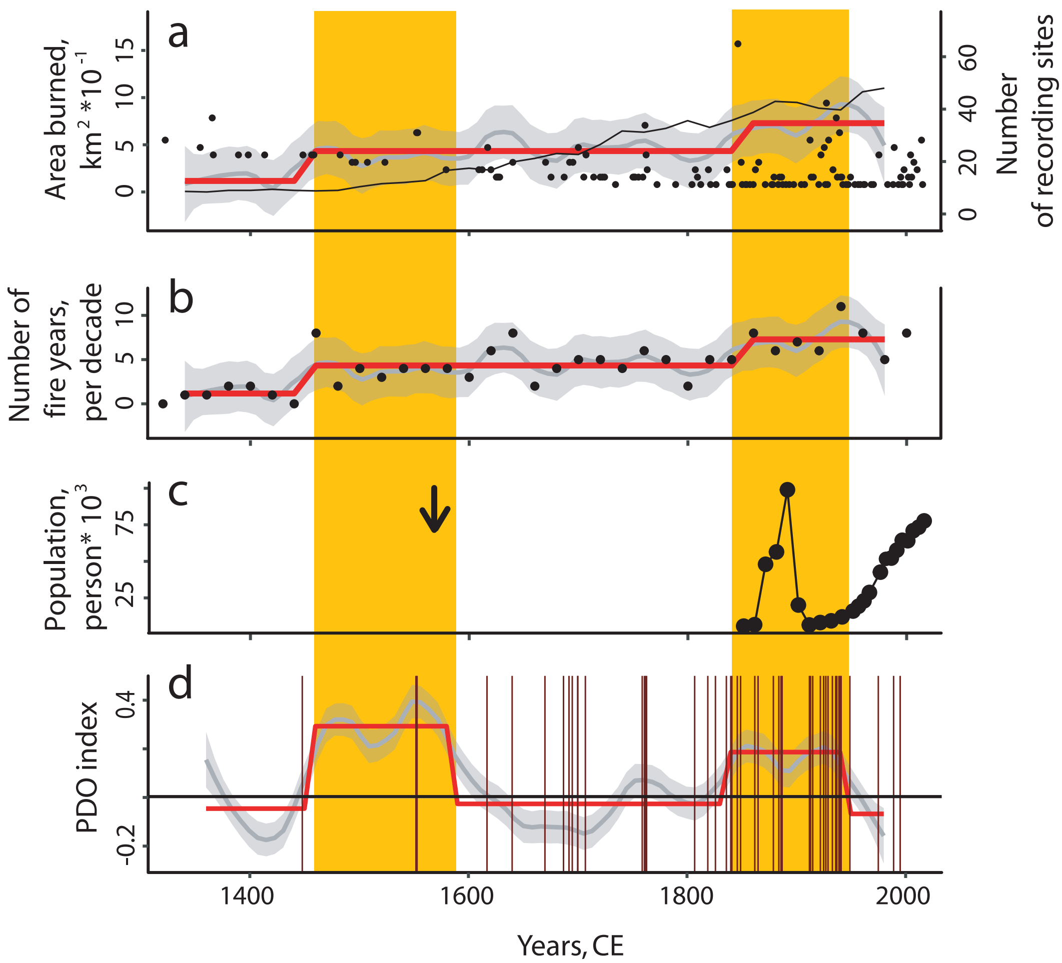

Figure 3. Reconstructed burned area (a) and number of fire years (b), both per decade; chronology of population density of the Northwest Territories (c); and Pacific Decadal Oscillation (PDO) (MacDonald & Case, 2005) (d). Red solid lines in (a, b and d) indicate the changes in fire regime identified by the regime shift analysis (Rodionov, 2004) on fire cycle (FC), fire occurrence and PDO. The black solid lines in (a) indicate site replication, which is also relevant to the interpretation of the data in (b, d). Black dots in (a, b) represent values for single fire years. Vertical dark-red bars on (d) represent fire years that occurred at two or more sites. Gray-shaded areas in (a, b and d) represent confidence intervals. The black vertical arrow in (c) indicates the onset of European colonization of the NWT. Yellow bars stretching across all plates indicate periods of positive PDO, as estimated by the regime shift analysis (d).

We observed an association between a shift toward positive PDO and reconstructed fires. The observed shifts from negative to positive phases of the PDO in 1460 and 1840 CE (Figure 3d) coincided with increases in fire activity (Figure 3a). Modern fire data indicated that positive phases of the PDO during the 1975–1995 CE period

Table 1
Reconstructions of the Fire Cycle and Fire Occurrence (Fire Years per Decade) in the Northwest Territories for the Periods Identified by Regime Shift Analysis

Statistics	Period, years CE	Mean, years	95% CI lower bound	95% CI upper bound
Fire cycle	1340–1440	572	400.35	1000.87
	1460–1840	171	150.63	195.04
	1860–2015	95	82.42	109.90
Decadal fire occurrence	1340–1440	1.00	0.57	1.43
	1460–1840	4.45	3.75	5.05
	1920–2015	7.63	6.38	8.50

Table 2
Reconstructed Ignition Frequencies in the Study Area of the Northwest Territories for Three Periods Identified by Regime Shift Analysis

Period, CE	Type of estimate	Frequency, km^{-2} $year^{-1}$
1340–1440	Conservative	$1.46*10^{-3}$
	Opportunistic	$7.50*10^{-6}$
1460–1840	Conservative	$5.74*10^{-3}$
	Opportunistic	$3.30*10^{-5}$
1860–2015	Conservative	$9.68*10^{-3}$
	Opportunistic	$1.23*10^{-4}$

Note. See *Methods* section for explanations concerning the types of estimates.

and since 2015 CE were associated with a higher frequency of LFYs (Table 3 and Figure 5). The other climate indices (ENSO and PNA) did not show any significant association with LFYs (Figures S2 and S3, and Table S1 in Supporting Information S1).

The contingency analysis showed that the majority of LFYs occurred during the positive phase of the PDO (Table 3, Figure 3d). This pattern was consistent for both the reconstructed (1400–1998 CE) and modern (1950–2019 CE) periods: the observed fire year frequencies reached 0.996 and 0.918 quantiles of the bootstrap-derived distributions of fire year frequencies during positive PDO phases (Table 3).

Modern LFYs occurred during years with low scPDSI and positive PDO (Figures 5 and 6a). Low scPDSI values (indicative of drought conditions) occurred during the same years as LFYs (Figure 6a), and positive PDO correlated with drier-than-average conditions across the study area (Figures 6b and 6c).

4. Discussion

We developed a 680-year-long annual reconstruction of forest fire activity in the area around Yellowknife, making it the longest record within the boreal subarctic landscape of the NWT. Unlike previous dendrochronological reconstructions of fire activity in the NWT, which only extended back to the 1600s–1700s CE (Lewis et al., 2019; Wallenius et al., 2011) and relied on fire interval data (Bothwell et al., 2004; de Groot & Chowns, 1994), our reconstruction featured sub-annual resolution and estimates of burned areas.

Long-term changes in annually resolved fire activity showed partial synchrony with changes in the PDO phases, suggesting climatic forcing of the fire regime, supporting our first hypothesis (H1). Statistically significant increases in fire activity in both the mid-1400s and mid-1800s followed shifts from negative to positive phases of the PDO and were not synchronized with human colonization waves. Higher fire activity after the mid-1800s does not support our second hypothesis (H2) of a decline in fire activity after the LIA in the NWT. The temporal association between population growth and increased fire activity in the mid-1800s in the boreal subarctic of the NWT suggests some human impact on fire activity at that time. Below, we discuss these findings in detail.

4.1. Climate and Fires in the Boreal Subarctic

The reconstruction of fire activity, based on fire scars, pointed to the PDO as the principal driver of regional fire activity in NWT. Two shifts toward higher fire activity (in the mid-1400s and mid-1800s) coincided with shifts

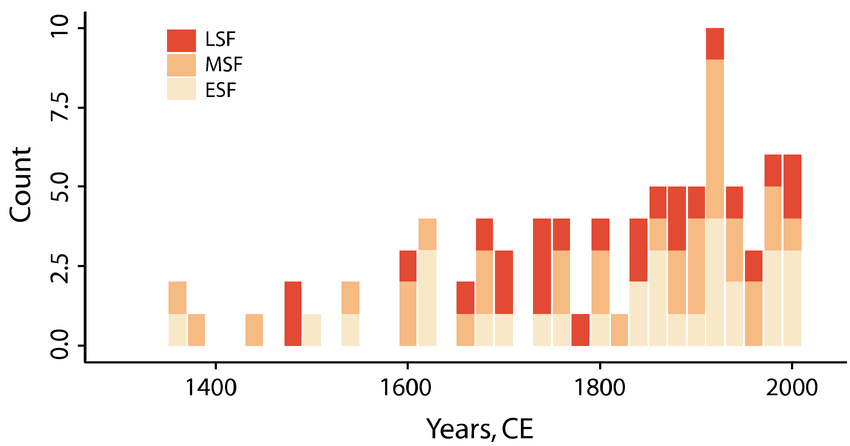

Figure 4. Reconstructed fire seasonality across the Yellowknife region. ESF, early season fires; MSF, mid-season fires; and LSF, late season fires.

Table 3
Contingency Analysis of the Large Fire Year (LFY) Frequencies Under Positive/Negative States of the Pacific Decadal Oscillation (PDO, MacDonald & Case, 2005)

Climate indices	Frequency of events, years		Quantiles	Number of LFY years
	Observed	Expected		
Reconstructed PDO (mostly historical period)				
PDO $^-$	0.0504	0.0725	0.006	20
PDO $^+$	0.108	0.0718	0.996	26
Modern PDO (modern period)				
PDO $^-$	0.15	0.214	0.115	6
PDO $^+$	0.3	0.215	0.918	9

Note. For the period 1400–1998 CE, probabilities of LFY occurrence were estimated from the reconstructed fire chronology (this study). For the period 1950–2021 CE, the probabilities were estimated using observational data and selected thresholds (see *Methods* section). Percentiles represent the proportion of the bootstrapped distribution of respective frequency to the left of the observed value; these can be viewed as estimates of the statistical significance of differences between observed and bootstrapped values.

from the negative to the positive phase of the PDO (Figures 3d and 5). In line with this observation, periods with positive PDO had a higher frequency of LFYs than periods with negative PDO (Table 3).

A close connection between PDO phases and the position of the winter jet stream (Gershunov et al., 1999) may explain PDO influence on forest fire activity. The positive phase of the PDO features warm SSTs in the Gulf of Alaska and cool temperatures in the broader North Pacific (Chen et al., 2021; Niebauer, 1998; Trenberth, 1992). In turn, the warmer SSTs contribute to the development of a high-pressure ridge in the North Pacific (Niebauer, 1998; Zhang & Chen, 2007) that can stretch from the Gulf of Alaska to the central North Pacific. The ridge modifies the flow of the jet stream, pushing it northward (Mantua et al., 1997), which leads to enhanced meridional flow of air masses and the intrusion of warmer, drier air from the south into western boreal Canada. These developments change storm tracks and reduce precipitation patterns over the NWT (Niebauer, 1998; Trenberth, 1992), likely resulting in longer and drier fire seasons. When associated with cyclonic storms, such ridges produce strong winds and lightning activity (Flannigan & Wotton, 2001; Gedalof et al., 2005), promoting ignition and fire spread. In line with this interpretation, analyses of observational fire and weather data over 1959–2019 CE indicated that dry periods in the NWT coincided with positive PDO (Figures 6b and 6c). In turn, the persistence of warm, dry weather contributes to the development of a water deficit in forest fuels (Girardin et al., 2004), preconditioning them for effective ignition and fire spread (Johnson & Wowchuk, 1993; Macias Fauria & Johnson, 2008). This pattern explains the association between modern LFYs in the study area and summer drought (scPDSI), which supports this interpretation (Figure 6a).

The earliest period in our reconstruction (1340–1440 CE) covers the late stages of the Medieval Warm Period (MWP) and featured a long FC (572 years), one of the longest FCs reported for conifer-dominated circumboreal forests in the Northern Hemisphere (Larsen & MacDonald, 1998; Niklasson & Granström, 2000; Rolstad et al., 2017). While some studies have characterized the MWP as a warm and dry period with increased fire activity in the Pacific Northwest (Marlon et al., 2012), others have suggested that the MWP period may not have been dry (Bracht-Flyr & Fritz, 2012; Steinman et al., 2012) and not particularly fire-prone (Holmquist et al., 2016). During the MWP, cool SSTs in the eastern tropical Pacific indicated persistent La Niña conditions, coupled with the sustained positive phases of PDO, NAO, and AO (MacDonald & Case, 2005; Ortega et al., 2015; Trouet et al., 2009). Winter precipitation in the Pacific Northwest and parts of boreal Canada is typically enhanced under these conditions (Henke et al., 2017; Holmquist et al., 2016; Shabbar, Higuchi, et al., 1997). The resulting increase in snow cover and shortening of the fire season might explain the lower fire activity in the NWT during the later stages of MWP.

A shift toward higher fire activity in the mid-1400s broadly coincided with the onset of the LIA. Studies of the fire history of the boreal biome have suggested that the LIA, characterized by a dry and unstable climate, represents the most fire-prone period in boreal forests (Bergeron & Flannigan, 1995; Drobyshev et al., 2016; Gavin

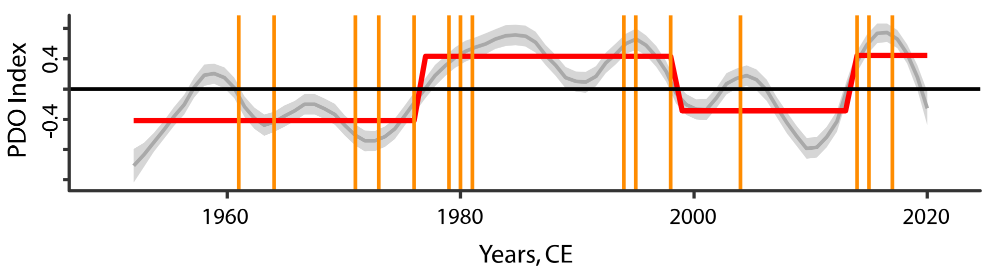

Figure 5. Pacific Decadal Oscillation (PDO) chronology (Japan Meteorological Agency, 2024) thin gray line, smoothed with a spline function and modern large fire years (LFYs) (vertical orange lines). The thick red line shows the outcome of regime shift analysis (Rodionov, 2004). The solid gray horizontal line refers to the PDO long-term average.

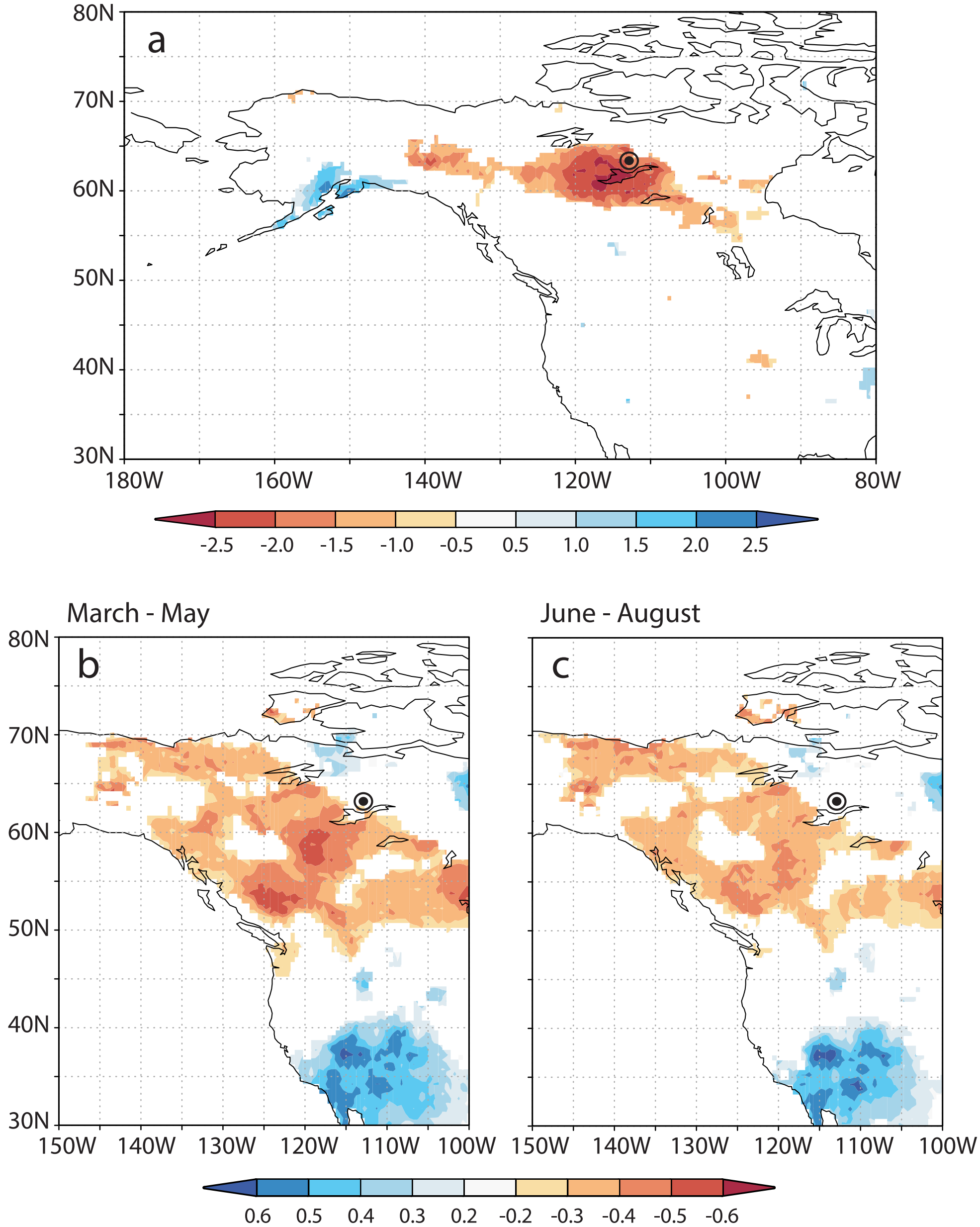

Figure 6. Teleconnection between the northern North Atlantic and fire weather in the Northwest Territories (NWT). (a) Superposed epoch analysis of the self-calibrated Palmer's Drought Severity Index scPDSI (Wells et al., 2004) from June to August and LFYs in the NWT over the 1959–2019 CE. Note that lower PDSI values mean increased drought conditions. Correlation between the Pacific Decadal Oscillation (PDO) and scPDSI fields for (b) March through May and (c) June through August during 1901–1996 CE. The location of the study area is marked with a dark circle. Colored areas in (a) indicate PDSI anomalies, significant at $p < 0.10$, and in (b, c) areas with the significance of the correlation coefficient being 0.10 or lower.

et al., 2003; Wallenius et al., 2007). Although cooling during the LIA has been consistently identified in a wide range of dendrochronological and paleoecological studies across northern latitudes, its offset and duration vary in different parts of the boreal biome (Cohen, 2003; Delwaide et al., 2021; Drobyshev et al., 2016; Gagen et al., 2011). In central NWT, the cooling trends attributed to the LIA have been dated to various periods: 1200–1750 CE (Dalton et al., 2018), 1250–1600 CE (Taylor et al., 2018), 1450–1850 CE (Tillman et al., 2010), and 1300–1850 CE (MacDonald et al., 2008). In the NWT, cooler periods have been associated with increased summer aridity (Kuosmanen et al., 2023), a pattern also observed in eastern Canada (Bergeron et al., 2001) and in Scandinavia (Drobyshev et al., 2016). An increase in fire activity in the NWT in the mid-1400s coincided with a positive PDO phase, which has been suggested to cause drier conditions in the Pacific Northwest (MacDonald & Case, 2005). Analysis of modern precipitation and temperature data for that region, however, does not suggest a correlation between these variables and PDO dynamics (Figures S4 and S5 in Supporting Information S1).

We lack a definitive explanation for the absence of a decline in fire activity following the shift from a positive to a negative PDO phase in the late 1500s (Figure 3d). We speculate that the fire-prone areas might consistently maintain a sufficient level of combustibility under different climatic conditions, even in cases where shifts in the PDO phases override the general cooling of the climate, as observed during the LIA.

Upon analyzing fire scar dates, we found no evidence of a decline in fire activity, contrary to the previously documented trend for the NWT since the mid-1800s CE (Larsen, 1997; Wallenius et al., 2011). In contrast, the period 1860–2015 CE had the shortest FC of 95 years (Figure 3a). This finding did not support the results of other studies in the Canadian boreal forest, which indicated a decrease in fire activity in the post-LIA period (Bergeron et al., 2001; Chavardès et al., 2022; Drobyshev et al., 2017; Kuosmanen et al., 2023). The lack of agreement between our fire scar reconstruction and those developed elsewhere may be due to the introduction of human ignitions (see Section 4.2). Moreover, Gaboriau et al. (2020) have shown that a decrease in fire frequency over the last 500 years was overcompensated by increased fire size, which might explain the short FC we observed.

4.2. Human Activities as a Potential Driver of Fire Regimes

Although human presence in the NWT has been documented to date back to at least 7000 BP (Ridington, 2012), it is unlikely that it had a significant impact on fire regimes. Until the late 1700s, the area was inhabited by nomadic Dene people who subsisted primarily on hunting, fishing, trapping, and gathering wild plants (Anonymous, 1970; Ridington, 2012). There is no record of an effect of Indigenous people on fire activity in the Yellowknife area, although it has been suggested that the Dene used fire to clear land around their traplines (Anonymous, 1970; Needlay et al., 2012; Ridington, 2012). Fires were typically set during periods of low fire susceptibility and, as a result, were small and of low intensity (Lewis, 1982; Turner, 1999). Given the small size of the fires and the low population density, it is likely that Dene influence on fire activity was minimal.

An increase in fire activity around Yellowknife occurred in the 1440s (Table 1, Figure 3a), that is, 350 years prior to European colonization in the late-1700s when European fur traders established trading posts across the NWT (Asch, 2012; Coates, 1985; Zaslow, 1971). European settlers used fires to hunt, eliminate insect pests, and create supplies of dry firewood (Turner, 1999). While increased human presence in the NWT in the late 1700s possibly contributed to additional ignition sources, the fire regime did not change until the mid-1800s (Figures 3a and 3b).

Slash-and-burn cultivation and activities carried out in connection with timber harvesting were the primary causes of human-related ignitions during the colonization period in the southern boreal zone (Boucher et al., 2014; Reich et al., 2001; Weir et al., 2000). Around Yellowknife, however, slash-and-burn agriculture was not practiced due to the harsh climate and nutrient-poor soils, with cold-resistant crops being introduced only in the early 1990s (Ridington, 2012). In nearby British Columbia, large-scale burning was used to clear land for mineral exploration and to promote grass growth for livestock, particularly in the 1800s (Turner, 1999). However, such practices were likely absent in the study area. The region around Yellowknife remained largely isolated, with European settlement and the associated mining activities only beginning after the discovery of gold deposits in the 1930s. Moreover, the low productivity of the boreal subarctic trees made these forests of little interest for modern forestry, with the vast majority of the landscape remaining unaffected by industrial clear-cutting.

The lack of a clear impact of human activities on the fire regimes around Yellowknife supports the view of climate as the leading factor. The vast majority of forests in the NWT are in Wildfire Management Zone 3 (Tymstra et al., 2020), which means that active fire suppression is not implemented due to the remoteness of these forests. Hence, wildfires are mostly left free to burn, unless they approach human settlements.

4.3. Ignition Frequencies

Ignition rates in the study area were generally low but broadly similar to those in other regions of the circumboreal forest, suggesting that the forests of the study area were exposed to near-natural ignition densities. Over the past 680 years, conservative estimates range from 0.002 to 0.009 ignitions per year per km^2, while opportunistic estimates range from $7.50*10^{-6}$ to $1.23*10^{-4}$ ignitions per year per km^2 (Table 3). These estimates are consistent with modern data on lightning flash densities and lightning efficiency coefficients (LEC, i.e., proportion of effective ignitions in the total pool of lightning strikes). The modern lightning flash density around Yellowknife is between 0.2 and 0.6 strikes per year per km^2 (Cecil, 2006), with lightning efficiency coefficients of $2*10^{-4}$ which would give an effective ignition rate of $0.4*10^{-3}$ to $1.2*10^{-3}$ ignitions per year per km^2.

Early and mid-season ignitions predominantly occurred over late-season fires across the Yellowknife region during the reconstruction period. Early- and mid-season fires were likely induced by lightning. The thunderstorm season in the NWT generally begins in late May, peaks in July, and decreases by late August (Kochtubajda et al., 2002). This pattern is attributed to the prevalence of fuel-drying high-pressure cells developing early in the fire season (Kochtubajda et al., 2019; Nash & Johnson, 1996; Skinner et al., 2002). In particular, the positive anomaly in the mid-tropospheric circulation forms a prominent ridge over the NWT, causing warm and dry conditions that dry out forest fuels (Flannigan & Wotton, 2001; Sharma et al., 2022; Skinner et al., 2002). The breakdown of such ridges often leads to the formation of thunderstorms and lightning systems that favor ignitions (Macias Fauria & Johnson, 2008; Skinner et al., 2002).

4.4. Future Fire in the Boreal Subarctic of the NWT

The association between the PDO and the reconstructed fire record suggests a teleconnection between ocean-atmospheric circulation and the natural disturbance regime of the boreal subarctic. The prediction of PDO trends might, therefore, be used to project regional fire activity over the NWT. Since PDO dynamics feature a strong decadal component and are inherently dependent on SST dynamics in the Pacific, predictions of PDO states are possible with lead times between 1 and 10 years, depending on the computational approach (Qin et al., 2023; Wiegand et al., 2019). Predictions of fire activity over the NWT, even with a 1-year lead time, would be highly instrumental in operational planning and preparedness. However, the actual response of forests to climate will likely depend on tree species composition (Gaboriau et al., 2023), which will have to be taken into account in projections.

Since 2018, the PDO has been in a negative phase, which is generally less conducive to fire (NCEI, 2023). Its evolution toward a positive phase over the next several decades is expected to increase fire activity in the boreal subarctic of the NWT. Paleoecological reconstructions from the same region indicate that past increases in fire activity resulted in changes in vegetation cover: the proportion of deciduous trees (primarily paper birch and trembling aspen) and jack pine increased at the expense of black spruce (Gaboriau et al., 2020; Sulphur et al., 2016). Similar trends are to be expected with an eventual future transition of the PDO into its positive state.

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Data Availability Statement

The data are available from the corresponding author upon reasonable request.

References

Anonymous. (1970). *Indians of Yukon and Northwest Territories*. Department of Indian Affairs and Northern Development. 20

Asch, M. I. (2012). Slavey. *The Canadian Encyclopedia*. Retrieved from https://www.thecanadianencyclopedia.ca/en/article/slavey-slave

Beaudoin, A., Bernier, P. Y., Guindon, L., Villemaire, P., Guo, X., Stinson, G., et al. (2014). Mapping attributes of Canada's forests at moderate resolution through *k*NN and MODIS imagery. *Canadian Journal of Forest Research*, *44*(44), 521–532. https://doi.org/10.1139/cjfr-2013-0401

Bergeron, Y., & Flannigan, M. D. (1995). Predicting the effects of climate change on fire frequency in the southeastern Canadian boreal forest. *Water Air and Soil Pollution*, *82*(1–2), 437–444. https://doi.org/10.1007/978-94-017-0942-2_41

Bergeron, Y., Gauthier, S., Kafka, V., Lefort, P., & Lesieur, D. (2001). Natural fire frequency for the eastern Canadian boreal forest: Consequences for sustainable forestry. *Canadian Journal of Forest Research*, *31*(3), 384–391. https://doi.org/10.1139/x00-178

Biondi, F. (2001). A 400-year tree-ring chronology from the tropical treeline of North America. *Ambio*, *30*(3), 162–166. https://doi.org/10.1579/0044-7447-30.3.162

Bonsal, B., & Shabbar, A. (2011). Large-scale climate oscillations influencing Canada, 1900–2008. In *Presented at the Canadian biodiversity: Ecosystem status and trends 2010—technical thematic report*. Canadian Councils of Resource Ministers. 15

Bothwell, P. M., de Groot, W. J., Dube, D. E., Chowns, T., Carlsson, D. H., & Stefner, N. C. (2004). Fire regimes in Nahanni National Park and the Mackenzie Bison sanctuary, Northwest Territories, Canada. In R. T. Engstrom, K. E. M. Galley, & W. J. de Groot (Eds.) (pp. 43–54). *Presented at the 22nd Tall Timbers Fire Ecology Conference: Fire in temperate, boreal and montane ecosystems*.

Boucher, Y., Grondin, P., & Auger, I. (2014). Land use history (1840–2005) and physiography as determinants of southern boreal forests. *Landscape Ecology*, *29*(3), 437–450. https://doi.org/10.1007/s10980-013-9974-x

Bracht-Flyr, B., & Fritz, S. C. (2012). Synchronous climatic change inferred from diatom records in four western Montana lakes in the U.S. Rocky Mountains. *Quaternary Research*, *77*(3), 456–467. https://doi.org/10.1016/j.yqres.2011.12.005

Canada Year Book, C. (2010). Canada Year Book. In *Table 24.1 Population, by province and territory, selected years, 1861 to 2009*. Retrieved from https://www150.statcan.gc.ca/n1/pub/11-402-x/2010000/chap/pop/tbl/tbl01-eng.htm

Cecil, D. J. (2006). LIS/OTD 0.5 degree High-Resolution Annual Climatology (HRAC). Retrieved from https://ghrc.nsstc.nasa.gov/home/documentation/lisotd-05-degree-high-resolution-annual-climatology-hrac

Chavardès, R. D., Danneyrolles, V., Portier, J., Girardin, M. P., Gaboriau, D. M., Gauthier, S., et al. (2022). Converging and diverging burn rates in North American boreal forests from the Little Ice Age to the present. *International Journal of Wildland Fire*, *31*(12), 1184–1193. https://doi.org/10.1071/wf22090

Chen, S., Yu, B., Wu, R., Chen, W., & Song, L. (2021). The dominant North Pacific atmospheric circulation patterns and their relations to Pacific SSTs: Historical simulations and future projections in the IPCC AR6 models. *Climate Dynamics*, *56*(3), 701–725. https://doi.org/10.1007/s00382-020-05501-1

Coates, K. (1985). *Canada's colonies: A history of the Yukon and Northwest Territories*. Lorimer.

Cohen, A. S. (2003). Paleolimnology: The history and evolution of lake systems. https://doi.org/10.1093/oso/9780195133530.001.0001

Dalton, A. S., Patterson, R., Roe, H., Macumber, A., Swindles, G., Galloway, J., et al. (2018). Late Holocene climatic variability in Subarctic Canada: Insights from a high-resolution lake record from the central Northwest Territories. *PLoS One*, *13*(6), e0199872. https://doi.org/10.1371/journal.pone.0199872

D'Arrigo, R., Villalba, R., & Wiles, G. (2001). Tree-ring estimates of Pacific decadal climate variability. *Climate Dynamics*, *18*(3), 219–224. https://doi.org/10.1007/s003820100177

de Groot, W. J., & Chowns, T. (1994). Fire history of the Fort Providence, NWT area: A preliminary assessment. In T. A. Duncan, W. A. D. Foster, & R. A. Lanoville (Eds.) (pp. 55–63). *Presented at the the 1992 annual meeting and workshop of the interior west fire Council on "managing fire dependant ecosystems: Options and technologies" (Oct.26-29, 1992, Yellowknife, NWT)*, Northern Forestry Centre.

Delwaide, A., Asselin, H., Arseneault, D., Lavoie, C., & Payette, S. (2021). A 2233-year tree-ring chronology of subarctic black spruce (Picea mariana): Growth forms response to long-term climate change. *Écoscience*, *28*(3–4), 399–419. https://doi.org/10.1080/11956860.2021.1952014

Drobyshev, I., Bergeron, Y., de Vernal, A., Moberg, A., Ali, A., & Niklasson, M. (2016). Atlantic SSTs control regime shifts in forest fire activity of Northern Scandinavia. *Scientific Reports*, *6*(1), 22532. https://doi.org/10.1038/srep22532

Drobyshev, I., Bergeron, Y., Girardin, M., Gauthier, S., Ols, C., & Ojal, J. (2017). Strong gradients in forest sensitivity to climate change revealed by dynamics of forest fire cycles in post Little Ice Age era. *Journal of Geophysical Research—Biogeosciences*, *10*, 100.

Drobyshev, I., Ryzhkova, N., Niklasson, M., Zhukov, A., Mullonen, I., Pinto, G., & Kryshen, A. (2022). Marginal imprint of human land use upon fire history in a mire-dominated boreal landscape of the Veps Highland, North-West Russia. *Forest Ecology and Management*, *507*, 120007. https://doi.org/10.1016/j.foreco.2022.120007

Dyke, A. (2005). Late quaternary vegetation history of northern NorthNorth America based on pollen, macrofossil, and Faunal remains. *Géographie Physique et Quaternaire*, *59*(2–3), 211–262. https://doi.org/10.7202/014755ar

Ecosystem Classification Group. (2008). Ecological regions of the Northwest territories-Taiga shield. 146

Epp, H., & Lanoville, R. (1996). Satellite data and geographic information systems for fire and resource management in the Canadian arctic. *Geocarto International*, *11*(2), 97–103. https://doi.org/10.1080/10106049609354537

Fedorov, A. V., Hu, S., Wittenberg, A. T., Levine, A. F. Z., & Deser, C. (2020). ENSO low-frequency modulation and mean state interactions. In *El Niño southern oscillation in a changing climate* (pp. 173–198). https://doi.org/10.1002/9781119548164.ch8

Felis, T., Suzuki, A., Kuhnert, H., Rimbu, N., & Kawahata, H. (2010). Pacific Decadal Oscillation documented in a coral record of North Pacific winter temperature since 1873. *Geophysical Research Letters*, *37*(14). https://doi.org/10.1029/2010GL043572

Flannigan, M., Amiro, B. D., Logan, K. A., Stocks, B. J., & Wotton, B. M. (2005). Forest fires and climate change in the 21st century. *Mitigation and Adaptation Strategies for Global Change*, *11*(4), 847–859. https://doi.org/10.1007/s11027-005-9020-7

Flannigan, M. D., & Wotton, B. M. (2001). Climate, weather, and area burned. In E. A. Johnson & K. Miyanishi (Eds.), *Forest fires: Behavior and ecological effects* (pp. 315–373). Academic Press.

Forster, W. (1995). Northwest Territories fire weather report. Fort Smith, Northwest Territories. 63

Gaboriau, D. M., Chaste, É., Girardin, M. P., Asselin, H., Ali, A. A., Bergeron, Y., & Hély, C. (2023). Interactions within the climate-vegetation-fire nexus may transform 21st century boreal forests in northwestern Canada. *iScience*, *26*(6), 106807. https://doi.org/10.1016/j.isci.2023.106807

Gaboriau, D. M., Remy, C. C., Girardin, M. P., Asselin, H., Hély, C., Bergeron, Y., & Ali, A. A. (2020). Temperature and fuel availability control fire size/severity in the boreal forest of central Northwest Territories, Canada. *Quaternary Science Reviews*, *250*, 106697. https://doi.org/10.1016/j.quascirev.2020.106697

Gagen, M., Zorita, E., McCarroll, D., Young, G. H., Grudd, H., Jalkanen, R., et al. (2011). Cloud response to summer temperatures in Fennoscandia over the last thousand years. *Geophysical Research Letters*, *38*(5), L05701. https://doi.org/10.1029/2010GL046216

Gavin, D. G., Brubaker, L. B., & Lertzman, K. P. (2003). Holocene fire history of a coastal temperate rain forest based on soil charcoal radiocarbon dates. *Ecology*, *84*(1), 186–201. https://doi.org/10.1890/0012-9658(2003)084[0186:hfhoac]2.0.co;2

Gedalof, Z., Mantua, N. J., & Peterson, D. L. (2002). A multi-century perspective of variability in the Pacific decadal oscillation: New insights from tree rings and coral. *Geophysical Research Letters*, *29*(24), 57. https://doi.org/10.1029/2002GL015824

Gedalof, Z., Peterson, D. L., & Mantua, N. J. (2005). Atmospheric, climatic, and ecological controls on extreme wildfire years in the northwestern United States. *Ecological Applications*, *15*(1), 154–174. https://doi.org/10.1890/03-5116

Gedalof, Z., & Smith, D. J. (2001). Dendroclimatic response of mountain hemlock (*Tsuga mertensiana*) in Pacific North America. *Canadian Journal of Forest Research*, *31*(2), 322–332. https://doi.org/10.1139/x00-169

Gershunov, A., Barnett, T., & Cayan, D. (1999). North Pacific interdecadal oscillation seen as factor in ENSO-related North American climate anomalies. *EOS Transactions*, *80*(3), 25–30. https://doi.org/10.1029/99EO00019

Girardin, M., Tardif, J., Flannigan, M., & Bergeron, Y. (2004). Multicentury reconstruction of the Canadian Drought Code from eastern Canada and its relationship with paleoclimatic indices of atmospheric circulation. *Climate Dynamics*, *23*(2), 99–115. https://doi.org/10.1007/s00382-004-0417-x

GNWT, [Government of the Northwest Territories]. (2008). *History of mining in the Northwest Territories*. Government of the Northwest Territories. Retrieved from http://www.iti.gov.nt.ca/about-iti/copyright.shtml

Grissino-Mayer, H. D. (2001). Evaluating crossdating accuracy: A manual and tutorial for the computer program COFECHA. *Tree-Ring Research*, *57*(2), 205–221.

Grissino-Mayer, H. D., & Swetnam, T. W. (2000). Century-scale climate forcing of fire regimes in the American Southwest. *The Holocene*, *10*(2), 213–220. https://doi.org/10.1191/095968300668451235

Hall, R., Erdélyi, R., Hanna, E., Jones, J. M., & Scaife, A. A. (2015). Drivers of North Atlantic polar front jet stream variability. *International Journal of Climatology*, *35*(8), 1697–1720. https://doi.org/10.1002/joc.4121

Hanes, C. C., Wang, X., Jain, P., Parisien, M. A., Little, J. M., & Flannigan, M. D. (2019). Fire-regime changes in Canada over the last half century. *Canadian Journal of Forest Research*, *49*(3), 256–269. https://doi.org/10.1139/cjfr-2018-0293

Hart, S. J., Smith, D. J., & Clague, J. J. (2010). A multi-species dendroclimatic reconstruction of Chilko River streamflow, British Columbia, Canada. *Hydrological Processes*, *24*(19), 2752–2761. https://doi.org/10.1002/hyp.7674
Helm, J. (1981). *Handbook of NorthNorth American Indians: Subarctic*. Smithsonian Institution. 853
Henke, L. M. K., Lambert, F. H., & Charman, D. J. (2017). Was the little ice age more or less El Niño-like than the medieval climate anomaly? Evidence from hydrological and temperature proxy data. *Climate of the Past*, *13*(3), 267–301. https://doi.org/10.5194/cp-13-267-2017
Hessl, A., Mckenzie, D., & Schellhaas, A. (2004). Drought and Pacific decadal oscillation linked to fire occurrence in the Inland Pacific Northwest. *Ecological Applications*, *14*(2), 425–442. https://doi.org/10.1890/03-5019
Heyerdahl, E. K., Brubaker, L. B., & Agee, J. K. (2002). Annual and decadal climate forcing of historical fire regimes in the interior Pacific Northwest, USA. *The Holocene*, *12*(5), 597–604. https://doi.org/10.1191/0959683602hl570rp
Heyerdahl, E. K., Morgan, P., & Riser, J. P. (2008). Multi-season climate synchronized historical fires in dry forests (1650–1900), northern Rockies, USA. *Ecology*, *89*(3), 705–716. https://doi.org/10.1890/06-2047.1
Holman, H. L. (1944). Report on forest fire protection in the Mackenzie District (Vol. 464, File 50050). National Archives of Canada, RG 39, Northwest Territory Lands, Parks and Forests Branch, Dominion Forest Service.
Holmes, R. L. (1983). Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bulletin*, *43*, 69–78.
Holmes, R. L. (1999). *Dendrochronological Program Library (DPL)*. Users Manual. Laboratory of Tree-Ring Research, University of Arizona. http://www.ltrr.arizona.edu/pub/dpl/
Holmquist, J. R., Booth, R. K., & MacDonald, G. M. (2016). Boreal peatland water table depth and carbon accumulation during the Holocene thermal maximum, Roman Warm Period, and Medieval Climate Anomaly. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *444*, 15–27. https://doi.org/10.1016/j.palaeo.2015.11.035
Japan Meteorological Agency. (2024). Reconstruction of the Pacific Decadal Oscillation (PDO) index [Dataset]. *Japan Meteorological Agency*. Retrieved from https://ds.data.jma.go.jp/tcc/tcc/products/elnino/decadal/pdo.html
Jia, X., & Ge, J. (2017). Modulation of the PDO to the relationship between moderate ENSO events and the winter climate over North America. *International Journal of Climatology*, *37*(12), 4275–4287. https://doi.org/10.1002/joc.5083
Johnson, E. A., & Miyanishi, K. (2012). The boreal forest as a cultural landscape. *Annals of the New York Academy of Sciences*, *1249*(1), 151–165. https://doi.org/10.1111/j.1749-6632.2011.06312.x
Johnson, E. A., & Wowchuk, D. R. (1993). Wildfires in the southern Canadian Rocky-mountains and their relationship to midtropospheric anomalies. *Canadian Journal of Forest Research*, *23*(6), 1213–1222. https://doi.org/10.1139/x93-153
June, H., & Andrews, T. D. (2009). The Canadian encyclopedia. Retrieved from https://www.thecanadianencyclopedia.ca/en/article/tlicho-dogrib
Justino, F., Bromwich, D. H., Schumacher, V., da Silva, A., & Wang, S.-H. (2022). Arctic Oscillation and Pacific-North American pattern dominated-modulation of fire danger and wildfire occurrence. *Npj Climate and Atmospheric Science*, *5*(1), 52. https://doi.org/10.1038/s41612-022-00274-2
Kasischke, E. S., & Turetsky, M. R. (2006). Recent changes in the fire regime across the North American boreal region—spatial and temporal patterns of burning across Canada and Alaska. *Geophysical Research Letters*, *33*(9), L09703. https://doi.org/10.1029/2006GL025677
Kochtubajda, B., Flannigan, M. D., Gyakum, J. R., Stewart, R. E., Logan, K. A., & Nguyen, T.-V. (2006). Lightning and fires in the Northwest Territories and responses to future climate change. *Arctic*, *59*(2), 211–221. https://doi.org/10.14430/arctic343
Kochtubajda, B., Stewart, R. E., Flannigan, M. D., Bonsal, B. R., Cuell, C., & Mooney, C. J. (2019). An assessment of surface and atmospheric conditions associated with the extreme 2014 wildfire season in Canada's Northwest Territories. *Atmosphere-Ocean*, *57*(1), 73–90. https://doi.org/10.1080/07055900.2019.1576023
Kochtubajda, B., Stewart, R. E., Gyakum, J. R., & Flannigan, M. D. (2002). Summer convection and lightning over the Mackenzie river basin and their Impacts during 1994 and 1995. *Atmosphere-Ocean*, *40*(2), 199–220. https://doi.org/10.3137/ao.400208
Kuosmanen, N., Väliranta, M., Piilo, S., Tuittila, E.-S., Oksanen, P., & Wallenius, T. (2023). Repeated fires in forested peatlands in sporadic permafrost zone in Western Canada. *Environmental Research Letters*, *18*(9), 094051. https://doi.org/10.1088/1748-9326/acf05b
Larkin, N. K., & Harrison, D. E. (2002). ENSO warm (El Niño) and cold (La Niña) event life cycles: Ocean surface anomaly patterns, their symmetries, asymmetries, and implications. *Journal of Climate*, *15*(10), 1118–1140. https://doi.org/10.1175/1520-0442(2002)015<1118:EWENOA>2.0.CO;2
Larsen, C. P. S. (1997). Spatial and temporal variations in boreal forest fire frequency in northern Alberta. *Journal of Biogeography*, *24*(5), 663–673. https://doi.org/10.1111/j.1365-2699.1997.tb00076.x
Larsen, C. P. S., & MacDonald, G. M. (1998). Fire and vegetation dynamics in a jack pine and black spruce forest reconstructed using fossil pollen and charcoal. *Journal of Ecology*, *86*(5), 815–828. https://doi.org/10.1046/j.1365-2745.1998.8650815.x
Larson, S. M., Okumura, Y., Bellomo, K., & Breeden, M. L. (2022). Destructive interference of ENSO on North Pacific SST and North American precipitation associated with Aleutian low variability. *Journal of Climate*, *35*(11), 3567–3585. https://doi.org/10.1175/JCLI-D-21-0560.1
Larsson, L. A. (2018). Cybis dendro dating program Vol. *9.1*.
Latifovic, R., Pouliot, D., & Olthof, I. (2017). Circa 2010 land cover of Canada: Local optimization methodology and product development. *Remote Sensing*, *9*(11), 1098. https://doi.org/10.3390/rs9111098
Lewis, H. T. (1982). *A time for burning*. Boreal Institute for Northern Studies, University of Alberta. 62
Lewis, K., Johnson, C., & Karim, M. (2019). Fire and lichen dynamics in the Taiga Shield of the Northwest Territories and implications for barren-ground caribou winter forage. *Journal of Vegetation Science*, *30*(3), 448–460. https://doi.org/10.1111/jvs.12736
Li, J., Xie, S.-P., Cook, E. R., Huang, G., D'Arrigo, R., Liu, F., et al. (2011). Interdecadal modulation of El Niño amplitude during the past millennium. *Nature Climate Change*, *1*(2), 114–118. https://doi.org/10.1038/nclimate1086
Liu, Z., Risi, C., Codron, F., He, X., Poulsen, C. J., Wei, Z., et al. (2021). Acceleration of western Arctic sea ice loss linked to the Pacific North American pattern. *Nature Communications*, *12*(1), 1519. https://doi.org/10.1038/s41467-021-21830-z
Liu, Z., Tang, Y., Jian, Z., Poulsen, C., Welker, J., & Bowen, G. (2017). Pacific North American circulation pattern links external forcing and North American hydroclimatic change over the past millennium. *Proceedings of the National Academy of Sciences*, *114*(13), 3340–3345. https://doi.org/10.1073/pnas.1618201114
Lyu, L., Büntgen, U., Treydte, K., Yu, K., Liang, H., Reinig, F., et al. (2019). Tree rings reveal hydroclimatic fingerprints of the Pacific decadal oscillation on the Tibetan plateau. *Climate Dynamics*, *53*(1), 1023–1037. https://doi.org/10.1007/s00382-019-04629-z
MacDonald, G. (1995). Vegetation of the continental Northwest Territories at 6 ka BP. *Géographie Physique et Quaternaire*, *49*(1), 37–43. https://doi.org/10.7202/033028ar
MacDonald, G., Porinchu, D., Rolland, N., Kremenetsky, K., & Kaufman, D. (2008). Paleolimnological evidence of the response of the central Canadian treeline zone to radiative forcing and hemispheric patterns of temperature change over the past 2000 years. *Journal of Paleolimnology*, *41*(1), 129–141. https://doi.org/10.1007/s10933-008-9250-2

MacDonald, G. M., & Case, R. A. (2005). Variations in the Pacific decadal oscillation over the past millennium. *Geophysical Research Letters*, *32*(8), L08703. https://doi.org/10.1029/2005GL022478
Macias Fauria, M., & Johnson, E. A. (2006). Large-scale climatic patterns control large lightning fire occurrence in Canada and Alaska forest regions. *Journal of Geophysical Research*, *111*(G4008). https://doi.org/10.1029/2006jg000181
Macias Fauria, M., & Johnson, E. A. (2008). Climate and wildfires in the North American boreal forest. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1501), 2317–2329. https://doi.org/10.1098/rstb.2007.2202
Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., Francis, R. C., Mantua, N. J., et al. (1997). A Pacific interdecadal climate oscillation with impacts on Salmon. *Production*, *78*(6), 1069–1079. https://doi.org/10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2
Marlon, J. R., Bartlein, P. J., Gavin, D. G., Long, C. J., Anderson, R., Briles, C. E., et al. (2012). Long-term perspective on wildfires in the western USA. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(9), E535–E543. https://doi.org/10.1073/pnas.1112839109
McLauchlan, K., Higuera, P., Miesel, J., Rogers, B., Schweitzer, J., Shuman, J., et al. (2020). Fire as a fundamental ecological process: Research advances and frontiers. *Journal of Ecology*, *108*(5), 2047–2069. https://doi.org/10.1111/1365-2745.13403
Nash, C. H., & Johnson, E. A. (1996). Synoptic climatology of lightning-caused forest fires in subalpine and boreal forests. *Canadian Journal of Forest Research*, *26*(10), 1859–1874. https://doi.org/10.1139/x26-211
Natural Resources Canada. (2019). Forest fact book 2018–2019. 52
NCEI, [National Centers for Environmental Information]. (2023). *Pacific Decadal Oscillation (PDO)*. National Oceanic and Atmospheric Administration. Retrieved from https://www.ncei.noaa.gov/access/monitoring/pdo/
Needlay, L., Needlay, E., Leverkus, K., & Wolfenden, S. (2012). The Dene interaction with fire: A traditional perspective amongst recovering wood Bison populations. In *The Dene fire project*.
Newman, M., Alexander, M. A., Ault, T. R., Cobb, K. M., Deser, C., Di Lorenzo, E., et al. (2016). The Pacific Decadal Oscillation, revisited. *Journal of Climate*, *29*(12), 4399–4427. https://doi.org/10.1175/JCLI-D-15-0508.1
Niebauer, H. J. (1998). Variability in Bering Sea ice cover as affected by a regime shift in the North Pacific in the period 1947–1996. *Journal of Geophysical Research*, *103*(C12), 27717–27737. https://doi.org/10.1029/98JC02499
Niklasson, M., & Granström, A. (2000). Numbers and sizes of fires: Long-term spatially explicit fire history in a Swedish boreal landscape. *Ecology*, *81*(6), 1484–1499. https://doi.org/10.1890/0012-9658(2000)081[1484:nasofl]2.0.co;2
NTENR, [Northwest Territories Environment and Natural Resources]. (2015). *2014 NWT fire season: Review report* (Vol. 17). Yellowknife. 25
Ortega, P., Lehner, F., Swingedouw, D., Masson-Delmotte, V., Raible, C. C., Casado, M., & Yiou, P. (2015). A model-tested North Atlantic Oscillation reconstruction for the past millennium. *Nature*, *523*(7558), 71–74. https://doi.org/10.1038/nature14518
Price, R. (1967). *Yellowknife*. Peter Martin Associates. 22
Qin, M., Hu, L., Qin, Z., Wan, L., Qin, L., Cao, W., et al. (2023). Pacific decadal oscillation forecasting with spatiotemporal embedding network. *Geophysical Research Letters*, *50*(16), e2023GL103170. https://doi.org/10.1029/2023GL103170
Ramos, R. D., Goodkin, N. F., Siringan, F. P., & Hughen, K. A. (2019). Coral records of temperature and Salinity in the tropical western Pacific reveal influence of the Pacific decadal oscillation since the late Nineteenth century. *Paleoceanography and Paleoclimatology*, *34*(8), 1344–1358. https://doi.org/10.1029/2019PA003684
Reich, P. B., Bakken, P., Carlson, D., Frelich, L. E., Steve, K., Reich, P. B., et al. (2001). Influence of logging, fire, and forest type on biodiversity and productivity in southern boreal forests. *Ecology*, *82*(10), 2731–2748. https://doi.org/10.2307/2679957
Ridington, R. (2012). Subarctic Indigenous peoples in Canada. *The Canadian Encyclopedia*. Retrieved from https://www.thecanadianencyclopedia.ca/en/article/aboriginal-people-subarctic
Rodionov, S. (2006). Use of prewhitening in climate regime shift detection. *Geophysical Research Letters*, *33*(12), L12707. https://doi.org/10.1029/2006gl025904
Rodionov, S., & Overland, J. E. (2005). Application of a sequential regime shift detection method to the Bering Sea ecosystem. *ICES Journal of Marine Science*, *62*(3), 328–332. https://doi.org/10.1016/j.icesjms.2005.01.013
Rodionov, S. N. (2004). A sequential algorithm for testing climate regime shifts. *Geophysical Research Letters*, *31*(9), L09204. https://doi.org/10.1029/2004gl019448
Rolstad, J., Blanck, Y. L., & Storaunet, K. O. (2017). Fire history in a western Fennoscandian boreal forest as influenced by human land use and climate. *Ecological Monographs*, *87*(2), 219–245. https://doi.org/10.1002/ecm.1244
Rowe, J. S. (1972). *Forest regions of Canada*. (P. No. 1300, Ed.) (p. 172). Canadian Forestry Service, Department of Fisheries and the Environment.
Ryzhkova, N., Pinto, G., Kryshen, A., Bergeron, Y., Ols, C., & Drobyshev, I. (2020). Multi-century reconstruction suggests complex interactions of climate and human controls of forest fire activity in a Karelian boreal landscape, North-West Russia. *Forest Ecology and Management*, *459*, 117770. https://doi.org/10.1016/j.foreco.2019.117770
Scholten, R. C., Jandt, R., Miller, E. A., Rogers, B. M., & Veraverbeke, S. (2021). Overwintering fires in boreal forests. *Nature*, *593*(7859), 399–404. https://doi.org/10.1038/s41586-021-03437-y
Shabbar, A., Bonsal, B., & Khandekar, M. (1997a). Canadian precipitation patterns associated with the Southern oscillation. *Journal of Climate*, *10*(12), 3016–3027. https://doi.org/10.1175/1520-0442(1997)010<3016:cppawt>2.0.co;2
Shabbar, A., Higuchi, K., Skinner, W., & Knox, J. L. (1997b). The association between the BWA index and winter surface temperature variability over eastern Canada and west Greenland. *International Journal of Climatology*, *17*(11), 1195–1210. https://doi.org/10.1002/(sici)1097-0088(199709)17:11<1195::aid-joc190>3.0.co;2-u
Sharma, A., Jain, P., Abatzoglou, J., & Flannigan, M. (2022). Persistent positive anomalies in geopotential heights promote wildfires in western North America. *Journal of Climate*, *35*(19), 6469–6486. https://doi.org/10.1175/JCLI-D-21-0926.1
Shen, C., Wang, W.-C., Gong, W., & Hao, Z. (2006). A Pacific decadal oscillation record since 1470 AD reconstructed from proxy data of summer rainfall over eastern China. *Geophysical Research Letters*, *33*(3), L03702. https://doi.org/10.1029/2005GL024804
Siqueira, L., Ramírez, E., & Camayo, R. (2019). *An overview of the El Niño, La Niña, and the southern oscillation Phenomena: Theory, observations, and modeling links BT—towards mathematics, computers and environment: A disasters perspective*. In L. Bacelar Lima Santos, R. Galante Negri, & T. J. de Carvalho (Eds.) (pp. 1–18). Springer International Publishing. https://doi.org/10.1007/978-3-030-21205-6_1
Skinner, W. R., Flannigan, M. D., Stocks, B. J., Martell, D. L., Wotton, B. M., Todd, J. B., et al. (2002). A 500 hPa synoptic wildland fire climatology for large Canadian forest fires, 1959–1996. *Theoretical and Applied Climatology*, *71*(3–4), 157–169. https://doi.org/10.1007/s007040200002
Statistics Canada, S. (2022). Population by province and territory (Northwest Territories). Retrieved from https://www.statsnwt.ca/population/population-estimates/

Steinman, B. A., Abbott, M. B., Mann, M. E., Stansell, N. D., & Finney, B. P. (2012). 1500 year quantitative reconstruction of winter precipitation in the Pacific Northwest. *Proceedings of the National Academy of Sciences*, *109*(29), 11619–11623. https://doi.org/10.1073/pnas.1201083109

Stocks, B. J., Mason, J. A., Todd, J. B., Bosch, E. M., Wotton, B. M., Amiro, B. D., et al. (2003). Large forest fires in Canada, 1959–1997. *Journal of Geophysical Research*, *107*(D1), 8149. https://doi.org/10.1029/2001jd000484

Stokes, M. A., & Smiley, T. L. (1968). *An introduction to tree-ring dating*. University of Chicago Press.

Sulphur, K. C., Goldsmith, S. A., Galloway, J. M., Macumber, A., Griffith, F., Swindles, G. T., et al. (2016). Holocene fire regimes and treeline migration rates in sub-arctic Canada. *Global and Planetary Change*, *145*, 42–56. https://doi.org/10.1016/j.gloplacha.2016.08.003

Swetnam, T. W. (1993). Fire history and climate-change in Giant Sequoia groves. *Science*, *262*(5135), 885–889. https://doi.org/10.1126/science.262.5135.885

Taschetto, A. S., Ummenhofer, C. C., Stuecker, M. F., Dommenget, D., Ashok, K., Rodrigues, R. R., & Yeh, S.-W. (2020). ENSO atmospheric teleconnections. In *El Niño southern oscillation in a changing climate* (pp. 309–335). https://doi.org/10.1002/9781119548164.ch14

Taylor, K., Mcginley, S., Potito, A., Molloy, K., & Beilman, D. (2018). A mid to late Holocene chironomid-inferred temperature record from northwest Ireland. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *505*, 274–286. https://doi.org/10.1016/j.palaeo.2018.06.006

Tillman, P., Holzkämper, S., Kuhry, P., Sannel, A., Loader, N., & Robertson, I. (2010). Long-term climate variability in continental subarctic Canada: A 6200-year record derived from stable isotopes in peat. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *298*(3–4), 235–246. https://doi.org/10.1016/j.palaeo.2010.09.029

Trenberth, K. (1992). *Climate system modelling*. Cambridge University Press. 788. https://doi.org/10.1002/joc.3370140208

Trouet, V., Taylor, A., Carleton, A., & Skinner, C. (2009). Interannual variations in fire weather, fire extent, and synoptic-scale circulation patterns in northern California and Oregon. *Theoretical and Applied Climatology*, *95*(3–4), 349–360. https://doi.org/10.1007/s00704-008-0012-x

Trouet, V., & Taylor, A. H. (2010). Multi-century variability in the Pacific North American circulation pattern reconstructed from tree rings. *Climate Dynamics*, *35*(6), 953–963. https://doi.org/10.1007/s00382-009-0605-9

Trouet, V., & van Oldenborgh, G. J. (2013). KNMI climate explorer: A web-based research tool for high-resolution Paleoclimatology. *Tree-Ring Research*, *69*(1), 3–13. https://doi.org/10.3959/1536-1098-69.1.3

Turner, N. J. (1999). Time to burn: Traditional use of fire to enhance resource production by aboriginal peoples in British Columbia. In R. Boyd (Ed.), *Indians, fire and the land in the Pacific Northwest* (pp. 185–218). Oregon State University Press.

Tymstra, C., Stocks, B. J., Cai, X., & Flannigan, M. D. (2020). Wildfire management in Canada: Review, challenges and opportunities. *Progress in Disaster Science*, *5*, 100045. https://doi.org/10.1016/j.pdisas.2019.100045

van der Schrier, G., & Barkmeijer, J. (2007). North American 1818–1824 drought and 1825–1840 pluvial and their possible relation to the atmospheric circulation. *Journal of Geophysical Research*, *112*(D13), D13102. https://doi.org/10.1029/2007jd008429

Van Wagner, C. E. (1978). Age class distribution and the forest fire cycle. *Canadian Journal of Forest Research*, *8*(2), 220–227. https://doi.org/10.1139/x78-034

Wallace, J. M., & Gutzler, D. S. (1981). Teleconnections in the geopotential height field during the northern Hemisphere winter. *Monthly Weather Review*, *109*(4), 784–812. https://doi.org/10.1175/1520-0493(1981)109<0784:TITGHF>2.0.CO;2

Wallenius, T., Pennanen, J., & Burton, P. (2011). Long-term decreasing trend in forest fires in northwestern Canada. *Ecosphere*, *2*(5), 53. https://doi.org/10.1890/ES11-00055.1

Wallenius, T. H., Lilja, S., & Kuuluvainen, T. (2007). Fire history and tree species composition in managed Picea abies stands in southern Finland: Implications for restoration. *Forest Ecology and Management*, *250*(1–2), 89–95. https://doi.org/10.1016/j.foreco.2007.03.016

Watt, E. (2013). Yellowknife. *The Canadian Encyclopedia*. Retrieved from www.thecanadianencyclopedia.ca/en/article/yellowknife-nwt

Weir, J. M. H., Johnson, E. A., & Miyanishi, K. (2000). Fire frequency and the spatial age mosaic of the mixed-wood boreal forest in western Canada. *Ecological Applications*, *10*(4), 1162–1177. https://doi.org/10.1890/1051-0761(2000)010[1162:FFATSA]2.0.CO;2

Wells, N., Goddard, S., & Hayes, M. J. (2004). A self-calibrating Palmer drought severity index. *Journal of Climate*, *17*(12), 2335–2351. https://doi.org/10.1175/1520-0442(2004)017<2335:aspdsi>2.0.co;2

Whitman, E., Parisien, M.-A., Thompson, D. K., Hall, R. J., Skakun, R. S., & Flannigan, M. D. (2018). Variability and drivers of burn severity in the northwestern Canadian boreal forest. *Ecosphere*, *9*(2), e02128. https://doi.org/10.1002/ecs2.2128

Wiegand, K. N., Brune, S., & Baehr, J. (2019). Predictability of multiyear trends of the Pacific decadal oscillation in an MPI-ESM hindcast ensemble. *Geophysical Research Letters*, *46*(1), 318–325. https://doi.org/10.1029/2018GL080661

Yasunari, T. J., Nakamura, H., Kim, K.-M., Choi, N., Lee, M.-I., Tachibana, Y., & da Silva, A. M. (2021). Relationship between circum-Arctic atmospheric wave patterns and large-scale wildfires in boreal summer. *Environmental Research Letters*, *16*(6), 064009. https://doi.org/10.1088/1748-9326/abf7ef

Zaslow, M. (1971). *The opening of the Canadian North, 1870-1914*. McClelland & Stewart. Retrieved from https://books.google.se/books?id=FTUlAAAAMAAJ

Zhang, Q., & Chen, W. (2007). Fire cycle of Canada's boreal region and its potential response to global change. *Journal of Forestry Research*, *18*(1), 55–61. https://doi.org/10.1007/s11676-007-0010-3