Université du Québec en Abitibi-Témiscamingue

HISTOIRE DES FEUX DANS LES FORÊTS CIRCUMBORÉALES : INTERACTION ENTRE L'ACTIVITÉ HUMAINE ET LA VARIABILITÉ CLIMATIQUE DANS LA FORMATION DES RÉGIMES DE FEU BORÉAUX

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FIRE HISTORY IN CIRCUMBOREAL FORESTS:
INTERPLAY OF HUMAN ACTIVITY AND CLIMATE VARIABILITY IN
SHAPING BOREAL FIRE REGIMES

Dissertation

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Avec un peu de volonté pi ben du crachat, un cheval peut mettre un chat

Québécois Old French Expression

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PREFACE

This thesis consists of five chapters. The first and last chapters are *the General Introduction* and *Conclusion*, respectively. The other three chapters are self-contained. They are, however, complementary to each other and together provide more complete information on the subject. The published chapters (II, III and IV) have been reformatted for consistency, but the text has not been changed. Chapters Two to Four are based on the following three manuscripts:

CHAPTER II: N. Ryzhkova, G. Pinto, A. Kryshen', Y. Bergeron, C. Ols, I. Drobyshev (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: 10.1016/j.foreco.2019.117770

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LIST OF ABBREVIATIONS

AL	Aleutian Low
CNFDB	Canadian National Fire Database
D	Dormant
EEW	Early earlywood
ELW	Early latewood
ENSO	El Niño Southern Oscillation
FC	Fire cycle
FERLD	Forêt d'enseignement et de recherche du lac Duparquet
HB	High Boreal
LIA	Little Ice Age
LEC	Lightning efficiency coefficients
LEW	Late earlywood
LFYs	Large fire years
LLW	Late latewood
MDC	Monthly Drought Code
MEW	Middle earlywood
MLW	Middle latewood
MWP	Medieval Warm Period
NAO	North Atlantic Oscillation
NWT	Northwest Territories
PDO	Pacific Decadal Oscillation
PNA	Pacific North American pattern
scPDSI	Self-calibrated Palmer's Drought Severity Index
SEA	Superposed epoch analysis
SST	Sea surface temperature

LIST OF SYMBOLS AND UNITS OF MEASUREMENT

Area	ha	hectare (= 10 000 m^2)
	km^2	square kilometer (= 100 ha)
Time	yrs	years
Temperature	°C	degrees Celsius

RÉSUMÉ

Les incendies de forêt constituent l'un des principaux agents de perturbation naturelle dans les forêts circumboréales. Tout au long de l'Holocène, le climat a représenté le moteur principal de l'activité des feux. Toutefois, au cours des derniers siècles, l'influence humaine a progressivement modifié les régimes d'incendie dans les régions boréales. Les méthodes dendroécologiques sont largement employées pour étudier les relations entre le feu, le climat et l'utilisation humaine des terres à différentes échelles spatiales et temporelles. Malgré de nombreuses reconstitutions détaillées, les dynamiques de feu à long terme demeurent mal comprises dans plusieurs zones de la ceinture circumboréale. Cette thèse examine la contribution de la variabilité climatique et des activités humaines aux régimes de feu historiques dans les forêts boréales de l'hémisphère Nord.

L'étude porte sur trois régions : la route 3 dans les Territoires du Nord-Ouest (TNO) au Canada, la réserve de biosphère de Pechora-Ilych (RBN Pechora-Ilych) et le parc national de Kalevalsky (PN Kalevalsky) en Russie. À partir de bois porteur de cicatrices de feu provenant de pin gris (*Pinus banksiana* Lamb.) et de pin sylvestre (*Pinus sylvestris* L.), les changements dans l'activité des feux ont été évalués dans le temps, tout comme les rôles relatifs du climat et de l'usage des terres par l'humain. L'ensemble de données comprend plus de 500 échantillons de pin sylvestre issus de sites xériques et mésiques, ainsi que plus de 1 000 échantillons de pin gris prélevés sur des affleurements rocheux. Au total, 475 années uniques de feu ont été identifiées à partir de 870 arbres porteurs de cicatrices, répartis sur 126 sites.

Si le climat demeure la force dominante dans la structuration des régimes d'incendie, les activités humaines ont significativement modifié les cycles de feu dans certaines régions au cours des deux derniers siècles. Dans les forêts boréales de l'Est européen, la suppression des incendies a vraisemblablement entraîné une diminution de la fréquence des feux et un allongement des intervalles entre ceux-ci. En revanche, dans le nord-ouest canadien, caractérisé par des paysages vastes et peu accessibles, l'intervention humaine est restée limitée, et le climat continue de régir l'activité des feux. Dans ces systèmes boréaux, la survenue des incendies est influencée à la fois par des configurations climatiques à grande échelle, telles que l'Oscillation Décennale du Pacifique (ODP), et par des systèmes régionaux de circulation atmosphérique, comme les blocages scandinaves, qui favorisent les sécheresses printanières au Canada et les épisodes climatiques extrêmes durant l'été en Europe orientale.

Mots-clés : variation climatique, perturbations naturelles, forêts circumboréales, régime de feu, forêts dominées par le pin, impact humain, régimes de circulation atmosphérique

ABSTRACT

Forest fires are a key natural disturbance in circumboreal forests. Throughout the Holocene, climate has been the primary driver of fire activity. However, in recent centuries, human influence has increasingly altered fire regimes in boreal regions. Dendroecological methods are widely used to study the relationships among fire, climate, and human land use at various spatial and temporal scales. Despite numerous detailed reconstructions, long-term fire dynamics remain poorly understood in several parts of the circumboreal zone. This thesis examines how climate variability and human activity contribute to historical fire patterns in boreal forests of the Northern Hemisphere.

The study focuses on three regions: Highway 3 in the Northwest Territories (NWT) in Canada, the Pechora-Ilych Biosphere Reserve (Pechora-Ilych NBR), and Kalevalsky National Park (Kalevalsky NP) in Russia. Using fire-scarred wood from jack pine (*Pinus banksiana* Lamb.) and Scots pine (*Pinus sylvestris* L.), we assessed changes in fire activity over time and evaluated the relative roles of climate and human land use. The dataset includes over 500 Scots pine samples from xeric and mesic sites and over 1,000 jack pine samples from rocky outcrops. In total, 475 unique fire years were identified from 870 fire-scarred trees sampled at 126 sites.

While climate remains the dominant force shaping fire regimes, human activity has notably altered fire cycles in certain regions over the past 200 years. In the eastern European boreal forest, fire suppression has likely reduced fire frequency and extended fire intervals. In contrast, northwestern Canada, characterized by vast and remote landscapes, has seen limited human intervention, and climate continues to be the main driver of fire activity. Fire occurrence in these boreal systems is influenced by both large-scale climatic patterns, such as the Pacific Decadal Oscillation (PDO), and regional circulation systems like Scandinavian blocking, which contribute to spring droughts in Canada and extreme summer weather in eastern Europe.

Keywords: Climate variation, Natural disturbances, Circumboreal forests, Fire regime, Pine-dominated forests, Human impact, Atmospheric circulation patterns

I. GENERAL INTRODUCTION

1.1 Background

1.1.1 Circumboreal forests

The circumboreal forest is the second largest terrestrial biome covering about 30% of the world's forested land area and plays an important role in the sequestration of carbon as well as due to the presence of extensive peatlands and carbon storing plants (Gorham, 1991; Pan et al., 2013; Sheng et al., 2004). Boreal forests provide diverse ecosystem services, support rural and urban economies, and contain biodiversity that is important for ecosystem functioning and well-adapted to the cold winters and short summers of high latitudes (Bergeron et al., 2004; Payette, 1992; Tarnocai et al., 2011).

Vegetation composition within the circumboreal zone markedly differs between North America and northern Europe. In large areas of boreal North America, the dominant tree species are adapted to survive in fire-prone environments, a phenomenon known as "fire embracers" (Rogers et al., 2015). This implies that the life cycles of the forests have evolved to enable them to sustain nearly complete burns (crown fires) and rapidly re-colonize an area after a fire. North American forests are characterized by the dominance of jack pine, black spruce (*Picea mariana* (Mill.) B.S.P.) and white spruce (*Picea glauca* (Moench) Voss.), which have evolved to have lower branches, thinner bark and cones that open after fire (Gauthier et al., 1996; Kneeshaw et al., 2011), and red pine (*Pinus resinosa* Ait.) being the only common species with thick bark and self-pruning ability (Bergeron and Brisson, 1990). In contrast, the boreal forests of northern Europe are dominated by fire-resistant species with thicker bark, wetter needles, and fewer low-hanging branches. These species are adapted to the low-intensity, mixed-severity fires that characterize fire regimes in northern Europe, where surface fires are common (Kuuluvainen and Aakala, 2011; Niklasson and Granström, 2000). In particular, Scots pine has adapted to fires by having a thick bark and self-pruning, i.e.

a tendency to shred branches with age, that helps trees survive recurrent low or moderate severity fires (Kuuluvainen, 2002; Zackrisson, 1977).

Fire is the dominant disturbance shaping the boreal forest structure and directly impacts the global carbon budget and levels of trace gases such as CO_2 in the atmosphere (Beck et al., 2011; Bond-Lamberty and Gower, 2007; Pyne, 1997). The severity, frequency, and size of these fires vary considerably between regions of circumboreal forests. In Northwestern Canada, boreal fire regimes are typically characterized by high-intensity, stand-replacing fires that recur every 30–200 years (Boulanger et al., 2012; Erni et al., 2017; Hart et al., 2019), primarily due to climate conditions, such as summer droughts (de Groot et al., 2013; Girardin and Wotton, 2009) and lightning strikes (Flannigan and Wotton, 1991; Kochtubajda et al., 2019; Stocks and Lynham, 1996). In contrast, boreal forests in northern Europe tend to have less frequent and smaller fires, largely due to a more humid climate, fewer lightning strikes, and a long history of fire suppression policies (Niklasson and Granström, 2000). Since the late 19th century, Northern Europe has exhibited a distinct west–east gradient in fire activity. In the west, fire suppression efforts have established an extended modern FC of 10–20k years (Drobyshev et al., 2021; Drobyshev et al., 2012). Conversely, northeastern Europe maintains a shorter FC of approximately 300–600 years (Drobyshev and Niklasson, 2004; Ryzhkova et al., 2022, 2020), reflecting fire frequencies observed before the onset of intensive forest management across Fennoscandia (Niklasson and Granström, 2000).

Despite these regional disparities, the fire regimes of North American and North European boreal forests have been impacted by climate change in ways that have resulted in long-term consequences for forest structure, carbon storage, and ecosystem stability (Cunningham et al., 2024; Hanes et al., 2019; Lehtonen et al., 2016). Understanding the spatio-temporal dynamics of fire regimes and the factors that influence them is essential for the sustainable management of boreal forests in the context of climate change (Flannigan et al., 2009; Whitman, 2019).

1.1.2 Weather and climate effects on the fire regime

In circumboreal forests, local weather conditions strongly influence fire behavior by affecting variables such as fuel moisture, wind speed, and relative humidity. Wind, in particular, can intensify a smoldering fire by increasing its rate of spread, generating turbulence, and raising the likelihood that the fire will jump over natural or artificial firebreaks (Bradstock, 2010; MSB, 2015; Stocks and Lynham, 1996). Warm temperatures and lower relative humidity make fuels easier to ignite and promote sustained fire activity (Flannigan and Wotton, 1991; Holsinger et al., 2016). In northwestern Canada, lightning strikes without rain (or dry lightning) are the primary natural ignition source for wildfires (Kochtubajda et al., 2019, 2006; Veraverbeke et al., 2017). Warm surface fires can form pyrocumulonimbus clouds, which create additional lightning and further spread fires (Fromm et al., 2010; Scott et al., 2014). These dynamics intensify during extended warm and dry spells, which increase both lightning frequency and fuel drying, impacting fire regimes in northwestern Canada and northern Europe (Dissing and Verbyla, 2003; Pisaric et al., 2009).

Climate has been the dominant factor controlling fire in circumboreal forests throughout the Holocene (Carcaillet et al., 2007; Drobyshev et al., 2016; Gaboriau et al., 2020). Key climatic conditions that promote fire include persistent positive geopotential height anomalies (ridges) in the mid-troposphere (500 hPa), which disrupt zonal air flow and lead to warmer, drier conditions that promote fuel drying (Macias-Fauria and Johnson, 2008). Increased air subsidence along the edges of these ridges increases fire risk beyond the high-pressure centers (Macias-Fauria and Johnson, 2006). In northern Europe, the formation of these high-pressure systems is largely controlled by the North Atlantic Oscillation (NAO), a major driver of tropospheric circulation and regional climate patterns (Deser et al., 2017), with notable effects on fire activity (Drobyshev et al., 2016). The NAO reflects variations in sea-level pressure (SLP) between the Icelandic Low and the Azores High, which influence storm tracks and the jet stream over the Europe-North Atlantic sector (Hurrell, 1996; Hurrell and Deser, 2009). The shifting configuration of the Icelandic Low and Azores High on seasonal to multi-decadal scales results in a high-pressure cell over Scandinavia, leading to dry and warm conditions (Folland et al., 2009) that promote fire hazard (Högbom and Wiksell, 1934). Indeed, fire activity in Sweden and across the European boreal zone has been linked to the summer NAO (Drobyshev et al., 2021, 2015).

In western North America, long-term trends in fire regimes are influenced by large-scale climate patterns such as the El Niño-Southern Oscillation (ENSO), the Pacific North American Pattern (PNA), and the Pacific Decadal Oscillation (PDO) (Bonsal and Shabbar, 2011; Heyerdahl, et al., 2008; Yasunari et al., 2021). The PNA pattern directly affects tropospheric anomalies in North America, the Polar Front Jet Stream, and regional climate. The PNA appears as a distinct Rossby wave train including four centers of activity, stretching from the North Pacific to the North American continent (Wallace and Gutzler, 1981). The Aleutian Low (AL), a low-pressure system (cyclone), serves as the principal activity center of the PNA. High-pressure anticyclones are located south of Hawaii, near the AL. The PNA appears as a mid-tropospheric ridge-trough configuration across North America in the downstream area. This system is characterized by an elevated geopotential height anomaly in western Canada and a diminished height anomaly in the southeastern United States (U.S.) (Wallace and Gutzler, 1981). This structure is significantly associated with positive temperature anomalies in western Canada and negative anomalies in the southern U.S. (Wallace and Gutzler, 1981), therefore connecting these dynamics to regional forest fuel moisture (Macias-Fauria and Johnson, 2008). The ridge-trough configuration significantly affects the location of the jet stream and the corresponding storm trajectories throughout North America. The PNA induces a meridional jet stream movement, decreasing Pacific-origin winter storm trajectories and dry anomalies, especially over the North American west coast (Rodysill et al., 2018).

ENSO is another significant regional climatic variable that shapes drought conditions over the continent and initiates the PNA pattern in North America. Warm SST anomalies in the Tropical Pacific occur during ENSO El Niño phases and cool during La Niña occurrences. El Niño events are commonly related to the deepening of the AL and the PNA pattern (Taschetto et al., 2020). Previous studies have shown that El Niño events may be conducive to forest fires in western North America, as they are often associated with warmer-than-average temperatures and below-average precipitation (Hess et al., 2001). Positive phases of the East Pacific teleconnection have been associated with surface high-pressure systems that block westerly flow, resulting in warmer temperatures, lower precipitation, and above-average area burned (Duffy et al., 2005). It has also been suggested that PDO correlates with the annual area burned along the west coast of North America (Duffy et al., 2005; Ryzhkova et al., 2025). Positive PDO phases generally result in warmer and drier winters, increasing the potential for fire by fuel drying and extending the fire season. During El Niño events, western North America experiences warm and dry conditions, with the reduced winter snowpack leading to earlier spring snowmelt and reduced soil and fuel moisture (Burton et al., 2020; Trenberth, 1997). These conditions are correlated with increased fire activity, as warmer temperatures and lower humidity promote both fuel drying and the likelihood of ignition sources leading to fire spread (Drury and Grissom, 2008; Duffy et al., 2005; Hess et al., 2001; Kitzberger et al., 2007). The interactions between ENSO and PDO further influence the fire risk (Mori, 2011), especially when both oscillations align during their warm phases. This alignment amplifies climate anomalies that can significantly increase fire activity in western North America by promoting extended droughts and fuel drying (Hessl et al., 2004; Hu and Huang, 2009). This effect is evident in the boreal forest landscapes of the NWT, where fire records indicate an increased frequency of large fire years (LFYs) during periods of prolonged drought associated with positive PDO phases (Pisaric et al., 2009; Ryzhkova et al., 2025). Other studies conducted across broader western North America support these patterns, even if not specific to the NWT (Schoennagel et al., 2005; Trenberth, 1992).

1.1.3 Human drivers of fire regimes

Human activities have also affected fire regimes in circumboreal forests (Niklasson et al., 2010; Pyne, 1997; Rolstad et al., 2017). These impacts typically involve using fire for agricultural purposes, such as slash-and-burn agriculture and, more recently, fire suppression policies. Modern human impacts are likely to reduce natural fire activity, although increasing human densities are associated with higher ignition rates (Pinto, et al., 2020). For example, forest fire activity in northern Europe has decreased since the late 19th century (Tryterud, 2003). In Scandinavia, two major shifts in fire regimes coincided with major socio-economic transitions. The first shift occurred around 1600 with the expansion of permanent settlements and the associated increase in anthropogenic fires. This shift was characterized by a decrease in fire size, increased fire frequency, and increased early-season fires (Niklasson and Drakenberg, 2001; Niklasson and Granström, 2000; Rolstad et al., 2017). The second shift, characterized by a drastic decrease in fire activity, is generally attributed to improvements in agricultural techniques and the increasing importance of the forest as a source of timber. This shift is conventionally dated to the early 1700s to early 1800s in southern Sweden (Niklasson and Drakenberg, 2001; Pinto et al., 2020) and the mid to late 1800s in the northern Sweden (Granström and Niklasson, 2008; Niklasson and Granström, 2000). The abandonment of agricultural and pastoral burning practices, followed by the introduction of fire suppression policies, contributed to a significant decline in fire activity across the European boreal region (Rolstad et al., 2017; Ryzhkova et al., 2022). In the eastern European boreal forests, the onset of detectable human influence on fire activity has occurred up to several centuries later (Drobyshev et al., 2004b; Ryzhkova et al., 2022, 2020) and generally – was mitigated by larger areas of forests and lower population densities, as compared to Scandinavian forests.

Studies of historical fire regimes in North America have shown that Native American land use practices played an important role in shaping the frequency of surface fires. Widespread Native American use of fire and comparisons with modern lightning-caused fires, which alone cannot explain the historically high fire frequency, are well documented (Johnson and Kipfmueller, 2016; Kay, 2000; Loope and Anderton, 1998). However, even with a dense pre-European population in some regions of North America, some forested regions experienced limited anthropogenic impacts (Oswald et al., 2020). In western Canada, Indigenous peoples have historically influenced local forest ecosystems by using fire (Johnson, and Miyanishi, 2012; Turner, 1999). They employed low- to moderate-intensity burns to remove underbrush, facilitate hunting, and encourage the growth of berry-producing shrubs. In some shield regions, these fires were often geographically limited, burning just a few hectares at a time (Turner, 1999). However, other areas, particularly the boreal plains experienced large-scale anthropogenic burning that maintained open landscapes, such as meadows (Lewis, 1982; Turner, 1999). These diverse practices reflect regional differences in land use, mobility, and ecological objectives. Overall, despite this human influence, climate remains a dominant factor shaping historical fire regimes at the regional scale (Bergeron, 1991; Drobyshev et al., 2012; Oswald et al., 2020). However, the increase of European colonization in the 18th and 19th centuries led to the extensive use of fire. In regions such as Alberta and British Columbia, fire has been deliberately employed as an effective method to clear extensive tracts of boreal forest for logging, mining, and agriculture, resulting in elevated rates of change in these places (Pisaric et al., 2009; Waito et al., 2018). In the 20th century, industrial expansion led to changes in fire regimes as infrastructure development, including roads, railways and mining, facilitated access to previously isolated areas, resulting in fuel-rich corridors and increased fire susceptibility (Waito et al., 2018; Wallenius, et al., 2011).

1.2. Thesis aim and objectives

Global climate change will likely lead to increased temperatures and droughts, as well as an increased risk of wildfires in circumboreal forests (Boulanger et al., 2014; Mäkelä et al., 2014; Wang et al., 2015). This may contribute to the accelerated transition of boreal forests to more open forests, or even to grassland (Stralberg et al., 2018). The effects of climate change have been observed in the fire regime and boreal forests of North America and Scandinavia. The fire season of 2014 in the Northwest Territories (NWT) and the 2014 and 2018 fire seasons in Sweden were marked by exceptional levels of wildfire activity. Of all the years studied in the NWT, 2014 stands out. That year, 3.4 million hectares burned, which is nearly six times the annual average between 2009 and 2019 (NTENR, 2015). In Sweden, the size of the Sala fire (2014 fire season) was almost 10 times larger than the largest fire recorded in the preceding few decades (Bodens kommun, 2006). This dissertation aimed to explain how climate and human activities have influenced fire regimes in circumboreal forests during historical periods.

The following specific objectives of this thesis were:

(1) to provide century-scale and spatially explicit reconstructions of fire activity with seasonal patterns in circumboreal forests, and (2) to evaluate the climatic and human forcing on fire regimes over this period.

III. MULTI-CENTURY RECONSTRUCTION SUGGESTS COMPLEX INTERACTIONS OF CLIMATE AND HUMAN CONTROLS OF FOREST FIRE ACTIVITY IN A KARELIAN BOREAL LANDSCAPE, NORTH-WEST RUSSIA

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2.1 Résumé

Les reconstructions spatiales explicites de l'activité des feux dans les forêts boréales européennes sont rares, ce qui limite notre compréhension des facteurs influençant la dynamique de la végétation dans cette partie du domaine boréal. Nous avons développé une reconstruction dendrochronologique spatiale explicite d'un régime de feu sur une zone de 25 × 50 km² au sein du biome boréal situé dans le parc national de Kalevalsky (PN de Kalevalsky), couvrant la période 1400–2010 après J.-C. Nous avons daté 184 années de feux à partir de 212 pins sylvestres (*Pinus sylvestris* L.) vivants et morts portant des cicatrices de feu, collectés sur 38 sites.

La période étudiée a révélé une variabilité prononcée des cycles des feux forestiers (CF) sur plusieurs siècles. La période ancienne (1400–1620) se caractérise par une faible activité des feux (CF = 178 ans), qui augmente durant la période 1630–1920 (CF = 46 ans), puis diminue entre 1930 et 2000 (CF = 283 ans). Les résultats dendrochronologiques n'ont pas fourni de réponse concluante quant aux origines des dynamiques de CF, bien que plusieurs indices suggèrent que le climat a provoqué l'augmentation de l'activité des feux au début des années 1600, tandis que des facteurs liés aux activités humaines expliquent en grande partie sa diminution au début des années 1900. Le CF actuel dans le PN de Kalevalsky est proche des estimations pour la période précoloniale en Scandinavie, ce qui suggère que les forêts de cette zone maintiennent actuellement un régime de feu proche de leur état naturel. Le feu a été le facteur central de la dynamique forestière dans ce biome, et la gestion forestière devrait en tenir compte dans l'élaboration de stratégies de conservation en Carélie et dans d'autres zones de forêts boréales européennes. L'introduction de brûlages dirigés de diverses intensités pourrait constituer un élément important de ces stratégies.

Mots-clés : variation climatique, perturbations naturelles, paysage boréal, forêts mixtes, régime de feu, forêts dominées par les pins, Russie du Nord-Ouest, risques naturels.

2.2 Abstract

Spatially explicit reconstructions of fire activity in European boreal forest are rare, which limits our understanding of factors driving vegetation dynamics in this part of the boreal domain. We have developed a spatially explicit dendrochronological reconstruction of a fire regime in a 25 × 50 km^2 area within boreal biome located within the Kalevalsky National Park (Kalevalsky NP), over the 1400–2010 AD period. We dated 184 fire years using 212 fire-scarred living and dead Scots pine (*Pinus sylvestris* L.) trees collected on 38 sites.

The studied period revealed a pronounced century-long variability in forest fire cycles (FC). The early period (1400–1620 AD) had low fire activity (FC = 178 yrs.), which increased during the 1630–1920 period (FC = 46 yrs.) and then decreased over the 1930–2000 period (FC = 283 yrs.). Dendrochronological results did not provide a conclusive answer on the origins of FC dynamics, although several lines of evidence suggest that climate drove the increase in fire activity in the early 1600s, while human-related factors were largely responsible for their decline in the early 1900s. The current FC in the Kalevalsky NP is close to the estimates reported for the pre-industrial colonisation period in Scandinavia, which suggests that the forests of the area currently maintain their close-to-natural fire regime. Fire has been the pivotal factor of forest dynamics in this biome and forest management should acknowledge that fact in developing conservation strategies in Karelia and other areas of European boreal forest. Introduction of prescribed burns of varying severity could be an important element of such strategies.

Key-words: climate variation, natural disturbances, boreal landscape, mixedwoods, fire regime, pine-dominated forests, North-west Russia, natural hazards

2.3 Introduction

Forest fires are the main drivers of forest ecosystem dynamics in the boreal biome. Fires are important to maintain the diversity and successional pathways of boreal forests (Bergeron, 2004; Melekhov, 1946; Payette, 1992; Zackrisson, 1977). Climate is the major factor controlling regional fire activity (Clark, 1990; Flannigan and Wotton, 2001; Johnson, 1992; Stocks and Lynham, 1996), influencing fuel, moisture conditions and ignition patterns. Topography and the related variation in soil moisture and vegetation affect the fire regime at finer scales (Girardin et al., 2013; Hellberg et al., 2004; Kuosmanen et al., 2014; Pitkanen et al., 2003). Humans has been an important agent of change in boreal fire activity (Rolstad et al., 2017; Wallenius, 2011). They affected fire regimes through slash-and-burn agriculture and associated forest clearcutting (Lehtonen and Huttunen, 1997; Niklasson and Granström, 2000; Wallenius et al., 2004), changes in fuel abundance and composition through livestock grazing (Grissino-Mayer et al., 2004; Savage and Swetnam, 1990) and more recently - through fire suppression policies (Drobyshev, et al., 2012; Drobyshev et al., 2004b; Niklasson and Granström, 2000; Tryterud, 2003).

Fire history studies in northern Europe have reported a decline in forest fire activity since the late 1800s, driven by cessation of land use practices involving fire and the increasing economic value of timber (Niklasson et al., 2010; Rolstad et al., 2017; Tryterud, 2003; Wallenius, 2011). For example, in Sweden, the forest fire cycle is currently (since late 1800s) around 10^4 years (Drobyshev, et al., 2012). By contrast, the fire cycle during the pre-industrial era (1300–1650 AD) was around 150–300 years (Niklasson and Granström, 2000), which corresponds to the modern fire cycle in the boreal forest of North-West Russia (Drobyshev and Niklasson, 2004; Gromtsev, 2002).

Despite a number of detailed dendrochronological (Aakala et al., 2018; Drobyshev et al., 2004a, 2004b; Lehtonen and Kolström, 2000; Wallenius et al., 2004) and paleochronological (Kuosmanen et al., 2016, 2014; Pitkanen and Gronlund, 2001) reconstructions, the long-term fire dynamics in the boreal section of Northern Europe remains poorly understood. A rich land use history of the region and climate variability, in part - synchronized with the changes in forest use, partitioning the effects of both factors on past fire activity challenging. Geographic variability in the strength of climate and human impacts on boreal fire regimes presents another challenge in partitioning to the effects of these two factors. For example, fire activity in the northern boreal forest has been predominantly related to summer drought conditions, whereas in the southern boreal forest, spring drought conditions are more important (Drobyshev, et al., 2012; Johnson et al., 1998). Partially as a result of this pattern, the studies have found large differences in sensitivity of fire regimes to climate variability between northern and southern boreal forests (Ali et al., 2012; Drobyshev et al., 2014).

Although the temporal resolution of dendrochronological records generally allows for analyses of many important properties of fire regime, such as fire seasonality, fire cycle and fire return interval, this proxy does not provide information on the origin of fire dynamics, which calls for analyses involving multiple proxies of past variability in climate and land use patterns.

We analyzed the fire history of a northern boreal landscape that is partially included in the Kalevalsky National Park, Republic of Karelia, North-West Russia. The area lies within the northern boreal vegetation zone on the Baltic Shield (Fennoscandia) at the southern spurs of the mountain range Maanselka. The forests of the Kalevalsky NP have been subject to selective cutting (Lehtonen and Kolström, 2000; Raevsky, 2017), though no industrial logging occurred in the area. As a result, large areas of old growth and deadwood-rich forests within and around the national park allow for long-term dendrochronological reconstructions of fire dynamics.

We used fire-scarred living and dead Scots pines to reconstruct the fire history and evaluate climatic and human forcing on fire regime dynamics over a period of 610 years (1400–2010). Our objectives were to (1) develop a spatially explicit fire history reconstruction in North-West Russia, (2) provide long-term and quantitative estimates of fire cycle and seasonal patterns of forest fires over the study period, and (3) evaluate the climatic and human forcing on fire regimes over this period.

2.4 Material and methods

2.4.1 The study area

The Kalevalsky NP (744 km^2) is located in the Russian Republic of Karelia (64°59′30″ N 30°12′45″ E, Fig. 2.1). It is considered to be the largest and the most western track of primeval northern boreal forests of European Russia (Gromtsev et al., 2003; Raevsky, 2017). The climate of the area is moderately continental with oceanic features (Alisov, 1936). The mean July temperature is 14.5°C and the mean January temperature is –12.5°C, with the effective temperature sum over the growing season being between 1450 and 1650°C (ASSR, 1989). Annual total precipitation ranges from 500 mm to 600 mm and accumulation of thick snow cover (50–70 cm) characterizes the winter period, which lasts from 170 to 180 days.

The Kalevalsky NP is located in the southeast slope of the Baltic (Fennoscandian) Shield. The underlying bedrock is composed of Pre-Cambrian crystalline rocks – granite or gneiss (ASSR, 1989). The topography of the study area is generally hilly, characterized by a mean altitude between 104 and 277 m above sea level (Gorkovets and Rayevskaya, 2002). The most common soil type is alluvial-humus-ferrous-sandy podzols. Marshy and marsh-podzol soils dominate the southwestern and northwestern sections of the area. The forests of the Kalevalsky NP cover 71% of its territory and belong to the northern boreal (northern taiga) subzone (Lavrenko et al., 1947; Yurkovskaya, 1993). It corresponds to the middle boreal zone in the classification of Ahti et al. (1968).

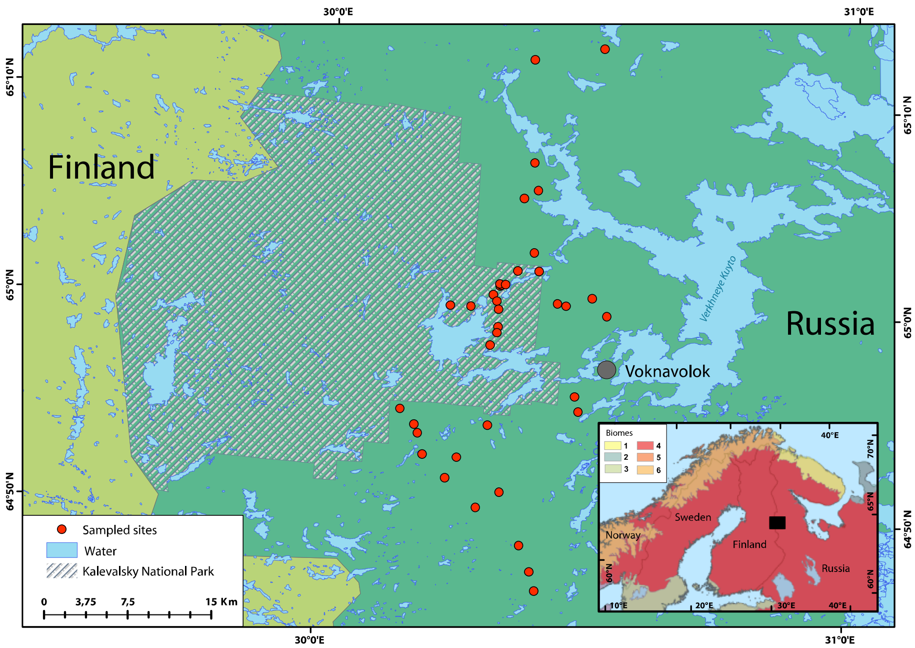

Figure 2.1 Location of the study area and the sampled sites within or in the vicinity of the Kalevalsky NP. The insert shows the location of the area on the map of biomes (Olson et al., 2001): 1, Kola Peninsula tundra; 2, Northwest Russian-Novaya Zemlya tundra; 3, Sarmatic mixed forests; 4, Scandinavian and Russian taiga; 5, Scandinavian coastal conifer forests; 6, Scandinavian Mountain birch forest and grasslands.

The park's common tree species are Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst), silver and downy birch (*Betula pendula* Roth. and *B. pubescens* Ehrh., respectively) and aspen (*Populus tremula* L.). Pine forests of the bilberry (*Vaccinium myrtillus* L.) type dominate the area and are particularly abundant on the rocky outcrops, hill slopes, and edges of various wetlands (Gromtsev, 2009; Raevsky, 2017; Ruokolainen and Kotkova, 2014). Spruce is common in the undergrowth, while pine regeneration is largely absent (Gromtsev et al., 2002). The historical fire regime has been suggested to maintain a dynamic balance between pine and spruce in the past (Gromtsev, 2002; Gromtsev et al., 2002). The area has a rich cultural history, with the first wave of human settlements dating back to 7000 BC (Juvelius, 1889; Zhulnikov, 1993).

2.4.2 Field sampling

We sampled 38 sites within the Kalevalsky NP (Fig. 2.1). We made an effort to distribute sampling sites in a regular fashion across the studied landscape, by randomly locating points for sampling along the roads within the park and its immediate vicinity. The sites were located from one to four km from each other. Areas of clear-cuts located outside the Kalevalsky NP border and mires were not generally sampled, due to difficulties in locating material for dating. A site represented an area of two–three ha in size and was inventoried over a period of one to two hours. We thoroughly searched each site for the presence of living and dead trees with fire scars. We used chainsaws to extract wedges from living trees and snags and, in the case of stumps, cross-sections to develop a fire chronology. Between four and 10 samples were collected on each site. In total, we acquired 257 samples of 71 living and 186 dead pine trees. Field sampling was carried out in the summers of 2014 and 2015.

Location of most of the sampling points near the forest roads could introduce a bias related to their use by local population in the past. In particular, one could expect inflation in the estimates of fire activity during the periods when the fire was an agricultural tool and its deflation - during the periods dominated by fire suppression policies. Historical records, however, indicate that the studied area had no forestry roads, which would support horse-drawn transportation, prior to 1908 (Golubtsov et al., 1908; Olenev, 1902). Instead, there were lakes, rivers, and footpaths, which were used for travel at that time. Records indicate that rafting on the lakes was the most convenient way to travel during summers (Golubtsov et al., 1908). The resulting site network covered an area of approximately 25x50 km^2. We considered the size of our study area to be exceeding the size of the largest fires, which might have occurred in the European boreal zone prior to the onset of intensive forest use and its fragmentation (Niklasson and Granström, 2000). The area was, therefore, considered sufficient to represent the dynamics of historical fire cycles in Kalevalsky NP.

2.4.3 Development of fire chronologies

All of the samples were air dried and sanded with progressively finer sandpapers with up to 400-grit to provide a clear view of the rings and fire scars under a binocular microscope with 40× magnification. We cross-dated samples primarily using the visual pointer year method (Stokes and Smiley, 1968), capitalizing on the point year chronology developed for that area. Examples of useful pointer years heavily used during cross-dating were: 1346 (pale latewood), 1354 (wide ring and dark latewood), 1448 (wide ring and dark latewood), 1453 (pale latewood), 1454 (wide ring and dark latewood), 1466 (narrow ring and pale latewood), 1547 (wide ring and dark latewood), 1567 (pale latewood), 1601 (pale latewood), 1655 (wide ring and dark latewood), 1703 & 07 (wide ring and dark latewood), 1763 (pale latewood), 1801 (wide ring and dark latewood), 1899 (pale latewood) and 1901 (wide ring and dark latewood).

To verify the dating, we correlated sample chronologies with a newly developed regional pine ring-width chronology. Initially, we took advantage of the Scots pine chronology ITRDB RUSS183 (Meriläinen et al., 2014), developed for an area located approximately 50 km away from the Kalevalsky NP. To measure tree rings, we obtained high-resolution (2400–3200 dpi) digital images of the samples with a flatbed scanner and used Cybis AB CooRecorder/CDendro 9.0 to measure the rings (Larsson, 2017). As a proxy of correlation strength, we relied on t test calculated in program COFECHA (Grissino-Mayer, 2001; Holmes, 1999, 1983).

Dating of fire scars associated a scar with a particular ring. We also attempted to identify scar position within a dated ring, which provided information on the seasonal occurrence of the fire event. Fire scars with seasonal dating were assigned to one of the following seven categories: early earlywood (EEW), middle earlywood (MEW), late earlywood (LEW), early latewood (ELW), middle latewood (MLW), late latewood (LLW) and dormant (D) (Baisan and Swetnam, 1990).

2.4.4 Reconstruction of historical fire cycles

We developed a spatial reconstruction of fires capitalizing on the fire dates independently identified across our site network. To transfer fire dates obtained at site level into the areal estimate, we assumed that a site represented the fire history of a certain area centered on the site center, later referred to as *unit*. By summing up the areas of these units for the years with dated fire events, we obtained an annual chronology of burned areas. Since some of these units had a portion of their area covered by water (lakes, streams, but not mires nor peatlands), their contribution to the annual amount of burned area was reduced accordingly, using spatial information on the regional hydrology from DIVA-GIS datasets, version 7.5 (Hijmans. et al., 2001). The territory of the Kalevalsky NP is a landscape mosaic pattern that includes different type of forests, mires, peatlands, and two types of permanent waterbodies - lakes and streams. Based on our knowledge of the topography of the Kalevalsky NP and the typical size and arrangement of firebreaks (such as lakes and streams), we tested unit radii ranging from 500 to 1500 m, which corresponded to unit sizes of 78.5 to 707 ha. By doing so, we wanted to check for the sensitivity of our results to changes in unit size. We elected to use the unit with the size of 314 ha (1000 m radius), which tend to place the units within one element of the landscape mosaic. The results obtained with other unit sizes are presented in Appendix A: Fig. S2. We converted the reconstructed burned areas into the estimates of fire cycle (FC) (Van Wagner, 1978). The area burned is the inverse of the FC, i.e. the length of time required for the area equal to the total study area to burn. FC was calculated as:

$$FC = \frac{TSA * TI}{TBA} \qquad (1)$$

where TI is the length of the time period studied (years) and TSA and TBA are the total studied area and the total burned area over this time period, respectively. We obtained 10% and 90% confidence limits for the FC through the bootstrap method, resampling our pool of sites 1000 times.

The decline in network spatial coverage over time (i.e., in the number of sites contributing to composite fire chronology) biased the results during the oldest portion of the reconstruction, through a reduction in the amount of reconstructed burned area. To address this issue, we adjusted the reconstructed burned areas by (a) calculating the proportion of sites recording fire in the total amount of recording sites for each fire year, and (b) randomly assigning burned/non-burned status to a proportion of the non-recording sites, as identified in step (a).

2.4.5 Identification of fire regime shifts

We used a regime shift detection algorithm (Rodionov, 2004) to identify changes in FC over the period covered by the reconstruction (1400–2010, minimum number of sites = 5). The algorithm is based on sequential t-tests that identify regime change, when the cumulative sum of normalized deviations from the mean value of a new regime is different from the meaning of the current regime, as calculated on a pre-defined moving timeframe. The algorithm uses "a cut-off length", i.e. a threshold, in years, below which the ability of the algorithm to detect regime changes is reduced. In the analysis, we set that threshold to 10 years (L parameter). The Hubert weight parameter, controlling for the weights assigned to the outliers, was set to 1 and the significance level t-tests - at 0.05. We opted for the 10 years as the value of the L parameter to increase the sensitivity of the algorithm to short-term changes in the fire cycle. The value of the Hubert parameter was set to 1, which is commonly considered as a default (Rodionov, 2004). We applied the procedure to reconstruct burned areas at the level of the studied landscape.

2.4.6. Analysis of association between fire history and environmental proxies

To test the association of fire events with regional weather states, we studied variability in mean summer geopotential height at 500-hPa (Luterbacher et al., 2002). Previous studies have shown a strong association between variations in the 500-hPa geopotential height level in the mid-troposphere and changes in the distribution, frequency and amount of precipitation (Girardin et al., 2006; Seftigen et al., 2013) and regional fire activity (Drobyshev et al., 2016; Le Goff et al., 2008). Dominance of high-pressure systems, reflected in higher values of 500-hPa heights, could contribute to the development of dry conditions that are more conducive to fire (Girardin et al., 2006; Potter et al., 2004; Seftigen et al., 2013).

We used the pressure chronology for the grid cell covering the territory of the Kalevalsky NP (63.75–66.25N, 28.75–31.25E), with the record starting in AD 1659. We carried out two analyses focusing on the relationship between pressure variability for the grid cell encompassing the Kalevalsky NP and fire at both high and low frequency domains. To study high frequency variability, we used superposed epoch analysis (SEA) (Grissino-Mayer and Swetnam, 2000; Swetnam, 1993) to evaluate the significance of departures in atmospheric pressure during the large fire years (LFYs) and to quantify the spatial pattern of these departures. We performed the analyses in KNMI Climate Explorer (Trouet and van Oldenborgh, 2013).

To study low frequency variability, we used the reconstruction to test for decade-long changes in the mean summer pressure over the whole period for which pressure reconstruction was available (1659–1999). To this end, we used a sequential t-test algorithm (see subsection above) (Rodionov, 2004) with the significance level of 0.05, Hubert parameter of 1 and L parameter of 10. Although our fire reconstruction and the pressure reconstruction provided only a partial overlap, the pressure chronology did cover the period with a decline in fire activity in the Kalevalsky NP.

The stream flow reconstruction based on sedimentary cladoceran fossils from the Kuhmo area, 150 km west of the Kalevalsky NP (Luoto and Helama, 2010), were used as a proxy of regional drought conditions during spring period. The stream level changes have been reconstructed using a site-specific cladoceran-based inference model fed with the sediment data from the lake Pieni-Kauro (Luoto and Helama, 2010).

The reconstruction reflects historical variability in winter precipitation (Helama et al., 2009; Luoto and Helama, 2010). Although the stream flow reconstruction extended back to AD 500, we included in our analyses, only the period covered by our fire reconstruction, i.e. 1400 to 2010 AD.

2.4.7 Large fire years and climate-fire relationships

LFY were defined as years when the reconstructed annually burned area was above 1000 ha (for the version of analyses with unit size of 314 ha). We used SEA to quantify the relationships between LFYs, and environmental variability as represented by ocean temperatures and air pressure patterns in Northern Europe. We studied the pattern of June-July Sea surface temperature (SST) anomalies over the area limited by 40°–80° N and -20°– 45° E during LFYs in the Kalevalsky NP. SST data originated from ERSSTv5 (Huang et al., 2017). We used a subset of the gridded June-July mean temperature anomalies over the area of northern Europe from HadCRUT4 (Morice et al., 2012). In both analyses, we quantified deviations of these variables during the LFYs from the long-term means and evaluated the spatial pattern of such deviations. The temperature record covered the 1850–1930 period and the SST record covered the 1854–1930 period. It contained five LFYs between 1855 and 1919. Significant departures were identified, as those exceeding the 95% confidence interval. SEA analyses were done with the KNMI Climate Explorer tool (Trouet and van Oldenborgh, 2013).

2.4.8 Population Data

To evaluate the association of fire activity with human activities, we developed a chronology of population density for the village of Voknavolok, a settlement located 15 km from the Kalevalsky NP. We used the modern census data (Statistics, 2010) and historical estimates dating back to AD 1679 (Kochkurkina, 2000). During the period between 1679 and 1782, the population data was available only for males, excluding women and children. To obtain total population estimates for that period we used a correction factor of 2.5.

2.5 Results

The fire chronology spanned the 1400–2010 AD period. We identified 184 fire years, based on the dating of a total of 630 fire scars found on 212 samples. The earliest fire was dated to 1390 AD and the most recent one – to 2007 AD. To ensure the minimum replication of fire events, we limited our analyses to the period from 1400 to 2010, for which each year was represented by at least five sites (Fig. 2.2a). The majority of the fires (85%) were below 500 ha, or 4% of the study area. Fire seasonality was successfully identified for 69% of the fires. The growing season fires accounted for 95% and 61% of these were early wood fires. Only 21 scars (5%) occurred in the dormant period.

We identified thirteen LFYs for the period 1400–2010 AD. These were AD 1570, 1634, 1640, 1660, 1730, 1750, 1824, 1826, 1855, 1858, 1883, 1914 and 1919 (Fig. 2.2b). During each of these events, the burned area exceeded 15 km^2 or 12 % of the studied area. Of these years, 1750 was marked as a year with exceptionally high fire activity, when the burned area reached 40 km^2 or 33% of the total study area.

Since 1400 AD, the FC underwent significant changes, resulting in three fire epochs, as identified by regime shift analysis. During the 1400–1630 AD period, the average FC was 178 yrs. (bootstrapped 90% confidence envelop 118 to 300 years). In the following period, 1640–1920 AD, the FC shortened to 46 yrs. (confidence envelop 39 to 53 years). In the most recent period (1930–2000 AD), the FC increased to 283 yrs. (confidence envelop 140 to 1421 years) (Table 2.1 and Fig. 2.3a).

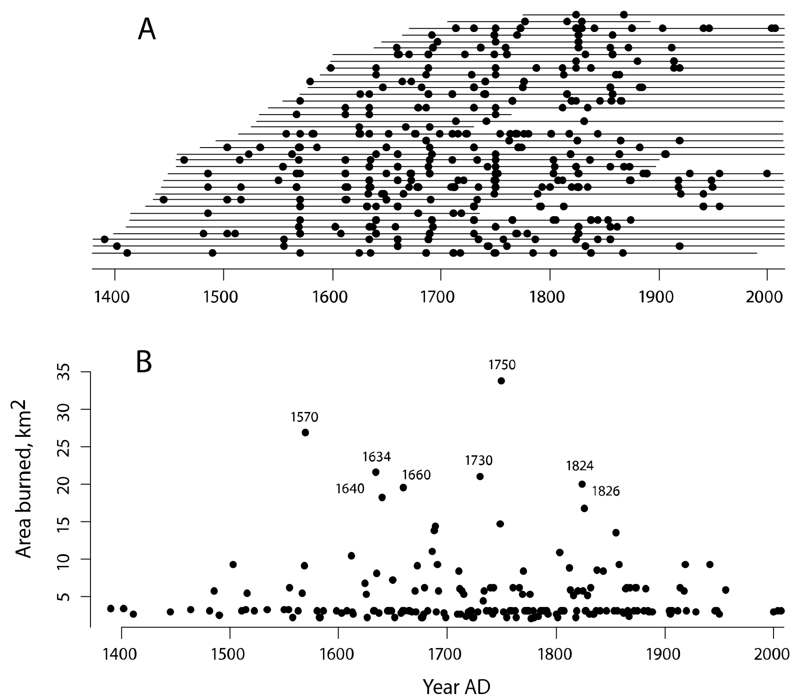

Figure 2.2 Dendrochronologically reconstructed fire history of Kalevalsky NP over the 1400–2010 CE. (A) Summary of fire scar dating with a single straight line representing a site and a dark circle representing a fire event. (B) Reconstructed chronology of annually burned areas with large fire years marked with dark circles.

To quantify the contribution of fires of different seasonality to the total fire activity, we run the regime shift detection algorithm separately for early-and late-season fires. For early-season fires, we identified three periods (1400–1610 AD, 1620–1880 AD, and 1890–1940 AD) with FC of 358, 78 and 223 yrs., respectively (Table 2.1 and Fig. 2.3a). For late-season fires, the change in fire activity occurred in 1810 with the FC of 873 yrs. prior to the change and of 115 yrs. afterwards (Table 2.1 and Fig. 2.3b).

Five LFYs in the Kalevalsky NP occurred in the period covered by SST reconstruction (1855, 1858, 1883, 1914, and 1919 AD). SEA revealed a positive association between LFYs and SST in the Norwegian Sea (Fig. 2.4a). We observed strong positive June-July temperature anomalies for the area of northern Europe during LFYs (Fig. 2.4b).

Table 2.1 Reconstructed FC with corresponding confidence intervals in the Kalevala NP for the periods identified by the regime shift analysis. FC estimates of two locations in Sweden are based on published reconstructions (Niklasson and Drakenberg, 2001; Niklasson and Granström, 2000) and the results of respective regime shift analyses (Drobyshev et al., 2016).

Epoch, years AD	Mean FC	95 % CI lower bound	95 % CI upper bound
All fires			
1400–1630	178	118.67	300.98
1640–1920	46	39.07	53.82
1930–2000	283	140.96	1421.89
Early season fires			
1400–1610	358	210.05	768.37
1620–1880	78	66.61	93.84
1890–1940	223	133.55	520.25
Late season fires			
1570–1810	873	408.25	6720.29
1820–1940	115	86.86	161.07
Tiveden (middle Sweden)			
~1500–1600	75	–	–
~1600–1700	63	–	–
~1700–1800	88	–	–
Bjuvholm (northern Sweden)			
~1500–1600	304	–	–
~1600–1700	217	–	–
~1700–1800	320	–	–
~1800–1900	233	–	–

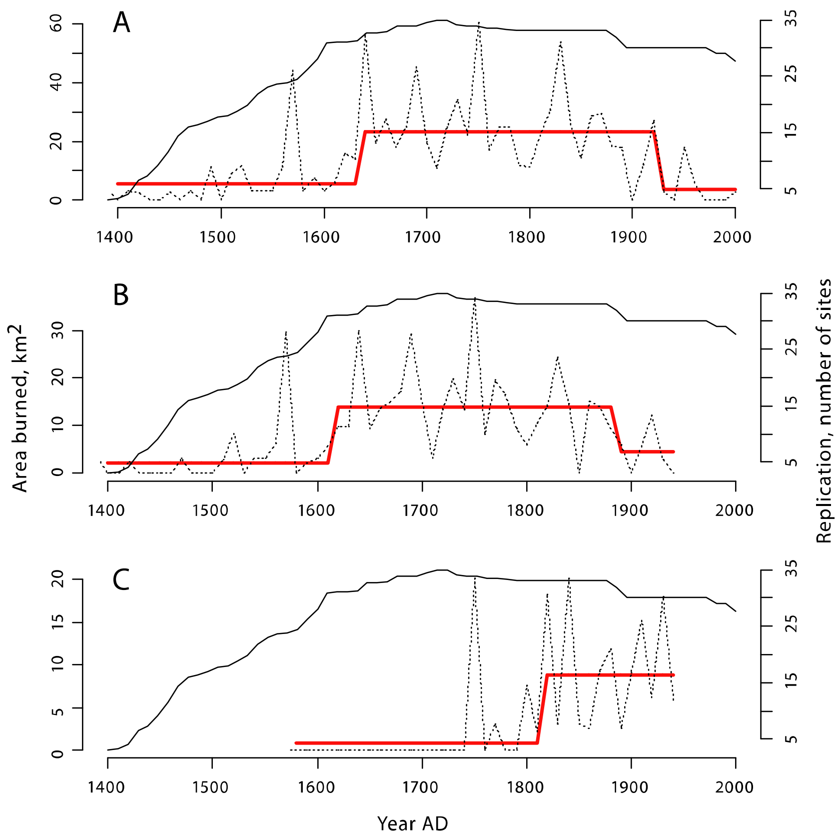

Figure 2.3 Changes in the FC of (A) all fires, (B) early season fires, and (C) late season fires in the Kalevalsky NP between 1400–2010 AD. Dashed lines represent decadal burned area, in km^2. The red line shows periods with similar fire cycles, as identified by the regime shift analysis (Rodionov, 2004) using a 10-year window. The solid black line indicates sample depth.

During the 1659–1740 AD period, mean summer 500-hPa geopotential height remained relatively low, which was characteristic of generally cyclonic conditions (Fig. 2.5). The pressure height increased over the second half of the 1700s towards the first quarter of the 1800s. Reduction in 500-hPa geopotential height occurred between 1820s and 1920s, followed by its increase in the last period (1930s–2000s AD).

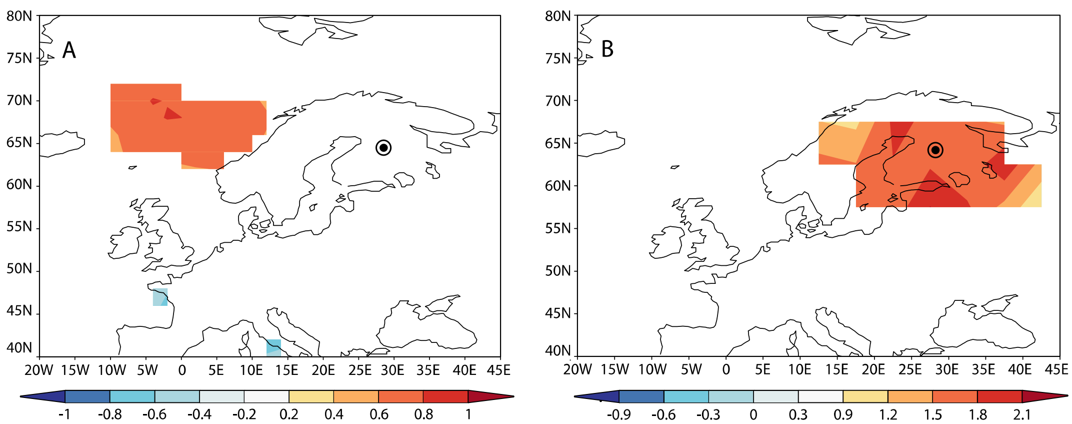

Figure 2.4 Relationship between LFYs in the Kalevala NP and (A) June–July sea-surface temperatures (Huang et al., 2017) over the 1854–1930 period, and (B) June–July temperature anomalies (Morice et al., 2012) over the 1850–1930 period. The location of the study area is marked with a dark circle. Colored areas indicate temperature anomalies, which were significant at $p < 0.10$.

2.6 Discussion

2.6.1 Human drivers of fire regime

FC changes in the Kalevalsky NP were likely affected by human land use. The area of the Kalevalsky NP has been initial colonized for at least 7000 years (Zhulnikov, 1993). Populations of semi-nomadic Saami (Lopari) people occasionally inhabited the area between ~1000 BC and the late 1300s (Kosmenko, 1978). Saami's primary occupations were fishing, hunting, and reindeer herding (Anonymous, 1957). Their use of fire was minimal (Anonymous, 1957; Ivanishcheva and Ershtadt, 2014; Klement'ev and Shlygina, 2003), since fire killed lichens, the main forage of deer in the winter (Sarvas, 1937). Archeological excavations have suggested that pre-industrial colonization by Karelians originating from the Ladoga Lake coasts intensified in the 1400–1500s (Zherbin et al., 1983), although the population density remained at an estimated 0.2 persons/km^2 (Miuller, 1978). We speculate that differences in typical land use patterns between two nationalities might be at play in promoting changes in FC. The proclivity of Karelians to settle permanently in a pre-industrial colonized area was in contrast to a predominantly nomadic habitation pattern of the Saami population. An increase in the Karelian’s population might facilitate transition to fire-intensive slash-and-burn practices. Historical sources have indicated that the land-use patterns of the Karelians compromised those of the Saami people, which resulted in local conflicts (Balagurov, 1959; Klement’ev and Shlygina, 2003) and, possibly, the use of fire by Karelians to secure their land rights. During the 1500–1600s period, the Kalevalsky NP was a territory of cross-border wars between Sweden and Russia that contributed to economic recession (Anonymous, 1957; Miuller, 1978). The wars likely hindered the expansion of land use practices involving fire. Historical records report low soil fertility and a harsh climate (Olenev, 1902), further limiting the area involved in farming (Golubtsov et al., 1908).

An increase in fire activity around the 1630s coincided with the signature of the Treaty of Stolbovo between Russia and Sweden (1617 AD) and the onset of economic recovery in the region (Anonymous, 1957). Industrial colonization of the area by Swedes and Finns (from the west) and by Novgorod Russians (from the east), contributed to a population increase during the 1600s (Pöllä, 1995). The mining and processing of iron ore drove economic development at that time (Chubinskii, 1866; Vasilevskii, 1949) and commercial deer hunting, tar extraction, charcoal burning and small-scale agriculture were popular occupations among the local population until the 1800s (Anonymous, 1957; Vasilevskii, 1949). All these activities likely contributed to fire ignitions and the amount of burned areas. Previous studies of fire activity in Scandinavia have consistently associated human land use with the increase in fire activity during 1600s (Niklasson and Granström, 2000; Wallenius, 2011; Wallenius et al., 2004), although not necessarily with the increase in the amount of burned area. In particular, the study of Wallenius et al (2004) related the increase in fire occurrence to the political urge from Stockholm for the people of Sweden to industrial colonize eastern fringes of the kingdom in 1673 (Veijola, 1998). In our study, however, the increase took place about 40 years earlier, which questions the role of policy changes in fire dynamics. Variation in both the sampled areas and the analyzed metrics of fire regime was a likely source of differences in studies' results. In our study, the area investigated totaled 119000 ha whereas in Wallenius et al (2004) it was 419 ha. Difference in fire metrics could further contribute to differences in the results between two studies: our study operated with an areal estimate of fire regime whereas the one of Wallenius et al. (2004) focused on the fire return intervals.

The observed decline in fire activity that occurred around 1920s might be a result of socio-economic changes, although the timing of this decline does not conclusively point to a particular event as a trigger of these dynamics. Since the early 1800s, the processing of iron ore has been losing its economic importance, due to the high duty on firewood imposed by the Russian state at that time (Chubinskii, 1866). Forest burnings have been criminalized since the 1870s (Chubinskii, 1866) and were largely replaced by a three-field system (Kochkurkina, 2000). The coup-d'état of 1917 and the political split among inhabitants of the Karelian countryside resulted in their mass immigration to Finland, followed by a deep economic recession in the region (Nygerd, 1980). Not until the end of 1923 (Kochkurkina, 2000), did most refugees return to Russian Karelia from Finland. However, the population of Voknavolok, a village located ~5 km away from the Kalevalsky NP, never reached the level observed prior to the coup-d'état (Fig. 2.5).

The dramatic shift from high to low fire activity appeared to coincide with changes in the economy of Karelian villages, which took place early during the Soviet period. Following the increase economic value of timber, the government organized state forest units during the 1920s and tasked them with fire prevention (Anonymous, 1918; Ulianov and Fotieva, 1920). The border protection zone was established on the Russian side of the Russian-Finnish border in the Soviet period (Gromtsev et al., 2003). This prevented most of the traditional activities in the area.

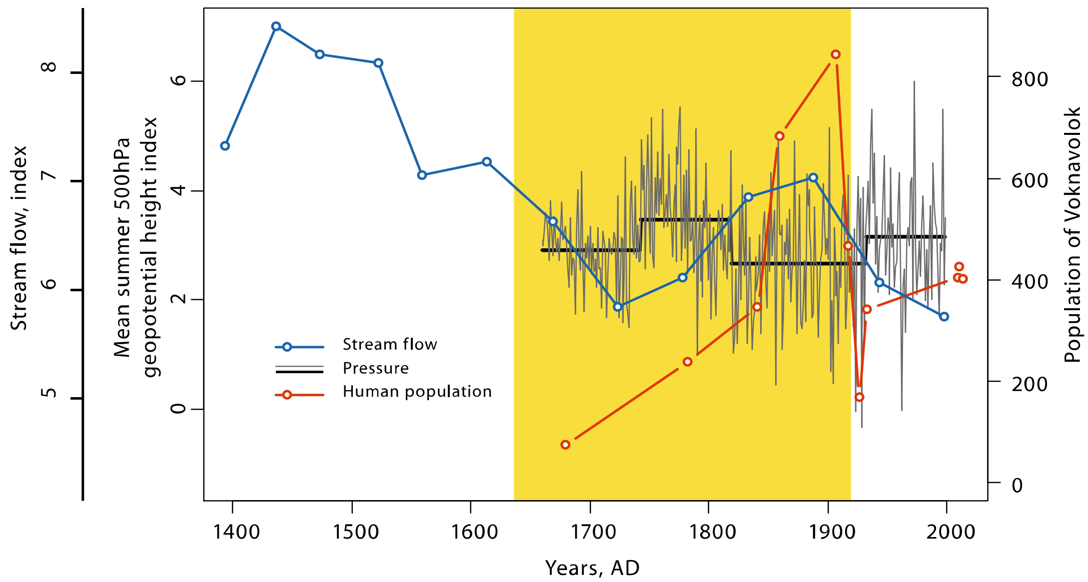

Figure 2.5 Chronologies of population density of Voknavolok (Kochkurkina, 2000), reconstructed summer 500-hPa pressure for the territory of Kalevalsky NP (Luterbacher et al., 2002), and stream flow reconstruction based on the sedimentary cladoceran fossils (Luoto and Helama, 2010). The yellow bar indicates the period with increased fire activity as revealed by dendrochronological reconstructions (see Fig. 2.3a).

2.6.2 Climate forcing upon fire regime

A low-frequency (centurial) synchrony between climate proxies and fire activity varied over the studied period. Overall, pressure pattern did not show a consistent association with the dynamics of fire cycle (Fig. 2.5). The periods with both higher and lower 500-hPa levels overlapped with the fire-prone epoch in the fire cycle reconstruction. We speculate that the result may reflect not the actual lack of a mechanistic link between two records, but the fact that the data extracted from the Luterbacher et al. (2002) represented the area located at the fringes of the region covered by this reconstruction product. It is also possible that the reconstruction record for the area had a limited ability to reflect water balance of forest fuels.

Instead, the reconstruction of the stream flow in an area about 150 km away from the Kalevalsky NP (Luoto and Helama, 2010) indicated a general trend towards drier conditions during the Little Ice Age (LIA). The onset of the period with shorter fire cycle in the Kalevalsky NP coincided with decline in stream flow (Fig. 2.5). The large fire year of 1570 AD occurred during the driest period observed between 1500 and 1600 AD, was possibly conditioned by lower amounts of winter precipitation (Fig. 2.5) (Luoto and Helama, 2010; Nevalainen et al., 2013). Four other LFYs in the Kalevalsky NP occurred during the period of more than a century long decrease of stream flow, between the 1600-1720s, which was likely associated with dryer forest fuels during spring. The dominance of early season fires prior to 1800s is consistent with dryer conditions at the starts of the fire seasons, indicating the principal role of climate in controlling fire cycle at that time. Instead, a decrease in fire activity was not consistent with a decline in stream flow around 1900s, suggesting a decline in climate forcing upon fire activity (Fig. 2.5).

At the annual time scale, the fire regime of the Kalevalsky NP synchronized with summer SST dynamics in the Norwegian Sea and summer temperature anomalies over northern Europe (Figs. 2.4a, 2.4b). The positive correlation between the occurrence of large fire years (LFYs) and two temperature variables suggested that the establishment of a high-pressure cell over northern Europe, warming up both the ocean and forest fuels, is likely behind the observed relationships. LFY identified in this study were not associated with the colder sea surface temperatures in the western North Atlantic, earlier shown to predict periods of regionally increased fire hazard in Northern Sweden (Drobyshev et al., 2016). It was therefore likely that the occurrence of LFY was driven primarily by regional climate dynamics rather than by large-scale transatlantic teleconnections. Both mechanisms likely rely on the inflow of dry-cold arctic air masses in the summer, preconditioning increased regional fire hazard (Drobyshev et al., 2016).

2.6.3 Temporal changes in forest FC dynamics in Fennoscandia

The earliest period in our reconstruction (1400–1620 AD) had a FC of 178 years. Although the period partially coincided with the wave of pre-industrial colonization of the area by Karelians in the 1400s, the population density apparently remained low during that period (Table 2.1 and Fig. 2.5). Prior to the wave of human colonization of the Northern Fennoscandia during the 1600s, the average FC in European boreal forests ranged ~ 40 to 300 years (Lehtonen, 1997; Lehtonen and Huttunen, 1997; Niklasson and Drakenberg, 2001; Niklasson and Granström, 2000; Rolstad et al., 2017). Our FC (178 years) was shorter than the length of FC reconstructed in Northern Sweden, estimated at 304 years (Drobyshev et al., 2016; Niklasson and Granström, 2000), but longer than in eastern Finland and south-central Norway, estimated at 107 and 73 years respectively (Lehtonen and Kolström, 2000; Rolstad et al., 2017). The similarity in FCs estimates suggested that a FC of about 200 years as a characteristic level of fire activity in Fennoscandia boreal forests, prior to the expansion of intensive forest use practices (Table 2.1).

The period of increased fire activity started in ~ the 1630s and was characterized by a three-fold increase in the amount of burned areas (Fig. 2.3a). The synthesis of boreal biome fire histories has proposed the 1600s as the most fire prone period in boreal forest, due to the dry and unstable climate of the Little Ice Age (Bergeron and Flannigan, 1995; Drobyshev et al., 2016; Gavin et al., 2003; Wallenius et al., 2007). In the Kalevalsky NP, this climate-driven pattern might be further enhanced by human population dynamics (see the discussion on that point above). Around the 1920s, the FC declined back to levels that are only marginally higher than the ones reconstructed for the earliest period. Similar changes in fire activity have been shown for northern Fennoscandia (Aakala et al., 2018; Drobyshev et al., 2016; Niklasson and Granström, 2000; Rolstad et al., 2017; Wallenius et al., 2007) and for boreal forests of North America (Bergeron et al., 2001; Weir et al., 2000). A large variability in the timing of the decline in fire activity, reported across European and North American sectors of boreal forest supports the view on these dynamics as driven primarily by cessation of land use practices involving fire, and not by active prevention or suppression policies. Indeed, efficient application of such policies would require the level of technological development, which was largely missing during the 1700s and 1800s.

In Russian Karelia, the differences among the period-specific FCs were considerably more pronounced than in the middle and northern Sweden, the only region of the European boreal forest with available analyses of FC regime shifts. Shifts in FC among periods in Karelia reached almost 150 years (Table 2.1), while in northern Sweden FC changes from one period to another did not exceed 100 years (Drobyshev et al., 2016; Niklasson and Granström, 2000). An even lower level of differences in FC has been reported for southern boreal forests in Sweden (Drobyshev et al., 2016; Niklasson and Drakenberg, 2001). The differences in the regional climate between Sweden and Karelia is a possible reason for the observed difference in the FC variability. The climate of the Kalevalsky NP is more continental (Alisov, 1936), which creates more fire-prone conditions, compared to Swedish sites. Karelia is a region with strong alternation between periods of cyclonic and anti-cyclonic activity, a pattern that likely promotes fires during drier periods (ASSR, 1989).

At the interannual scale, the list of LFYs identified here differed markedly from LFYs obtained in the landscapes located only 50-170 km west of our study area (Lehtonen and Huttunen, 1997; Lehtonen and Kolström, 2000; Wallenius et al., 2004). Over 1400-2007, only two (1570 AD, 1634 AD) out of 13 identified LFYs were common between the North Karelia and the eastern Finland (Lehtonen and Huttunen, 1997). We speculate that such moderate level of synchrony is caused by the differences in the data collection protocols, rather than differences in climate or landscape properties among the locations. Lack of synchrony might be due to the limited size of the areas sampled in the earlier studies, which might act towards increasing the stochastic behavior of the fire records.

2.6.4 Seasonality fires in Kalevalsky NP

Seasonal patterns of fire occurrence may provide an insight into the relative contributions of natural vs. human-mediated ignitions upon fire activity. The large proportion (61 %) of early season fires in the Kalevalsky NP might point to the natural origin of fire ignitions, despite the view on the dominance of spring and early summer fires as an indicator of human activities in northern European forests (Groven and Niklasson, 2005; Niklasson and Drakenberg, 2001). Observations have documented that lightning-ignited fires in the European part of the Russian boreal zone predominantly occur early in the fire season, due to frequent high pressure cells established over that region immediately after the snowmelt (Kurbatsky, 1976a; Stolyarchyuk and Belaya, 1982). Kalevalsky NP is located in the part of the European boreal forest north of 59°N, which has been designated as a "May-June forest fire belt" (Melekhov, 1946) due to the dominance of such early season fires.

The origin of an increase in late season fires (Fig. 2.3c) from the early 1800s until the mid-1900s remains unclear. However, we speculate that the pattern was likely of a human population. We observed a strong association between the onset of a period with increased late season fires ~1810 and the time of peaking population density in the area (Fig. 2.5). Late-season fires can be potentially of higher severity and are more difficult to control (Ferrenberg et al., 2006), which make them a type of event not commonly used in the past as an agricultural tool. However, an increase in population density early in that period might have contributed to additional, not necessarily "agricultural" ignitions, which were spread over the whole fire season. The increase in the amount of area burned late in the fire season was relatively minor, since it did not appear to affect the overall FC dynamics (Fig. 2.3a).

2.7 Management implications

The forests of the Eastern Fennoscandia are dominated by pine, whose cohort dynamics is driven by a combination of repeated surface and stand replacing fires (Niklasson and Granström, 2000; Wallenius et al., 2004; Zackrisson, 1977). Quickly decreasing with time, the number of trees representing older cohorts make reconstruction of fire severity in these forests difficult. However, the common presence of trees and deadwood with multiple fire scars and the large amount of dead wood in the studied stands indicate that low-severity surface fires prevailed across the landscape of Kalevalsky NP in the past. Even the most pronounced fire years, such as 1640 and 1750, left behind a large number of scarred trees, many of which had earlier fire scars, pointing to a largely non-stand replacing type of these events.

Our findings demonstrate that fires have been an important factor affecting the forests of the Kalevalsky NP over the past 600 years. Conservation management of this area and similar protected areas of Eastern Fennoscandia should, therefore, acknowledge the role of this disturbance agent. We argue that a balance is needed between fire suppression activities dictated by the economic value of the forest and fire risks to human lives and infrastructure, on one hand, and the preservation of fire as a driver of vegetation dynamics, on another. The value of this nature-based approach has been convincingly demonstrated across a wide range of ecosystems, where fire acts as the primary disturbance factor (Clear et al., 2013; Conedera et al., 2009; Peterson and Reich, 2001).

A prolonged absence of fire prevents the natural regeneration of pine and promotes its replacement by shade-tolerant trees. The pattern has been documented in the pine-dominant forests of the Kalevalsky NP (Gromtsev et al., 2003), in other parts of Fennoscandinavia (Kuuluvainen, 2002; Niklasson and Drakenberg, 2001; Wallenius et al., 2004) and in European Russia (Gromtsev et al., 2002; Kuosmanen et al., 2016, 2014). Prescribed surface fires can be instrumental in maintaining habitats for pine regeneration (Kuuluvainen and Rouvinen, 2000). These fires may also minimize the risks of large stand-replacing fires, by reducing the amount and continuity of fuels (Angelstam and Kuuluvainen, 2004; Drobyshev et al., 2008).

2.8 Acknowledgements

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III. CLIMATE DROVE THE FIRE CYCLE AND HUMANS INFLUENCED FIRE OCCURRENCE IN THE EAST EUROPEAN BOREAL FOREST

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3.1 Résumé

Comprendre les historiques de feux dans les paysages boréaux sur le long terme est essentiel pour modéliser les interactions climat-feu et le rôle de l'influence humaine sur les régimes de feux naturels. Les sections orientales de la zone boréale européenne manquent actuellement de séries chronologiques, de feux annuelles et centenaires. Pour combler cette lacune, nous avons reconstruit dendrochronologiquement les 600 années d'histoire des feux dans un paysage boréal moyen dominé par les pins dans la partie sud de la République de Komi, en Russie. Nous avons combiné la reconstruction des cycles de feu (CF) et des occurrences de feu avec les données de création des villages et des indicateurs climatiques, en discutant la contribution relative du climat par rapport à l'usage humain des terres dans la formation des régimes de feux historiques. Entre 1340 et 1610, le territoire présentait un-CF de 66 ans (intervalle de confiance de 90 % entre 56,8 et 78,6 ans). L'activité des feux a augmenté durant la période 1620–1730, avec un CF atteignant 32 ans (31,0–34,7 ans). Entre 1740 et 1950, le CF a augmenté à 47 ans (41,9–52,0). La période la plus récente, 1960–2010, marque le maximum historique du CF, avec une moyenne de 153 ans (102,5–270,3 ans).

La création de villages, souvent de petits ports sur la rivière Pechora, a été associée à une augmentation non significative des occurrences de feux près des villages ($p = 0{,}07$–$0{,}20$). Nous avons toutefois observé une association temporelle entre la fondation des villages et l'occurrence des feux à l'échelle du paysage étudié. Il n'y avait pas d'association positive entre cette création de villages et les CF. En fait, nous avons documenté une diminution de la superficie brûlée, suivant une vague d'implantation de villages dans la seconde moitié du XVIIe siècle et la première moitié du XVIIIe siècle. L'absence de lien entre la dynamique des CF et les dates de fondation des villages, ainsi que l'association significative entre les années de grands feux (LFYs) et la chronologie du bois précoce de pin, utilisé comme indicateur historique de sécheresse, suggèrent indirectement que le climat était le principal déterminant des CF à l'échelle du paysage dans les forêts étudiées. Les forêts dominées par les pins de la République de Komi peuvent occuper une position unique en tant qu'écosystème avec l'histoire la plus courte de modifications des cycles de feux liés à l'homme dans la région boréale européenne.

Mots-clés : variation climatique, perturbations naturelles, paysage boréal, régime de feu, forêts dominées par les pins, nord-est de la Russie, risques naturels.

3.2 Abstract

Understanding long-term forest fire histories of boreal landscapes is instrumental for parameterizing climate-fire interactions and the role of humans affecting natural fire regimes. The eastern sections of the European boreal zone currently lack a network of annually resolved and centuries-long forest fire histories. To fill in this knowledge gap, we dendrochronologically reconstructed the 600-year fire history of a middle boreal pine-dominated landscape of the southern part of the Republic of Komi, Russia. We combined the reconstruction of fire cycle (FC) and fire occurrence with data on the village establishment and climate proxies and discussed the relative contribution of climate vs. human land use in shaping historical fire regimes. Over the 1340–1610 CE period, the territory had a FC of 66 years (with the 90% confidence envelop of 56.8 and 78.6 years). Fire activity increased during the 1620–1730 CE period, with the FC reaching 32 years (31.0–34.7 years). Between 1740–1950, the FC increased to 47 years (41.9–52.0). The most recent period, 1960–2010, marks FC's historical maximum, with the mean of 153 years (102.5–270.3). Establishment of the villages, often – as small harbors on the Pechora River, was associated with a non-significant increase in fire occurrence in the sites nearest the villages ($p = 0.07$–0.20). We, however, observed a temporal association between village establishment and fire occurrence at the scale of the whole studied landscape. There was no positive association between the former and the FC. In fact, we documented a decline in the area burned, following the wave of village establishment during the second half of the 1600s and the first half of the 1700s. The lack of association between the dynamics of FC and the dates of village establishments, and the significant association between large fire years (LFYs) and the earlywood pine chronology, used as historical drought proxy, indirectly suggests that the climate was the primary control of the landscape-level FCs in the studied forests. Pine dominated forests of the Komi Republic may hold a unique position as the ecosystem with the shortest history of human-related shifts in fire cycles across the European boreal region.

Keywords: climate variation, natural disturbances, boreal landscape, fire regime, pine-dominated forests, north-eastern Russia, natural hazards

3.3 Introduction

Forest fires are an integral part of the natural disturbance regime in boreal regions (Johnson, 1992; Johnstone and Chapin, 2006), shaping the dynamics of this biome (Bowman et al., 2009; Buma, 2015; Granström, 2001) since they maintain ecosystem functions and complex successional pathways (Bergeron et al., 2004; Bourgeau-Chavez et al., 2000; Payette, 1992; Pyne, 1997). Regional fire activity is primarily controlled by climate (Clark, 1990; Flannigan and Wotton, 2001; Johnson, 1992; Stocks and Lynham, 1996) that directly influences the moisture content of the fuels and ignition patterns, and indirectly – the fuel type and loads. Topography affects variation in soil moisture and vegetation cover that, in turn, introduces spatial variability in the fire regime at finer scales (Girardin et al., 2013; Hellberg et al., 2004; Kuosmanen et al., 2014; Pitkanen et al., 2003).

The reconstructions of fire activity in the European boreal forest have indicated that there is a considerable low-frequency variability in the amounts of forest burned area in Northern Europe since 1400s CE, likely reflecting both climatic and human forcing (Drobyshev et al., 2016; Pinto et al., 2020; Ryzhkova et al., 2020; Wallenius et al., 2007). An increase in the amount of burned forest areas during the coldest period of the Little Ice Age (LIA), the 1600s, (Drobyshev et al., 2016; Ryzhkova et al., 2020) was followed by a pronounced decline in fire activity that started in the mid-1800s. The decline was likely driven by climate variability (Bergeron et al., 2004; Drobyshev et al., 2016; Girardin et al., 2006; Tardif, 2004), cessation of land use practices involving fire, and some rudimentary fire suppression (Niklasson et al., 2010; Rolstad et al., 2017; Tryterud, 2003; Wallenius, 2011). The current net human impact on forest fire translates into a decrease in fire activity, even though increasing human densities are linked to a higher density of ignitions (Groven and Niklasson, 2005; Marlon et al., 2008; Niklasson and Granström, 2000; Zhang and Chen, 2007). For example, in the second half of the 20th century, the FC in most parts of the Northern European boreal forests varied among hundreds or thousands of years (Drobyshev et al., 2021). In comparison, the FC prior to the 1700s ranged from 30 to 300 years (Drobyshev et al., 2012; Niklasson and Granström, 2000; Pinto et al., 2020; Ryzhkova et al., 2020). These estimates largely reflect western sections of the European boreal biome, since the vast majority of dendrochronological fire reconstructions in boreal Europe have been carried out in the Fennoscandia (Aakala et al., 2018; Drobyshev et al., 2014; Niklasson and Granström, 2000; Nilsen et al., 2019; Rolstad et al., 2017; Wallenius et al., 2004). The knowledge of historical forest fire regimes of the eastern sections of the boreal zone remains limited.

Humans have been an important agent of change in fire regimes across the European boreal biome (Groven and Niklasson, 2005; Knorr et al., 2016; Rolstad et al., 2017; Stocks et al., 2002; Wallenius, 2011; Weir et al., 2000). The extent that humans affected fire activity in the boreal zone is currently being debated, with some studies arguing for the almost comprehensive spread of fire-supported agriculture across the European boreal zone (Aleinikov, 2017a; Degteva et al., 2015; Gromtsev, 2002), while others suggesting a strong climate control of boreal fire activity (Aakala et al., 2018; Drobyshev et al., 2016). In Europe, and in particular – in the Fennoscandia, population expansion increased fire frequency and reduced the dominant fire size through the use of slash-and-burn agriculture and associated forest clear-cutting (Hellberg et al., 2009; Lehtonen and Huttunen, 1997; Niklasson and Granström, 2000; Wallenius et al., 2004). The production of charcoal (Östlund, 1993) and reindeer herding (Hörnberg et al., 2018) further affected fire activity through their impact on forest fuels. In contrast to Fennoscandia, the eastern fringes of the European boreal zone currently lack studies on human-fire interactions, done at the annual or near-annual resolution and extending beyond the colonization period to debate the interplay among climate, humans, and fire over the most recent centuries.

The Pechora-Ilych Nature Biosphere Reserve (from this point forward Pechora-Ilych NBR) located in the southeastern portion of the Komi Republic protects an area of the European middle boreal forests, often designated as the Virgin Komi Forests (Anufriev, 2000; Yudin, 1954). The Reserve consists of two geographically separated sections: one with predominantly flat terrain lying within the Pechora Lowland in the vicinity of Yaksha village (Fig. 3.1) and a mountainous area forming the Pechora-Ilych watershed (Dedeev, 1997; Varsanof'eva, 1940). Pine-dominated forests grow on areas with flat topography, and are particularly abundant on the sandy soils of the Pechora River and fluvioglacial lowland (Anufriev, 2000). The nutrient poor soils and the low population densities, well below 1 pers./km^2, had limited the expansion of slash-and-burn agriculture in this area in the past (Aleinikov, 2014) (Fig. 3.3). However, the area had an important geopolitical role between 1500 and the 1800s, due to the presence of three portage routes. Two of them connected the Northern Dvina and the Pechora watersheds (and in this way – to the coasts of the Arctic Ocean) with the Kama Basin and Caspian Sea. The third connected the Northern Dvina and the Pechora watersheds with each other (Dmitriev, 1893; Korchagin and Lobanova, 2012; Velikanov, 1887). Colonization of the area by Russians as late as the middle 1400s, the harsh climate, the complex topography and the lack of a developed market for timber products, all protected the region from large-scale timber harvesting until the late 1800s (Aleinikov, 2014; Popova et al., 2012). Although industrial forestry operations had a considerable impact on the regional forest cover in the early and middle parts of the 20th century, creation of the Pechora-Ilych NBR in 1930 helped to maintain a considerable portion of the landscape with well-preserved fire-scarred live trees and deadwood.

To advance our understanding of the interplay between climate and human forcing upon forest fire regimes in the Eastern boreal forest, we developed a 600-year long spatially explicit reconstruction of the fire regime in a 20x30 km^2 area in the vicinity of Pechora-Ilych NBR, relying on the dating of fire-scarred living and dead Scots pines.

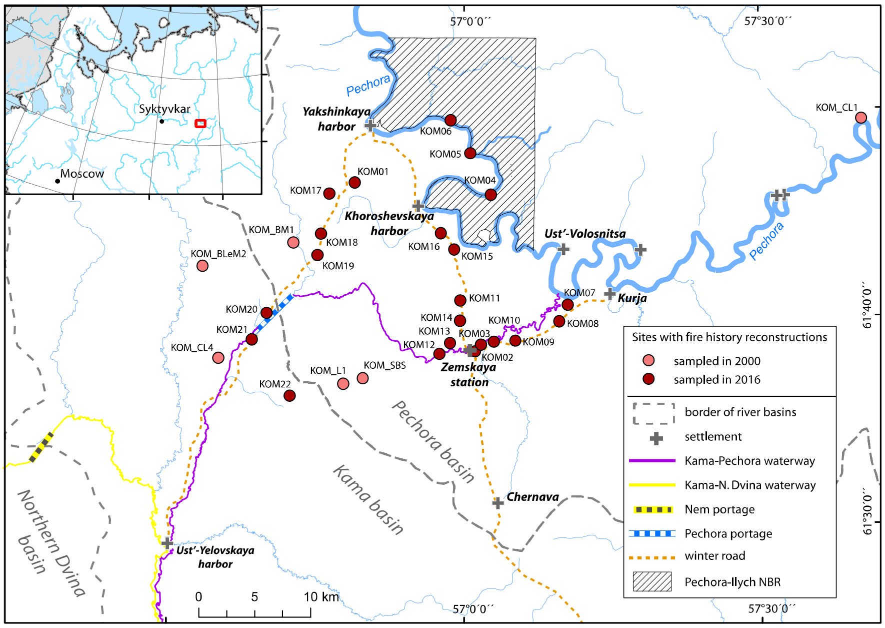

Figure 3.1 Location of the study area and the sampled sites within or in the vicinity of the Pechora-Ilych NBR. The area marked as a Pechora-Ilych NBR on the map is the western portion of the reserve.

We hypothesized that (H1) the onset of the main wave of human colonization in the area resulted in the increases of both areas burned (H1.1) and fire occurrence (H1.2). To support the discussion of H1, we took advantage of the information on the location and establishment dates for individual villages, transit portages and harbors that were recovered from documentary sources. We further hypothesized that (H2) the Pechora-Ilych NBR exhibited the most fire-prone period during the LIA, a cold period of the Maunder Minimum, apparently characterized by a dry and unstable climate and centered on the 1600s and 1700s. Previous research in other parts of the European boreal zone has associated the LIA with increased fire activity levels and, possibly, more frequent conditions of extreme fire hazard (Drobyshev et al., 2016; Ryzhkova et al., 2020). H2, therefore, tested for a broad similarity between the fire history of the Pechora-Ilych NBR and those in the western sections of the European boreal biome.

Finally, considering the low population density and low intensity of historical forest management, we hypothesized (H3) that the historical fire regime was strongly influenced by annual climate variability. To test H3, we evaluated the associations between LFYs in the Pechora-Ilych NBR and the regional earlywood-width Scots pine chronology, which served as a proxy for historical drought conditions.

3.4 Material and methods

3.4.1 The study area

The study area was located in the southeastern part of the Komi Republic, which is one of the most forest-rich regions in European Russia (Taskaev, 2006). Climatologically, the area lies within the Atlantic–continental province (Stolpovski and (eds), 1997) (Appendix B: Fig. S3.1). The annual average temperature is around 1 °C and the average length of the growing season (i.e. the number of days with an average daily temperature above 10 °C) is around 110 days. Average daily temperatures commonly exceed 10 °C during the first 10-day period of June and then fall below this value in the first week of September. Annual precipitation averages 700 mm and accumulation of thick snow cover (70–80 cm) is characteristic for the winter period, which lasts for 130–200 days. Snow melt in the pine forests occurs in mid-May and the first snow cover usually occurs in the first week of October (Appendix B: Fig. S3.1).

The area is situated on the western fringe of the Russian Plain (Dedeev, 1997). The underlying bedrock is dominated by sand and moraine loam and covered by the quaternary glacial drifts (Zaboeva, 1997). The prevailing vegetation is of the middle taiga type (Larin, 1997), broadly corresponding to boreal mixedwoods of Northern America. Scots pine (*Pinus sylvestris* L.), Siberian spruce (*Picea obovata* Ledeb.), and Siberian fir (*Abies sibirica* Ledeb.) dominate. Stands of arctic white birch (*Betula pubescens* Ehrh.), silver birch (*B. pendula* Roth) and aspen (*Populus tremula* L.) typically mark the early stages of post-fire and post-felling succession. Siberian pine

(*Pinus sibirica* Du Tour) and larch (*Larix decidua* Mill.) are both minor components of the vegetation.

Fire is the one of the major natural disturbance factors in the Komi pine-dominated forests (Drobyshev et al., 2004a, 2004b; Drobyshev and Niklasson, 2004; Manov and Kutyavin, 2018). Historical stand-level fire frequency in the pine-dominated forests in the region ranged from 60 to 220 years (Barhoumi et al., 2020; Drobyshev et al., 2004b).

A reconstruction of sediment charcoal data in the Komi Republic suggested a gradual Holocene-long increase in fire activity in the boreal Komi, driven largely by the climate, vegetation composition and, possibly, the human use of fires (Barhoumi et al., 2019). However, at the annual scale, fire activity in pine-dominated forests revealed a large temporal variability (Drobyshev et al., 2004b) and its strong connection to the summer drought conditions (Drobyshev and Niklasson, 2004). Human settlements in this region have been shown to modulate climate forcing upon the fire regime, with the distance from a site to the nearest village accounting for 50% of the variation in statistical fit between fire occurrence and tree-ring proxy of fire weather (Drobyshev et al., 2004b).

3.4.2 Human population of the area

A mixture of several nationalities forms the population of the area. The main nationalities are Mansi (Voguls) and Russian people, each featuring characteristic land-use patterns. In the High Middle Ages (1000 to 1500 CE), the territory belonged to the nomadic Mansi people, who were a part of the aboriginal population of the Ural Mountains. Mansi people were involved in hunting, gathering, reindeer herding and fishing (Chagin, 2017; Popova et al., 2012).

During the 1500s–1800s, the area had two major transit portages (volok, in Russian) bridging three important waterways: the Nemski portage connected the watersheds of the Kama and Northern Dvina rivers, while the Pechora portage connected the Kama and Pechora watersheds. The first reference to the Nemski portage dates back to 1517–1520 (Dmitriev, 1893; Zherebtsov et al., 2014). Its abandonment in the 1820s was associated with the construction of the Northern Catherine Canal (Chagin, 2017; Dmitriev, 1893; Rychkov, 1770). The Pechora route was first mentioned in the records in the 1671–1681 period (Chagin, 2017) and the establishment of Ust'-Volosnitsa village has been linked to the route activities (Chagin, 2015; Popova et al., 2012). To increase the storage capacity for the goods transported along the trade routes, several river harbors were established. Two of them were Ust'-Elovka on the Elovka River and Khoroshevskaya harbor on the Pechora River. In 1770, the latter was moved to the current location of the Yaksha village, which is currently the largest village in the area. The establishment of trade routes and villages followed the immigration of Russians into the area from 1650 to the 1700s. Russians worked mostly with various transportation services associated with the trade routes. Since the late 1800s, Russians shaped the timber market by actively engaging in the timber harvesting (Popova et al., 2012). An expedition in the area, arranged in 1912, noted numerous signs of selective cuts in the area (Nat, 1915a, 1915b).

3.4.3 Field sampling

The sampled sites were located within and in proximity to the Pechora-Ilych NBR, within 61°43'–63°16' N and 56°52'–59° 39' E (Fig. 3.1). Using the existing forest road network and the Pechora River, we placed sites by randomly locating points for sampling along the roads and the river. To ensure sufficient site density for estimating the size of individual fires, we kept the distance between neighboring sites within two to five km. We sampled both forested areas and areas with recent clear-cuts, since they both provided material for dendrochronological dating. Mires (mostly fens) were generally not sampled, since these locations were generally devoid of old wood. However, we collected a large number of samples on the interfaces between mires and the drier portions of the landscape. Each site represented an area of two to three hectares. To ensure an equally distributed sampling effort, we inventoried each site during a 1.5–two-hour period, by thoroughly searching the area for the presence of living and dead trees with fire scars. At a site, we inventoried the area, using a combination of the random walk approach and an inventory of the habitats located at the interfaces between more xeric and more humid areas. These locations often host old and fire-scarred deadwood. We used chainsaws to extract wedges from living trees and snags and, in the case of stumps, cross-sections. Between six and 15 samples were collected on each site. We acquired a total of 179 samples of 51 living and 128 dead pine trees. We carried out our sampling in 2016 and integrated this dataset with a portion of the data from our earlier study (Drobyshev et al., 2004a). In particular, we screened the 2004 dataset and selected the oldest sites without a suspected hiatus in site fire chronologies. In total (2004 and 2016 datasets), our analyses operated on 30 sites and 247 trees.

Since all of our sites were located along the transport routes, the fire history reconstructed on these sites might, to a certain degree, reflect the use of fire by the local population. In particular, the use of fire for agricultural purposes, typically in the vicinity of the villages, could inflate the estimates of the natural fire activity as reconstructed on such sites. In this study, we explicitly test this assumption, by analyzing fire return intervals prior to and following the dates of village establishment in the area (see the subsection Analyzing the effect of human settlements below in this section).

To evaluate similarity in fire ignitions over the dendrochronologically reconstructed period and modern times (i.e. the second half of the 20th century), we used records of fires available for the area of the Yaksha section of the reserve, which was partly covered by our reconstruction. The area of the Yaksha section is 15800 ha and has a vegetation cover dominated by pure and mixed pine forests, i.e. similar to the cover of the area sampled for the dendrochronological reconstruction. The record spanned the 1936-1996 period and contained information on the date and origin of recorded fires.

3.4.4 Development of fire chronologies

We air dried and sanded samples with progressively finer sandpapers with up to 400-grit to secure a clear view of the rings and fire scars under a binocular microscope with 40× magnification. We cross-dated samples using the visual pointer year method (Stokes and Smiley, 1968), capitalizing on the point year chronology developed for that area. We provided information on the most useful pointer years in the Appendix B: Text B1. To verify the dating, we correlated sample chronologies with an earlier developed Scots pine ring-width chronology (Drobyshev et al., 2004a). Measuring rings and building ring-width chronologies provided the means to verify the dating quality. To measure tree rings, we obtained high-resolution (2400–3200 dpi) digital images of the samples with a flatbed scanner and used Cybis AB CooRecorder and CDendro 9.0 to measure the rings (Larsson, 2018). As a proxy of correlation strength, we relied on a t-test calculated in the programs COFECHA (Grissino-Mayer, 2001; Holmes, 1999, 1983) and CDendro (Larsson, 2018).

Dating of scars allowed us to associate the 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 identify scar position within a dated ring, which provided information on the seasonal occurrence of fire. We assigned to the fire scars one of the following four categories: no seasonal dating, earlywood scar (a scar located in early, middle and late earlywood), latewood scar (a scar located in early, middle or late latewood), and dormant scar. Dormant scars were located on the interface between two rings. The exact determination of the year for that scar was not possible. In this case, we assigned the year and season, based on the seasonal dating of scars dated at the same site and to the years in question. This approach is supported by the observation that in the parts of the boreal zone with extensive snow cover during the cold season, the "survival" of forest fires over such a period and their occurrences in two consecutive years on the same site are highly unlikely.

3.4.5 Reconstruction of historical FC and identification of FC regime shifts

Spatial reconstruction of fires relied on the fire dates independently identified across the network of sites. To convert point data (i.e. frequency estimates for a site) into the areal estimates, we assumed that a site fire chronology represented the fire history of a certain area centered on the site center, later referred to as unit. By summing up the areas of these units for the years with dated fire events, we obtained an annual chronology of burned areas. The studied territory featured the mosaic of boreal vegetation types that included pine and spruce-dominated stands, transitional mires and, rarely, bogs. Since the Pechora River was the only permanent waterbody in the area, we excluded the proportions of the units containing the river surface from calculations. In the analysis, we tested unit radii ranging from 200 to 600 m, which corresponded to unit sizes of 12.5 to 113.1 ha. By doing so, we wanted to check for the sensitivity of our FC reconstruction to changes in unit size. We elected to use the unit with the size of 78.5 ha (500 m radius), which tends to place the units within one element of the landscape mosaic. We refer the reader to the Supplementary Information section (Appendix B: Fig. S3.2) for the results obtained with other unit sizes. We converted the reconstructed burned areas into the estimates of FC (Van Wagner, 1978), which is the length of time required for the area equal to the total study area to burn:

$$FC = \frac{TSA}{TBA*TI} \qquad (2)$$

where TI is the length of the time period studied (in years) and TSA and TBA are the total studied 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 sections of the area-wide chronology, we adjusted the estimates of the area burned using an earlier developed protocol (Ryzhkova et al., 2020). We estimated fire occurrence as the number of fire years aggregated into 10-year periods in the whole area studied.

We used a regime shift detection algorithm (Rodionov, 2004) to identify changes in FC and fire occurrence over the period covered by the reconstruction (1400–2010, minimum number of sites = 5). The algorithm uses sequential t-tests to identify a regime change. Specifically, a new regime 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. See details of the algorithm used in the context of FC analyses in Ryzhkova et al. (2020). The algorithm was run with the L parameter set to 10, the Hubert weight parameter set to 1 and with the significance level of 0.05. The Rodionov algorithm represented, therefore, the dynamics of fire activity at the level of the whole studied area. To assess the sensitivity of the results to a particular combination of sites, we used bootstrapping to obtain 10% and 90% confidence limits for the FC, resampling our pool of sites 1000 times. We did not introduce any adjustments for the fire occurrence chronology to account for the decline in sampling coverage in the early period. The rationale for that was our interest in avoiding an additional assumption on the spatial distribution of fire ignitions over our study area.

3.4.6 Analysis of association between fire history and environmental proxies

We used superimposed epoch analysis (SEA) to assess the role of climate forcing upon fire activity. In the analysis, we used two LFYs data sets. The selection of the large fire years for the SEA was a trade-off between (a) maximizing the climate forcing upon fire activity in selected years and (b) ensuring sufficient replication of data for the analysis itself. Two “extreme” solutions, i.e. consideration of the largest fire year and the use of all fire years, would make the analysis impossible due to the lack of replication (the first alternative) or due to a diluted climate signal in the fire record (Drobyshev et al., 2012). Keeping these considerations in mind, we selected for the

SEA, the five largest fire years, based on our spatial reconstruction of fire activity in the Pechora-Ilych NBR. This number corresponded to approximately 4% of all fire years dating from 1400 AD. We run two versions of SEA, feeding the routine with years dominated by fires of different seasonality. In doing so, we wanted to test whether the differences in fire seasonality during LFYs have an effect on the statistical significance of the results.

The region of the south-eastern Komi Republic does not currently possess precipitation or drought reconstructions, which could act as a proxy for historic climate variability in fire-prone conditions. We, therefore, elected to use earlywood and latewood width chronologies of Scots pine, developed within the framework of our earlier study (Drobyshev et al., 2004b). These chronologies served as a proxy for early- and late-season drought conditions. To ensure the presence of the drought signals in these chronologies, we run response function analyses correlating that chronology with the Monthly Drought Code (MDC) over the period when both datasets were available (1901-1998). The MDC calculation used the instrumental monthly precipitation total and maximum monthly temperatures from the CRU dataset TS v. 4.02 (Harris et al., 2014). Details on the protocol of MDC calculation are available in Appendix B: Text B2.

Prior to SEA, we fit an autoregressive time series model to the pine chronology, using R function dplR::chron (Bunn, 2010). The routine used Akaike Information Criterion to choose the order of the autoregressive model and Tukey's Biweight Robust Mean to produce the master chronology.

3.4.7 Analyzing the effect of human settlements

To study the association between shifts in fire activity and human activities, we obtained establishment dates for villages or small harbors on the Pechora River from historical sources (Chagin, 2015; Popova et al., 2012; Rychkov, 1770; Sivokha, 2001).

We evaluated differences in the distributions of fire intervals prior to and following the establishment of the villages with a Chi-square test utilizing both complete (uncensored) and censored observations. We combined fire histories of three sites nearest to a village into a composite (village-specific) chronology for three villages located within the sampled area. To represent the probability of a fire in the sites nearest to the villages, we used the survivorship analysis and the Kaplan-Meier estimator (Kaplan and Meier, 1958):

$$S(t) = \prod_{j=1}^{t} \left[(n-j)/(n-j+1)\right]^{\delta(j)}, \quad (3)$$

where S(t) is the site survivorship function estimated for a period t; n is the total number of observations; $\prod$ is the product (geometric sum) across all cases less than or equal to *t* (in years), and δ (j) is a constant that equals 1 in case of complete and 0 in case of censored intervals. In the context of the current study, survivorship was understood as a probability for a site to escape fire over period *t*.

3.5 Results

We dated 449 fire scars found on 247 dated samples corresponding to a total of 106 unique fire years, from both currently developed and earlier published datasets combined (Fig. 3.2). The fire chronology for the study area covered 739 years, with the first fire dated to 1271 CE and the most recent fire dated to 2010 CE. To ensure sufficient density of sites for spatial reconstruction of fire activity, we selected the period from 1400 to 2010, for which each year was represented by at least ten sites (Fig. 3.2). Fire seasonality was successfully identified for 65% of the fires. Our evaluation of the fire season based on the intra-annual position of scars showed that 97% of fires occurred during the growing season, 60% of scars were in the earlywood and 37% were in the latewood. Dormant-season fires constituted 3% of all scars dated with seasonal resolution.

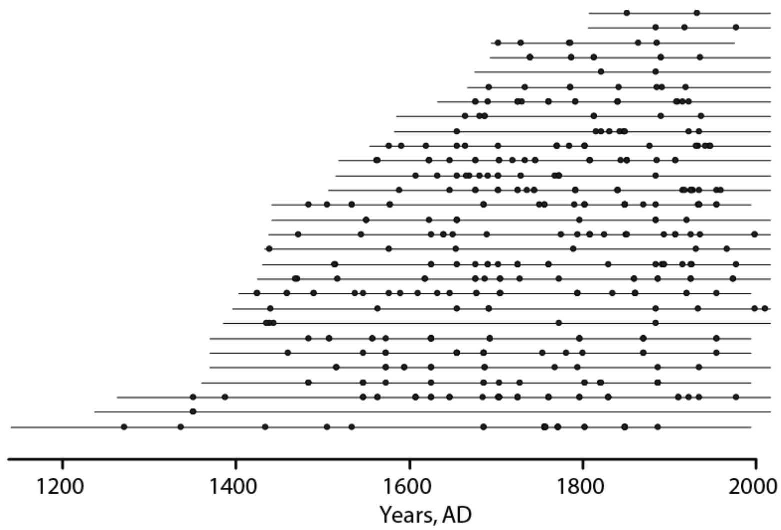

Figure 3.2 Dendrochronological reconstruction of the fire history in the Pechora-Ilych BR over the 1271–2010 period. A single straight line represents each study site, and a dark circle represents a fire event.

We assessed the regime shifts separately for the FC (Fig. 3.3a) and for the fire occurrence (Fig. 3.3b). In the reconstructed area burned, we observed four periods with FC changes according to regime shift analysis (Table 3.1 and Fig. 3.3a). In the earliest epoch, 1340–1610 CE, the mean FC was 66 years with a 90% confidence envelop of 57–79 years. In the next epoch, 1620–1730 CE, the FC was reduced to 33 years and then increased to 47 years during 1740–1950 CE. In the latest epoch, 1960–2010 CE, the FC increased to 152 years with a confidence envelop of 102–270 years.

We identified three regimes in the historical dynamics of fire occurrence since 1340 CE. During the first period, 1340–1660 CE, fires occurred at a relatively low rate (1.52 per decade) (Table 3.1 and Fig. 3.3B). The fire occurrence was maximum (3.55 fires per decade) during 1670–1950 CE. In the latest period, 1960–2010 CE, the number of the fires (0.83 per decade) had declined two to fourfold, as compared to the previous period.

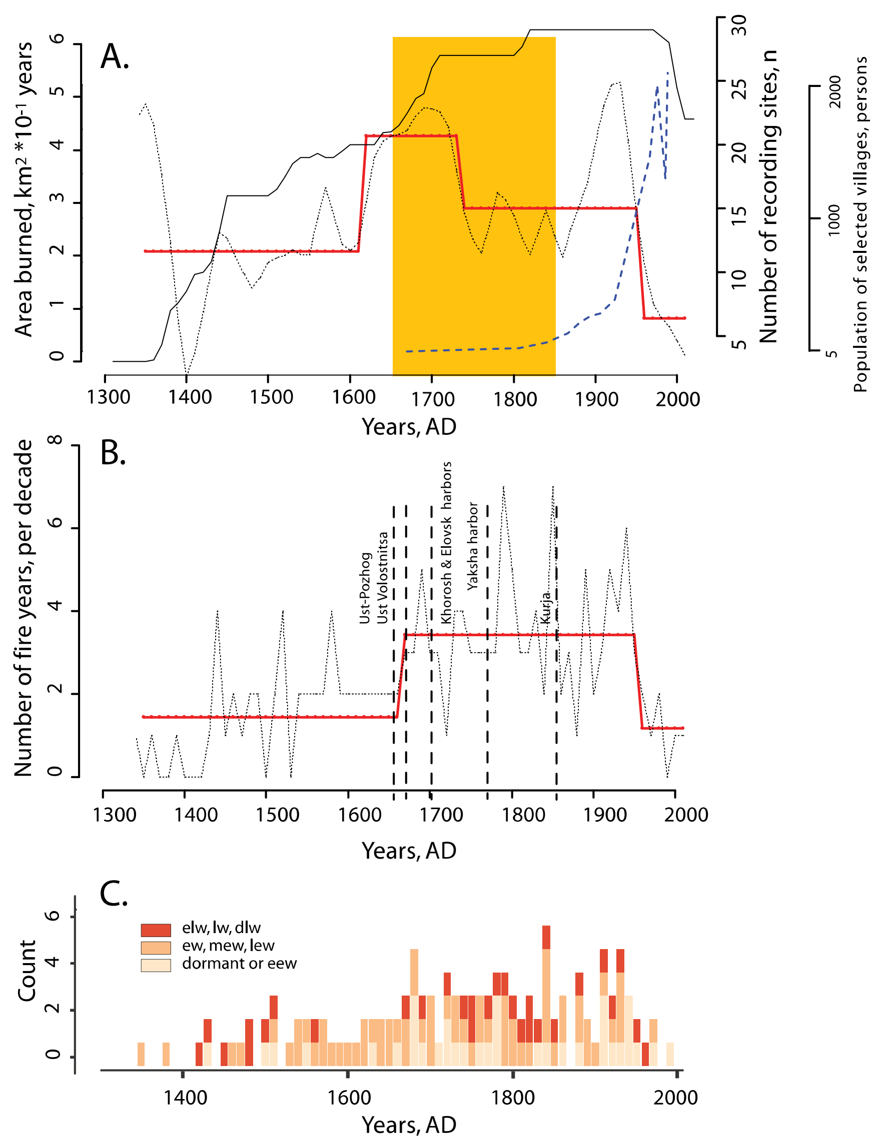

Figure 3.3 The reconstructed burned area (A) and the number of fire years (B), both per decade, are shown by the black dashed lines. Shifts in the FC (A) and the fire occurrence (B) as identified by the regime shift analysis (Rodionov, 2004), are represented by red lines. Site replication (A) is shown by the black solid lines. Blue dashed line indicates dynamics of the total population of four villages (Ust' Pozheg, Yaksha, Kurja and Ust' Volosnitsa) (Sivokha, 2001). The period when villages were established is indicated by yellow bar (A). The establishment date of settlements is shown by solid dash lines (B). (C) – dynamics of fire seasonality, for fires dated with seasonal resolution. The abbreviations for the seasons of the dated fire scars: elw – early latewood fire, lw – latewood, dlw – dormant latewood, ew – earlywood, mew – middle earlywood, late earlywood, eew – early earlywood.

Table 3.1 Reconstructions of the FC and fire occurrence in the Pechora-Ilych NBR for the periods identified by the regime shift analysis.

Statistics	Epoch, years CE	Mean, years	95 % CI lower bound	95 % CI upper bound
FC	1340–1610	66	56.77	78.55
	1620–1730	33	30.98	34.68
	1740–1950	47	41.89	52.00
	1960–2010	153	102.47	270.29
Decadal fire occurrence	1340–1660	1.52	1.18	1.85
	1670–1950	3.55	3.10	3.96
	1960–2010	0.83	0.67	1.50

The response function analysis confirmed the presence of early- and late-season drought signals in the earlywood and latewood pine chronologies, respectively (Figs. 3.4A and 3.4B). Earlywood chronology exhibited a significant negative correlation with May Monthly Drought Code (Fig. 3.4A). This was consistent with the assumption that negative anomalies in the earlywood chronology reflected drier-than-average conditions and indicated periods with increased fire risk early in the fire season. The latewood chronology revealed a significant positive correlation with September Monthly Drought Code (Fig. 3.4B), justifying its use a proxy for late season fire weather conditions.

The five largest years selected for SEA were 1625, 1655, 1573, 1563, and 1676 (in order of the amount of area burned). During these years, the fires burned 12.6, 10.2, 6.3, 5.5, and 5.5 km^2, respectively. Out of these years, the three largest featured mid-season fires (1625, 1655, and 1573), and two – early-season fires (1563, 1676).

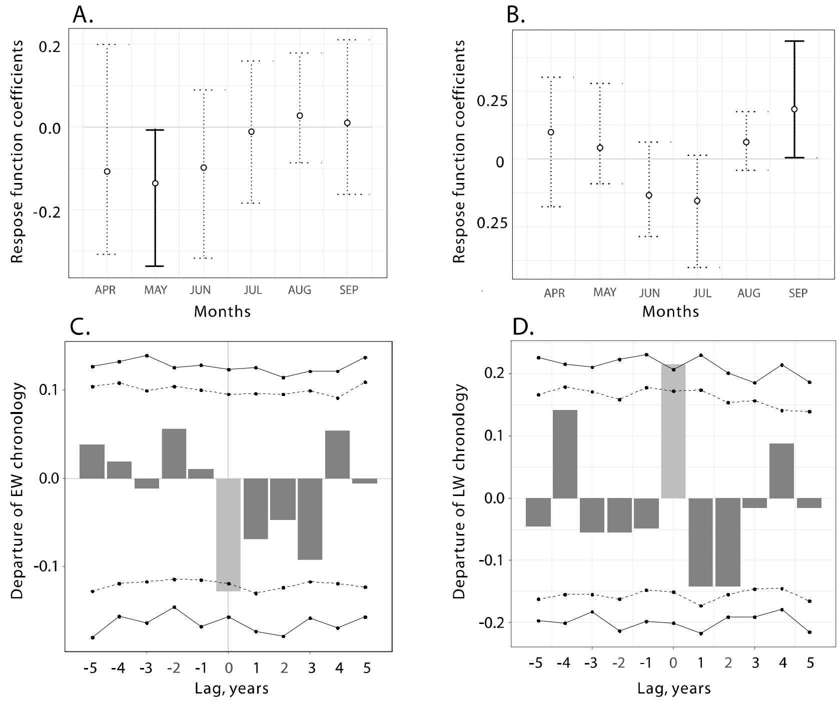

Figure 3.4 Response function analysis of the earlywood (A) and latewood (B) Scots pine chronologies, used as a proxy of fire weather conditions, and Monthly Drought Code (MDC) during April through September. C and D are the results of superimposed epoch analyses (SEA): C – SEA on the largest fire years in the Pechora-Ilych BR (all - early- and mid-season fires) and the earlywood chronology (n = 5), and D – SEA on the largest late season fire years and the latewood chronology (n = 5). Solid lines on A and B refer to significant response function coefficients. Dashed and solid lines in C and D refer to the 0.95 and 0.99 confidence intervals, respectively, as estimated by bootstrapping.

SEA revealed a significant ($p = 0.04$) negative departure of earlywood pine chronology during these years (Fig. 3.4C). Since none of these years featured late-season fires as the dominant type of fire events, we re-run the analysis using the five largest fire years with fires in the late season. These years were 1686 (4.7 km^2 burned), 1702 (5.5 km^2), 1761 (3.14 km^2), 1885 (5.5 km^2), and 1934 (3.9 km^2). We observed a significant positive departure of the latewood chronology (Fig. 3.4D), which was consistent with the notion of drier-than-average conditions at the end of the fire season during these years. The site survivorship function, reflecting time-dependent probability for an area in the vicinity of the village to escaping a fire event, showed a non-significant (p =

0.07-0.20) increase in the fire occurrence for the period following the village's establishment (Fig. 3.5 and Appendix B: Fig. S3.3). For example, during the period prior to the village establishment, the site nearest to the village had an approximately 50% probability of escaping fire after 30 years since the last time it burned. This probability was, on average, only 25% after the village establishment dates. The pattern, although non-significant, was consistent across other combinations of number of sites and the period lengths considered (Appendix B: Fig. S3.3). Observational records of fires in the Yaksha section of the reserve over the 1936–1996 period documented 60 fires ignited by lightning strikes, which corresponded to 0.63 ignitions per km^2 and year.

3.6 Discussion

For the past 670 years, the forest fire has been a common disturbance agent in the Scots pine dominated forests of the Pechora-Ilych NBR. The fire activity revealed a considerable historic variability: the early period (1340 to 1610 CE) had a FC of 66 years, followed by a period (1620–1730 CE) of an increase in fire activity (FC = 32 years) and then two periods with progressively decreasing fire activity. Since then1960s, the estimated FC was 153 years, the longest over the last 600 years that was covered by our reconstruction. The dynamics of FC and fire occurrence, and the SEA results representing largely the period prior to 1900 (Fig. 3.4), suggested that climate was a driver of the FC prior to the 20th century, while human activities were the factor controlling decadal fire occurrence. We discuss these findings in detail below.

3.6.1 Impacts of land-use changes on the historical fire regime

The presence of the temporary hunting camps and sites identified as mammoth burial grounds suggested that human occupation of the area around the Pechora-Ilych NBR started in approximately 40 000 BC (Degteva et al., 2015; Guslitser and Kanivets, 1965; Pavlov et al., 2004). Although human presence in the area has been well-documented since that time, it is unlikely that it had a tangible impact on fire regimes. There is no evidence suggesting that ancient humans used even rudimentary slash-and-burn agriculture during this period (Degteva et al., 2015). From ~900 CE until the late 1700s, nomadic Mansi (Voguls) people had inhabited this area, subsisting mainly on reindeer herding, hunting, fishing and gathering (Chagin, 2012; Melnikov, 1852; Sokolova, 2009). The use of fires by the Mansi people in the pine-dominated forest of the Pechora-Ilych NBR is currently being debated (Abramov, 2017; Aleinikov, 2017a; Golovnev, 1993; Slezkine, 1994). It has been hypothesized that Mansi people could have burned mesic spruce forests in the upper reaches of Pechora, e.g. spruce forests of Myrtillus type, to maintain early successional stands dominated by young deciduous trees as forage grounds for moose, which were hunted (Aleinikov, 2017b). However, the common pine lichen forests in the study area were unlikely targets for such burns, since they served as winter pastures for the reindeers until the late 1800s. Records document the fear from the local population of escaping fires that could destroy reindeer feeding grounds (Milovanovich, 1926; Varsanofieva, 1929). Similarly, studies in the Nordic countries have suggested that reindeer herders were careful in their use of fire because it removed the ground lichens (Collins et al., 2011; Laestadius, 1833; Sarvas, 1937; Wallenius et al., 2005; Wretlind, 1934), with their recovery taking up to 100 years in this forest type (Gorshkov et al., 1996).

FC did not reveal changes associated with the colonization waves (refuting H1.1), while a change in fire occurrence was synchronized with the second colonization wave, supporting H1.2 (Fig. 3.2). The first wave of colonization was formed by Russians coming from the East and dates back to the middle of the 1400s. Russians pushed the Mansi people eastwards, into the highlands of the Ural mountains (Glushkov, 1900; Popov, 1892). Development of the network of portages was both the sign and the driver of this colonization wave. The earliest portage, the Nemski portage route, dates back to 1517–1520, and was actively used until the construction of the Northern Catherine Canal in the 1820s (Chagin, 2017; Dmitriev, 1893; Rychkov, 1770).

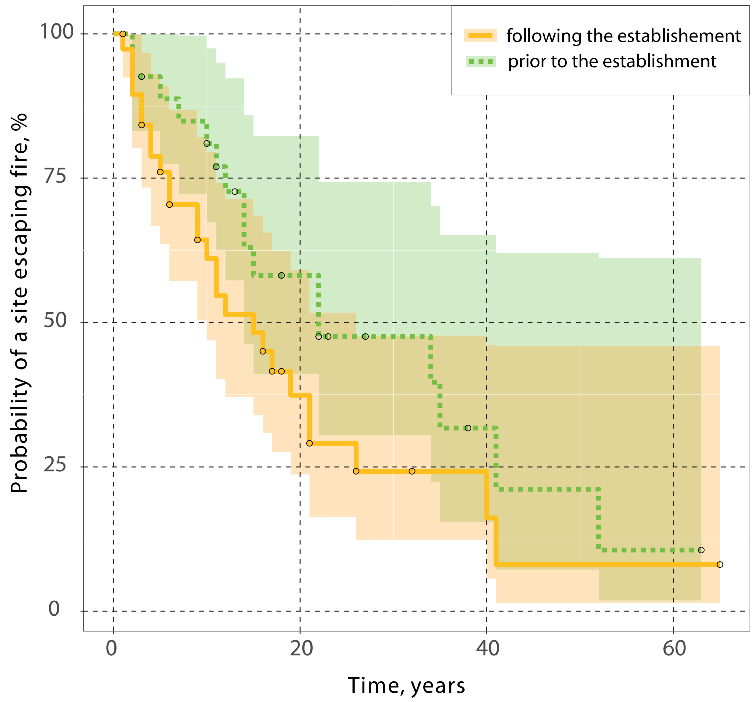

Figure 3.5 Effect of village establishment on the frequency of fires in the neighboring sites, as estimated by the Kaplan-Meier estimator. Green and red lines represent the dynamics of the probability for a site to escape fire along the time gradient. The 95% confidence intervals are shown as shaded areas of the respective colors. Small empty circles represent fire return intervals on the studied sites.

The second wave of Russian colonization began in the second half of the 1600s, followed by the establishment of new trade routes. The Pechora route, first referenced between 1671–1681 (Chagin, 2017), contributed to the increase in the traffic of commercial goods between the basin of the Pechora River with the basin of the Kama, a tributary of the Volga (Korchagin and Lobanova, 2012; Popova et al., 2012; Zherebtsov et al., 2014). Since the late 1600s, and possibly earlier, people from the Perm region actively traveled into the Upper Pechora area to fish and hunt (Lashuk, 1958). These activities might contribute to fire ignitions and the amount of burned areas. A similar pattern has been documented in Fennoscandia, where hunter and shepherd camps were sources of ignitions (Groven and Niklasson, 2005). In the studied area, this development resulted in the establishment of homesteads, each consisting of one to five families, between 1670 and 1810 (Zherebtsov, 1972). Their livelihoods relied on fishing, hunting, and their services as construction workers to build barges on the trade route between the river Kama basins and the Pechora area. The appearance of these homesteads, often as small harbors on the Pechora River, coincided with the doubling of the decadal fire occurrence in the area (Table 3.1, Fig. 3.2). We propose that this pattern was a result of human activities contributing with additional sources of ignitions that are consistent with hypothesis H1.2. However, village-centered analysis showed a non-significant increase in fire occurrence (Fig. 3.4), suggesting a limited effect of these ignitions, even on the local scale.

Fire cycle and fire occurrence in the Pechora-Ilych NBR appeared to be driven by different sets of factors. Indeed, in contrast to fire occurrence (i.e. the frequency of fire years, estimated at the decadal scale), there was no obvious temporal synchrony between the dynamics of the FC and known trends in regional colonization events, which disproved the hypothesis H1.1. Specifically, the dynamics of the FC did not reveal any synchrony with the second colonization wave: the increase in fire activity (i.e. the shortening of the FC) occurred half a century earlier, around the 1610s. The increase occurred about one century after the onset of the Nemski portage activities (1517 CE). We also noted that the shorter FC was associated with the period of minimal population density, while the onset of the longer FC happened during the late 1700s, the period when the portage-centered transportation activities were at their highest.

A common view of the fire history of the European boreal forest is that human forest use and particularly – slash-and-burn agriculture, resulted in higher fire activity (Lehtonen and Huttunen, 1997; Niklasson and Granström, 2000; Rolstad et al., 2017; Wallenius et al., 2004). This pattern may not hold in the Upper Pechora region. At the beginning of 1600s, the use of fire to create arable land in the Upper Pechora was very limited due to climate conditions that were unfavorable for cultivation and generally infertile soils (Krivoshchekov, 1914; Popov, 1801). The wheat and rye was actually delivered to the Upper Pechora through the Pechora portage (Zherebtsov et al., 2014).

An expedition diary into the study area in early 1800s reads: "There were few people that are engaged in agriculture: rye rarely ripen, and they do not have a profit from cattle breeding either. Hunting is the main trade" (Latkin, 1843). The importance of Yaksha harbor and Ust'-Volosnisa, the first Russian village established in 1671 (Popova et al., 2012; Sivokha, 2001), as principal hubs on the Pechora trade route further disfavored investments in agriculture, and in particular – in slash-and-burn practices. However, historical records documented the building of riverboats, including steamships in Ust'-Volosnisa (Aleinikov and Chagin, 2015; Krivoshchekov, 1914; Popov, 1801), suggesting that the clearing of the forest and eventual human-related ignitions did occur in proximity to the villages.

Continuing colonization of the area by Russians contributed to a population increase during the 1800s – 1900s (Popova et al., 2012; Sivokha, 2001). The increase in the economic value of timber and profit from the transportation services drove economic development at that time. Barge building, fishing and fur extraction were popular occupations among the local population, until the late 1800s (Sivokha, 2001). The increasing presence of humans in the forest likely contributed to additional ignition sources. However, our reconstruction did not indicate an increase in the fire occurrence nor in the amount of burned area during that period, indicating that the effect of these land-use patterns on the fire regime was minimal. We speculate that a combination of few slash-and-burn activities, a rudimentary fire control, and a progressively less fire-prone climate in the post-LIA era could explain the observed pattern.

The earliest available documented evidence of fires in proximity to the Pechora-Ilych NBR dates back to forestry reports of the late 1800s and early 1900s, indicating that the majority of the fires were caused by lightning strikes (Cherdyn Regional Museum. Forestry Fund., 1910, 1894) (Table 3.2). The report listed four fires, three of which were present in our dendrochronological record. One of these years, 1885, was noted as a year with just six ha burned in a single fire. In contrast, the dendrochronological reconstruction identified this year as the year with one of the largest amounts of reconstructed area burned in the studied area since the 1400s. Two other fires, in 1887 and 1907, were dated as multi-site fires, with the location of the sites corresponding well to the fire localization in the forestry records (Table 3.2). The size of the 1907 fire was probably larger than the size reported in the historical sources, since it affected a large portion of the area outside the area the historical records focused on. This comparison suggests that historical sources, while providing important information on fire occurrence, may significantly underestimate the level of fire activity, with the bias likely to be substantial in sparsely populated regions. Some impact of general economic recession following the coup-d'état of 1917 and the establishment of the Pechora-Ilych NBR in 1930 that effectively halted most of the traditional activities in the area (Aleinikov et al., 2015; Degteva et al., 2015) might further reduce fire activity, by lowering the number of human-related ignitions. The observed decline in fire activity that occurred around the 1960s likely reflected the onset of active fire suppression. Effective fire suppression in Russia began in the early 1930s, following the establishment of the forest protection program based on aerial reconnaissance and air-borne fire suppression brigades. Demobilized military paratroopers joined these brigades, following the end of World War II (Kozubov and Taskaev, 1999; Stocks and Conard, 2000). The 1960s also mark the onset of the extensive use of helicopters by the Russian Aerial Forest Protection Service (Avialesookhrana) (Bryukhanov and Korshunov, 2017), coinciding with the shift from high to significantly lower fire activity in the Pechora-Ilych NBR. Until the early 1990s, Russia had the world's largest fire suppression system, which led to the successful reduction of the burned area, especially around settlements (Goldammer, 2006). The State Forest Enterprise (Lespromkhoz) drove industrial-scale harvesting operations in the area during 1940–1960s (Popova et al., 2012). Road building in connection with these activities improved the possibility of suppressing fires (Kozubov and Taskaev, 1999).

Table 3.2 The earliest forestry records on forest fires in the proximity of Pechora-Ilych NBR (Cherdyn Regional Museum. Forestry Fund., 1910, 1894).

Date	Area burned, ha		Location	Notes from forestry records
	reported	reconstructed		
1875, September	N/A	not recorded	In proximity of Ust'-Elovka harbor	N/A
1885, August 27	6	3.86 km^2 (386 ha)	Vogulka river	"The cause of the fire is unknown. Surface fire, growing pines were not damaged"
1887, July 20	1250	1.55 km^2 (155 ha)	Right coast of the Volosnitsa river, along the portage and south to the Vogulka river	"Lightning-ignited fire. Young pine-dominated forests were burned down"
1907, July 1–2	110	0.77 km^2 (77 ha)	1 km far away from Ust'-Volosnitsa village	"Lightning-ignited forest fire following a severe drought"
1907, July 6–8	N/A		Yaksha route	"Lightning-ignited forest fire following a severe drought"

3.5.2 Climate and fires

Lack of regional reconstruction of drought conditions, preserving variability at both low and high frequency bands, makes it difficult to convincingly discuss the role of climate in shaping fire activity in the Pechora-Ilych NBR. Since the region lies on the eastern fringes of the European boreal domain, it is generally not represented by reconstructions done in more western sections of boreal Europe. Analysis of recent dynamics of fire weather suggest, in fact, that summer drought conditions over the Komi Republic tend to be in antiphase with those in the western section of Northern Europe (Drobyshev et al., 2021). To address this challenge, we relied on the earlywood and latewood pine chronologies, which were sensitive to the drought conditions in the study area (Fig. 3.4A).

SEA revealed a significant ($p = 0.04$) negative departure of the earlywood pine chronology in the analysis with the five largest fire years (all – early- and mid-season fires) and a significant ($p = 0.01$) negative departure of the latewood chronology for the largest late-season fires (Figs. 3.4C and 3.4D). The pattern was broadly consistent with the notion of LFYs occurring during drier-than-average conditions that supported hypothesis H3. Since the five largest years included both early- and mid-season fires, the significant results of SEA suggested that spring droughts might predispose high levels of fire activity towards the mid-season. This pattern has been recently demonstrated in the attribution study of the 2018 fire season in Sweden (Krikken et al., 2019). The early season fires were likely of lightning origin: such fires in the European part of the Russian boreal zone have been reported to predominantly occur early in the fire season, due to fuel-drying high pressure cells being common early in the fire season (Kurbatsky, 1976; Stolyarchyuk and Belaya, 1982). In Russian fire literature, this period has been known as "May-June forest fire belt (Melekhov, 1946). The association between LFYs dominated by late-season fires and the latewood chronology exhibited a higher degree of statistical significance (as compared to the earlywood chronology), possibly pointing to the stronger climate forcing upon late-season fires.

Concerning the low-frequency variability in fire activity, we documented an increase in forest fire activity in the early 1600s. The region of southern Komi currently lacks precipitation or drought reconstructions which extended over the period covered by our fire reconstruction, which would support discussion of low-frequency trends in climate forcing upon fire activity. However, borehole temperature reconstructions have indicated that the temperature in the Ural region was approximately one degree lower during the 1600–1800s, as compared to the year 2000 (Pollack et al., 2003), supporting a wider pattern of cooling of the Northern Hemisphere during the LIA. It follows that the observed pattern was broadly similar to the pattern observed in the Northern Hemisphere boreal forest, where shortening of fire cycles (i.e. increase in the amount of area burned) tends to coincide with the cold period of the LIA with unstable atmosphere and the dominance of dry Arctic air masses over the boreal region (Bergeron and Flannigan, 1995; Drobyshev et al., 2016; Gagen et al., 2011). This suggests climate forcing this shift. Indeed, the timing of the increase in fire activity in the study area was not synchronized with a shift in the land-use patterns of the region, as suggested by the history of land-use and, specifically – the dates of village establishments. The relative role of climate vs. fire suppression in the decline in fire activity since the 1960s remains unclear, although it is highly probable that fire suppression played a role in this dynamic (see the previous sub-section).

3.6.3 Ecology and fire regime of the Komi pine-dominated forests

Extending the analyses to the less exploited sections of the European boreal zone provides a possibility to better parameterize the role of fires in shaping disturbance regimes of this biome. Modern lightning ignition frequency in the studied forests was 0.63 per km^2 and year. This is much higher than previously reported for other sections of the European boreal region. For example, in central and northern Sweden these levels have been estimated at 0.05–0.15 per km^2 and year (Granström, 1993). The difference might be due to a variation in the density of lightning flashes. The majority of the Komi Republic experiences two to four lightning flashes per km^2 and year, which is considerably higher than in the Swedish central and northern boreal regions (0.2–0.6 flashes per km^2 and year, Cecil, 2006).

Under an assumption that a fire year corresponded to a single fire within our study area, the reconstructed ignition frequencies in the Komi boreal forests were at the range of 0.02 to 0.03 per km^2 and year. These estimates were close to those obtained in the Swedish boreal forest. We noted, however, that more than 75% of the years in the modern dataset had multiple lightning-ignited fires within a single year, which indicated that our historical estimates of ignition frequencies were overly conservative. Reanalysis of the modern dataset under the same assumption (i.e. assuming that one fire year “hosts” a single fire) gave 0.25 ignition per km^2 and year, i.e. a three-fold decrease. Adjusting for this bias in the reconstructed data would result in ignition frequencies in the range of 0.05–0.08 per km^2 and year over the reconstructed period. The reasons for the large difference between the modern and reconstructed ignition frequencies are less clear. We can speculate that a portion of smaller fires were not picked up by our reconstruction. These fires were common among lightning ignited fires in the modern dataset, with 33% of all these fires were below one ha and 53% below five ha.

Both variability in ignition frequencies and frequencies of fire-prone episodes likely contributed towards high variability in the FC prior to the onset of the modern fire suppression era. We documented two-fold changes in the FC between the most and least fire-prone periods over that time (Table 3.1). However, we observed a limited variability in the absolute estimates of the fire cycles under generally low levels of human forest use. Indeed, prior to the 1960s, the variability in the reconstructed FC was limited from ~30 to 70 years. The observation highlights a degree of resilience of the boreal fire regime to variability in climate settings. The fact that we reconstructed such short fire cycles during the 1800s, the period when most Fennoscandian studies have documented a sharp decline in the fire activity (Granström and Niklasson, 2008; Lehtonen et al., 1996), supports the notion of that decline being driven primarily by the change in land-use patterns, and not climate variability.

Since our sampling protocol excluded humid sites with very limited availability of fire-scarred and old trees, our FC estimates reflected predominantly a more xeric portion of the landscape. This explains why most of the previous studies reported longer FCs (see reviews in Ryzhkova et al. 2020; Wallenius 2011). Such short FCs and commonly observed multiple scars on living and dead trees pointed to low severity of the historical fires, which did not impede pine regeneration in the studied stands. Low-severity surface fires are often considered as a characteristic feature of the Eurasian boreal fire regimes (de Groot et al., 2013), and our study supports this assertion. The dominance of early-season fires (Fig. 3.3) (Shvidenko and Nilsson, 2000), which occur when deep organic layers are still well-hydrated following the snow melting, is a feature of the seasonal fire dynamics that likely keeps the fire severity low and also removes the portion of fuels which would be available for late-season fire activity. It also appears that such short fire cycles were controlled, to a considerable degree, by fuel accumulation rates (Schimmel and Granström, 1996) rather than the frequency of extreme fire-prone periods. Fuel recovery time in both Eurasian and North American boreal forests has been reported to approach a few decades (Bernier et al., 2016; Schimmel and Granström, 1997). A study of a gradient of boreal forest types in North American boreal forest has estimated fuel recovery times in most of the forest types to vary between six to 30 years (Thompson et al., 2017). Both estimates are well consistent with the suggestion of an important role of fuel recovery in controlling fire cycles in the pine-dominated Komi forests and is of direct relevance for the development of nature-based fire management strategies (Adams, 2013; Bergeron et al., 2001; Swetnam et al., 1999).

Does the variability in reconstructed FC prior to the onset of modern fire suppression reflect the dynamics of its natural drivers? We tend to answer positively to this question. Previous studies of fire activity in Fennoscandia have consistently pointed to the strong influence of human colonization (Niklasson and Granström, 2000; Rolstad et al., 2017; Wallenius, 2011), and the impact of in forest-use practices (Hellberg et al., 2009; Lehtonen et al., 1996; Wallenius et al., 2004) on forest fires in European boreal forest. In our study, however, we observed no synchronization between the colonization waves and the dynamics of the fire cycle. Although earlier analyses of historical records has suggested that Russian colonists played an important role in shaping the historical fire regimes in Upper Pechora (Aleinikov, 2019; Aleinikov and Chagin, 2015), these impacts might have been relatively local and largely limited to the dynamics of fire occurrence. Humans did affect FC in these ecosystems, but it happened as late as in the 1960s, about one to two and a half centuries later than in

Fennoscandia (Lehtonen et al., 1996; Niklasson et al., 2010; Pinto et al., 2020; Wallenius, 2011). The pine-dominated forests of the Komi Republic may, therefore, hold a unique position as the ecosystem with the shortest history of human-related shifts in fire cycles across the European boreal region.

3.7 Acknowledgements

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IV. PDO DYNAMICS SHAPE THE FIRE REGIME OF BOREAL SUBARCTIC LANDSCAPES IN THE NORTHWEST TERRITORIES, CANADA

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4.1. Résumé

Les reconstructions spatiales explicites de l'activité des feux dans le nord-ouest de la forêt boréale canadienne sont rares, bien qu'elles soient essentielles pour modéliser les régimes de perturbation actuels et futurs et la dynamique forestière. Nous présentons une reconstruction dendrochronologique de l'activité historique des feux le long de la Route 3 dans les Territoires du Nord-Ouest (TNO), Canada, au sein de la zone boréale subarctique. Nous avons daté 129 incendies ayant eu lieu entre 1202 et 2015, à partir d'échantillons de 479 pins gris (*Pinus banksiana* Lamb.) vivants et morts portant des cicatrices de feu. Trois périodes distinctes se dégagent en termes de cycle de feu (CF) et d'occurrence des feux. Dans un premier temps (1340-1440), l'activité des feux était faible (CF=572 ans; 1 feu/décennie), avant d'augmenter considérablement entre 1460 et 1840 (CF=171 ans; 4,45 feux/décennie), puis encore davantage dans les périodes récentes (1860-2015; CF=95 ans; 7,63 feux/décennie).

Le climat a joué un rôle important dans les changements de fréquence des feux et des cycles de feu dans les TNO depuis les années 1300. Les décennies 1440 et 1850 correspondent à des périodes d'intensification de l'activité des feux, synchronisées avec des passages de phases négatives à positives de l'Oscillation Décennale du Pacifique (ODP). Depuis le milieu des années 1800, les activités humaines ont peut-être contribué à l'augmentation de l'activité des feux, bien que le climat demeure le facteur principal. Durant le 20e siècle, les années de grande superficie brûlée correspondaient à des périodes plus sèches que la moyenne, associées aux phases positives de l'ODP, ce qui suggère que l'activité des feux dans la région étudiée est encore influencée par le climat. Les téléconnexions spatiales entre l'ODP, la sécheresse et les années de grands feux (AGF) dans les TNO révèlent des relations persistantes entre les régimes de circulation océan-atmosphère et l'activité des feux. La dynamique de l'ODP offre un fort potentiel pour prédire les risques régionaux d'incendies dans le nord-ouest de l'Amérique du Nord.

Mots-clés : Echangement climatique, perturbations naturelles, paysage boréal, régime de feu, aléas naturels, circulation océan-atmosphère

4.2 Abstract

Spatially explicit reconstructions of fire activity in northwestern boreal Canada are rare, despite their importance for modelling 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 having 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.

Keywords: climate change, natural disturbances, boreal landscape, fire regime, natural hazards, ocean-atmosphere circulation

4.3 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 and 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) that block zonal atmospheric circulation (Johnson & Wowchuk, 1993; Justino et al., 2022; Skinner et al., 2002). During such events, the lack of rainfall and the predominantly meridional flow of warm air rapidly dry out forest fuels over large areas, increasing the climatological fire hazards and, eventually, 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 and Shabbar, 2011; Macias-Fauria and Johnson, 2006). Large-scale atmospheric circulation patterns, therefore, define 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 dominated the causes of forest fires (Wallenius, et al., 2011), while others suggest a stronger climate control (Hanes et al., 2019; Macias-Fauria and 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, the long-term fire dynamics remain poorly understood.

We developed a 680-year spatially explicit reconstruction of 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 pines trees (*Pinus banksiana*). The reconstructed period included the Little Ice Age (LIA, ~1300-1850s, 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.

4.4 Material and methods

4.4.1 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; Fig. 4.1). 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 (-6 to - 8°C) and July the warmest (15 to 16°C). Annual precipitation averages 280 to 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 a 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).

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).

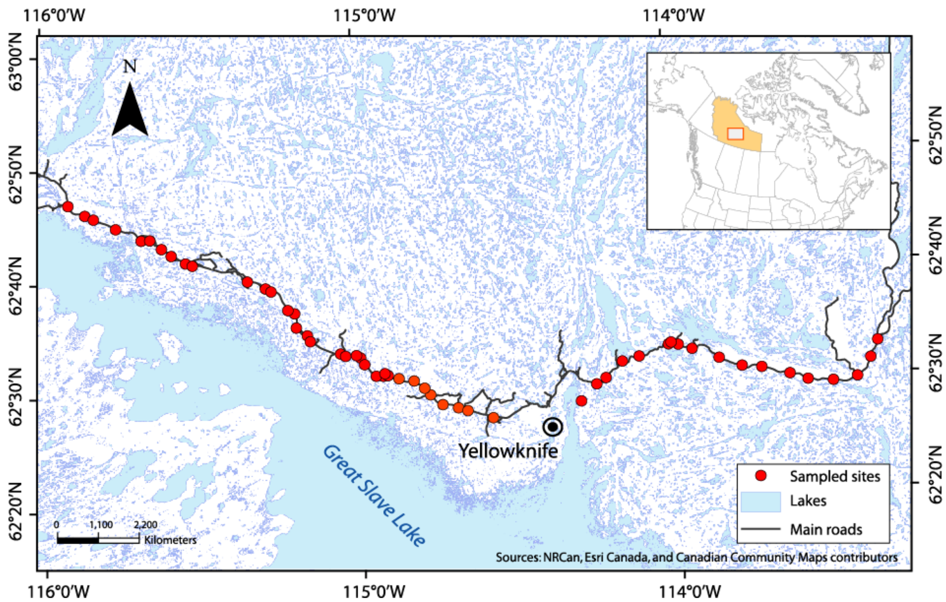

Figure 4.1 Location of the study area and sampled sites in the Northwest Territories (NWT), Canada.

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).

4.4.2 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 and 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, e.g., 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 (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 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).

4.4.3 Field sampling

Sampling sites were located in proximity to Yellowknife, NWT (Fig. 4.1). 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 two hours. The sampling was carried out by two experienced teams in parallel with partially overlapping "zones of responsibility", i.e., 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", i.e., 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.

4.4.4 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 40× magnification. We cross-dated cross sections using the visual pointer year method (Stokes and Smiley, 1968), capitalizing on the pointer year chronology developed for that area. Information on the most useful pointer years is provided in Text C1 of the Appendix C. To measure tree rings, we obtained high-resolution (2400–4800 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, 1999, 1983) 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).

4.4.5 Reconstruction of historical fire cycle and identification of fire regime shifts

The spatial reconstruction of fires relied on the 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 up 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 requires 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 6000 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 distance 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), i.e., 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 “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., 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:

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

The regression provided us with an estimation 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", 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 analysis of dendrochronological reconstruction of fire activity are provided in (Ryzhkova et al., 2020).

4.4.6 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 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).

4.4.7 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 hydro climate (Liu et al., 2017; van der Schrier & Barkmeijer, 2007; Shabbar, Bonsal et al., 1997). 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 and 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., 2021, 2017). The typical periodicity for the PNA is two to three 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 the ENSO is three to five 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 and 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, e.g., prior, during and following the LIA. Here, we used a tree-ring-based reconstruction of the PDO based on limber pine (*Pinus flexilis*) growing in California and Alberta, which spans over 1000 years to cover periods with contrasting climate regimes (MacDonald & Case, 2005).

4.4.8 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 values of climate 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) 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.

4.4.9 Climate-fire associations in the modern record

We used superposed epoch analysis, SEA (Grissino-Mayer and 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.

4.4.10 Population data

To assess the relationship between fire activity and human presence, we developed a chronology of population density covering 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 covered both the NWT and Nunavut, we used combined NWT and Nunavut population data after 1991 to track population trends in the NWT.

4.5 Results

We dated 349 fire scars found on 479 samples, corresponding to a total of 129 unique fire years (Fig. 4.2). 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 ten sites (Fig. 4.2).

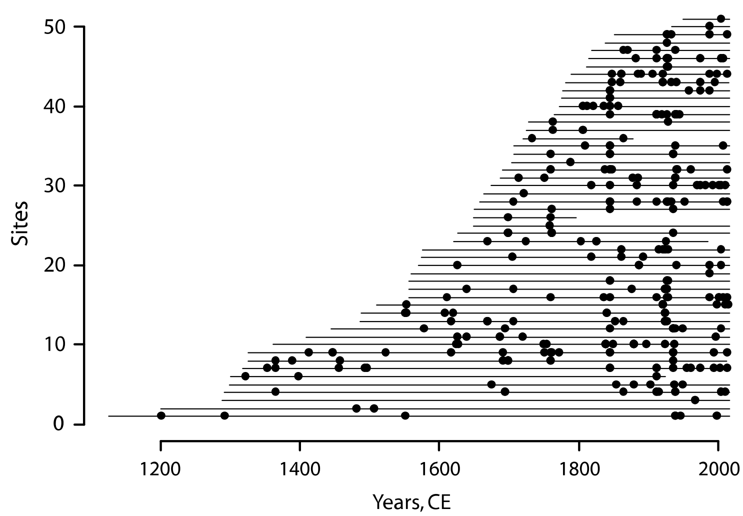

Figure 4.2 Dendrochronologically reconstructed annual fire history of the NWT over 1200–2018 CE. A single straight horizontal line represents a site, and a dark circle represents a fire event. Each line extends over the period covered by chronologies of at least five trees.

We assessed the regime shifts separately for the FC (Fig. 4.3A) and for the decadal fire occurrence (Fig. 4.3B). During the 1340–1440 CE, the mean FC was 572 years (95% confidence intervals, CI 400.4–1000.9 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 4.1, Fig. 4.3A). 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 4.2).

Table 4.1 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

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 4.1 and Fig. 4.3B). 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 (Appendix C: Fig. S4.6). Our dataset 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 towards increased fire activity as reconstructed from fire scar data (Fig. 4.3A). The temporal resolution of the regeneration data remains limited, precluding further detailed conclusions on fire regime dynamics across the landscape.

Table 4.2 Reconstructed ignition frequencies in the study area of the Northwest Territories for three periods identified by regime shift analysis. See Methods section for explanations concerning the types of estimates.

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

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 (Fig. 4.4). 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, i.e., 3% of all fires dated with seasonal resolution, occurred in the dormant season.

We observed an association between a shift towards positive PDO and reconstructed fires. The observed shifts from negative to positive phases of the PDO in 1460 and 1840 CE (Fig. 4.3D) coincide with increases in fire activity (Fig. 4.3A). Modern fire data indicated that positive phases of the PDO during the 1975-1995 CE period and since 2015 CE were associated with a higher frequency of LFYs (Table 4.3 and Fig. 4.5). The other climate indices (ENSO and PNA) did not show any significant association with LFYs (Appendix C: Figs. S4.2, S4.3 and Table S4.1).

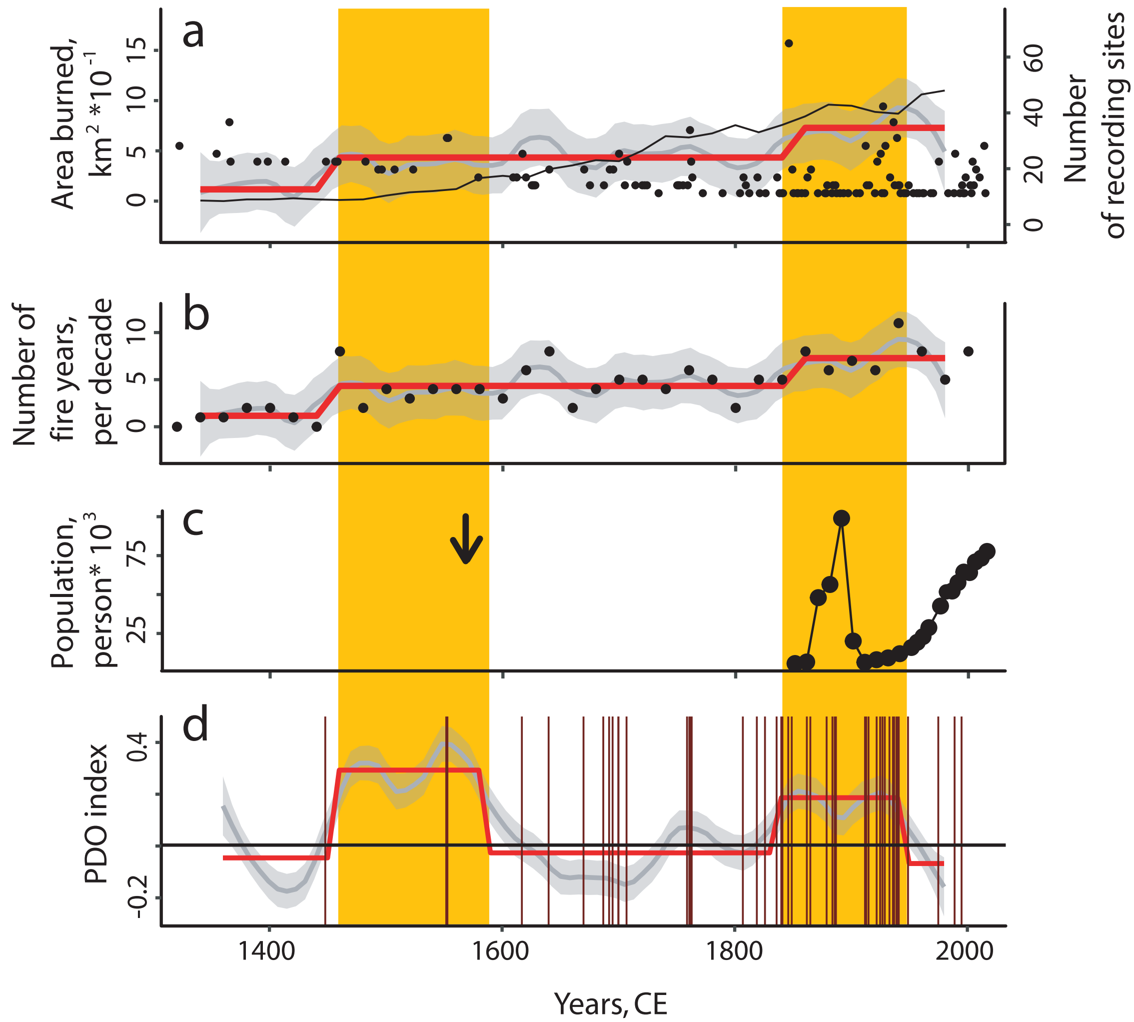

Figure 4.3 Reconstructed burned area (a) and number of fire years (b), both per decade; chronology of population density of the Northwest Territories (c); and Pacific Decadal Oscillation (PDO) (MacDonald, and Case, 2005) (d). Red solid lines in (a), (b) and (d) indicate the changes in fire regime identified 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) and (d). Black dots in (a) and (b) represent values for single fire years. Vertical dark-red bars on (d) represent fire years that occurred at two or more sites. Grey-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).

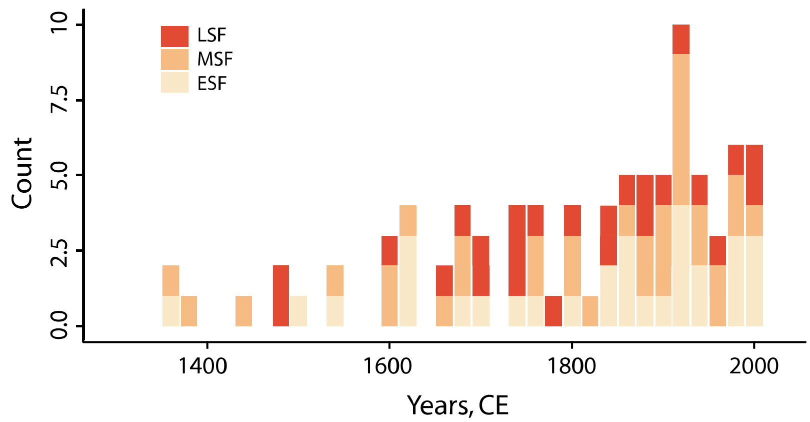

Figure 4.4 Reconstructed fire seasonality across the Yellowknife region. ESF – early season fires, MSF – mid-season fires, and LSF – late season fires.

Table 4.3 Contingency analysis of the large fire year (LFY) frequencies under positive/negative states of the Pacific Decadal Oscillation (PDO, MacDonald, & Case, 2005). 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 statistical significance of differences between observed and bootstrapped values.

Climate indices	Frequency of events, years		Percentiles	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

The contingency analysis showed that the majority of LFYs occurred during the positive phase of the PDO (Table 4.3, Fig. 4.3D). 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 percentiles of the bootstrap-derived distributions of fire year frequencies during positive PDO phases (Table 4.3).

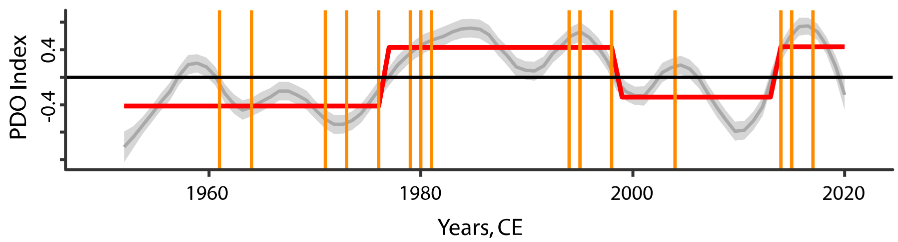

Figure 4.5 Pacific Decadal Oscillation (PDO) chronology (MacDonald, and Case, 2005) thin grey line, smoothed with a spline function) and modern large fire years (LFYs) (vertical orange lines). The thick red line shows the outcome of regime shift analysis (Rodionov, 2004). The solid gray horizontal line refers to the PDO long-term average.

Modern LFYs occurred during years with low scPDSI and positive PDO (Fig. 4.5 and Fig. 4.6A). Low scPDSI values (indicative of drought conditions) occurred during the same years as LFYs (Fig. 4.6A), and positive PDO correlated with drier-than-average conditions across the study area (Fig. 4.6B, 4.6C).

4.6 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 1600-1700s CE (Lewis et al., 2019; Wallenius, et al., 2011) and relied on fire interval data (Bothwell et al., 2004; de Groot and 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, hence 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.

4.6.1 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 towards higher fire activity (in the mid-1400s and mid-1800s) coincided with shifts from negative to positive phase of the PDO (Fig. 4.3D and Fig. 4.5). In line with this observation, periods with positive PDO had a higher frequency of LFYs as compared with periods with negative PDO (Table 4.3).

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 and 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), leading to enhanced meridional flow of air masses and the intrusion of warmer and 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 (Fig. 4.6B, 4.6C). In turn, the persistence of warm and dry weather contributes to the development of a water deficit in the 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 (Fig. 4.6A).

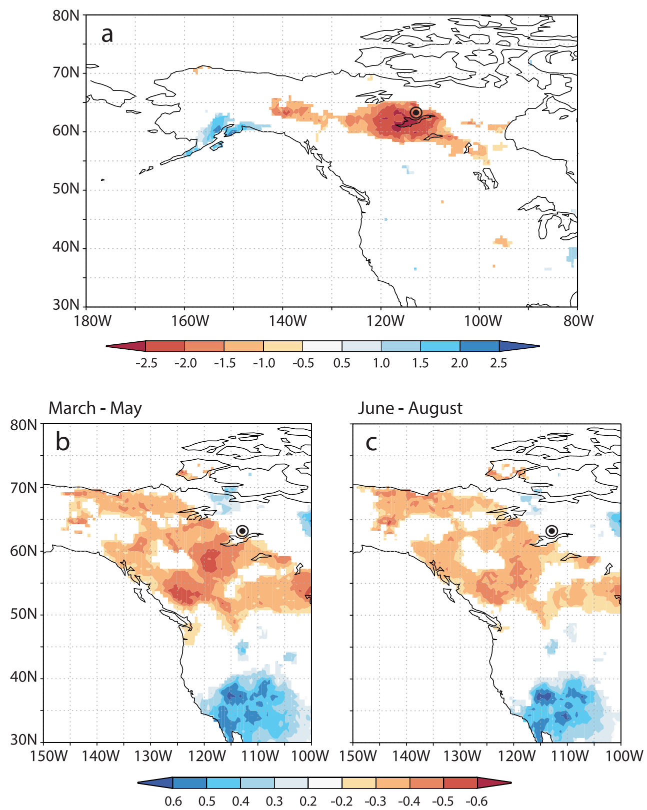

Figure 4.6 Teleconnection between the northern North Atlantic and fire weather in the Northwest Territories (NWT). (a) Superposed epoch analysis of the self-calibrated Palmer's Drought Severity Index scPDSI (Wells et al., 2004) from June to August and LFYs in the NWT over the 1959–2019 CE. Note that 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 significance of the correlation coefficient being 0.10 or lower.

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), which is one of the longest FC reported for conifer-dominated circumboreal forests in the northern Hemisphere (Larsen and MacDonald, 1998; Niklasson and 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 and 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 et al., 1997b). 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 towards 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 and Flannigan, 1995; Drobyshev et al., 2016; Gavin 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 (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 (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 (Appendix C: Figs. S4.4-S4.5).

We lack a definitive explanation for the absence of a decline in fire activity following a shift from a positive to a negative PDO phase in the late 1500s (Fig. 4.3D). 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 (Fig. 4.3A). 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 next section). 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.

4.6.2 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, they 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 4.1, Fig. 4.3A), i.e., 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 (Fig. 4.3A and 4.3B).

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 the introduction of cold-resistant crops occurring 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 from our 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.

4.6.3 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 4.3). These estimates are in concordance 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 ridge often leads to the formation of thunderstorms and lightning systems that favor ignitions (Macias-Fauria and Johnson, 2008; Skinner et al., 2002).

4.6.4 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. 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 one-year lead-time, would be highly instrumental in operational planning and preparedness. However, the actual response of the 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 generally less conducive to fire (NCEI, 2023). Its evolution towards a positive phase over the next several decades should increase fire activity in the boreal subarctic of the NWT. Paleoecological reconstructions from the same region indicate that past increases in fire activity incurred changes in vegetation cover: the proportion of deciduous (primarily paper birch and trembling aspen) and jack pine had been increasing 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.

4.7 Acknowledgements

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V. GENERAL CONCLUSION

Disentangling the role of human activities and climate on fire activity is a complicated task, as the two closely interact at multiple temporal and spatial scales. The results of this thesis demonstrate the complex relationship between climate and humans in determining fire regimes in circumboreal forests. Forest fire activity in the circumboreal biome remains strongly linked to annual climate variability. Humans have been an important agent of change in boreal fire activity over the last 200 years, influencing fire regimes through slash-and-burn agriculture and associated clear-cutting, and more recently - through fire suppression policies.

In the Republic of Karelia, we have shown several lines of evidence indicating that climate was a major factor in increasing fire activity in the early 1600s, while anthropogenic impacts likely contributed to its decline in the early 1900s (Chapter II). An increase in fire activity in the early 1600s coincided with a decrease in reconstructed spring streamflow, indicating drier conditions during the LIA, a pattern previously noted in other studies (Bergeron and Flannigan, 1995; Drobyshev et al., 2016; Gagen et al., 2011). Periods of increased fire activity in Kalevalsky NP were associated with the formation of Scandinavia blocking during the summer, which contributed to drier forest fuels (Drobyshev et al., 2016; Seftigen et al., 2013). The dramatic increase in fire activity in the early 1600s occurred at a time when local population densities were very low, suggesting that climate was the primary driver at that time. In contrast, the decrease in fire activity in the early 1900s was likely due to changes in forest management practices, particularly the increased emphasis on timber production.

A study of historical fire regimes in boreal forests of the Republic of Komi has underscored the significant role of human influence in controlling fire occurrence, while climate emerged as the main factor controlling the amount of burned area (Chapter III). Village establishment in the area around the 1650s coincided with an increase in fire occurrence. However, there was no clear relationship between village establishment and area burned. Changes in the fire cycle were not synchroniszed with dates of village establishment. We observed a strong association between large fire years and spring droughts, suggesting that climate was the primary driver of FC in these forests.

For northwestern Canada, we demonstrated that climate variability, PDO in particular, is the dominant force controlling regional fire (Chapter IV). Years with significantly higher fire activity in the reconstructed and modern fire records were consistently associated with the positive phases of the PDO. This suggests that the Pacific Ocean climate is likely an important control on future boreal fire activity in the western sections of North American boreal forest. The PDO has been in a negative phase since 2018, making it less conducive to fire. As the PDO evolves towards a positive phase, a suggested return to drier climate regimes will imply an increase in the area burned in the boreal subarctic of the NWT.

5.1 Comparison of Canadian and Northern European boreal forest fire regimes

The fire regime of the Canadian boreal forest is typically dominated by high-severity, stand-replacing crown fires (Flannigan et al., 2009; Kasischke and Stocks, 2000). Our results (Chapter IV) indicate, however, that the fire regime of subarctic boreal landscapes in the NWT does not fully conform to this pattern, but instead exhibits characteristics of a mixed-severity fire regime. Sites on rocky outcrops with jack pine-dominated stands exhibited a discontinuous canopy and fragmented fuel bed, conditions that reduce the likelihood of high-intensity crown fires. The presence of multiple fire scars in 39.4% of sampled trees (with at least two scars) and a relatively short mean fire return interval (62 years) suggest that these rocky sites experienced frequent, low- to moderate-intensity surface fires, rather than being predominantly shaped by stand-replacing events. This pattern is consistent with observations in jack pine forests in very dry habitats in Quebec, where open canopy pine stands were associated with a mixed-severity fire regime (Smirnova et al., 2008). In open jack pine stands, where fuel discontinuity and drier conditions limited crown fire spread, moderate-severity fires were shown to be more frequent.

Low severity surface fires are a characteristic feature of Eurasian boreal fire regimes (de Groot et al., 2013), and our study supports this assertion (Chapters II and III). Fire dynamics in the boreal forests of Northern Europe are closely related to the dominant tree species. In pine-dominated forests, surface fires are more common, but stand-replacing fires can also occur (Aakala and Kuuluvainen, 2011; Wallenius et al., 2004). The natural loss of older cohorts over time makes it difficult to reconstruct the severity of past fires, but multiple fire scars on both live and dead trees, coupled with the abundance of coarse woody debris, suggest that low-severity surface fires historically dominated the eastern European boreal landscape. Mean fire return intervals in pine-dominated eastern European boreal forests (39 years in Kalevalsky NP and 48 years in Pechora-Ilych NBR, respectively) were comparable to those in northwestern Canada. It appears that such short fire return intervals were controlled, to a considerable degree, by fuel accumulation rates (Schimmel and Granström, 1996; Shvidenko and Nilsson, 2000) rather than the frequency of extreme fire-prone periods. Fuel recovery times in both Eurasian and North American boreal forests have been reported to approach a few decades (Bernier et al., 2016; Schimmel and Granström, 1997). A study of a gradient of boreal forest types in North American forests has estimated fuel recovery times in most of the forest types to range from six to 30 years (Thompson et al., 2017). These estimates strongly support the idea that fuel recovery plays a key role in regulating fire return intervals in the pine-dominated boreal forests of northwestern Canada and eastern Europe. This finding is directly relevant to the development of nature-based fire management strategies (Bergeron et al., 2001; Swetnam et al., 1999).

Research methods for reconstructing fire history should consider the characteristics of fire regimes, because fires can affect forests in ways that depend on their frequency, severity, and extent. Although age analysis is the most commonly used method for reconstructing disturbance histories in systems dominated by stand-replacing events (Bergeron, et al., 2017; Portier et al., 2016; Reed, 2000; Weir et al., 2000), it provides only a coarse estimate of regime change that is further degraded for older regeneration chronologies. Historical fire regimes in the boreal forests of North America have largely been reconstructed using methods designed to capture infrequent stand-replacing fires (Bergeron, et al., 2017; Reed, 2000) that burn thousands of hectares (Kasischke and Turetsky, 2006). As a result, low-intensity fires have often been underestimated or ignored. Our methods reconstructed fire regimes at finer spatial and temporal scales, and we detected frequent low-severity fire events that have been largely overlooked in North American boreal forests (Alfaro Sánchez et al., 2024). Our results indicate that low-severity fire events were frequent, widespread, and an important component of the fire regime of subarctic boreal landscapes in northwestern Canada. Detecting and quantifying variability in fire regimes that include frequent, low-severity fires and infrequent, high-severity fires is a critical step in identifying the ecological consequences of altered fire regimes (McLauchlan et al., 2020) and understanding the implications of altered fire dynamics in circumboreal forests.

5.2 Management implications

Understanding regional fire regimes provides critical knowledge for the effective management of forest fires and their impacts, which is particularly important in the context of climate change (Stephens et al., 2013). Projections for western North America indicate warmer temperatures, earlier snowmelt, and longer fire seasons with increased drought, potentially leading to more frequent, larger, and more severe wildfires (Flannigan et al., 2009, 2005; Qin et al., 2023). These climate impacts may be exacerbated by land use change, fire exclusion, and urban expansion (Moritz et al., 2014). Adapting forest management to climate change requires understanding the impacts of climate on forests, industries, and communities; predicting how these impacts may change over time; and incorporating this knowledge into management decisions (Boulanger et al., 2025; Keenan, 2015). A preventive approach is essential in the face of uncertain global warming. Monitoring of PDO trends can improve fire risk assessments by identifying periods of increased fire hazard in the boreal subarctic (Ryzhkova et al., 2025), which can aid in resource allocation and preparedness for fire-prone periods (Bergeron et al., 2004; Macias-Fauria and Johnson, 2006). This approach may extend regional climate-sensitive fire management strategies that use models to predict forest fire risk at monthly, seasonal, and above-annual time scales (Eden et al., 2020; Raita-Hakola and Pölönen, 2024). A better prediction of future fire activity should help limit the economic and social impacts of fires (Coogan et al., 2019), and specifically - preserve ecosystem services (Cuerrier et al., 2015), and minimise the costs associated with firefighting (Stocks and Martell, 2016), which requires increasingly significant material and human resources (Hope et al., 2016).

In the boreal forests of Eastern Europe, fire has historically been a major disturbance (Barhoumi et al., 2020; Ryzhkova et al., 2022, 2020), but today it is a rare event (Drobyshev et al., 2021), which in itself is a threat to biodiversity. Therefore, maintaining fire in forest landscapes is essential, but the negative aspects of fire also have to be considered. Although future fire activity is uncertain, there are indications that forest fires will become more frequent in certain regions of northern Europe due to global warming (Lehtonen et al., 2016). Conservation management of the eastern fringes of the European boreal zone should therefore recognize the role of this disturbance agent. A balance needs to be struck between fire suppression activities dictated by the economic value of the forest and the risk of fire to human life and infrastructure, on the one hand, and the maintenance of fire as a driver of vegetation dynamics, on the other. The value of this nature-based approach has been convincingly demonstrated in a wide range of ecosystems where fire is the primary disturbance (Clear et al., 2013; Conedera et al., 2009; Peterson and Reich, 2001). Prescribed fire may be the key to preserving fire ecological functions (Granström, 2001; Kuuluvainen et al., 2002). In addition, increased pressure on forest ecosystem goods and services in the future is expected to have negative impacts on biodiversity, highlighting the need for effective conservation measures. Although the value of prescribed fire for biodiversity conservation is widely recognized, more research is needed to increase the effectiveness of prescribed fire there (Koivula and Vanha-Majamaa, 2020; Kuuluvainen et al., 2002).

5.3 Research prospects

Circumboreal forest ecosystems are exposed to a higher degree of warming than the global average as a result of warming-induced environmental changes (Cunningham et al., 2024; Ummenhofer and Meehl, 2017). These changes could affect different ecosystem services, such as carbon storage and biodiversity preservation, and also impact the availability of forest products (Adams, 2013; Allen et al., 2024; Bergeron et al., 2001). Boreal forests are experiencing increased extreme fire events (Cunningham et al., 2024), resulting in extraordinary carbon dioxide emissions and smoke (Zheng et al., 2023). A 2021 was an anomalous year because the North American and Eurasian boreal forests synchronously experienced their largest water deficits. Increasing numbers of extreme fire events and stronger climate-fire feedbacks challenge climate mitigation efforts (Zheng et al., 2023). Indeed, generally extreme events rather than average changes have the greatest impact on ecosystems and human populations (Stocks et al., 2002). This is why policymakers need not only knowledge of extreme fire events, but also robust risk assessments, predictive tools, and adaptation strategies that can guide proactive management.

In a context where extreme fire years could multiply in the future, it is important to continue improving our understanding of the factors governing LFYs. Further dendroecological studies in areas with relatively high (e.g., eastern Siberia) and low (e.g., eastern Europe) fire activity are appropriate to obtain a broader coverage history of fire regimes in the boreal biome. Despite a large amount of dendroecological work on forest fires in circumboreal forests, we still lack replicated and adequately resolved multi-century estimates of area burned in individual landscapes, especially in the Siberian cector of the boreal biome. This lack of data hinders analyses of long-term variability in fire regimes, their effects on successional pathways, contribution to the C cycle, and resilience to future climate change. Adequate reference and verification datasets provide the basis for interpreting past and modeling future fire activity. This knowledge is also critical for understanding sub-regional patterns of fire activity across the boreal biome, especially in the context of recent studies suggesting region-specific responses of fire regimes to future climate (Girardin et al., 2009; Marlon et al., 2009). To characterize fire regimes more broadly and to better understand the spatiotemporal dynamics of extreme fire years, it would be necessary to incorporate information on fire severity (Whitman et al., 2018). In addition, the operation of high-resolution models and improved monitoring systems targeting extreme fire years should be developed (Walsh et al., 2020). Modeling techniques for boreal ecosystems and fire regimes could be improved by incorporating climate-fire interactions, fine-scale fuel dynamics, and post-fire vegetation recovery rates for more accurate and realistic simulations (Kim et al., 2024; Molinari et al., 2020; Schuur et al., 2008). Further work is also needed on the effects of extreme fire years on ecosystems and human societies, to guide forest management agencies towards management practices designed to limit fire-related threats in the regions concerned.

APPENDIX A - MULTI-CENTURY RECONSTRUCTION SUGGESTS COMPLEX INTERACTIONS OF CLIMATE AND HUMAN CONTROLS OF FOREST FIRE ACTIVITY IN A KARELIAN BOREAL LANDSCAPE, NORTH-WEST RUSSIA

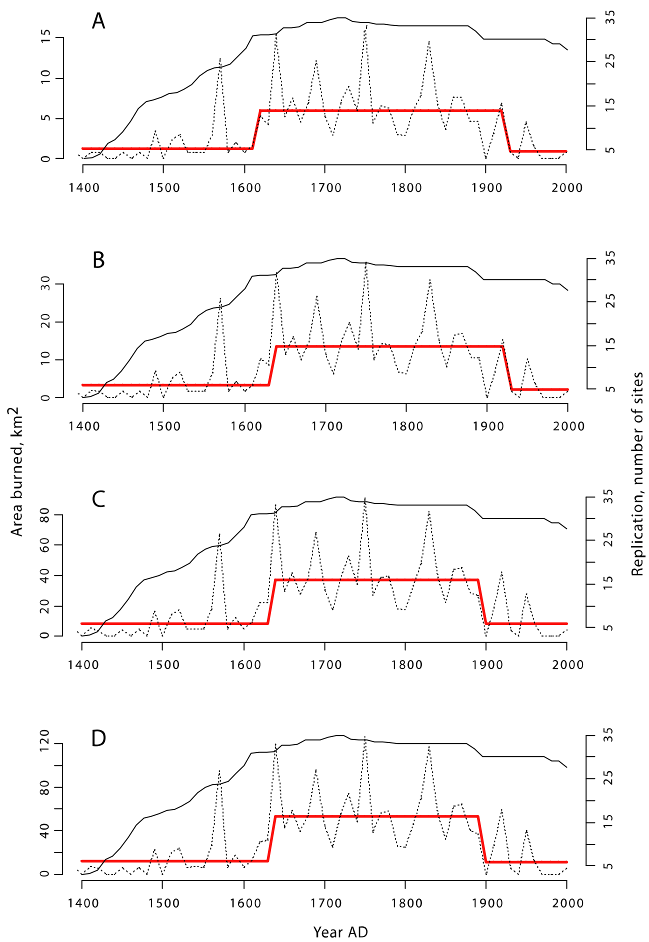

Figure S2.1 Dynamics of the FC for (A) unit size of 78.5 ha, corresponding to a circle with 500 m radius; (B) unit size of 177 ha with 750 m radius; (C) unit size of 491 ha with 1250 m radius; and (D) unit size of 707 ha with 1500 m radius in the Kalevalsky NP over 1400–2010 AD. Dashed lines represent burned area in km^2 and a decade. Red line show periods with similar fire cycle as identified by regime shift analysis (Rodionov 2004) using a 10-year window. Solid black line indicates represents sample depth.

APPENDIX B - CLIMATE DROVE THE FIRE CYCLE AND HUMANS INFLUENCED FIRE OCCURRENCE IN THE EAST EUROPEAN BOREAL FOREST

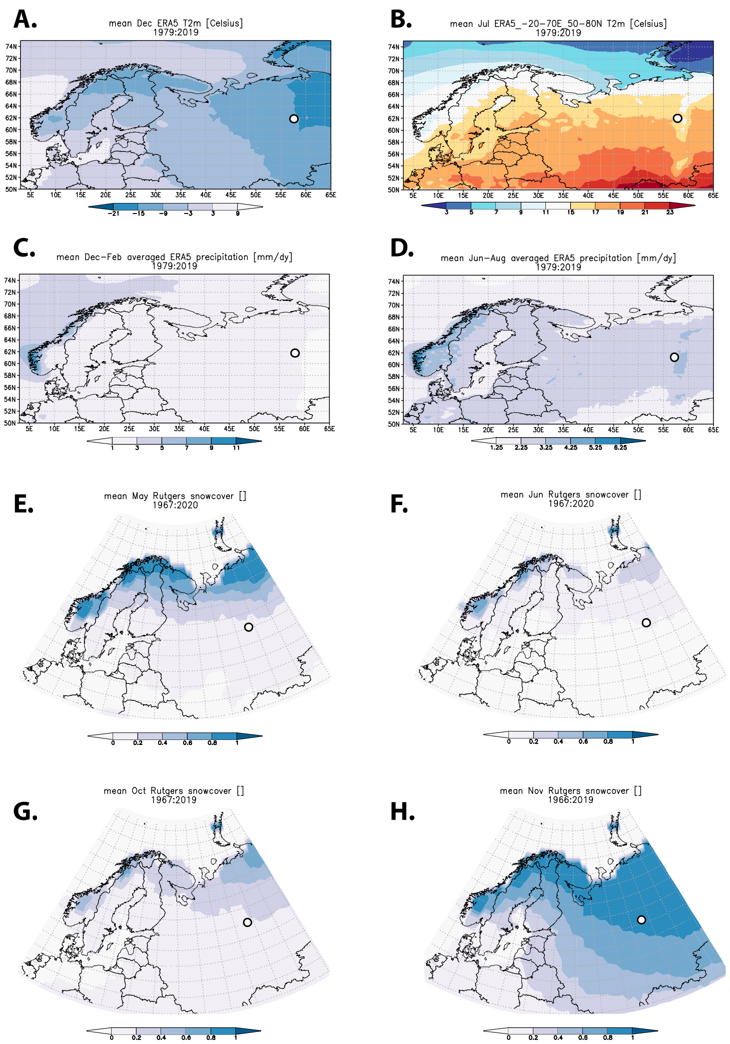

Figure S3.2 Climatology of the EBZ, based on the ERAS 5 reanalysis data. The snow cover data are available from https://doi.org/10.7289/V5N014G9. A – mean December temperature, B – mean July temperature (both - in degree Celsius), C – mean winter (DJF) precipitation, D – mean summer precipitation (both – in mm/day). Snow cover depth, in m, for May (E), June (F), October (G) and November (H). The empty circle represents the study area.

Text B1. The list of the most useful "pointer year" rings in the Yaksha Scots pine chronology.

The following rings were instrumental in dating:

1993 (wide ring and dark latewood),

1992 (a ring with narrow latewood),

1969 (a narrow ring with pale latewood),

1862 (a narrow ring with pale latewood),

1861 (a wide ring with dark latewood),

1799, 1789, and 1779 (all with narrow latewood),

1728 (a wide ring with dark latewood),

1699 (a narrow ring and pale latewood),

1698 (a wide ring with dark latewood),

1601 (a ring with pale latewood),

1551 (a wide ring with dark latewood),

1466 (a narrow ring with pale latewood),

1378 (narrow latewood),

1296, 1282, and 1281 (all wide rings with dark latewood),

1280, 1278, and 1274 (all with narrow rings with pale latewood)

Text B2. Calculation of the MDC.

The MDC value is calculated as

$$MDC = (MDC_0 + MDC_m)/2\ ,$$

where MDC0 is the value of the index at the end of the previous month and MDC_m is the estimate of the drought code (DC) value at the end of the focal month. In turn, MDC_m is calculated as

$$MDC_m = 400 \ln (800/Q_{mr}) + 0.25E_m,$$

where

$$Q_{mr} = 800e^{(DC_{HALF}/400)} + 3.937RM_{EFF}$$

where $RM_{EFF} = 0.83r_m$. If $Q_{mr} > 800$ in the equation above, then Q_{mr} should be set equal to 800. E_m is the potential evapotranspiration, which is is calculated as follows:

$$E_m = N\,[0.36\ \ (TempMax) + L_f]\ .$$

Here *TempMax* is the monthly mean of daily maximum temperatures, L_f is the standard day length adjustment factor, and *N* is the number of days in the month.

DC_{HALF} is the value drought code at the middle of the month:

$$DC_{HALF} = MDC_0 + 0.25\ E_m\ .$$

In turn, DC is calculated as

$$DC = 400 \ln (800/Q_r) + 0.5E_d,$$

Where E_d is the daily version of potential evapotranspiration and Q_r is the moisture equivalent in the organic soil layer after rain. Further detail in MDC calculation is available in (Girardin and Wotton, 2009).

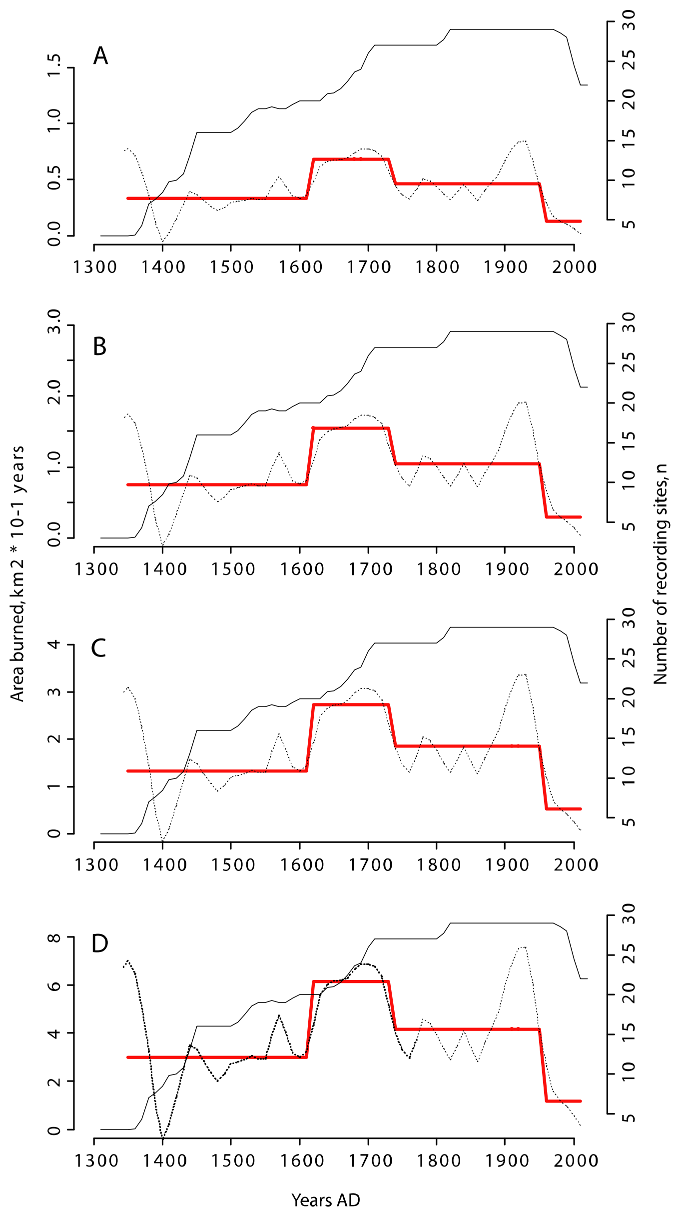

Figure S3.3 Dynamics of the FC for (A) unit size of 12.5 ha with 200 m radius; (B) unit size of 28.3 ha with 300 m radius; (C) unit size of 50.3 ha with 400 m radius; and (D) unit size of 113 ha with 600 m radius in the Pechora-Ilych NBR over 1300–2010 AD. Dashed lines represent burned area in a decade. Red line show periods with similar FC as identified by regime shift analysis (Rodionov, 2004) using a 10-year window. Solid black line indicates represents sample depth.

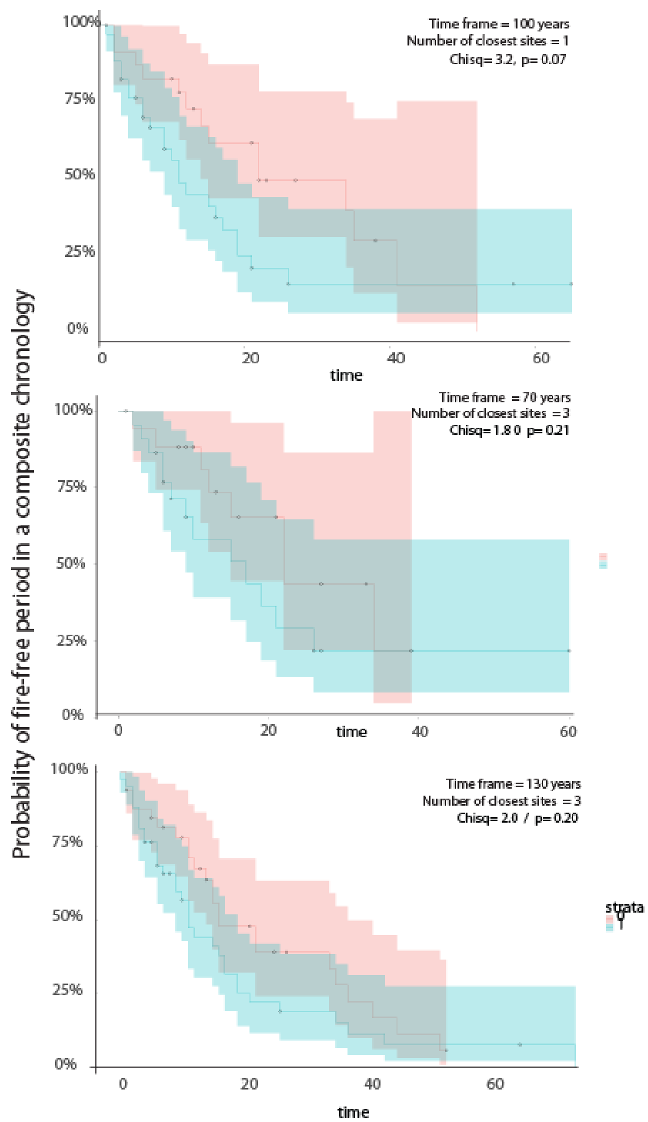

Figure S3.4 Effect of village establishments, as revealed by survivorship analyses with varying input parameters. Red color represents the period prior to village establishment and the blue color – period following the village establishment. The number of sites considered, and the length of periods compared for particular analysis are indicated on each graph.

APPENDIX C - PDO DYNAMICS SHAPE THE FIRE REGIME OF BOREAL SUBARCTIC LANDSCAPES IN THE NORTHWEST TERRITORIES, CANADA

Text C1. The list of the most useful "pointer year" rings in the Yellowknife jack pine chronology. The following rings were instrumental in dating:

2014 (narrow and pale latewood);

1991, 1984 and 1957 (all with dark latewood);

1975, 1964 and 1927 (all with narrow latewood);

1836 (narrow and pale latewood);

1761, 1754 and 1704 (all with narrow latewood);

1657 (a wide ring with dark latewood);

1602 (narrow and pale latewood);

1527 (dark latewood);

1423 (narrow and pale latewood);

1393, 1364, 1323, 1288 and 1274 (all with narrow latewood);

1281, 1268 and 1256 (dark latewood).

Table S4.1 Contingency analysis of the large fire years (LFY) frequencies under positive/negative climate states. For the period 1400-1998 CE, probabilities of LFY occurrence were estimated from reconstructed fire chronology (this study). For the period 1950-2021 CE, we estimated the probabilities 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 statistical significance of difference between observed and bootstrapped values.

Climate indices	n	Frequencies of events, years		Percentiles	Number of LFY years
		Observed	Expected		
Reconstructed PNA					
PNA -	270	0.115	0.0719	1	31
PNA +	367	0.0409	0.0724	0	15
Reconstructed ENSO					
ENSO -	17	0.118	0.0695	0.905	2
ENSO +	620	0.0710	0.0723	0.328	44
Modern PNA					
PNA -	32	0.25	0.215	0.816	8
PNA +	38	0.184	0.214	0.355	7
Modern ENSO					
ENSO -	27	0.185	0.215	0.418	5
ENSO +	43	0.233	0.214	0.777	10

Table S4.2 Results of Poisson regression test trends in the number of fires across different seasonal categories (early, mid and late) for the period 1600-1900 CE. Fire counts were aggregated by century. The fixed factor was the start of the period (century), and the dependent variable was the number of fires within each season. Poisson regression coefficients and p-values are reported for each seasonal category. A significant positive trend was observed for mid-season fires. Corresponding graphics are presented in Fig. 4.4 in the main text.

Season	Coefficient	p-value
Early Season	1.15*10-2	0.633
Mid-Season	4.19*10-2	0.021
Late Season	9.55*10-3	0.626

Table S4.3 Results of Fisher's exact tests for differences in fire occurrences across different combinations of seasons since the 1600s. Fisher's exact tests were used to assess whether there are significant differences in the distribution of fire occurrences between early, mid, and late seasons. p-values are reported for each comparison, showing no significant differences in fire occurrences between seasons.

Comparison	p-value
Early vs Mid-Season	0.454
Early vs Late-Season	0.875
Mid vs Late-Season	0.875

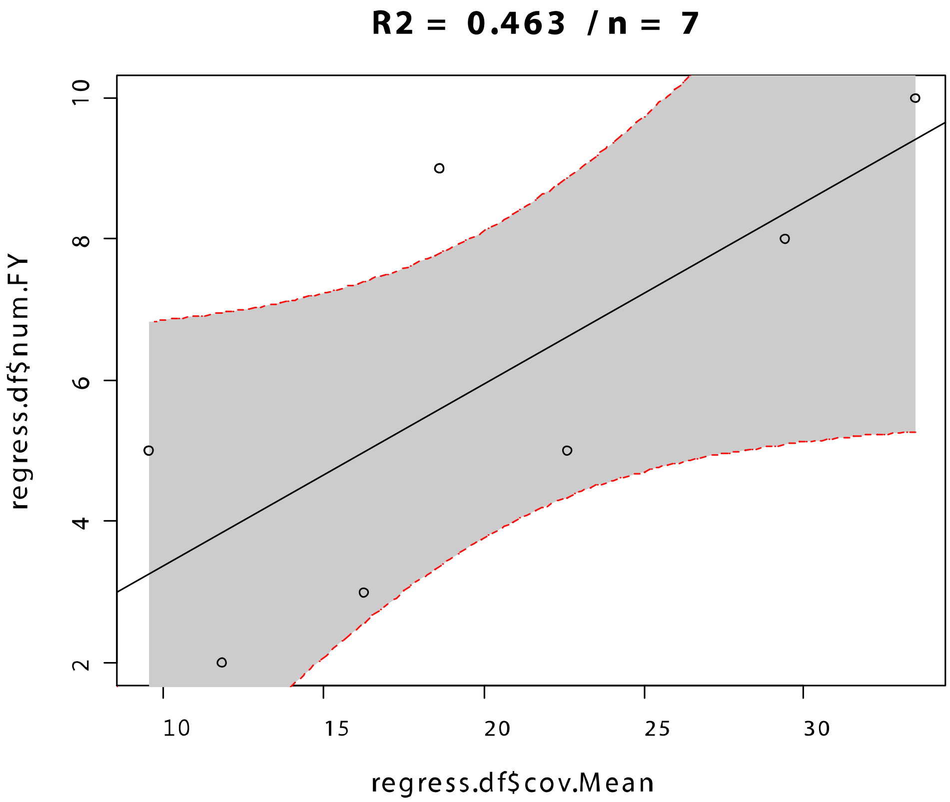

Figure S4.1 Adjustment of the fire occurrence for the decline in the site coverage of older part of the fire chronology. Each point represents a single 20-year period with corresponding number of fire years and the amount of "recording sites", i.e. sites which covered the period in question. The shaded area represents a confidence envelope for a linear regression with R2 = 0.46.

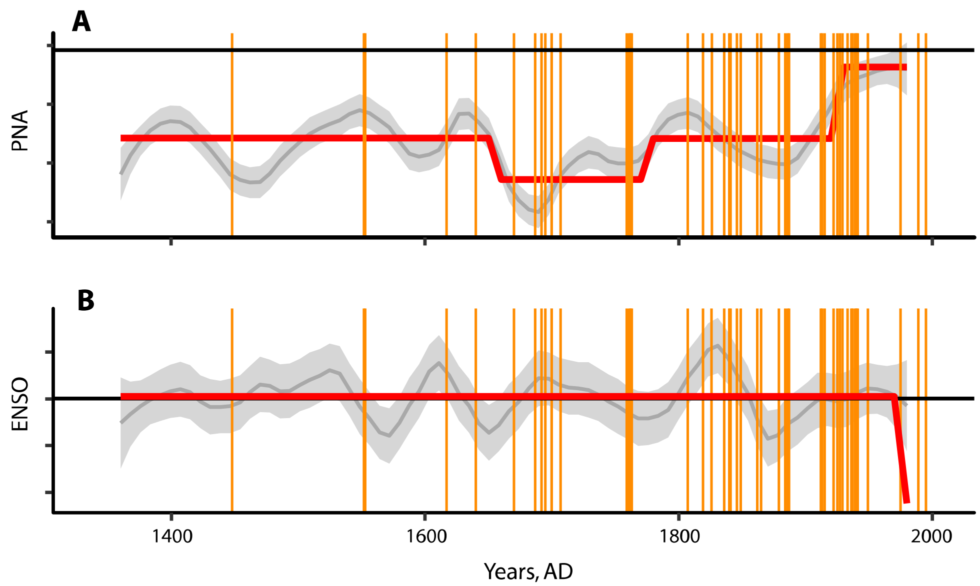

Figure S4.2 Historical Pacific North American teleconnection (PNA) index (A), El Niño-Southern Oscillation (ENSO) reconstruction (B) (both thin grey lines, smoothed with a spline function) and modern large fire years (LFYs) (vertical orange lines). The thick red line shows the outcome of regime shift analysis (Rodionov, 2004). The solid gray horizontal line refers to the climate index long-term average.

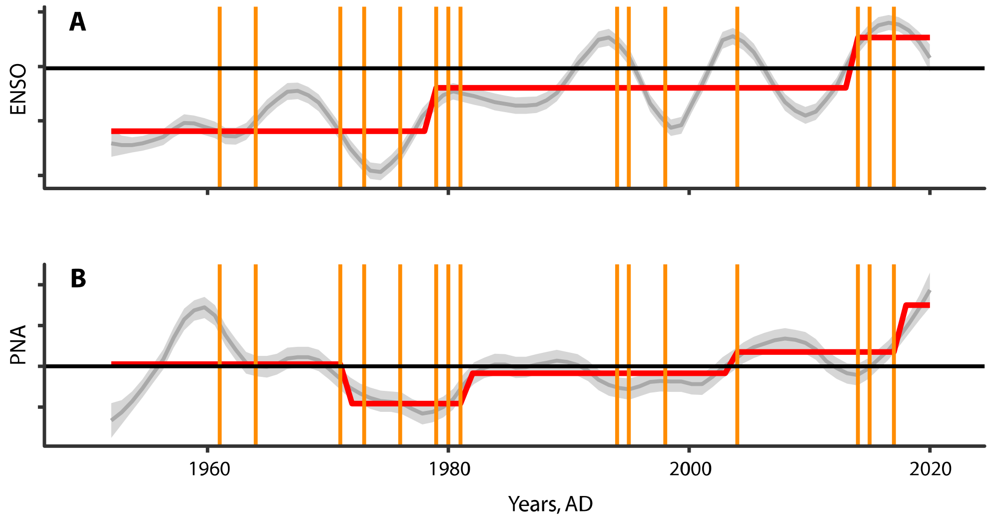

Figure S4.3 Modern Pacific North American teleconnection (PNA) index (A), El Niño-Southern Oscillation (ENSO) reconstruction (B) (both thin grey lines, smoothed with a spline function) and modern large fire years (LFYs) (vertical orange lines). The thick red line shows the outcome of regime shift analysis (Rodionov, 2004). The solid gray horizontal line refers to the climate index long-term average.

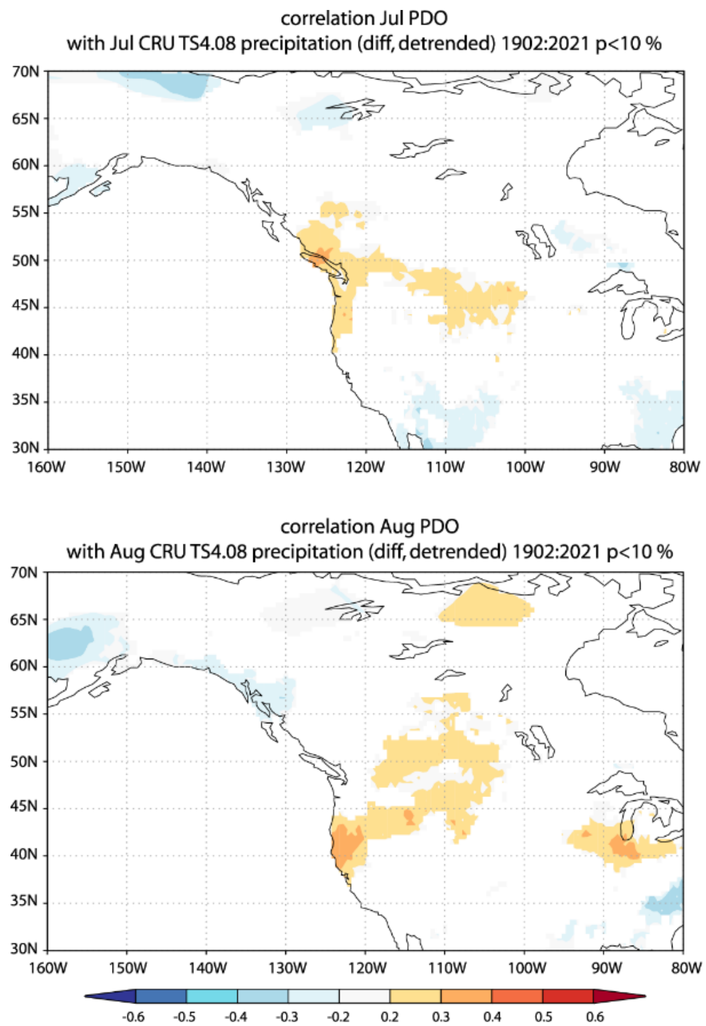

Figure S4.4 Correlation between July and August Pacific Decadal Oscillation (PDO) and CRU TS4.08 monthly precipitation fields over the 1902-2021 period. Colored areas indicate a significant level of correlation coefficient at p < 0.10.

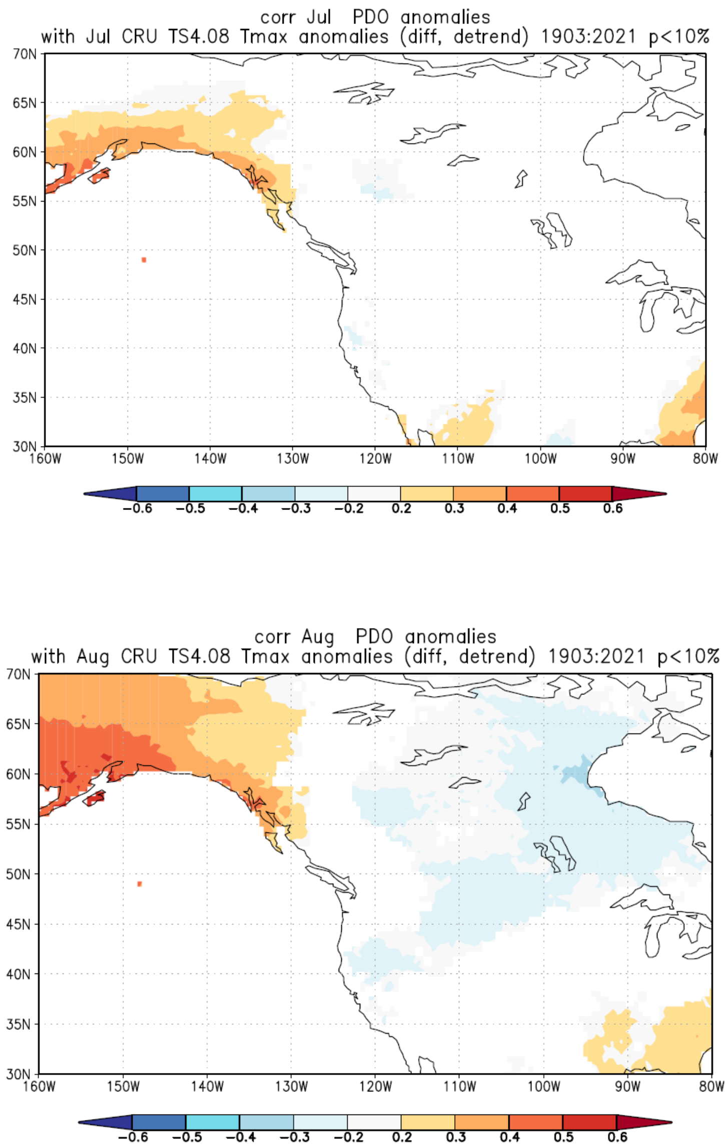

Figure S4.5 Correlation between July and August PDO and CRU TS4.08 Tmax anomalies over the 1902-2021 period. Colored areas indicate a significant level of correlation coefficient at p < 0.10.

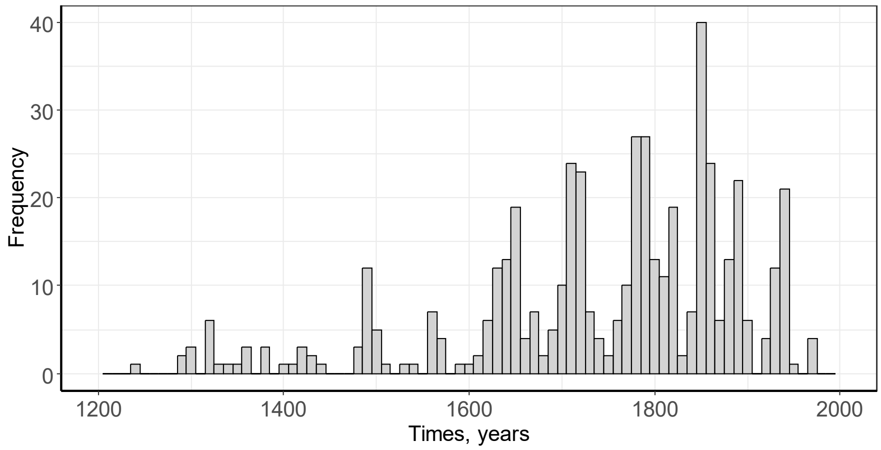

Figure S4.6 Frequency of tree pith dates for sampled dead and live trees over time.

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