UNIVERSITÀ DEGLI STUDI DI PADOVA

Department of Land, Environment Agriculture and Forestry

MASTER’S DEGREE IN FOREST SCIENCE

Northern Fennoscandian fire activity exhibits strong links with proxies of solar activity

Supervisor:

Prof. Marco Carrer

Co-supervisor:

Prof. Igor Drobyshev

Submitted by:

Federico Corrò

Student n. 2043091

ACADEMIC YEAR 2021-2022

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Fire has been a major factor shaping the vegetation of the boreal zone over the Holocene. The Common Era, or the last 2000 years, is of particular interest as it represents an important period in the development of the boreal forest post-glaciation. Analysing past patterns and trends of forest fires activity in relation to their causes is crucial for understanding long-term dynamics within the forest and projecting future fire activity. While earlier studies have mostly focused on associations between fire activity and proxies of ocean-atmosphere conditions, solar irradiance, which has an important role as source of climate variability, has been understudied.

In this study, I explored forest fire activity over the Common Era in northern Fennoscandia and its relationship with climate, specifically solar irradiance, through a synthesis of high fire activity periods from available charcoal and dendrochronological records over the last 2000 years. The charcoal and dendrochronological based fire activity syntheses resulted into differences in the occurrence of high fire activity periods which can be related to a number of limitations in the two methods. The differences in temporal resolution and methodology applied to assess the peaks in fire activity between the two syntheses suggest higher accuracy of the dendro record. However, both the dendrochronological and the charcoal record point to general decline in fire activity across Fennoscandia over the 20th century, in accordance with earlier studies.

I analyzed the relationship between fire activity and total solar irradiance for the reconstructed period by conducting contingency analysis with non-parametric bootstrapping to test if there is a significant difference in the likelihood of fire prone periods to occur under a specific solar irradiance state over the same period. I concluded that low solar activity is positively correlated to high fire activity, whereas neutral solar activity is negatively correlated to high fire activity, as they differ significantly from what is expected in a random process. Therefore, low solar activity resulted as a fire-prone climate state in northern Fennoscandia, whereas neutral solar activity can be identified as a non-fire-prone state.

1 INTRODUCTION

Fire has been probably the most relevant natural hazard shaping the vegetation in the boreal zone over the Holocene (Bradshaw et al., 2010). Its activity influences the development of natural vegetation, shaping the forest ecosystem through both direct and indirect effects (e.g. forest structure, biodiversity, release of gases into the atmosphere). Fire activity has varied considerably through time and space due to natural factors and human land use (Carcaillet et al., 2007, Rogers et al., 2015). Analysing past patterns and trends of forest fires activity in relation to their causes is crucial for understanding long-term dynamics within the forest and projecting future fire activity (Kasischke et al., 1995). The history of forest fires in the boreal region has been studied by paleochronological and dendrochronological methods, and through studies of historical records. Paleo records from organic sediments contain charcoal data that can generate fire chronologies that cover the whole Holocene but with low temporal resolution (i.e. several decades). Dendrochronology has been widely used to analyze forest fire regimes. Tree rings-based fire records are normally only a few centuries long but they provide higher temporal resolution, accuracy, and spatial detail compared to charcoal-based fire records (Remy et al., 2018). New regional datasets of dendrochronologically resolved fire dates over different parts of Scandinavia have been produced in the last decade which help understanding the major trends in forest fire regimes over the history and their correlation with climatic and anthropogenic factors.

The Common Era, or the last 2000 years, is of particular interest as it represents an important period in the development of the boreal forest post-glaciation. Even though it is a period relatively well covered by climate and fire reconstructions, studies about climate-fire links that cover the whole Common Era sometimes are lacking. While earlier studies have mostly focused on associations between fire activity and proxies of ocean-atmosphere conditions that affect local climate such as drought, precipitation and temperature, having a direct impact on fire activity (e.g. Drobyshev et al., 2014; Drobyshev et al., 2016), solar irradiance, which has an important role as source of climate variability, has been understudied.

The main purpose of this study is to analyse the fire history of a boreal landscape and understand the relative role of climate, specifically total solar irradiance (TSI), on forest fires in northern Fennoscandia over the Common Era.

Our specific objectives are:

i. to build a discrete chronology of fire activity over the last 2000 years in northern Fennoscandia through the synthesis of fire prone periods/large fire years at different temporal resolution.

We are going to synthesize fire data from available charcoal and dendrochronological records over the last 2000 years.

ii. to test if there is a significant difference in the likelihood of fire prone periods to occur under a specific climate state by looking at global TSI reconstructions over the same period. That is to understand if there are TSI regimes that show increased likelihood of forest fires.

2 REVIEW OF LITERATURE

2.1 The role of fire in the boreal forest

Fire has been a major factor shaping the vegetation of the boreal zone over the Holocene (Bradshaw et al., 2010). Its activity influences the development of natural vegetation, shaping the forest ecosystem through both direct and indirect effects (e.g. forest structure, biodiversity, release of gases into the atmosphere) (Drobyshev et al., 2015). Post-fire forest structure highly depends on the severity of the fire and the tree morphology. Higher live-crown-bases and thicker barks usually determine higher chances of survival post-fire (Ryan, 2002), whereas the understory shows higher mortality to fire, resulting in a time lag in canopy replacement (Johnson, 1992). Frequency of fire represents another fundamental factor in forest dynamics. The length of the fire cycle, which is the time required to burn the equivalent of a specified area, has an important control on regional vegetation cover dynamics (Drobyshev et al., 2017). The fire cycle affects successional pathways (Johnson, 1992) and the transitions between temperate and boreal forests (Bergeron et al., 2004) and from closed to open canopy forests (Gauthier et al., 2015; Blarquez et al., 2015).

While for many years forest fires have been seen only as a threat to human activities, nowadays, many studies acknowledge also their importance as a process for maintaining community and landscape biodiversity in boreal ecosystems (Johnson, 1992). Many species of fungi, beetles and trees are dependent on fire to survive (Niklasson and Drakenberg, 2001). Thus, large efforts have been made to reintroduce fire in northern Sweden forests in order to sustain and improve biodiversity.

Forest fires also exercise an important role in the amount of gases released into the atmosphere. Boreal fire activity accounts for approximately 12% of the total annual biomass burned globally (McRae et al., 2006), directly affecting the global carbon balance and the atmospheric concentration of gases, primarily carbon dioxide (Bond-Lamberty et al., 2007; Bowman et al., 2013).

2.2 Uncover fire history

The history of forest fires in boreal region has been studied by paleochronological and dendrochronological methods, and through studies of historical records (e.g. Niklasson and Granstrom, 2000; Drobyshev et al., 2014; Carcaillet et al., 2007). Paleo records from organic sediments allow for different paleoecological techniques, namely pollen, macrofossil, charcoal, and fossil insect and wood analysis (Lindbladh et al., 2013). Charcoal records contain charcoal data that can generate fire chronologies that cover the whole Holocene but with low temporal resolution (i.e. several decades). Fires or increased fire activity are individuated usually by looking at the peaks in the charcoal accumulation rate (CHAR, particle·cm-2·year-1). The sources of organic sediments usually come from lakes or peats. Lakes represent a more reliable source because they well preserve the charcoal in anoxic conditions and collect sediments from large areas providing a regional signal. Whereas, in peat sediments the accumulation of organic material can be lost (e.g. fire burns the organic layer), resulting in different rates of accumulation that can mislead the interpretation. Numerous studies include charcoal analysis that frequently extends the temporal records to thousands of years revealing recurring fires, although typically with marked spatial and/or temporal variability (Ohlson et al., 2006; Pitkanen et al., 2002; Tryterud, 2003). In fact, the relationship between charcoal abundance and fire history is rather complex and sometimes difficult to obtain (Carcaillet, 2007). Higuera et al. (2005) in a comparison between dendrochronological record and charcoal peaks found that not all the dated fires from scars corresponded to distinct charcoal peaks. Low-intensity fires often do not have a significant impact on the sediment charcoal, so they cannot be individuated by charcoal analysis (Niklasson et al., 2002). Besides, micro and macro-charcoal provide information on fires on a different scale. It seems that micro-charcoal (<100 lm) is relatable only to regional fires, whereas macro-charcoal (>200 lm) is likely to remain within 1000 m from the source, thus providing information on local fires (Clark, 1988). Therefore, despite paleo-records have the potential to reveal millennial-scale fire histories, they are not able to provide high temporal resolution and sufficient spatial resolution.

Dendrochronology has been widely used to analyze forest fire regimes. Tree-rings-based fire records are normally only a few centuries long but they can provide higher temporal resolution, accuracy, and spatial detail compared to longer records such as charcoal fire records (Remy et al., 2018). Forest fires often leave a signal on the trees named fire scar, which represents the response of the tree to recover after the damage caused by the fire. Fire history can be reconstructed by cross-dating the fire scars individuated on the tree rings. The use of fire scars to date fires has been an important research tool in Fennoscandia for some time (Lehtonen and Huttunen, 1997; Niklasson and Granström, 2000; Zackrisson, 1977; Drobyshev et al., 2014; Aakala et al., 2018). In the last two decades it has also been demonstrated how dendrochronology can cover long chronologies up to 700 years (Drobyshev et al., 2015) or even millennium-long (Wallenius et al., 2010) with annual resolution by individuating large fire years (LFYs). However, a number of limitations to this method need to be taken into consideration. For instance, so far dendrochronological fire records in Fennoscandia have been produced mainly relying on conifer wood, particularly *Pinus*. This species is in fact well resistant to fire and can grow on drier substrates, where the decay of the deadwood preserving the scars occurs at a slower rate (Drobyshev et al., 2021). Potential bias is therefore entailed as pines have to be a component of the forest, and a few individuals need to survive the fire, hopefully forming a fire scar (Piha et al., 2013). Thus, sampling sites are not established randomly in the forest landscape, but where good-recording trees can be found (Linderberg et al., 2021). Furthermore, relying on data from drier parts of the landscape may overestimate fire activity (Drobyshev et al., 2021).

Another important source of data to analyze forest fire regimes is represented by documentary records (e.g. historical and modern observational datasets). By looking at records of annually burned forest area it is possible to define LFYs when the burned area exceeds a certain threshold (Drobyshev et al., 2012). Fire records of this type are usually available only for the modern time, limiting the chronology length to one or two centuries. For example, in Sweden data on country-wide fire activity are available since the late 1800s (Högbom, 1934). However, these records are often discontinuous, with large gaps in data availability (Drobyshev et al., 2012), and they can be county-specific or country-wide. Besides, the spread of fire suppression techniques in Scandinavia in the 20th century makes it difficult to rely on annually burned areas to define LFYs (Drobyshev et al., 2015). Forest fire datasets are usually provided by forestry statistics state authorities, such as the Swedish Forestry Board (www. svo.se, Skogsstyrelsen, 1945) and the Swedish Civil Contingencies Agency (Myndigheten för samhällskydd och beredskap, www.msb.se), or by other online available datasets on burned areas, such as the Global Fire Emissions Database (GFED) (Giglio et al., 2013).

2.3 Projecting fire risk

As wildfires are related to a diverse set of environmental, social and economic impacts, current research has been focusing on providing information about predicted fire risk at monthly to seasonal timescales in order to mitigate these impacts (Eden et al., 2020). However, forecasting fire risk is relatively novel and has resulted rather complicated (e.g. Marcos et al., 2015; Bedía et al., 2018; Turco et al., 2018). A large number of factors must be considered as many different aspects contribute to fire risk. Different methods have been used to make fire risk predictions. A common approach relies on the Canadian Fire Weather Index (FWI; Van Wagner, 1987) "a weather-based system that models soil moisture at three different depths and, based on the upper soil moisture content and wind speed, creates an estimate for the initial spread rate of fire" (Krikken et al., 2021). Krikken et al. (2021) and Lehtonen and Venäläinen (2020) used the FWI in an analysis of the fires that raged through large parts of Sweden and Finland in the summer of 2018. Lehtonen et al. (2016) used the same method to assess the impact of projected climate change on forest-fire activity in Finland with special emphasis on large-scale fires. As this method only attributes meteorological aspects to fire events, it carries a certain degree of uncertainty. Ignition sources, forest management and ecology represent some of the important aspects for determining forest fire risk that are not considered by the FWI (Krikken et al. 2021).

While these studies focused mainly on the impact of climatic variables on fire risk, Backman et al. (2021) conducted an analysis on the effect of projected climate change on fire activity based on the land surface model JSBACH (Kaminski et al., 2013) and the mechanistic fire model SPITFIRE (Thonicke et al., 2010; Lasslop et al., 2014). The JSBACH model simulates vegetation growth and changes in the fuel load driven by climate model data, whereas the SPITFIRE model simulates the fire risk, the number of fires and the burnt area fraction, driven by meteorology, vegetation cover, fuel load and fuel properties. Precise information on forest management and its effects especially on the amount of fine fuels can increase the accuracy of this model (Backman et al., 2021).

2.4 Study area

The study region covered the area called northern Fennoscandia, including northern Sweden, northern Norway, northern Finland, and north-western Russia (Fig. 2.4.1). Most of the bedrock in Fennoscandia is made up of Precambrian granites and gneisses, covered by young Quaternary and Holocene sediments, consisting mainly of podzolized moraines (Lidmar-Bergström and Näslund, 2005). The topography and vegetation of Fennoscandia highly variates according to the different bioclimatic domains. In the west the Scandes reach heights between 1000 and 2500 m above sea level (a.s.l.), whereas Finland and the southern part of Sweden are mainly lowland, and Norway only has a narrow strip of lowland lying along the coastline (Kuuluvainen and Aakala, 2011).

The main bioclimatic domains are: the artic zone, the alpine zone, the boreal zone, the boreal-nemoral zone, and the nemoral zone.

The arctic zone, also called tundra, is the northernmost region, located north of the climatic forest line. The vegetation here is dominated by sedges, dwarfed shrubs, herbs, lichens and mosses, with some occasional trees in the southern tundra border, but no forest (Elmhagen, 2021). The alpine zone can be seen as a southern extension of the arctic zone that dominates the mountainous area of most of Norway and the Norwegian-Swedish border. Vegetation and climate are similar to the tundra. Further south of the arctic zone, away from the mountains, there is the boreal zone. The main tree species in the boreal zone are Norway spruce (*Picea abies* (L.) H.Karst), Scots pine (*Pinus sylvestris* L.), with birch (*Betula pubescens* Ehrh. and *B. pendula* Roth) representing the deciduous vegetation

(Drobyshev et al., 2015). *P. sylvestris* is considered a shade-intolerant pioneer species frequently dominant in xeric and nutrient-poor sites, while *P. abies* is a shade-tolerant late-successional species generally dominant in mesic and nutrient-rich sites (Aakala et al., 2018). Both species can dominate the sub-xeric and mesic sites, and their proportion in a stand is largely dependent on the disturbance history (Kuuluvainen and Aakala, 2011). In the boreal-nemoral and nemoral zone, *Betula* spp. or in rare instances *Populus tremula* L. (aspen) may dominate high-elevation and mesic and herb-rich post-disturbance stands.

The boreo-nemoral zone is considered a transitional zone. Forests here can be dominated by either coniferous or broadleaf species depending on the site conditions. Besides birch and aspen, pine and spruce remain common tree species, but there are also hardwood broadleaved species such as oak, elm, ash and maple (Elmhagen, 2021). In this area, many forests growing on rich soils have often been converted to agricultural lands. The nemoral zone corresponds to the southernmost region of Fennoscandia and is characterised by deciduous broadleaf forests dominated by oak (*Quercus* L.), beech (*Fagus* L.) and elm (*Ulmus* L.). Due to the higher productivity offered by the site conditions in this area, most of the natural forests have been converted to arable agriculture (Elmhagen, 2021).

Climate in Fennoscandia is influenced by the vicinity to the Atlantic Ocean and the Eurasian continent. Air masses come both from the Atlantic region, especially during the winter season, and more occasionally from the Arctic, in the form of cold and dry air masses (Kuuluvainen and Aakala, 2011; Drobyshev et al., 2015). The climatic zones vary from maritime in the western part to more temperate in the eastern part. As a whole the region shows a rather continental climate, with mean temperature of the warmest month (July) ranging from 17 °C in southern Sweden to 13 °C in some areas of Lapland. In northern Sweden the mean July temperature varies between 12 and 16 ˚C. The mean temperature of the coldest month (February) ranges between –3.5 °C in southern Sweden to –14.7 °C in northern Finland (FAO, 2005).

In the area covered by boreal forest, the mean temperature of the warmest month (July) ranges from 17 °C n the southern Sweden to 13 °C in some areas of Lapland. The mean temperature of the coldest month (February) varies from –3.5 °C in southern Sweden to –14.7 °C in northern Finland (FAO, 2005). In the whole area precipitation are at least moderate throughout the year. Total annual precipitation also highly varies according to the region, from over 2000 mm on the Norwegian coast to 500-1400 mm in the Scandinavian Mountains, and from 600-700 mm in northern Sweden to 450–500 mm in the interior of northern Lapland (Tikkanen, 2005). In northern Sweden between 30 and 50% of the precipitation comes as snow, with a mean number of days with snow cover ranging from 170 to 225 (Raab and Vedin, 1995). In southwestern Norway only 11% of the precipitation falls as snow (FAO, 2005). Hence, northern Fennoscandia is characterised by harsher winters with a long-lasting snow-cover and a short growing season in summer, whereas southern Fennoscandia shows little or no snow in winter and a long-lasting growing season.

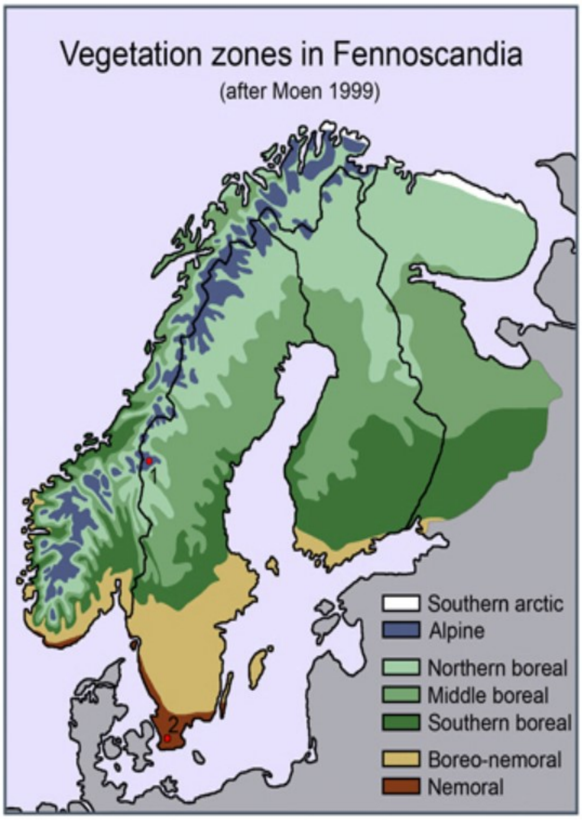


Figure 2.4.1. Vegetation zones in Fennoscandia (Elmhagen, 2021).

2.5 *Fire activity in northern Fennoscandia*

Current fire activity in Fennoscandia is relatively low compared to the rest of the boreal zone of the Northern Hemisphere, particularly Russia and Canada (Drobyshev et al., 2015). The fire cycle in northern Sweden (time required to burn the area equal to the studied landscape, *sensu* Johnson and Gutsell, 1994) is currently 10^3–10^4 years (Drobyshev et al., 2012). In Finland the fire cycle in the last decades has been estimated 30 x 10^3 years (Linderberg et al., 2021). Despite the long fire cycles and the relatively short fire season (June-August), Fennoscandian forests produce energy rich fuels highly flammable (Lindberg et al., 2021). However, large variability of fire intervals has been detected depending on meteorological factors, dominant tree species, vegetation changes, fire suppression and general human influence (Wallenius, 2004; 2011). Besides, significant geographical variability has been reported (e.g. northern vs southern Sweden, Drobyshev et al., 2012) and fire intervals can significantly vary depending on the time period (Wallenius et al., 2007).

During the Holocene, these areas experienced many shifts in the fire regime due to natural and anthropogenic causes. Historical periods of higher fire activity than average in the Swedish boreal forest have been found by sediment analysis between 7500 and 4500 and after 2500 cal. yr BP with regional fire frequency of around 280 years (Carcaillet et al., 2007). On average, fire history in northern Sweden has been characterized by long fire-free intervals (around 300 years) over the last 10 000 years, and it might be argued that fire is therefore naturally infrequent in northern Sweden when mostly triggered by natural factors such as climate (Carcaillet et al., 2007). However, fire occurrence is largely variable across different areas, and sediment based fire records do not provide spatial detail (Niklasson and Granström, 2000). Dendrochronological fire chronologies provide higher temporal and spatial resolution starting from around 1200 AD onwards.

Figure 2.5.1 reports the average fire return intervals detected by dendrochronological reconstructions across Sweden (Drobyshev et al., 2014). Besides the remarkable differences between norther sub-regions and southern sub-regions, most likely due to climatic factors (Drobyshev et al., 2014), it is clear that fire activity is highly variable even within short periods (e.g. 500 years). Over 1270–1700 AD, the average return interval for large fire years in northern Sweden was 40-50 years (Drobyshev et al., 2015). The second part of the 1600 s, one of the coldest periods of the Little Ice Age (LIA) in Scandinavia (Gouirand et al., 2008), coincided with an increase in fire activity, which then declined again in the 1700s. However, Niklasson and Granström (2000) found in a previous study of a Swedish boreal landscape that the decrease in fire occurrence in the 1700s only interests the very beginning of the century (i.e. until 1730).

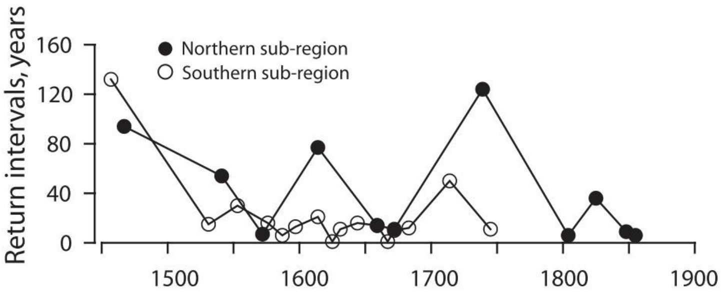
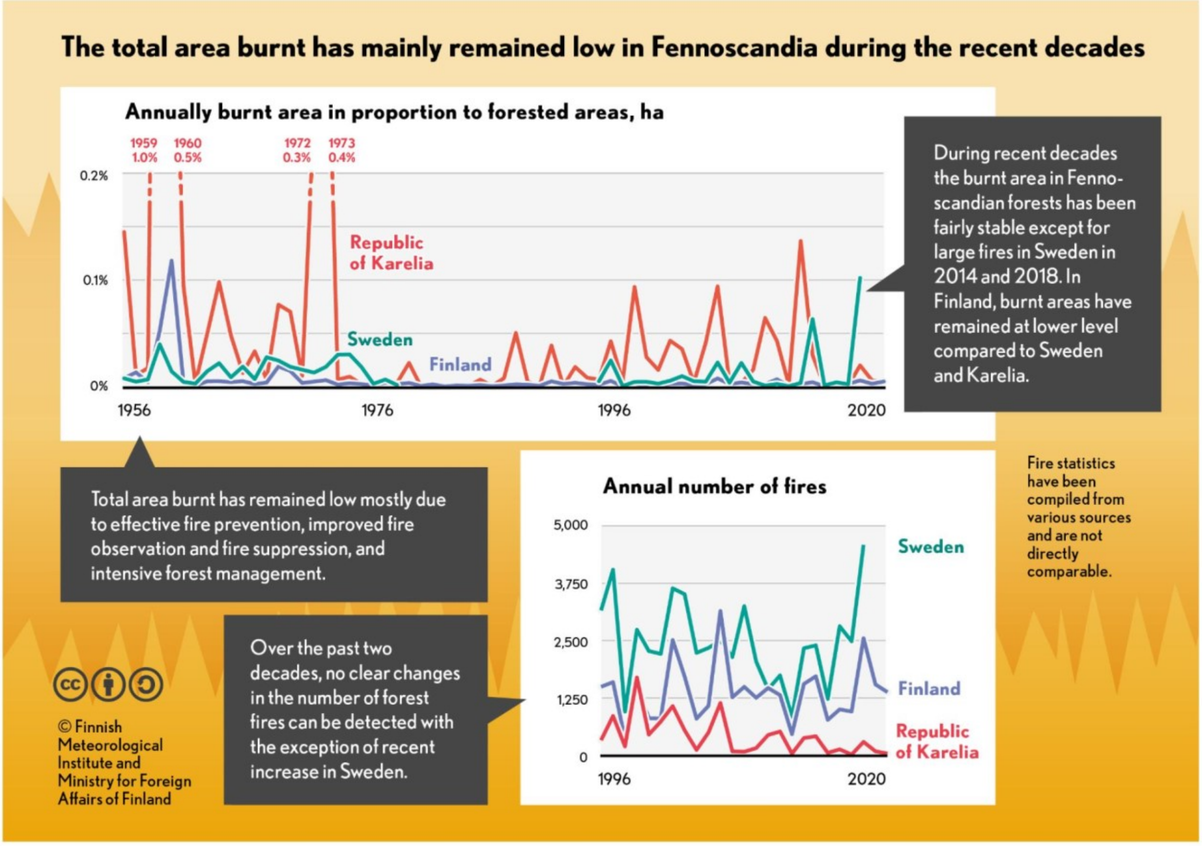


Figure 2.5.1. Temporal dynamics of return intervals of LFYs for northern (filled circles) and southern (empty circles) subregions. Points represent middles of respective intervals (Drobyshev et al., 2014).

There is much agreement on the increase of fire activity since the early 1800s, marked by shorter fire intervals (Drobyshev et al., 2014; Drobyshev et al., 2016) and reaching the highest peak in estimated number of fires per unit area and time in the mid-1800s (Niklasson and Granström, 2000). However, it is very difficult to extrapolate a general fire regime for the whole northern Fennoscandia. While Sweden disposes of a larger number of charcoal and dendrochronological records that date forest fires across the whole Holocene, sediment fire records in the rest of northern Fennoscandia are lacking. Even though dendrochronological records are now largely available also for northern Finland and north-western Russia, they point at a large variation of fire intervals in the last centuries. They range from a few decades-long (Lehtonen et al., 1996), to around 100 years (Aakala, 2018), or even longer (350 years) (Wallenius et al., 2010). Similarly to all the studies dealing with fire chronology in boreal Fennoscandia, pronounced century-long variability in forest fire cycles is also documented within the same studies (Ryzhkova et al., 2020).

However, a general dramatic decline in the annually burnt area over the course of the 19th and 20th centuries has been demonstrated throughout Fennoscandia (Fig. 2.5.1; 2.5.2) (Lindeberg et al., 2021; Niklasson and Granström, 2000; Drobyshev et al. 2012; Ryzhkova et al. 2020). Such decrease has been attributed mostly to the enhanced fire suppression policies and changes in forest management (Lindeberg et al., 2021). It has been estimated that modern forest fire activity in Sweden is one to two orders of magnitude lower than the levels showed over 15–18th centuries (Niklasson and Granström, 2000). In the 20th century, the fire cycle in northern Sweden ranged from 10×10^3 to 20×10^3 years (Drobyshev et al., 2012). However, during the last decade there has been a sharp increase in the area burnt in Sweden due to some exceptionally large fires (e.g. in year 2018) (Lindeberg et al., 2021). Unlike in Sweden and Finland, in the Republic of Karelia in north-west Russia the fire size has remained relatively large, showing that it is difficult to define a common trend for the whole Fennoscandia (Lindeberg et al., 2021).



The total area burnt has mainly remained low in Fennoscandia during the recent decades

During recent decades the burnt area in Fennoscandian forests has been fairly stable except for large fires in Sweden in 2014 and 2018. In Finland, burnt areas have remained at lower level compared to Sweden and Karelia.

Total area burnt has remained low mostly due to effective fire prevention, improved fire observation and fire suppression, and intensive forest management.

Fire statistics have been compiled from various sources and are not directly comparable.

Over the past two decades, no clear changes in the number of forest fires can be detected with the exception of recent increase in Sweden.

© Finnish Meteorological Institute and Ministry for Foreign Affairs of Finland

Figure 2.5.2. Total area burnt and number of fires in Fennoscandia over the last decades (Lindeberg et al., 2021).

2.6 *Climatic drivers*

Climate is considered the most important driver of fire regimes at large scale in the boreal biome (Carcaillet et al., 2002). Climate controls boreal wildfires at different timescales. At seasonal scale, climate drives wildfires by influencing the ignition probability, fuel moisture, and the spread of ignited fires (Flannigan et al., 2000; Flannigan and Wotton, 1991). At annual to interannual scales, climate influences the type and abundance of fuels by controlling successional pathways in vegetation (Gedalof, 2011).

Climate variability (i.e. deviation from the mean state of the climate system) is categorized as (a) internally generated or (b) externally-forced. Internal climate variability refers to changes caused by natural processes intrinsic to the climate system's components, i.e. the atmosphere and the oceans, and their interactions. This internally generated variability results in synoptic modes that can be represented by climate indices. One of the most relevant climate indices in northern European boreal forest' climate is the summer North Atlantic Oscillation (SNAO). SNAO alters precipitation, cloudiness and radiation's variation in time and space (Bengtsson et al., 2006). SNAO can yield warmer and drier conditions in its negative phase in northern Sweden, while wetter and milder conditions can be found in southern Sweden (Linderholm et al., 2010). For example, the increase in LFYs during the 1800 s corresponds to a period of predominantly negative SNAO (Drobyshev et al., 2015).

On the other hand, natural and anthropogenic factors are sources of externally forced climate variability. Among the natural sources of climate variability there is Earth's solar irradiance. It depends on the energy output of the Sun, which variates in time and affects the Earth's and boreal forests' climate. When all the radiation is measured it is called Total Solar Irradiance (TSI), while when measured as a function of wavelength, it is Solar Spectral Irradiance (SSI). TSI is the electromagnetic energy produced by the Sun that the Earth receives. Fluctuations in the Sun's magnetic field originate TSI variability on different time scales, most significantly on the 11-year solar cycle, becoming brighter than average at solar maximum (high-magnetism) and dimmer at solar minimum (low-magnetism). The amplitude of the change of the TSI between the minimum and maximum 11-year solar cycles is just about 0.1%. However, the solar radiation absorbed by Earth's atmosphere and surface is highly wavelength dependent. For example, the variations of the solar spectral irradiance (SSI) in the UV spectral region are much larger (4-8%) (Ermolli et al., 2013). The TSI exercises a bottom up propagation of the solar signal from the Earth's surface up to the atmosphere mediated by the coupling of ocean and air (van Loon et al., 2007). The most significant effect of TSI changes affects cloud-free subtropical oceans. During solar maxima, an intensification of the evaporation occurs in this region as the radiation absorbed by the oceans increases. Water vapor is then transported to the tropical convergence zone, i.e., the Intertropical Convergence Zone (ITCZ)/ South Pacific convergence zone (SPCZ), where the latent heat is released as precipitation, strengthening the Hadley and the Walker circulations.

Climate variability generated by internal or external factors is then described by different climate variables that directly affect forest fire activity. For example, negative SNAO that caused higher fire activity in the 1800s is related to increased frequency of summer and late summer droughts (Drobyshev et al., 2015). Besides drought, also precipitation, temperature and atmospheric pressure seem to be related to the occurrence of LFYs. The increased fire activity during the colder periods of the Little Ice Age suggests stronger controls by precipitation rather than temperature on fire activity (Aakala et al., 2018). Hence, drier conditions during the LIA seem to be the main cause of fire prone conditions (Bergeron and Flannigan, 1995; Gavin et al., 2003; Wallenius et al., 2007; Drobyshev et al., 2016). Periods of water deficit increase forest fire activity by prolonging drying of forest fuels

(Drobyshev et al., 2012). As pointed by Drobyshev et al. (2016), "between 1300 and 1880, LFYs occurred significantly more frequently during the cooler than warmer periods" in northern Sweden. This correlation might be due to the association of low atmospheric humidity and increased frequency of high pressure systems dominated by cold and dry air masses with cooler climate in Scandinavia (Drobyshev et al., 2016). Furthermore, unstable circulation modes and increase in meridional flow in northern Fennoscandia might lead to more severe climatic extremes during colder periods (Jonsson et al., 2010). Drobyshev et al. (2016) found a previously undocumented teleconnection between the dynamics of Atlantic Ocean and the regional fire activity in northern Europe. The low sea surface temperatures over the northern North Atlantic seem to contribute to redirect southward the precipitation over Scandinavia, leading to strong high-pressure systems and increased regional fire activity in northern Fennoscandia (Drobyshev et al., 2016). Overall, it appears that the decoupling between fire activity and increasing temperatures is due to the dominating effect of precipitation and atmospheric humidity (Drobyshev et al., 2016). However, a positive correlation with temperature and occurrence of LFYs has been found in a Karelian boreal landscape (North-West Russia), where synchrony of the fire regime with summer SST dynamics in the Norwegian Sea and summer temperature anomalies over northern Europe has been individuated (Ryzhkova et al., 2020). In this case, it is likely that high-pressure originates over northern Europe and warms up both the ocean and the forest fuels (Ryzhkova et al., 2020). Moreover, Drobyshev et al. (2014) found temporal correlation of LFYs with positive temperature and negative precipitation anomalies in northern Sweden, which seemed to be more sensitive to past summer climate than the southern Swedish boreal forest.

Thus, uncertainty arises from the various studies on the correlation between climate variables and fire activity, which can partly be explained by strong geographical variability. However, at the larger geographical scale, forest fire activity of the European boreal zone generally shows a strong coupling with climatic variability (Drobyshev et al., 2012; Drobyshev et al., 2021; Carcaillet et al., 2002; Aakala et al., 2018), which should enable for predictions of future fire hazard in response to climate change.

Climate change is likely to have a significant impact on fire regimes in boreal forests. The strong link between fire activity and climate and the vulnerability of boreal forests to climate change (i.e. climate change is amplified at high latitudes of the Norther Hemisphere) (Serreze et al., 2000) strongly suggests significant changes in future boreal fire regimes. The rate of warming in Fennoscandia is expected to exceed the global average by a factor of approximately two (Backman et al., 2021). However, climate change will affect boreal forest fires differently depending on geographical areas. The general trend of warming temperatures worldwide in recent decades has had significant impacts on fire activity in North American and Russian boreal forests for example by increasing the area burned (Kukavskaya et al., 2016; Conard et al., 2002). On the contrary, fire activity has decreased in Scandinavia over the last centuries. However, this has been attributed to human fire suppression and changes in land use (Wallenius, 2011). Most of the literature suggests that global warming in northern Fennoscandia will lead to enhanced evapotranspiration, which further decreases the soil moisture content, likely increasing the fire risk and the frequency of fire weather conditions (Flannigan et al., 1998, 2000; Stocks et al., 1998; Kilpeläinen et al., 2010; Mäkelä et al., 2014; Lehtonen et al., 2016). However, along with temperature, an increase in precipitation is projected (Flannigan et al., 1998). As precipitation seems to exercise stronger control on fire activity than temperature, it might partly offset the enhanced fire risk caused by warming temperatures (Backman et al., 2021), or even decrease the risk of fire ignition and spread (Flannigan et al., 1998). However, the projected increase in precipitation over Fennoscandia appears to be more associated with winter periods than summer (Hanssen-Bauer et al., 2005), and considerable variability is projected in temperature and, most importantly, precipitation changes (Backman et al., 2021). Therefore, climate-driven projections of future fire hazard hold a significant degree of uncertainty (Drobyshev et al., 2012), both regarding the rate of the projected increase in the severity of fire weather, and the direction of the change (Backman et al., 2021).

2.7 Human impact

Wildfires have always existed in history as a natural disturbance variating across time and space. However, the degree at which humans have influenced and shaped fire regimes remains still unclear. Humans are “unique” in that they are fire-generating species, even though fire is a natural disturbance factor. Ever since human activities started, they have become the main reason for fire ignitions (Gromtsev, 2002). Nowadays, natural ignition (e.g. lightning strikes) only accounts for approximately 8% of all wildfires in Sweden and 13% in Finland (Granström, 1993; Larjavaara et al., 2005). Besides, humans have the potential of igniting fire whenever fire spread is possible (e.g. dry fuels) (Granström and Niklasson, 2008), whereas lightning ignition occurs primarily around the peak of the summer and in periods of prolonged drought (Kinnman, 1936; Nash and Johnson, 1996).

Throughout the Holocene, land use has varied consistently, and humans altered the fire regime in different ways, namely, (i) by changing the number of ignitions and their location and timing and (ii) by hindering fire spread (Granström and Niklasson, 2008). An example is represented by the Saami culture. The Saami people started settling in Fennoscandia around 1500-2000 years BP (Aronsson, 1994). Their impact on fire regimes when reindeer husbandry became the dominant type of land use in the early middle ages (Storli, 1993), has been largely debated. Due to their dependence on reindeer, the Saami people are commonly seen as adverse to fire, because it would burn the main winter feed for reindeers, namely *Cladonia* lichens (Nieminen and Heiskari, 1989; Baskin and Danell, 2003). However, a study from northern Sweden by Hörnberg et al. (1999) suggests that Saami nomads may have actively used fires to reduce the cover of shrubs and mosses and favour the growth of grazable liches by the reindeers (*Cladina*).

Another relevant anthropogenic impact to the fire regime in Fennoscandia has been attributed to the slash-and-burn agriculture which became widespread in Fennoscandia between 1600 to late 1800s (Ruokolainen and Salo, 2006). Slash-and-burn agriculture consists of felling living trees, letting them dry, burning the biomass, and planting a crop in the highly fertile ashes during the appropriate season (Ruokolainen and Salo, 2006). The use of fire for agriculture and to improve the forest grazing habitat for cattle resulted in smaller but more frequent fires (Rolstad et al., 2017; Storaunet et al., 2013; Wallenius, 2011; Niklasson and Granström, 2000). However, slash-and-burn methods highly varied depending on the locality, predominantly practiced in the southeastern parts rather than in the northernmost regions (Heikinheimo, 1915).

The dramatic drop in fire frequency starting from the late 1800s has also been attributed to changes in land tenure and livelihoods. The value of slash-and-burn agriculture started to decline as the forest industry became a primary source of revenue (Ruokolainen and Salo, 2006; Granström and Niklasson, 2008; Aakala et al., 2018). Fire was considered a threat to silvicultural resources and fire suppression activities began to spread over northern Europe (Cogos et al., 2020).

Even though it seems clear that humans can have a relevant impact on the fire regime, it is often difficult to distinguish between human and natural causes in fire-regime changes (Pausas and Keeley, 2009). Most retrospective studies based on fire scars or sediment chronologies have focused on changes in fire frequency to detect the human signal (Granström and Niklasson, 2008), however, these changes can often been explained by changing climate (e.g. Bergeron and Archambault, 1993). Since the human influence on the boreal fire regimes differs depending on socio-cultural contexts and regions, combining information on palaeoclimate, archaeology and fire/vegetation patterns, or focusing on changes in spatial or seasonal distribution of fires may be a better indicator of human influence (Granström and Niklasson, 2008).

3 METHODS

3.1 Norrbotten fire activity reconstruction (laboratory work)

I carried out the laboratory work in the Dendrochronological laboratory of SLU in Alnarp (DELA) to date fire scars in >300 samples collected from the Norrbotten county (northern Sweden) in summer 2020. It consisted of different stages. The first was aimed at the preparation of the study material. I dried and polished wood samples up to 800-grid with a sanding machine and through different sand belts, starting from P40. Once the wood samples were cleaned and cleared from dust by air compression, I scanned them with high-resolution (2400 dpi) to make tree rings clearly visible for measuring. The following step consisted in tree ring measuring through the software CooRecorder 9.8.0. I then proceeded with cross-dating the samples with two master chronologies available for the site through the software CDendro 9.8.0. I used a T-test to check the validity of the dating for each sample. The longer the length of the chronology, the higher the T-value threshold considered. When uncertainty was still present, I combined cross-dating with the visual pointer years method (Stokes and Smiley, 1968), using a newly-developed pointer years chronology for the site. Eventually, I dated fire scars individuated within the samples using a binocular microscope with 40 times magnification lens.

I did not take part in the rest of the analysis to determine large fire years in the Norrbotten county. For further information regarding the analysis of large fire years and data collection in the Norrbotten county I refer to the study by Jabłońska (2021).

3.2 Building a fire history database

I built a newly developed and updated fire history database for northern Fennoscandia during the Common Era. I carried out a quantitative and qualitative analysis of the existing fire reconstructions based on charcoal-inferred fire records in northern Fennoscandia through a literature review and the Global Paleofire Database (IPN, 2022). Besides, I used two existing reviews of tree-rings-based fire records in Scandinavia and the above-mentioned reconstruction by Jabłońska (2021) (see this paragraph below). Even though dendrochronologically-resolved records are more accurate and characterised by finer temporal resolution, I chose to use also charcoal-inferred fire records as a proxy because they could extend the time span covered to the whole Common Era. I conducted the literature review by searching the online database Web of Science typing the keywords: "fire reconstructions", "charcoal", "palynological evidence", in combination with the geographical references: "northern

Sweden OR Finland OR Norway" and "western Russia". I sorted by relevancy of the title and abstract all the resulting papers suggested by the online database, and if the papers were considered relevant at this stage, they were fully read. To increase the data availability, I also used selected papers within reference lists. The inclusion criteria for the literature review and the Global Paleofire Database are listed in Table 3.2.1.

Criteria	Inclusion factors considered for each criterion	
Geographical position of the study site	Latitude	Southern limit = 64.40
Proxy	Charcoal	Micro and macro
Proxy source	Lake	All types of chronology lengths
	Peat / mire / bog	Chronologies focused exclusively on about the last 4000 years or less

Table 3.2.1. Inclusion criteria for the synthesis of charcoal-based fire records

When I found some pre-existing synthesis and multiple sites studies, not all the study sites within the single study fully fulfilled the above-mentioned criteria. Therefore, I considered each site's charcoal fire record individually. I assumed that a fire occurred when a peak in the charcoal accumulation rate (CHAR, particle·cm-2·year-1) graphs could be identified. To standardize the fire data across the different sites, I developed a fire index that classifies each peak by their magnitude, according to the scale HIGH, MODERATE, LOW. The magnitude of each peak was visually examined relatively to each other for each site's record for the last 2000 years portion of the graph. The CHAR graphs allowed for 50 years resolution, (i.e. it was possible to discern the presence or absence of fire peaks every 50 years). Extracting fire data from the graphs adds some uncertainty to the dataset. As a proxy for the extent of fire activity, I used the number of sites with a high and moderate fire index every 50 years. Thus, I created a 2000 years fire activity chronology with 50 years resolution based on charcoal moderate and high peaks in the accumulation rate.

For each paper I checked if the methods to calculate the charcoal accumulation rate were consistent. Charcoal-inferred fire records were not included in the selection for this study if: (i) ages were quoted as uncalibrated radiocarbon years, (ii) age-depth models were not uniform, (iii) ages of the chronology were not clearly visible in the charcoal accumulation rate graphs. Besides, I collected some additional information for each selected fire record to increase the quality of the data. These are: (i) total chronology cover, (ii) number of C14 dates, (iii) length of the core sampled, (iv) temporal resolution.

I built a second fire history database based on dendrochronological fire records. To do so, I relied on two previously developed reviews of dendrochronological forest fire history reconstructions from northern Sweden (Drobyshev et al., 2015) and eastern Fennoscandia (Aakala et al., 2018). These two studies compile both existing and unpublished, annual-resolution, tree-ring-based fire-scar chronologies, from a total of 56 sites (31 in northern Sweden and 25 in eastern Fennoscandia). I extracted large fire years individuated by these two syntheses and I merged them together to obtain a single forest fire chronology for northern Fennoscandia with annual resolution. I considered large fire years present in both synthesis as single ones. Besides, I added to this chronology the large fire years resulted in Jabłońska (2021) from the Norrbotten county. LFYs are defined as years where fires have occurred at multiple sites and/or large areas were burned.

3.3 Climate data and temporal resolution alignment

I included one climate variable associated with forest fires in my analysis, the total solar irradiance (TSI). I used the Steinhilber et al. (2012) 9400-year long TSI reconstruction based on ice cores and tree rings compiled as 22-year TSI averages. I then aligned the TSI temporal resolution to the resolution of the fire history chronologies. To this end, I adopted different methods to produce 2 different chronologies. I adopted the general criteria of upscaling the finer resolution to the coarser. (1) To align TSI to the 50-years-resolved charcoal record I upscaled the TSI data to 50 years resolution by first estimating annual TSI values through a spline approximation and then aggregating them into 50 years averages. (2) To align TSI to the annually-resolved dendrochronological record, I upscaled the dendro data to 22 years by summing up the large fire years over the 22-years TSI intervals. Thus, I ended up with (1) a 2000 years-long chronology of fire activity and corresponding TSI values every 50 years, (2) a 700 years-long chronology of fire activity and corresponding TSI values every 22 years.

3.4 Analysis of climate and fire associations

I analyzed the relationship between fire activity in northern Scandinavia and global TSI for the whole study period in the reconstructed records. I used the R software to conduct contingency analysis with non-parametric bootstrapping to test if there is a significant difference in the likelihood of fire prone periods (HFAPs) to occur under a specific climate state over the same period. As climate indices normally exhibit autocorrelation, I established a protocol to remove autocorrelated TSI data based on AIC modelling at multiple frequency bands to produce non-autocorrelated chronologies. By doing so, I could enhance the signal at the frequency band which is preselected (i.e. dictated by the resolution of the dendro/charcoal data). I then classified the resulting TSI chronologies into negative, neutral, or positive "states". I defined anomalous positive and negative states as the upper (or lower) 20% of the index value distribution over the reconstructed period, whereas neutral state corresponded to the central 60% of the index value distribution. Besides, I reclassified the fire activity reconstructions into binary chronologies defined by the values "1" and "0". Specifically, for the dendro data I calculated a fire index for each 22-years interval as the sum of large fire years within each interval divided by the 22. For the charcoal data I calculated a fire index for each 50-years interval as the sum of sites revealing high and moderate peaks within each interval divided by the total number of sites. I then assigned the value "1" to intervals where fire indices were above their long-term mean, and the value "0" to intervals where fire indices were below their long-term mean. I considered every interval to which it was assigned the value "1" as high fire activity period (HFAP). Thus, I created 2 data frames based on (1) the classification of each 22-years interval over the 1270-1960 AD with respect to both climate state and dendrochronological HFAPs, (2) the classification of each 50-years interval over the last 2000 years with respect to both climate state and charcoal HFAPs. By treating the two chronologies individually, I evaluated combinations with HFAP occurrence that exceeded HFAP occurrence expected by chance (i.e. under a random process). To this end, I calculated observed frequencies of HFAP under negative, neutral and positive climate states. Then I used the bootstrap method, which runs a certain number of random replications of climate states and HFAPs and creates a distribution of the booted frequencies of HFAPs under the different climate states. The mean value of the distributions for each climate state represents the probability of occurrence of HFAP in the respective climate state under a random process (i.e expected frequency), whereas observed frequencies refer to the empirically observed probability of HFAP occurrence. The number of bootstrap replications was set equal to 1000, as it was considered a number large enough to provide statistical significance. To compare between observed and expected frequencies I estimated the percentiles of each observed frequency in the random distribution corresponding to the same climate state. This way I could estimate what is the likelihood of the empirically observed frequencies of HFAP being observed also in the random process (i.e. whether the associations between climate state and HFAP occurrence are likely a realization of a random process or not).

To improve the analysis of the associations between charcoal fire record and TSI I ran the R code again changing the classification of the TSI states from “negative, neutral and positive” to “low and high”, respectively when TSI values sat below or above the overall TSI mean over the reconstructed period.

4 RESULTS

4.1 *Fire history reconstructions*

According to the inclusion criteria mentioned in Table 3.2.1 (see Methods), for the charcoal record I selected 5 papers to which correspond 9 independent fire record sites. 55% (n = 5) of them came from sediment samples collected from mires and bogs, whereas 45% (n = 4) of them derived from samples collected from lake sediments.

The temporal resolution visually assessed varies from 20 to 200 years. The number of carbon dates (C14) used to build individual fire records ranges from 3 to 11 with an average of 5. The longest chronology dates back to 10000 cal. yr BP, while the shortest dates back to 1300 cal. yr BP. All but 2 records (78%) extend until present (2000 AD). 89% (n = 8) of the charcoal records are from northern Sweden. The only one selected outside Sweden is from Norway. The longest core of sediment collected in the studies is 255 cm, whereas the shortest is 45 cm. The sites included in the synthesis and their information are listed in Appendix A.

I obtained a 2000 years-long fire activity reconstruction with 50-years temporal resolution and 60 charcoal moderate/high peaks (i.e. Number of sites, Fig. 4.1.1).

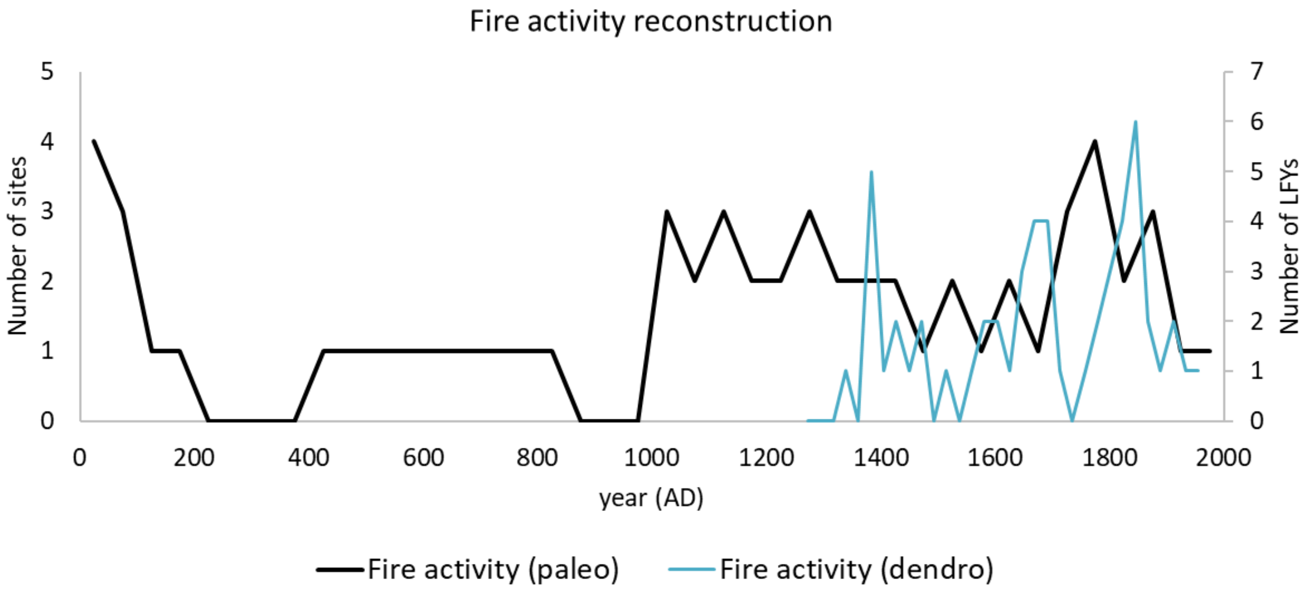


Figure 4.1.1. Fire activity over the last 2000 years in northern Fennoscandia according to the synthesis of charcoal (paleo) and dendrochronological (dendro) records. The black line refers to the number of sites with moderate/high peaks in the charcoal accumulation rate every 50-years interval, whereas the blue line indicates the number of large fire years (LFYs) every 22-years interval.

According to the charcoal record (black line) (Fig. 4.1.1), increased fire activity occurs mostly in the first century, followed by a drop until around 1000 AD, which leads to a new rise between 1000 and 1300 AD. Aftewards, the number of sites recording peaks slightly decreases till around 1700 AD. The right portion of the graph (1700-1900 AD) is marked by another peak in the charcoal accumulation rate, except for the 20th century. The moderate and high peaks in the charcoal record over high fire activity periods range from 2 to 4.

From the dendrochronological database I extracted 54 different large fire years covering the period from 1270 AD to 1960 AD. 20 LFYs belong to the synthesis by Aakala et al. (2018), 34 belong to the synthesis by Drobyshev et al. (2015), and 4 come from the Norrbotten county (Jabłońska, 2021). Figure 4.1.1 shows the number of large fire years every 22 years (blue line). From the dendrochronological record we can distinguish high frequency of LFYs between 1372-1394 AD, which falls gradually until 1548 AD, when it starts rising again until 1702 AD. Afterwards, there is a dramatic drop until 1746 AD, followed by a gradual increase till 1834-1856 AD, which corresponds to the highest peak in the dendro record (6 LFYs). Since then, the LFYs frequency gradually goes down until the end of the reconstructed period (1960 AD). The number of LFYs within high fire activity periods differs from 2 to 6.

Figure 4.1.2 below shows the reclassified chronologies of fire activity used in the contingency analysis according to the binary classification with the value "1" assigned to HFAP (see Methods).

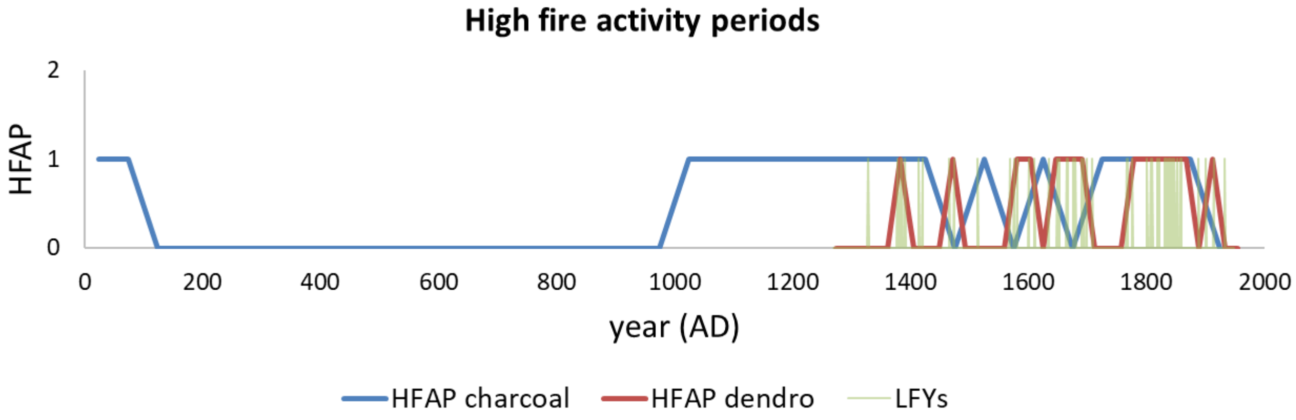


Figure 4.1.2. High fire activity reconstructions used for contingency analysis according to high fire activity periods (HFAPs). The blue line indicates HFAPs from the charcoal record; the red line shows HFAPs from the dendrochronological records; green lines represent large fire years (LFYs).

4.2 Climate data

The global TSI record throughout the last 2000 years is shown in Figure 4.2.1 according to (1) the 22-years resolution provided by Steinhilber et al. (2012), and (2) the 50-years resolution used for comparison with the charcoal record. Total solar irradiance (W/m^2) is given as difference to the value of the PMOD composite during the solar cycle minimum of the year 1986 AD (1365.57 W/m2) as given in Fröhlich (2009).

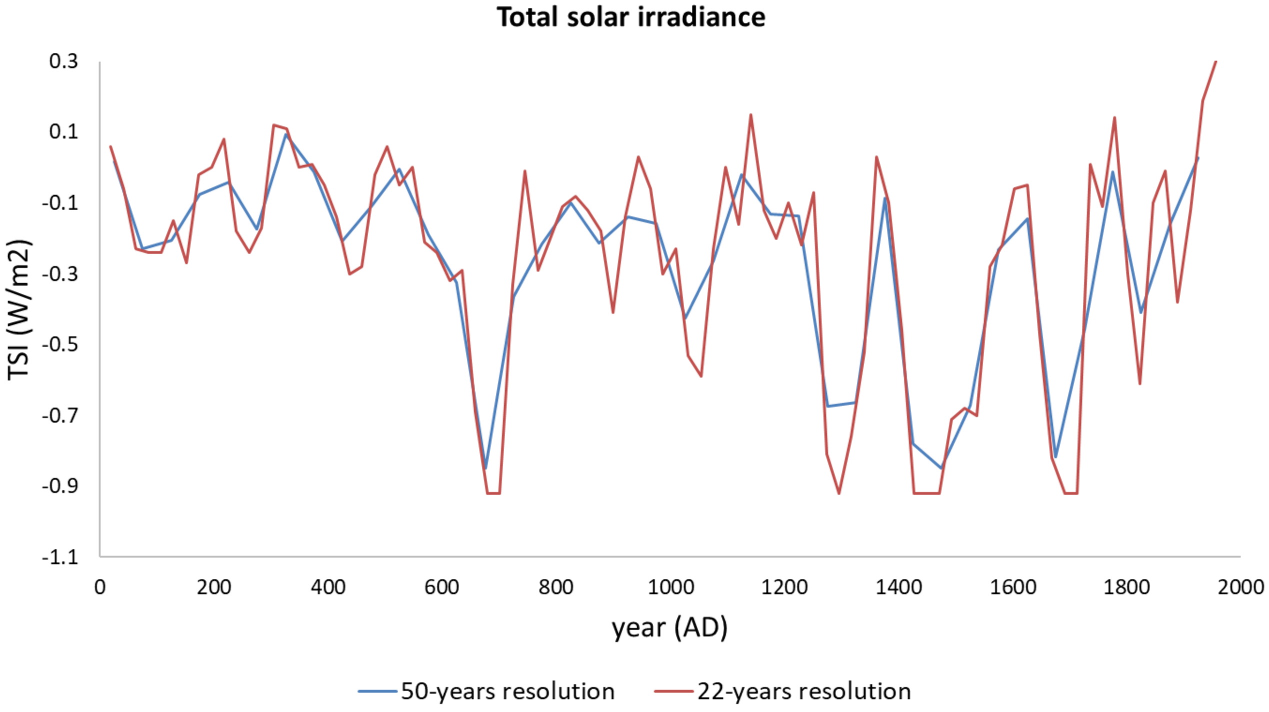


Figure 4.2.1. Total solar irradiance global distribution over the last 2000 years according to 50-years resolution (blue line) and 22-years resolution (red line)

4.3 Climate and fire activity associations

In the analysis of associations between fire activity and climate I considered total solar irradiance states (negative, neutral, positive) as climate states and paired them to HFAPs. The analysis produced different results depending on the reconstruction used (i.e. charcoal or dendrochronological), and temporal resolution (i.e. 22-years, 50-years). In this section I report the results obtained separately according to the charcoal and the dendrochronological fire activity records.

4.3.1 Charcoal record and TSI states

With the charcoal record, contingency analysis revealed relevant results for each TSI state. Specifically, both negative and positive TSI resulted as significant fire-prone states, whereas neutral TSI appeared as significant non-fire-prone state. The observed frequency of HFAPs during the period covered by the chronology under negative TSI was equal to 0.625, compared to the expected frequency of 0.444. The observed frequency was within the upper 6% (percentile = 0.94) of the bootstrap-derived distribution of HFAPs frequencies under the assumption of a random process. Positive TSI revealed almost the same numbers. The observed frequency of HFAPs under neutral TSI was equal to 0.318, compared to the expected frequency of 0.448. In this case, the observed frequency sits within the lower 7% (percentile = 0.067) of the bootstrap-derived distribution of HFAPs frequencies in the random process. Results are summarized in Table 4.3.1.

Climate state	n	Observed frequency of HFAPs	Expected frequency of HFAPs	Percentile
Negative TSI	8	0.625	0.444	0.94
Neutral TSI	22	0.318	0.448	0.067
Positive TSI	8	0.625	0.450	0.94

Table 4.3.1. Results from contingency analysis with TSI states and the charcoal record. TSI is classified as positive and negative states as the upper (or lower) 20% of the index value distribution, whereas neutral state corresponds to the central 60% of the index value distribution. n is the number of times a climate state occurs. Observed frequencies refer to HFAPs occurrence under the climate state. Expected frequencies show the booted frequencies of HFAPs under the climate state. The last column shows the percentiles of each observed frequency in the random distribution corresponding to the climate state.

I conducted a second contingency analysis for the charcoal record classifying the TSI states as low and high depending on the TSI's values being below or above the TSI mean respectively. In this case, the analysis revealed low TSI as significant fire-prone state. Specifically, the observed frequency of HFAPs during the period covered by the chronology under low TSI was equal to 0.615, compared to the expected frequency of 0.447. The observed frequency sits within the upper 3% (percentile = 0.97) of the bootstrap-derived distribution of HFAPs frequencies under the assumption of a random process. Results are summarized in Table 4.3.2.

Climate state	n	Observed frequency of HFAPs	Expected frequency of HFAPs	Percentile
Low TSI	13	0.615	0.447	0.97
High TSI	25	0.36	0.447	0.123

Table 4.3.2. Results from contingency analysis with TSI states and the charcoal record. TSI is classified as low (below its mean over the reconstructed period) and high (above the mean) states. n is the number of times a climate state occurs. Observed frequencies refer to HFAPs occurrence under the climate state. Expected frequencies show the booted frequencies of HFAPs under the climate state. The last column shows the percentiles of each observed frequency in the random distribution corresponding to the same climate state.

4.3.2 Dendrochronological record and TSI states

With the dendrochronological record, contingency analysis revealed negative TSI as significant fire-prone state, whereas neutral TSI resulted as close to significant non-fire-prone state. The observed frequency of HFAPs under negative TSI was equal to 0.833, compared to the expected frequency of 0.468, falling within the upper 1% (percentile = 0.997) of the bootstrap-derived distribution of HFAPs frequencies under the assumption of a random process. The observed frequency of HFAPs under neutral TSI was equal to 0.333, compared to the expected frequency of 0.462, sitting within the lower 10% (percentile = 0.096) of the bootstrap-derived distribution of HFAPs frequencies in the random process. Results are listed in Table 4.3.3.

Climate state	n	Observed frequency of HFAPs	Expected frequency of HFAPs	Percentile
Negative TSI	6	0.833	0.468	0.997
Neutral TSI	18	0.333	0.462	0.096
Positive TSI	6	0.5	0.480	0.711

Table 4.3.3. Results from contingency analysis with TSI states and the dendrochronological record. TSI is classified as positive and negative states as the upper (or lower) 20% of the index value distribution, whereas neutral state corresponds to the central 60% of the index value distribution. n is the number of times a climate state occurs. Observed frequencies refer to HFAPs occurrence under the climate state. Expected frequencies show the booted frequencies of HFAPs under the climate state. The last column shows the percentiles of each observed frequency in the random distribution corresponding to the same climate state.

5 DISCUSSION

In this study, I explored forest fire activity over the Common Era in northern Fennoscandia and its relationship with climate, specifically solar irradiance, an important component of climate variability. As it appears from the literature, the whole period of the Common Era is not well covered by studies regarding climate-fire links, even though it represents an important period in the development of the boreal forest post-glaciation. Similarly, solar irradiance, which has an important role as source of climate variability, has been understudied. Earlier studies have mostly focused on associations between fire activity and climate indices such as the North Atlantic Oscillation (NAO), El Niño–Southern Oscillation (ENSO), or Pacific Decadal Oscillation (PDO), which are proxies of ocean-atmosphere conditions that affect local climate such as drought, precipitation and temperature, having a direct impact on fire activity.

I will discuss in the following section the use of charcoal-based and dendrochronological-resolved fire records for the reconstruction of fire history across the Common Era in norther Fennoscandia. Then I will discuss my findings on the fire-climate links, proving recommendations for further research and speculations about future fire risk in relation to TSI.

5.1 Fire history reconstruction

The two different reconstructions of fire history resulted from the synthesis of charcoal-based and dendrochronologically-resolved fire records show some differences in the occurrence of high fire activity periods. First thing we notice comparing the two reconstructions is the gap in the chronology covered by the dendrochronological record, which extends only from present to 1270 AD, whereas the charcoal reconstruction covers the whole Common Era. I faced here one of the common limitations of dendrochronological-based fire records, which offer finer temporal resolution and spatial detail, but with shorter temporal coverage.

Most importantly, the peaks of fire activity (i.e. the number of sites with high/moderate peaks in the charcoal accumulation rate and the number of LFYs) are not always synchronous between the two syntheses (Fig. 4.1.1). For example, the second part of the 1600s reports high frequency of LFYs that suddenly drops until the end of 1700s, while the charcoal record shows reduced fire activity between 1650-1700 AD followed by a major peak around 1750 AD. The differences of fire activity peaks reported by the two syntheses could be related to a multitude of factors. For the dendro-based fire peaks I considered annually-resolved large fire years, whereas the charcoal record peaks are the product of my own visual assessment over the last 2000 years for each site with a resolution of 50 years (see Methods). This implies a higher precision in the dendro record compared to the charcoal chronology. Uncertainty related to the charcoal record often derives also by the methodology used to calculate the charcoal accumulation rate. However, I believe I reduced that degree of uncertainty by establishing inclusion criteria for the selection of papers and by checking their methods. For example, I prioritized lake sediments in the selection as they do not risk burning during forest fires, as opposed to peat sediments.

Another important factor underlying the differences in fire activity could be represented by the geographical differences in the sites included in the two analyses. The dendrochronological records used in this analysis are from northern Sweden and Finland, whereas the charcoal records are from sites situated further north and mostly in northern Sweden (only one from Norway). Significant geographical variability in fire intervals has already been detected by previous studies within the Swedish landscape (e.g. Drobyshev et al., 2012). Supporting our findings, Higuera et al. (2005) in a comparison between dendrochronological record and charcoal peaks found as well that not all the dated fires from scars corresponded to distinct charcoal peaks, as sediment analysis fail to detect low-severity fires. It is worth mentioning that differences in the two fire history reconstructions could also be related to dendrochronology limitations. Particularly, dendro data could lead to an overestimation of fire activity as they are normally collected from drier parts of the landscape (Drobyshev et al., 2021).

Looking at temporal trends of fire activity resulted from the two syntheses, both the dendrochronological and the charcoal record point to general decline in fire activity across Fennoscandia over the 20th century, as demonstrated by earlier studies (Lindeberg et al., 2021). Similar trends to those revealed by the charcoal reconstruction are found in a previous synthesis of charcoal-based fire records in northern Fennoscandia (Molinari et al., 2018). High biomass burning was registered in the first century, followed by a sharp decline until early 1000s, which then rises again until present. However, results from Molinari et al. (2018) must be carefully interpreted as no clear criteria has been adopted in the selection of charcoal records regarding the methods used to estimate accumulation rates.

The temporal trends depicted by the dendro record reflect those already revealed by the two papers I used for the synthesis (i.e. Drobyshev et al., 2015; Aakala et al., 2018), which point at higher frequency of LFYs during the latter half of the 17th century and during the 1800s. The highest frequency of LFYs occurred in the mid-1800s, which is in line with findings from previous studies in the Swedish boreal forest (Niklasson and Granstrom, 2000).

5.2 Climate-fire links

As revealed by contingency analysis, some particular climate regimes show significant increased likelihood of forest fires in the boreal zone, whereas others show a tendency to create non-fire-prone conditions. Overall, the analysis of associations between TSI states and fire activity provided similar results for the charcoal and dendrochronological reconstructions. Despite the different temporal resolutions and methodologies used to extract fire activity data, both reconstructions point at a strong positive correlation between negative TSI (i.e. lower 20% of the index value distribution) and fire activity. This is in line with what Robles (2021) found in a study about climate change and fire activity links in the boreal biome. She classified TSI states over the last 2000 years according to Regime Shift Analysis (RSA) and found that fire activity was significantly higher during low TSI periods in the Eurasian boreal region. However, the same study revealed that the response of fire activity to changes in TSI is characterized by continental variability. The north American boreal region showed higher fire activity during high TSI, as opposed to the Eurasian trend. These findings may support the notion of external forcing of the Earth's solar irradiance on climate. Indeed, solar irradiance does not affect directly surface climate conditions of boreal forests, which are rather modulated by large-scales modes of ocean-atmospheric climate variability, such as El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and the North Atlantic Oscillation (NAO) (Robles, 2021). Solar irradiance partly influences NAO, which has an important role in the climate of the European boreal forest and thus fire activity by influencing the position of the storm tracks in the region. Storm tracks play a significant role in mid- to high-latitude climate by influencing precipitation, cloudiness and radiation and their variation in time and space (Bengtsson et al., 2006). The Summer North Atlantic Oscillation (SNAO) can generate fire-prone conditions by yielding warmer and drier climatic conditions in its negative phase in northern Sweden (Linderholm et al., 2010). The increase in frequency of LFYs during the 1800 s has already been related to a period of predominantly negative SNAO, which increased the frequency of summer and late summer droughts (Drobyshev et al., 2015). However, while there is much agreement on the positive correlation between negative SNAO and fire activity, the relationship between SNAO and TSI seems still unclear. Some authors claim that solar activity is positively correlated to NAO/ Northern Hemisphere annular mode (NAM) (Ruzmaikin and Feynman, 2002), whereas others found different NAO index-solar radiation correlations for southern and northern Europe (Pozo-Vázquez et al., 2004). Findings from this study suggest that, due to its positive correlation with fire activity during its negative phase and its influence on NAO, the negative TSI state may trigger a negative phase in SNAO.

Supporting this theory, NAO and solar irradiance show a similar impact on blocking events in the North Atlantic. Specifically, negative NAO generates a more favorable environment for blocking events which become more frequent and with a duration that varies considerably. The average length of blocking during the negative phase is nearly twice as long as the length observed during the positive phase of NAO (Shabbar et al., 2001). Similarly, during low solar activity, North Atlantic blockings also last longer, are located further east and become more intense than during high solar irradiance (Barriopedro et al., 2008). Blocking events in the North Atlantic influence cyclonic activity and precipitation anomalies. Results from Sousa et al. (2016) indicate a "split of the storm-tracks north and south of blocking systems, leading to an almost complete reduction of cyclonic centers in northern and central Europe and increases in southern areas, where cyclone frequency doubles during blocking episodes". Thus, negative TSI and NAO may create fire-prone conditions in the European boreal forest by enhancing the frequency and duration of blocking events, which reduce cyclonic centers in the European boreal zone, leading to lower precipitation and warmer temperatures. In fact, the combination warm and dry is a typical pattern under summer-time anticyclonic conditions, as indicated by mid-Holocene reconstructions in central Scandinavia (Antonsson et al., 2008).

It is noteworthy that similarly to TSI, the impact of NAO on fire activity seems to have continental differences. Indeed, positive NAO phase has been associated with higher fire activity in the red pine distribution area in northern America (Robles et al., 2022). The effect exercised by NAO on blocking events in northern America leads to opposite climatic conditions in respect to northern Europe. Specifically, NAO controls the thermal contrast between the North Atlantic Ocean and the adjacent landmass in eastern North America by warming up the ocean while lowering inland temperatures during the negative NAO state, inverting the configuration as it slides to the positive phase. Therefore, drying of fuels and longer fire seasons might identify positive NAO as a fire-prone state in northern America (Robles et al., 2022).

From contingency analysis with the charcoal record in this study, also positive TSI (i.e. upper 20% of the index value distribution) appears as a fire-prone state. This would suggest that both minima and maxima extremes in solar activity create conditions conducive to high fire activity, with milder solar fluctuations (neutral TSI) identified as non-fire-prone conditions. With the purpose of testing the credibility of these findings, however, the second analysis with the classification of TSI states by the mean (i.e. low TSI, high TSI) revealed that only TSI below its long-term mean is significantly associated with high fire activity. Therefore, while low solar activity seems to be strongly correlated to high fire activity, the results of high solar activity as fire-prone state in northern Fennoscandia appear misleading, likely caused by approximations in the visual assessment of fire peaks from charcoal data.

Supporting the association between low solar irradiance and high fire activity, the peak in fire activity during the LIA (Drobyshev et al., 2015) seems to be related to the occurrence of particularly extreme solar minima: the Spörer Minimum (1420-1500 AD) and the Maunder Minimum (1645-1705 AD). Additionally, the increase in fire activity recorded in the first half of the 1800s might be associated to another extreme solar minima, the Dalton Minimum (1800-1820 AD) (Eddy, 1976; Lamb, 1979; Mörner, 2010), which may have partly caused the predominant negative SNAO occurred in this period. North Atlantic blocking events became longer and shifted towards east causing cold spells over northern Europe (Barriopedro et al., 2008). This finding supports the belief that in these periods climate forcing upon fire activity was a predominant factor (Drobyshev et al., 2015; Ryzhkova et al., 2020), even though increased fire activity during the 1600s in Scandinavia has been consistently associated to human land use and population growth (Niklasson and Granström, 2000; Wallenius, 2011).

On the other hand, the consistent decline in fire activity over the 20th century seems to be related to higher solar irradiance as this century coincides with one of the highest TSI regimes (Robles, 2021). However, earlier studies largely demonstrated that the dramatic decrease in annually burnt area over the 20th century is mainly due to the human impact through enhanced fire suppression policies and changes in forest management (Lindeberg et al., 2021). Further analysis is therefore needed to investigate deeper into temporal patterns between solar irradiance and fire activity.

My findings from contingency analysis with the dendrochronological record, which are considered more reliable as characterized by higher temporal resolution and precision, support the same idea that negative TSI states promote fire activity with a high degree of significancy. Indeed, the observed frequency of HFAPs indicated by the dendro record under negative TSI was almost twice as much as the frequency expected under the assumption of a random process (Tab. 4.3.3). It is interesting that similarly to the results from the analysis with the charcoal record, neutral solar activity shows a close to significant reduction in fire activity. These results suggest that rather than periods of extreme solar maxima, it is more likely that milder solar fluctuations create non-fire-prone conditions. By considering LFYs for the contingency analysis with the dendro record I excluded the presence of human impact underlying my results. LFYs are indeed a product of synchronicity in fire occurrence at regional scale that strongly indicates climatic control on fire regimes (Drobyshev et al., 2015).

Summing up, I can argue with a relevant degree of certainty that there is significant difference in the likelihood of fire prone periods (HFAPs) to occur under specific TSI states over the Common Era in northern Fennoscandia. Specifically, low solar activity (negative/low TSI) is positively correlated to high fire activity, whereas neutral solar activity (neutral TSI) is negatively correlated to high fire activity, as they differ significantly from what is expected in a random process.

5.3 Future predictions

The most recent solar minima occurred in 2019/20 (Finsterle et al., 2021). Consequently, considering the 11-years solar cycle, the next one should be in 2030/31. As we associated higher fire activity to lower solar irradiance, an increase in fire activity may be expected in Europe over the next years leading to the solar minima. However, the magnitude of the next solar minima is still uncertain, potentially falling into the definition of neutral TSI states according to this study, which seem to have the opposite impact on fire activity. Therefore, any prediction of fire activity in relation to TSI above mentioned is considered as pure speculation. Additionally, there is a significant degree of uncertainty into climate-driven projections of future fire activity that are not tackled within the scope of this study.

5.4 Limitations and recommendations for further research

The low resolution of the fire data from the charcoal record might be considered as a limitation of the analysis with TSI, however, solar irradiance is characterized by low-frequency periodicity. I adopted its 22-years periodicity (11-year cycles of a solar minimum and maximum) in the analysis with LFYs. Its 120-years grand minima periodicity (Velasco et al., 2015) is even longer than the 50-years resolution of the charcoal record. For these reasons low resolution of fire data is not considered a major drawback in this study.

The fire data I used in the synthesis come from different published papers from different authors, besides, some LFYs come from a yet unpublished study (i.e. Jabłońska, 2021). Additionally, the visual assessment of the charcoal peaks in the accumulation rate to build the charcoal fire history reconstruction records could be considered as too much of an approximation. Thus, the fire history reconstructions I developed entail a certain degree of uncertainty. However, I included only moderate/high peaks in the synthesis, leaving out the low peaks. Besides, in the contingency analysis I defined HFAPs only when fire indices were above their long-term mean. Thus, the reconstructions take into consideration only extreme events in fire activity, reducing the uncertainty related to bias in the visual assessment. To better assess temporal patterns in TSI-fire links, I suggest Regime Shift Analysis to be conducted both for the fire records and for the TSI distribution.

The synthesis of charcoal records generated a fire database from sites located almost entirely in northern Sweden. It might be argued that the validity of the findings from this study is therefore limited to northern Sweden instead of the entire northern Fennoscandia. However, consistent charcoal-based fire records are largely missing over other regions in northern Fennoscandia. Furthermore, the synthesis of dendrochronological fire reconstructions included sites from eastern Fennoscandia which expanded the geographical scope of this study to a larger area than northern Sweden alone.

Finally, limiting contingency analysis to only one climate index might oversimplify and potentially miss important interactions within the climate system. Further analysis on dynamics that drive the solar irradiance's impact on fire activity should be conducted to better understand these interactions and the mechanism through which solar irradiance affects fire activity. A possibility would be to conduct contingency analysis with combinations of two climate indices, such as TSI and NAO, and evaluate what is their correlation with fire activity. However, contingency analysis normally assumes that the climate variables considered are independent from each other. As NAO oscillations can be caused by solar activity, other types of analysis may be better. An example is Superposed Epoch Analysis (SEA), a statistical method used to identify the link between discrete events and continuous-time or spatiotemporal processes and test the probability of such an association occurring by chance (Haurwitz and Brier, 1981).

6 CONCLUSIONS

Analysing forest fire activity links with climatic conditions is crucial for understanding long-term dynamics within the forest and projecting future fire activity. In this study, I built a network of fire history records based on existing sediment-based (i.e. charcoal) and dendrochronological resolved (i.e. tree-ring-based fire scars) fire activity reconstructions to explore boreal forest fire activity over the Common Era in northern Fennoscandia and its relationship with solar irradiance, an important component of climate variability.

The charcoal and dendro based fire activity syntheses resulted into differences in the occurrence of high fire activity periods which can be related to a number of limitations in the two methods. The differences in temporal resolution and methodology applied to assess the peaks in fire activity between the two syntheses suggest a higher accuracy of the dendro record. However, both the dendrochronological and the charcoal record point to general decline in fire activity across Fennoscandia over the 20th century, in accordance with earlier studies.

Analyzing climate-fire links, contingency analysis revealed with a relevant degree of certainty that there is significant difference in the likelihood of fire prone periods to occur under specific TSI states over the Common Era in northern Fennoscandia. Specifically, low solar activity (negative/low TSI) is positively correlated to high fire activity, whereas neutral solar activity (neutral TSI) is negatively correlated to high fire activity, as they differ significantly from what is expected in a random process. Therefore, low solar activity resulted as a fire-prone climate state in northern Fennoscandia, whereas neutral solar activity can be identified as non-fire-prone state.

Further research is needed to better assess temporal patterns in TSI-fire links and understand the dynamics underlying the solar irradiance’s impact on fire activity, which could help forecasting fire risk in response to changes in solar activity.

7 REFERENCES

Aakala, T. (2018). Forest fire histories and tree age structuries in Värriö and Maltio Strict Nature Reserves, northern Finland. Boreal Environment Research 23: 209–219.

Aakala, T., Pasanen, L., Helama, S., Vakkari, V., Drobyshev, I., Seppä, H. (2018). Multiscale variation in drought controlled historical forest fire activity in the boreal forests of eastern Fennoscandia. In: Ecol Monogr n. 1, 88, pp. 74–91. DOI: 10.1002/ecm.1276.

Antonsson, K., Chen, D., Seppä, H. (2008). Anticyclonic atmospheric circulation as an analogue for the warm and dry mid-Holocene summer climate in central Scandinavia. In: Clim. Past n. 4, 4, pp. 215–224. DOI: 10.5194/cp-4-215-2008.

Aronsson K-Å (1994). Pollen evidence of Saami settlement and reindeer herding in the boreal forest of northernmost Sweden—an example of modern pollen rain studies as an aid in the interpretation of marginal human interference from fossil pollen data. Rev Palaeobot Palynol 82:37–45. https://doi.org/10.1016/0034-6667(94)90018-3

Backman, L., Aalto, T., Lehtonen, I., Thölix, L., Vanha-Majamaa, I., Venäläinen, A. (2021). Climate change increases the risk of forest fires. In Aalto, J. and Venäläinen, A. (eds.), Climate change and forest management affect forest fire risk in Fennoscandia. (pp. 66-91). Finnish Meteorological Institute Reports 2021: 3.

Barriopedro, D., García-Herrera, R., Huth, R. (2008). Solar modulation of Northern Hemisphere winter blocking. In: J. Geophys. Res. n. D14, 113. DOI: 10.1029/2008JD009789.

Baskin, L., Danell, K. (2003). Ecology ofungulates. A handbook of species in eastern Europe and northern and central Asia. Berlin, Germany: Springer.

Bedía, J., Golding, N., Casanueva, A., Iturbide, M., Buontempo, C. and Gutiérrez., J.M. (2018) Seasonal predictions of Fire Weather Index: Paving the way for their operational applicability in Mediterranean Europe, Clim. Serv., 9, 101-110.

Bengtsson, L., Hodges, K.I., Roeckner, E. (2006). On the natural variability of the pre-industrial European climate. Climate Dynamics 27: 743–760.

Bergeron, Y., Flannigan, M.D. (1995). Predicting the effects of climate-change on fire frequency in the southeastern Canadian boreal forest. Water Air Soil Pollut. 82, 437–444.

Bergeron, Y., Archambault, S. (1993). Decreasing frequency offorest fires in the southern boreal zone of Quebec and its relation to global warming since the end of the ‘Little Ice Age’. Holocene 3, 255–259.

Bergeron, Y., Gauthier, S., Flannigan, M., Kafka, V., (2004). Fire regimes at the transition between mixedwood and coniferous boreal forest in northwestern Quebec. In: Ecology n. 7, 85, pp. 1916–1932. DOI: 10.1890/02-0716.

Blarquez, O., Ali, A. A., Girardin, M. P., Grondin, P., Fréchette, B., Bergeron, Y., Hély, C. (2015). Regional paleofire regimes affected by non-uniform climate, vegetation and human drivers. In: Scientific reports n. 1, 5, p. 13356. DOI: 10.1038/srep13356.

Bond-Lamberty, B., Peckham, S.D., Ahl, D.E., Gower, S.T. (2007). Fire as the dominant driver of central Canadian boreal forest carbon balance. Nature, 450, 89-92.

Bowman, D.M., Murphy, B.P., Boer, M.M. (2013). Forest fire management, climate change, and the risk of catastrophic carbon losses. Frontiers in Ecology and the Environment, 11, 66-68.

Bradshaw, RHW., Lindbladh, M., Hannon, GE. (2010). The role of fire in southern Scandinavian forests during the Late Holocene. International Journal ofWildland Fire 19: 1040–1049.

Carcaillet, C. (2007). Charred particle analysis. In: Elias, S.A. (Ed.), Encyclopedia of Quaternary Science. Elsevier, Amsterdam, The Netherlands, pp. 1582–1593.

Carcaillet, C., Almquist, H., Asnong, H., Bradshaw, R. H.W., Carrion, J. S., Gaillard, M. J. (2002). Holocene biomass burning and global dynamics of the carbon cycle. In: CHEMOSPHERE n. 8, 49, pp. 845–863. DOI: 10.1016/S0045-6535(02)00385-5.

Carcaillet, C., Bergman, I., Delorme, S., Hornberg, G., Zackrisson, O. (2007). Long-term fire frequency not linked to prehistoric occupations in northern Swedish boreal forest. In: Ecology n. 2, 88, pp. 465–477. DOI: 10.1890/0012-9658(2007)88[465:LFFNLT]2.0.CO;2.

Clark, J.S. (1988). Particle motion and the theory of charcoal analysis – source area, transport, deposition, and sampling. Quaternary Res. 30, 67–80.

Cogos, S., Roturier, S., Östlund, L. (2020). The origins of prescribed burning in Scandinavian forestry: the seminal role of Joel Wretlind in the management of fire-dependent forests. In: Eur J Forest Res n. 3, 139, pp. 393–406. DOI: 10.1007/s10342-019-01247-6.

Conard, S. G., Sukhinin, A. I., Stocks, B. J., Cahoon, D. R., Davidenko, E. P., Ivanova, G. A. (2002). Determining Effects of Area Burned and Fire Severity on Carbon Cycling and Emissions in Siberia. In: Climatic Change n. 1, 55, pp. 197–211. DOI: 10.1023/A:1020207710195.

Drobyshev, I., Bergeron, Yves., Girardin, M. P., Gauthier, S., Ols, C., Ojal, J. (2017). Strong Gradients in Forest Sensitivity to Climate Change Revealed by Dynamics of Forest Fire Cycles in the Post Little Ice Age Era. In: J. Geophys. Res. Biogeosci. n. 10, 122, pp. 2605–2616. DOI: 10.1002/2017JG003826.

Drobyshev, I., Bergeron, Y., Linderholm H. W., Granström A., Niklasson, M., (2015). A 700-year record of large fire years in northern Scandinavia shows large variability and increased frequency during the 1800 s. In: J. Quaternary Sci. n. 3, 30, pp. 211–221. DOI: 10.1002/jqs.2765.

Drobyshev, I., Bergeron, Y., Vernal, A. de., Moberg, A., Ali, A. A., Niklasson, M., (2016). Atlantic SSTs control regime shifts in forest fire activity of Northern Scandinavia. In: Scientific reports, 6, p. 22532. DOI: 10.1038/srep22532.

Drobyshev, I., Granström, A., Linderholm H. W., Hellberg, E., Bergeron, Y., Niklasson, M., (2014). Multi-century reconstruction of fire activity in Northern European boreal forest suggests differences in regional fire regimes and their sensitivity to climate. In: J Ecol n. 3, 102, pp. 738–748. DOI: 10.1111/1365-2745.12235.

Drobyshev, I., Niklasson, M., Linderholm, H. W. (2012). Forest fire activity in Sweden: Climatic controls and geographical patterns in 20th century. In: Agricultural and Forest Meteorology, 154-155, pp. 174–186. DOI: 10.1016/j.agrformet.2011.11.002.

Drobyshev, I., Ryzhkova, N., Eden, J., Kitenberga, M., Pinto, G., Lindberg, H. (2021): Trends and patterns in annually burned forest areas and fire weather across the European boreal zone in the 20th and early 21st centuries. In: Agricultural and Forest Meteorology, 306, p. 108467. DOI: 10.1016/j.agrformet.2021.108467.

Eddy, J.A. (1976) The Maunder Minimum. Science, 192, 1189-1202. http://dx.doi.org/10.1126/science.192.4245.1189

Eden, J. M., Krikken, F., Drobyshev, I. (2020). An empirical prediction approach for seasonal fire risk in the boreal forests. In: Int J Climatol n. 5, 40, pp. 2732–2744. DOI: 10.1002/joc.6363.

Elmhagen, B. (2021). Fennoscandia vegetation and climate. Available at http://www.bodilelmhagen.se/fenno.html. Visited on 28/07/2022.

Ermolli, I., Matthes, K., Dudok de Wit, T., Krivova, N. A., Tourpali, K., Weber, M. et al. (2013). Recent variability of the solar spectral irradiance and its impact on climate modelling. In: Atmos. Chem. Phys. n. 8, 13, pp. 3945–3977. DOI: 10.5194/acp-13-3945-2013.

FAO (2005). NewLocClim: Local climate estimator. Environment and Natural Resources, Working Paper 20. (CD-Rom).

Finsterle, W., Montillet, J.P., Schmutz, W. *et al.* (2021). The total solar irradiance during the recent solar minimum period measured by SOHO/VIRGO. *Sci Rep* **11**, 7835. https://doi.org/10.1038/s41598-021-87108-y

Flannigan, M., Stocks, B., Wotton, M. (2000). Climate change and forest fires. In: The Science of the total environment, 262, pp. 221–230. DOI: 10.1016/S0048-9697(00)00524-6.

Flannigan, M., Wotton, M., (1991). Lightning-Ignited forest fires in Northwestern Ontario. In: Can. J. For. Res., 21, pp. 277–287. DOI: 10.1139/x91-035.

Flannigan, M., Bergeron, Y., Engelmark, O., Wotton, B. M. (1998). Future wildfire in circumboreal forests in relation to global warming. Journal of Vegetation Science 9: 469–476.

Fröhlich, C. (2009). Evidence of a long-term trend in total solar irradiance. In: *A&A* n. 3, 501, L27-L30. DOI: 10.1051/0004-6361/200912318.

Gauthier, S., Bernier, P., Kuuluvainen, T., Shvidenko, A., Schepaschenko, D. (2015). Boreal forest health and global change. In: Science (New York, N.Y.), 349, pp. 819–822. DOI: 10.1126/science.aaa9092.

Gavin, D.G., Brubaker, L.B., Lertzman, K.P., (2003). An 1800-year record of the spatial and temporal distribution of fire from the west coast of Vancouver Island, Canada. Can. J. Forest Res.-Rev. Can. Rech. Forest. 33, 573–586.

Gedalof, Z. (2011). Climate and spatial patterns of wildfire in North America. Pages 89–115 in D. McKenzie, C. Miller and D. A. Falk, editors. The landscape ecology of fire. Springer, Dordrecht, The Netherlands.

Giglio, L., Randerson, J.T., van der Werf, G.R. (2013). Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4). J. Geophys. Res. 118, 317–328.

Gouirand, I., Linderholm, H.W., Moberg, A. (2008). On the spatiotemporal characteristics of Fennoscandian tree-ring based summer temperature reconstructions. Theoretical and Applied Climatology 91: 1–25.

Granström A., Niklasson M., (2008). Potentials and limitations for human control over historic fire regimes in the boreal forest. In: Philosophical transactions of the Royal Society of London. Series B, Biological sciences n. 1501, 363, pp. 2353–2358. DOI: 10.1098/rstb.2007.2205.

Granström, A. (1993). Spatial and temporal variation in lightning ignitions in Sweden. Journal of Vegetation Science 4: 737–744.

Gromtsev, A. (2002). Natural disturbance dynamics in the boreal forests of European Russia: a review. Silva Fennica 36: 41–55.

Hanssen-Bauer, I., Achberger, C., Benestad, R.E., Chen, D., Forland, E.J. (2005). Statistical downscaling of climate scenarios over Scandinavia. Clim. Res. 29, 255–268.

Haurwitz, M. W., Brier, G. W. (1981): A Critique of the Superposed Epoch Analysis Method: Its Application to Solar–Weather Relations. In: *Mon. Wea. Rev.* n. 10, 109, pp. 2074–2079.

Heikinheimo, O. (1915). Der Einfluss der Brandwirtschaft auf die W€alder Finnlands. Acta Forestalia Fennica 4:1–264 [In Finnish with German summary].

Higuera, P.E., Sprugel, D.G., Brubaker, L.B. (2005). Reconstructing fire regimes with charcoal from small-hollow sediments: a calibration with tree-ring records of fire. Holocene 15, 238–251.

Högbom, A.G. (1934). On Forest Fires Now and in The Past and Their Role in Forest Succession (Om skogseldar förr och nu och deras roll i skogarnas utvecklingshistoria). Almqvist & Wiksell, Uppsala & Stockholm.

Hörnberg, G., Östlund, L., Zackrisson, O., Bergman*, I. (1999). The genesis of two Picea-Cladina forests in northern Sweden. Journal of Ecology 87, 5, 800-814.

IPN (2022). International Paleofire Network. Available at: https://www.paleofire.org/index.php. Visited on 05/2022.

Jabłońska, A. (2021). Uncovering climate and human signals in near-millennium annual fire chronology for Norrbotten county, Northern Sweden. Swedish University of Agricultural Sciences, SLU. Publisher (Faculty/Department/Collaborative Centre). Master thesis.

Johnson, E. A. (1992). Fire and vegetation dynamics. Studies from the North American boreal forest. Cambridge, New York: Cambridge University Press (Cambridge studies in ecology).

Johnson, E. A., Gutsell, S. L. (1994). Fire frequency models, methods and interpretations. Advances in Ecological Research, 25(25), 239–287.

Jonsson, C. E., Rosqvist, G. C., Leng, M. J., Bigler, C., Bergman, J., Tillman, P. K., Sloane, H. J. (2010). High-resolution diatom delta O-18 records, from the last 150 years, reflecting changes in amount of winter precipitation in two sub-Arctic high-altitude lakes in the Swedish Scandes. J. Quaternary Sci. 25, 918–930, doi: 10.1002/jqs.1372.

Josefsson, T., Hörnberg, G., Östlund, L. (2009). Long–term human impact and vegetation changes in a boreal forest reserve: implications for the use of protected areas as ecological references. Ecosystems, 12, 1017–1036.

Kamerling, I. M., Schofield, J. E., Edwards, K. J. (2021). Palynological evidence for pre-agricultural reindeer grazing and the later settlement history of the Lycksele region, northern Sweden. In: Archaeological and anthropological sciences n. 3, 13, p. 42. DOI: 10.1007/s12520-021-01275-7.

Kaminski, T., Knorr, W., Schürmann, G., Scholze, M., Rayner, P.J., Zaehle, S., Blessing, S., Dorigo, W., Gayler, V., Giering, R., Gobron, N., Grant, J.P., Heimann, M., Hooker-Stroud, A., Houweling, S., Kato, T., Kattge, J., Kelley, D., Kemp, S., Koffi, E.N., Köstler, C., Mathieu, P.-P., Pinty, B., Reick, C. H., Rödenbeck, C., Schnur, R., Scipal, K., Sebald, C., Stacke, T., Terwisscha van Scheltinga, A., Vossbeck, M., Widmann, H., Ziehn, T. (2013). The BETHY/JSBACH Carbon Cycle Data Assimilation System: experiences and challenges. Journal of Geophysical Research: Biogeosciences 118: 1414–1426.

Karl-Dag Vorren. (2005). Stone Age settlements at Soroya, sub-arctic Norway: impact on the vegetation.

Kasischke, E. S., N. L. Christensen, and B. J. Stocks. (1995). Fire, global warming, and the carbon balance of boreal forests. Ecological Applications 5:437–451.

Kennedy, M. C., and McKenzie, D. (2010). Using a stochastic model and cross-scale analysis to evaluate controls on historical low-severity fire regimes. Landscape Ecology 25:1561–1573.

Kilpeläinen, A., Kellomäki, S., Strandman, H., Venäläinen, A. (2010). Climate change impacts on forest fire potential in boreal conditions in Finland. Climatic Change 103: 383–398.

Kinnman, G. (1936). Skogseldsrisken och vaderleken. Svenska Skogsva˚rdsfo¨reningens Tidskrift 34, 481–512.

Krikken, F., Lehner, F., Haustein, K., Drobyshev, I., van Oldenborgh, G. J. (2021). Attribution of the role of climate change in the forest fires in Sweden 2018. In: Nat. Hazards Earth Syst. Sci. n. 7, 21, pp. 2169–2179. DOI: 10.5194/nhess-21-2169-2021.

Kukavskaya, E. A., Buryak, L. V., Shvetsov, E. G., Conard, S. G., Kalenskaya, O. P. (2016). The impact of increasing fire frequency on forest transformations in southern Siberia. In: Forest Ecology and Management, 382, pp. 225–235. DOI: 10.1016/j.foreco.2016.10.015.

Kuuluvainen, T., Aakala, T., (2011). Natural forest dynamics in boreal Fennoscandia: a review and classification. In: Silva Fenn. n. 5, 45. DOI: 10.14214/sf.73.

Lamb, H.H. (1979) Climate Variation and Changes in the Wind and Ocean Circulation. Quaternary Research, 11, 1-20. http://dx.doi.org/10.1016/0033-5894(79)90067-X *(19) (PDF) The Approaching New Grand Solar Minimum and Little Ice Age Climate Conditions*.

Larjavaara, M., Pennanen, J., Tuomi, T. (2005). Lightning that ignites forest fires in Finland. Agricultural and Forest Meteorology 132: 171–180.

Larsen, C. (1997). Spatial and temporal variations in boreal forest fire frequency in northern Alberta. Journal of Biogeography 24:663–673.

Lasslop, G., Thonicke, K., Kloster, S. (2014). SPITFIRE within the MPI Earth system model: Model development and evaluation. Journal of Advances in Modeling Earth Systems 6: 740– 755.

Lehtonen, H., Huttunen, P., Zetterberg, P. (1996). Influence of man on forest fire frequency in North Karelia, Finland, as evidenced by scars on Scots pines. Annales Botanici Fennici 33: 257–263.

Lehtonen, H., Huttunen, P. (1997). History of forest fires in eastern Finland from the fifteenth century AD – the possible effects of slash-and-burn cultivation. Holocene 7, 223–228.

Lehtonen, I., Venäläinen, A., Kämäräinen, M., Peltola, H., Gregow, H. (2016). Risk of largescale fires in boreal forests of Finland under changing climate. Natural Hazards and Earth System Sciences 16: 239–253.

Lehtonen, I., Venäläinen, A. (2020). Metsäpalokesä 2018 muuttuvassa ilmastossa − poikkeuksellinen vuosi vai uusi normaali? Ilmatieteen laitos, Raportteja 2020:2, 26 p + Appendix. [Forest fire season 2018 in a changing climate – an exceptional year or new normal? Finnish Meteorological Institute Reports [in Finnish with abstract in English].]

Lidmar-Bergström, K. & Näslund, J.-O. (2005). Major landforms and bedrock. In: Seppälä, M. (ed.). The physical geography of Fennoscandia. Oxford University Press, UK. p. 3–16.

Lindberg, H., Granström, A., Gromtsev, A., Levina, M., Shorohova, E., Vanha-Majamaa, I. (2021). The annually burnt forest area is relatively low in Fennoscandia. In Aalto, J. and Venäläinen, A. (eds.), Climate change and forest management affect forest fire risk in Fennoscandia. (pp. 28-65). Finnish Meteorological Institute Reports 2021: 3.

Lindbladh, M., Fraver, S., Edvardsson, J., Felton, A. (2013). Past forest composition, structures and processes – How paleoecology can contribute to forest conservation. In: Biological Conservation, 168, pp. 116–127. DOI: 10.1016/j.biocon.2013.09.021.

Linderholm, H.W., Bjorklund, J.A., Seftigen, K. (2010). Dendroclimatology in Fennoscandia – from past accomplishments to future potential. Climate ofthe Past 6: 93–114.

Mäkelä, A., Enno, S.-V., Haapalainen, J. (2014). Nordic lightning information system: Thunderstorm climate of Northern Europe for the period 2002–2011. Atmospheric Research 139: 46–61.

Marcos, R., Turco, M., Bedía, J., Llasat, M.C. and Provenzale, D. (2015). Seasonal predictability of summer fires in a Mediterranean environment, Int. J. Wildland Fire, 24, 1076-1084.

Marlon, J. R., Bartlein, P. J., Carcaillet, C., Gavin, D. G., Harrison, S. P., Higuera, P. E., Joos, F., Power, M. J., Prentice, I. C. (2008). Climate and human influences on global biomass burning over the past two millennia. Nature Geoscience 1:697–702.

McRae, D., Conard, S., Ivanova, G. (2006) Variability of fire behavior, fire effects, and emissions in Scotch pine forests of Central Siberia. Mitigation and Adaptation Strategies for Global Change, 11, 45-74.

Molinari, C., Lehsten, V., Blarquez, O., Carcaillet, C., Davis, B. A. S., Kaplan, J. O. et al. (2018). The climate, the fuel and the land use: Long-term regional variability of biomass burning in boreal forests. In: *GLOBAL CHANGE BIOLOGY* n. 10, 24, pp. 4929–4945. DOI: 10.1111/gcb.14380.

Mörner, N.-A. (2010). Solar Minima, Earth's Rotation and Little Ice Ages in the Past and in the Future. The North At-lantic-European Case. Global Planetary Change, 72, 282-293. *(19) (PDF) The Approaching New Grand Solar Minimum and Little Ice Age Climate Conditions*.

Nash, C. H., Johnson, E. A. (1996). Synoptic climatology of lightning-caused forest fires in subalpine and boreal forests. Can. J. Forest Res. 26, 1859–1874.

Nieminen, M., Heiskari, U. (1989). Diets of freely grazing and captive reindeer during summer and winter. Rangifer 9, 17–34.

Niklasson, M., Drakenberg, B. (2001). A 600-year tree-ring fire history from Norra Kvills National Park, southern Sweden: implications for conservation strategies in the hemiboreal zone. In: Biological Conservation n. 1, 101, pp. 63–71. DOI: 10.1016/S0006-3207(01)00050-7.

Niklasson M., Granström, A. (2000). Numbers and sizes of fires: long-term spatially explicit fire history in a Swedish boreal landscape. In: ECOLOGY n. 6, 81, pp. 1484–1499. DOI: 10.1890/0012-9658(2000)081[1484:NASOFL]2.0.CO;2.

Niklasson, M., Lindbladh, M., Björkman, L. (2002). A long-term record of Quercus decline, logging and fires in a southern Swedish Fagus-Picea forest. J. Veg. Sci. 13, 765–774.

Ohlson, M., Korbol, A., Okland, R.H. (2006). The macroscopic charcoal record in forested boreal peatlands in southeast Norway. Holocene 16, 731–741.

Pausas, J. G., Keeley, J. E. (2009). A burning story: the role of fire in the history of life. BioScience, 59(7), 593-601

Piha, A., Kuuluvainen, T., Lindberg, H., Vanha-Majamaa, I. (2013). Can scar-based fire history reconstructions be biased? An experimental study in boreal Scots pine. Canadian Journal of Forest Research 43: 669−675.

Pitkanen, A., Huttunen, P., Jungner, H., Tolonen, K. (2002). A 10,000 year local forest fire history in a dry heath forest site in eastern Finland, reconstructed from charcoal layer records of a small mire. Can. J. For. Res. 32, 1875–1880.

Pozo-Vázquez, D., Tovar-Pescador, J., Gámiz-Fortis, S. R., Esteban-Parra, M. J., Castro-Díez, Y. (2004). NAO and solar radiation variability in the European North Atlantic region. In: *Geophys. Res. Lett.* n. 5, 31, n/a-n/a. DOI: 10.1029/2003GL018502.

Raab, B., Vedin, H. (1995). Klimat, sjoar och vattendrag. Sveriges National Atlas. SNA Forlag: Stockholm.

Remy, C. C., Fouquemberg, C., Asselin, H., Andrieux, B., Magnan, G., et al. (2018). Guidelines for the use and interpretation of palaeofire reconstructions based on various archives and proxies. Quaternary Science Reviews, Elsevier, 193, pp.312-322. ff10.1016/j.quascirev.2018.06.010ff. ffhal-02081257f.

Robles, D. (2021). What have been the effects of climate regime shifts on boreal fire activity over the last 2000 years? Unpublished.

Robles, D., Bergeron, Y., Meunier, J., Stambaugh, M., Raymond, P., Kryshen, A., Goebel, C., Eden, J., Drobyshev, I. (2022). Climatic controls of fire activity in the red pine forests of Eastern North America. Unpublished.

Rogers, B.M., A. J. Soja, M.L.Goulden, J. T. Randerson. (2015). Influence of tree species on continental differences in boreal fires and climate feedbacks. Nature Geoscience 8:228–234.

Rolstad, J., Blanck, Y.-l., Storaunet, K.O. (2017). Fire history in a western Fennoscandian boreal forest as influenced by human land use and climate. Ecol. Monogr. 87 (2), 219–245.

Rosén, P., Segerström, U., Eriksson, L., Renberg, I., Birks, H. J.B. (2001). Holocene climatic change reconstructed from diatoms, chironomids, pollen and near-infrared spectroscopy at an alpine lake (Sjuodjijaure) in northern Sweden. In: The Holocene n. 5, 11, pp. 551–562. DOI: 10.1191/095968301680223503.

Ruokolainen, L., Salo, K. (2006). The succession of boreal forest vegetation during ten years after slash-burning in Koli National Park, eastern Finland. Annales Botanici Fennici, Vol. 43, No. 5 (2006), pp. 363-378. Finnish Zoological and Botanical Publishing Board. Stable URL: https://www.jstor.org/stable/23727593

Ryan, K., (2002) Dynamic interactions between forest structure and fire behavior in boreal ecosystems. In: Silva Fenn. n. 1, 36. DOI: 10.14214/sf.548.

Ryzhkova, N., Pinto, G., Kryshen', A., Bergeron, Y., Ols, C., Drobyshev, I. (2020). Multi-century reconstruction suggests complex interactions of climate and human controls of forest fire activity in a Karelian boreal landscape, North-West Russia. In: Forest Ecology and Management, 459, p. 117770. DOI: 10.1016/j.foreco.2019.117770.

Ruzmaikin, A., Feynman, J. (2002). Solar Influence on a Major Mode of Atmospheric Variability. Journal of Geophysical Research: Atmospheres, 107, ACL 7-1-ACL 7-11. https://doi.org/10.1029/2001JD001239

Serreze, M. C., Walsh, J. E., Chapin, F. S., Osterkamp, T., Dyurgerov, M., Romanovsky, V. (2000). Observational Evidence of Recent Change in the Northern High-Latitude Environment. In: Climatic Change n. 1, 46, pp. 159–207. DOI: 10.1023/A:1005504031923.

Shabbar, A., Huang, J., Higuchi, K. (2001). The relationship between the wintertime north Atlantic oscillation and blocking episodes in the north Atlantic. In: Int J Climatol n. 3, 21, pp. 355–369. DOI: 10.1002/joc.612.

Skogsstyrelsen. (1945). Skogsstatistisk a˚rsbok (Statistical Yearbook of Forestry). Skogsstyrelsen: Jonkoping.

Sousa, P. M., Trigo, R. M., Barriopedro, D., Soares, P. M. M., Ramos A. M., Liberato M. L. R. (2016). Responses of European precipitation distributions and regimes to different blocking locations.

Steinhilber, F., Abreu, J. A., Beer, J., Brunner, I., Christl, M., Fischer, H. et al. (2012). 9,400 years of cosmic radiation and solar activity from ice cores and tree rings. In: *Proceedings of the National Academy of Sciences of the United States of America* n. 16, 109, pp. 5967–5971. DOI: 10.1073/pnas.1118965109

Stocks, B.J., Fosberg, M.A., Lynham, T.J., Mearns, L., Wotton, B.M., Yang, Q., Jin, J.-Z., Lawrence, K., Hartley, G.R., Mason, J.A., McKenney, D.W. (1998). Climate change and forest fire potential in Russian and Canadian boreal forests. Climatic Change 38: 1–13.

Storaunet, K.O., Rolstad, J., Toeneiet, M., Blanck, Y.-l. (2013). Strong anthropogenic signals in historic forest fire regime: a detailed spatiotemporal case study from southcentral Norway. Can. J. For. Res. Can. Rech. For. 43 (9), 836–845.

Storli, I. (1993). Sami Viking Age Pastoralism – or “The fur trade Paradigm” reconsidered. Norweg. Archaeol. Rev. 26, 1–20.

Thonicke, K., Spessa, A., Prentice, I.C., Harrison, S.P., Dong, L., Carmona-Moreno, C. (2010). The influence of vegetation, fire spread and fire behaviour on biomass burning and trace gas emissions: results from a process-based model. Biogeosciences 7: 1991–2011.

Tikkanen, M. (2005). Climate. In: Seppälä, M. (ed.). The physical geography of Fennoscandia. Oxford University Press, UK. p. 97–112.

Tryterud, E. (2003). Forest fire history in Norway: from fire-disturbed pine forests to fire-free spruce forests. Ecography 26, 161–170.

Turco, M., Jerez, S., Doblas-Reyes., F.J., AghaKouchak, A., Llasat, M.C., Provenzale, A. (2018) Skilful forecasting of global fire activity using seasonal climate predictions, Nat. Commun., 9:2718.

van Loon, H., Meehl, G. A., Shea, D. J. (2007). Coupled air-sea response to solar forcing in the Pacific region during northern winter. In: J. Geophys. Res. n. D2, 112. DOI: 10.1029/2006JD007378.

Van Wagner, C. E. (1987). Development and structure of the Canadian forest fire index system, Forestry Technical Report, Canadian Forestry Service Headquarters, Ottawa.

Velasco, H., Victor, M., Mendoza, B., He, G. (2015). Reconstruction and prediction of the total solar irradiance: From the Medieval Warm Period to the 21st century. In: New Astronomy, 34, pp. 221–233.

Wallenius, T. (2004). Fire histories and tree ages in unmanaged boreal forests in Eastern Fennoscandia and Onega peninsula. Academic Dissertation, Department of Biological and Environmental Sciences, Faculty of Biosciences, and Department of Forest Ecology, Faculty of Agriculture and Forestry. University of Helsinki. 61 pp.

Wallenius, T. (2011). Major Decline in Fires in Coniferous Forests - Reconstructing the Phenomenon and Seeking for the Cause. Silva Fenn. 45, 139–155.

Wallenius, T.H., Lilja, S., Kuuluvainen, T., (2007). Fire history and tree species composition in managed Picea abies stands in southern Finland: Implications for restoration. For. Ecol. Manage. 250, 89–95.

Wallenius, T. H., Kauhanen, H., Herva, H., Pennanen, J. (2010). Long fire cycle in northern boreal Pinus forests in Finnish Lapland. In: Can. J. For. Res. n. 10, 40, pp. 2027–2035. DOI: 10.1139/X10-144.

Whitlock, C., Higuera, P. E., McWethy, D. B., Briles, C. E. (2010). Paleoecological perspectives on fire ecology: revisiting the fire-regime concept. Open Ecology Journal 3:6–23.

Zackrisson, O. (1977). Influence of forest fires on North Swedish boreal forest. Oikos 29, 22–32.

Zumbrunnen, T., Menndez, P., Bugmann, H., Conedera, M., Gimmi, U., Burgi, M. (2012). Human impacts on fire occurrence: a case study of hundred years of forest fires in a dry alpine valley in Switzerland. Regional Environmental Change 12:935–949.

8 APPENDICES

Appendix A. Sites included in the charcoal-based fire activity synthesis.

Site name	***Location***	***Charcoal source***	***Temporal resolution***	***Core lenght (cm)***	***No. of C14 dates***	***Chronology cover (cal yrs BP)***	***Source***
Lattok	Northern Sweden (65.96,18.34)	lake	200 yrs	176	8	10000 - present	Carcaillet et al., 2007
Lovnas	Northern Sweden (66.31,17.9)	lake	200 yrs	240	5	9500 - present	Carcaillet et al., 2007
Raigejegge	Northern Sweden (66.16,18.21)	lake	200 yrs	132	8	9000 - present	Carcaillet et al., 2007
Vatnan5	Norway (70.53,22.9)	bog	200 yrs	171	3	5900 - 0	Karl-Dag Vorren, 2005
Sjuodjijaure Lake	Northern Sweden (67.36,18.06)	lake	200 yrs	255	11	9000 - 26	Rosén et al., 2001
Low Impact Area	Northern Sweden (66.62,17.82)	bog	50 yrs	45	3	2000 - present	Josefsson et al., 2009
Akkapakte	Northern Sweden (66.63,17.68)	bog	50 yrs	45	3	2700 - present	Josefsson et al., 2009
Gammelhemmet	Northern Sweden (64.44,18.62)	mire	20 yrs	64	4	1750 - 350	Kamerling et al., 2021
Hornmyr	Northern Sweden (64.4,18.42)	mire	20 yrs	90	4	1300 - 150	Kamerling et al., 2021

ACKNOWLEDGEMENTS

I want to thank the Swedish University of Agricultural Sciences (SLU) for giving me the possibility to develop this project during my stay in Alnarp (Sweden) in an enlightening collaboration. A special thank goes to my co-supervisor Igor Drobyshev who helped me throughout the whole process and gave me the opportunity to study these topics and learn from his experience.

I want to thank also my family who sustained me over these two years of Master, allowing me to take part in the best experience of my life so far.