Burning boreal forests: how did fire regimes in Fennoscandia change during the Holocene and why?

Writing Assignment

Ida van Heusden

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Supervisor: Thomas Giesecke (Utrecht University)

Examiner: Timme Donders (Utrecht University)

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Contents

Plain language summary

The occurrence of fires is important to keep forests in Fennoscandia healthy. These fires are increasing in number and can cause large amounts of damage, which is why knowledge on the natural occurrence of fires and patterns therein is needed. With this knowledge, appropriate management solutions can be made. This knowledge can be gained by looking at the behaviour of fires in the past, before humans started impacting the landscape at large scales. In this review, knowledge on wildfire behaviour in Fennoscandia over the last 12000 years and the causes of the behaviour of fires is summarised. This is done to see in what way data on forest fires in the past is relevant to the management of forests and forest fires in Fennoscandia. The review will also try to identify the main challenges that researchers face. The different methods with which forest fires can be looked at all have their own advantages and disadvantages. Depending on what is being investigated, the best method should be chosen. Forest fire behaviour varied over the last 12000 years, and could usually be explained by climate, the plants that were present and the behaviour of humans during a period. However, connecting a change in fire behaviour to a cause is still difficult, because climate, plants and humans interact with each other, and there are still uncertainties about past climate in Fennoscandia. Aside from this, studies are done in different places where the environment is different, which makes connecting the cause and effect of a fire more difficult. By looking at fire behaviour, climate and the past landscape with more methods at the same time, a more complete picture of the past landscape, and the processes that took place can be given. Then, the results of research into fire behaviour can be used in the management of forests and forest fires in Fennoscandia.

Abstract

Wildfire is an important natural phenomenon that affects Fennoscandian boreal forest ecosystems and their functioning. Due to the increase in large boreal wildfires and the damage they cause, knowledge on the natural fire regime is needed to manage these fires. This knowledge can be gained through the reconstruction of fire histories with methods such as palaeoecological studies of past ecosystems, which are able to look back to the period when humans had little impact on the landscape. This review aims to summarise knowledge on wildfires in Fennoscandian boreal forests throughout the Holocene and their drivers. This is done in order to discuss how the study of historical wildfires may be relevant for the management of future wildfires, and where the main challenges lie. Different methods for the reconstruction of fire regimes have their own strengths and weaknesses, and depending on the objectives of a study, the most suitable approach should be chosen. Wildfire regimes in Fennoscandia changed throughout the Holocene and were mostly driven by climate, vegetation and different forms of human activity. However, connecting drivers to fire regimes remains a large challenge, due to the interactions between the different drivers and varying local conditions and variables between study sites. Moreover, there still exist uncertainties about climate in Fennoscandia during the Holocene. Multi-proxy approaches may be a valuable addition to the toolbox of fire history reconstruction, as they can provide a more complete picture of past ecosystems, climates and fire histories. The outcomes of palaeoecological research can then be applied to appropriate management for boreal forests and wildfires in those ecosystems.

1. Introduction

Fires are a naturally occurring phenomenon in boreal forests and affect both the forest structure by affecting forest rejuvenation (Kuuluvainen & Gauthier, 2018; Zackrisson, 1977), and fire affects ecosystem functioning as well (Flannigan et al., 2009a). Recently, large fire events have been occurring in boreal forests worldwide (Scholten et al., 2024). In Canada, 15 million hectares of forests were burnt in 2023, which was the most intense wildfire season to date (Jain et al., 2024), while in Europe, Sweden experienced the worst fires in decades in 2018, with 25000 hectares of forest burnt (Kelly et al., 2021). Boreal wildfires lead to carbon loss, biodiversity loss, economical damage and have large societal impact (Bond-Lamberty et al., 2007; Drobyshev et al., 2021; Kelly et al., 2021; Stephens et al., 2014). Boreal forests in Europe are located in Fennoscandia, and they are dominated by the coniferous species *Pinus sylvestris* (Scots pine) and *Picea abies* (Norway spruce). Additionally, deciduous taxa such as *Betula* (birch) form the treeline (Kuuluvainen et al., 2017; Remy et al., 2023).

Because severe wildfires have the potential to affect large areas and their destructiveness, knowledge on how to manage them is needed. However, since human impact in Fennoscandia has been high for the last few centuries, there is very little evidence on the naturally occurring fire regime in Fennoscandia. Since historical data is needed in order to develop appropriate management strategies for forests, long time fire histories need to be reconstructed, preferably from before significant human activities started taking place, which is where palaeoecological studies can play a significant role (Clear et al., 2013; Kuuluvainen et al., 2017). Palaeoecological studies of the Holocene (11700 years calibrated before present (cal. BP) until now) can be used to reconstruct past ecosystems and climates, as well as past fires. By determining what the drivers of fires were and how ecosystems responded to them in the past, insight into ecosystem responses to present and future conditions can be gained, which is useful for the conservation and management of boreal forests (Lindbladh et al., 2013).

Here, the literature concerning wildfires in Fennoscandian boreal forests throughout the Holocene will be reviewed, as well as literature on the human influence on wildfires in Fennoscandia. The aims of this review are:

- To describe the different methods for the reconstruction of fire histories and their advantages and disadvantages.
- To describe how wildfire regimes changed throughout the Holocene and with what drivers changes in wildfire regimes are associated.
- To describe how human activities have affected wildfire regimes throughout the Holocene.
- To discuss the main challenges and knowledge gaps in the research field.

This will be done to give a view on the potential that studies on fire histories have for future management of wildfires in Fennoscandia, and to indicate what the main challenges for the research field are.

2. Methods for the reconstruction of fire regimes

Fire regimes can be described by combining variables such as fire size and frequency, the amount of biomass burning (BB; indicative of the severity of the fire), as well as location and seasonality of the occurring fires (Marlon, 2020). In this chapter, different methods for fire reconstruction and their advantages and disadvantages will be outlined.

2.1 Historical accounts

Historical accounts of wildfires can be provided with documents, reports and field studies that describe past fires in an area. Statistics on wildfires are nowadays being reported through databases such as the European Forest Fire Information System (http://effis.jrc.ec.europa.eu/) (Marlon, 2020). The compilation of materials from different sources makes this method complex for comparison of fire history data. The Swedish Forest Agency has data on forest fires in the period from 1944-1979 (MSB, 2017), which immediately shows one of the biggest limitations of historical records of fires, namely the gaps in the records. Gaps in historical records can be problematic when these records are used for the reconstruction of fire histories and the causes of historical fires (Östlund & Zackrisson, 2000). However, when available, written accounts can give indications on the drivers of wildfires and shifts in patterns thereof, as well as detailed descriptions of human activities that took place during a certain time period (Östlund & Zackrisson, 2000; Rolstad et al., 2017).

2.2 Dendrochronology

Dendrochronological data comes from trees and scrubs that have been scarred by past wildfires. After a (partial) cross-section is taken from a tree, fire scars can be dated by cross-dating them to a reference chronology. Then, the exact timing, and sometimes even the seasonality, of the fire can be determined (Conedera et al., 2009; Marlon, 2020). Dendrochronological reconstruction of fires is a very temporally and spatially robust method. It gives accurate data on time scales of a few centuries (Granström & Niklasson, 2007; Marlon, 2020; Rolstad et al., 2017). The spatial accuracy is better when more samples are taken over larger areas (Niklasson & Granström, 2000).

Dendrochronological data is generally a good method for the reconstruction of fire regimes. However, it also has its limitations. For example, stand-replacing fires cannot be detected with dendrochronology, since these fires destroy the wood that is needed for dendrochronological approaches (Niklasson & Granström, 2000). Thus, dendrochronological records cannot always provide a complete fire history, and are more suitable for regions that are less prone to stand-replacing fires, and instead experience less severe fires (Conedera et al., 2009; Rolstad et al., 2017). To put this practice to use well, sufficient samples need to be available for a dendrochronological approach. In Fennoscandia, this can be particularly difficult, due to large-scale forestry having removed large numbers of trees (Niklasson & Granström, 2000; Rolstad et al., 2017).

2.3 Palaeoecological reconstruction

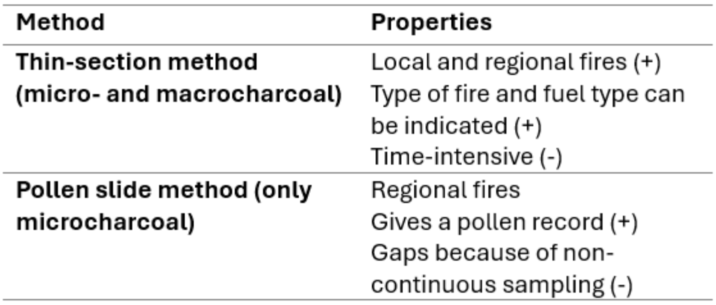
Palaeoecological reconstruction of fires relies on the presence of charcoal particles in cores from lake sediments or peat bogs (Conedera et al., 2009; Marlon, 2020). After a fire has occurred, charcoal particles are dispersed and deposited into sediments, and their morphology remains intact. Charcoal assemblages from lake sediments and peatlands can then be analysed and dated with different methods (e.g. radiocarbon dating, stratigraphy markers). With palaeoecological reconstructions of fires, fire histories can be reconstructed on multimillennial time scales (Conedera et al., 2009; Marlon, 2020).

Reconstruction of fire histories from lake sediments follows a few steps. First, a sediment core is taken from the bottom of a lake and charcoal is sampled from the core. Then, the samples are extracted from the sediment and prepared for a quantification procedure. After the charcoal particles have been identified and quantified, the data is analysed and a fire history can be reconstructed (Conedera et al., 2009).

Oftentimes, palaeoecological records of fire use the charcoal accumulation rate (CHAR), which is reflected in charcoal pieces per square cm per year and allows for the reconstruction of individual fires and fire frequency (Marlon, 2020). For the reconstruction of individual events, charcoal peaks should be higher than a given background accumulation rate, with peaks indicating separate fire events. This allows for the reconstruction of a fire-return interval (FRI). However, the ability to reconstruct a FRI is limited by the need for a high sediment accumulation rate and large and severe fires occurring (Conedera et al., 2009; Marlon, 2020). Since FRI is an important metric that is often used in management (Marlon, 2020), it is important that methodologies to reconstruct this are improved.

The origin of charcoal particles can be local, regional and sometimes even global. Particle size gives indications on the origin of the particle. Large (macroscopic) particles often originate from a nearby fire, while smaller microcharcoal particles give information about the regional fire history due to their ability to be transported by the wind (Table 1; Conedera et al., 2009). Moreover, by looking at the size of the charcoal particles and their morphology, the type of fire and fuel type can also be identified (Feurdean et al., 2017; Marlon et al., 2016).

Table 1: Two methods of palaeoecological sampling and their properties. (+) = advantage, (-) = disadvantage.



Method	Properties
Thin-section method (micro- and macrocharcoal)	Local and regional fires (+) Type of fire and fuel type can be indicated (+) Time-intensive (-)
Pollen slide method (only microcharcoal)	Regional fires Gives a pollen record (+) Gaps because of non-continuous sampling (-)

To get accurate results, sampling for macroscopic charcoal particles should be done in a continuous sequence, after which particles in each sample are counted. The reconstruction of local fires can be done well with a thin-section method, which is , however, time-intensive and expensive to do (Conedera et al., 2009).

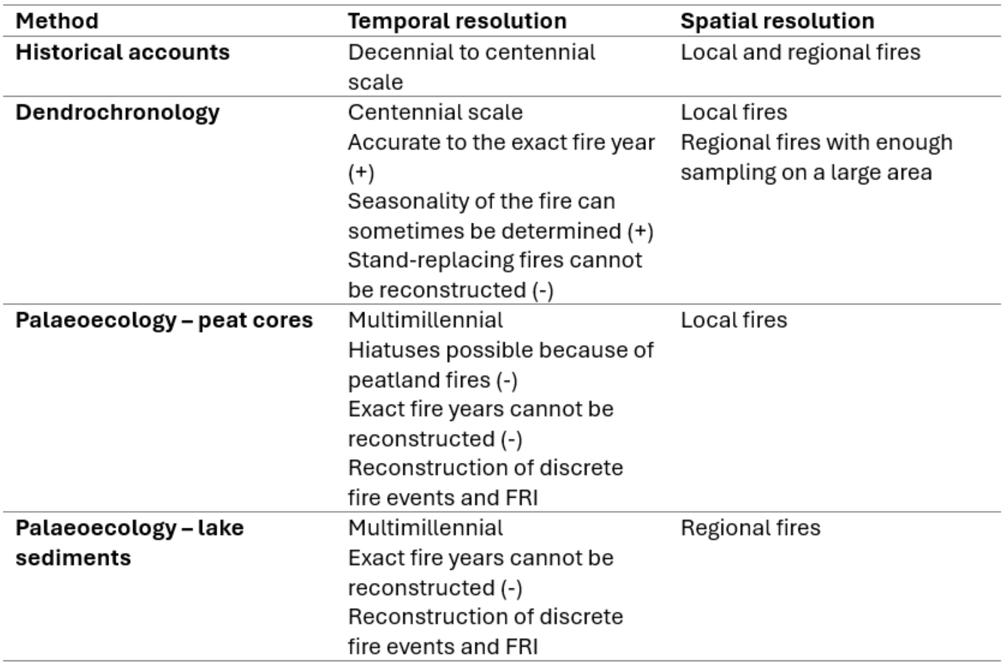
When methods derived from pollen slides are used, macroscopic charcoal pieces are often filtered out and only microscopic charcoal is counted, thereby giving less information about local fire histories. These methods are thus often used to reconstruct fire histories on a regional scale. However, due to the time-intensive sampling procedure for microscopic charcoal detection with pollen-slide methods, the desired continuous record of samples is usually not provided. This makes the reconstruction of regional fire histories complex, but the method can still provide information on the trends in changing fire regimes (Conedera et al., 2009). By using pollen records, an indication of the possible relationship between vegetation and fire can be given, and pollen of species that are indicative of human activities can also be included in the reflection of the past landscape (Conedera et al., 2009; Granström & Niklasson, 2007).

The origin of a charcoal deposit affects the type of information that can be inferred from the record. Charcoal sequences taken from peat cores generally give information about fires on a very local scale. Furthermore, peatlands may burn during very dry periods, which can lead to the loss of parts of a peatland sequence, thereby increasing uncertainty in the record (Marlon, 2020). Therefore, lake sediments generally give a more accurate indication of the fire history of a region and are generally the preferred palaeoecological method (Conedera et al., 2009). Further disadvantages of the use of palaeoecological reconstructions of fire regimes are the limited ability of this method to reflect individual fires and a limited temporal and spatial resolution (Granström & Niklasson, 2007; Marlon, 2020).

2.4 The multi-proxy approach

Every method for reconstruction of fire histories has its own properties, advantages and disadvantages (Table 2). Therefore, depending on the objectives of a study, the most appropriate method should be chosen. For reconstruction of situations in which humans were not present and did not affect the landscape, palaeoecological reconstructions are the best option, since dendrochronological studies and historical accounts can only be used on a decennial to centennial time-scale in which humans were already present.

Table 2: Different methods for the reconstruction of fires and their properties of temporal and spatial resolution. (+) = advantage, (-) = disadvantage.



Method	Temporal resolution	Spatial resolution
Historical accounts	Decennial to centennial scale	Local and regional fires
Dendrochronology	Centennial scale Accurate to the exact fire year (+) Seasonality of the fire can sometimes be determined (+) Stand-replacing fires cannot be reconstructed (-)	Local fires Regional fires with enough sampling on a large area
Palaeoecology – peat cores	Multimillennial Hiatuses possible because of peatland fires (-) Exact fire years cannot be reconstructed (-) Reconstruction of discrete fire events and FRI	Local fires
Palaeoecology – lake sediments	Multimillennial Exact fire years cannot be reconstructed (-) Reconstruction of discrete fire events and FRI	Regional fires

Nonetheless, no single proxy can give a complete view of a past ecosystem. A limited number of studies attempts to combine different methodologies in order to provide a more complete picture of the past fire regime or ecosystem. The results of these studies show promising results, despite the sometimes complex procedures that are needed for the integration of different proxies (Edvardsson et al., 2022; Stivrins et al., 2019).

3. Wildfire regimes in Fennoscandian boreal forests during the Holocene and their drivers

3.1 The natural drivers of wildfire regimes during the Holocene

Fires are a naturally occurring disturbance in boreal forests in Fennoscandia. Most fires in European boreal forests are surface fires of low intensity and low frequency (de Groot et al., 2013; Feurdean et al., 2017; Ohlson et al., 2011). The prerequisites for the occurrence of wildfires are a fuel source, favourable conditions and an ignition source (Marlon, 2020). The only natural cause of wildfires in Fennoscandia is ignition by lightning strikes. With increasing latitude, the frequency of lightning strikes decreases, resulting in a lower amount of natural ignitions in northern Fennoscandia (Granström, 1993; Larjavaara et al., 2005). Lightning strikes occur most often from June to August, while peaking in July, coinciding with the period of most lightning-ignited forest fires in Sweden (Granström, 1993; Rolstad et al., 2017). Favourable conditions and fuel are provided by climate and vegetation (Marlon, 2020), and will be further discussed in the following sections.

3.1.1 Climate

Climate affects the occurrence of wildfires because it determines the temperature, humidity and weather events that lead to favourable conditions for the ignition of wildfires (Marlon, 2020). Climate during the Holocene was variable, with both warmer and cooler periods occurring in Scandinavia. The earlier Holocene in Europe was relatively cool, although northern Fennoscandia was already warmer than during pre-industrial times (Mauri et al., 2015). After the cool 8.2 ka event, mid-Holocene climate was warmer in Scandinavia during the "Holocene Thermal Maximum" (HTM; ~8000-4000 cal. BP)(Mauri et al., 2015; Seppä et al., 2009). From ~5000 cal. BP until now, a cooling trend exists in Fennoscandia, which is interrupted by warmer and cooler intervals (Figure 1a & Figure 1c; Seppä et al., 2009). At least two distinctive climatic intervals can be identified during the late Holocene: the Medieval Warm Period, which was a somewhat warmer and moister period between ~1000-500 cal. BP; and the Little Ice Age, which was a period with cooler and drier conditions around 500-200 cal. BP (Edwards et al., 2017; Seppä et al., 2009). Throughout the Holocene, precipitation amounts were generally lower during summers, while winters were relatively wet. In Fennoscandia, a gradient from west to east was reconstructed, with areas westward from the mountains being wetter than areas on the east side of the mountains (Mauri et al., 2015).

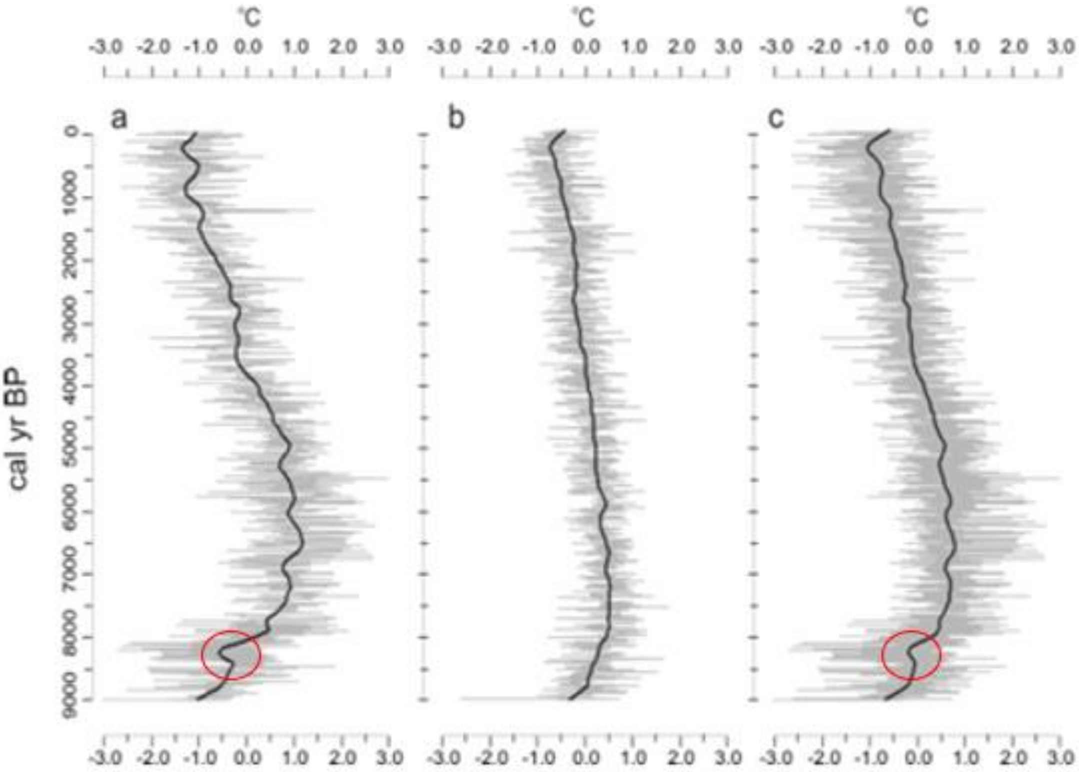


Figure 1: Reconstructed temperature record for Northern Europe over the past 9000 years. Data is assimilated form pollen records. Panel (a) shows the annual temperature deviation from the mean temperature, (b) shows the July temperature record, (c) shows the combined curve of the annual and July temperature records. Red circle indicates the 8.2 ka event. Adapted from Seppä et al. (2009).

Changes in temperature and moisture are the two main climatic conditions with which fluctuations in fire activity appear to correlate. Increases in fire frequency are associated with higher temperatures, and dry summers are associated with higher amounts of biomass burning in Fennoscandia (Aakala et al., 2018; Carcaillet et al., 2012; Drobyshev et al., 2014; Molinari et al., 2018).

Temperature influences fire activity through different processes (Figure 2). Firstly, higher temperatures cause increased evapotranspiration, transporting moisture from the vegetation into the atmosphere, thereby causing vegetation (which acts as fuel) to be drier. Secondly, higher temperatures may result in more lightning strikes, increasing the number of ignitions. Lastly, increased temperature can cause longer fire seasons, because conditions remain favourable for longer periods of time (Flannigan et al., 2009b).

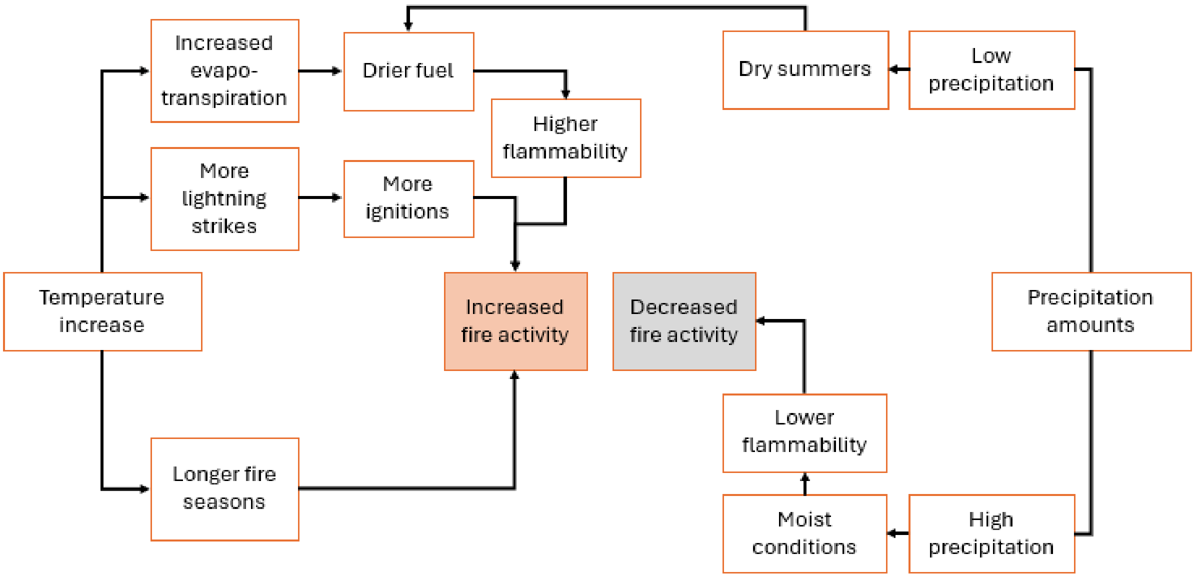


Figure 2: The effects of increased temperature and precipitation amounts on fire activity. Dotted lines depict possible directions of an effect. Arrows show the relationship between a variable and its outcome. Data is from Flannigan et al. (2009b) and Aakala et al. (2018).

The importance of the amount of precipitation (drought occurrence in particular), as a driver of wildfires is reflected in fire synchrony. Extremely dry summers are correlated with synchronised peak fire activity (large fire years; Drobyshev et al., 2014) at locations that are large distances apart from each other in eastern Fennoscandia (Aakala et al., 2018). Aakala et al. (2018) also mention that large fire years overlap little in western and eastern Fennoscandia. It is likely that this difference is related to these systems experiencing different amounts of influence from the Atlantic Ocean and the Eurasian continent (Aakala et al., 2018), as well as possible differences in the amount of precipitation (Mauri et al., 2015).

Conversely, wetter conditions will presumably lead to decreased fire activity. Higher amounts of precipitation cause moist conditions, which lead to a lower flammability of the fuel (Figure 2). Additionally, higher amounts of precipitation likely prevent fires from spreading over larger areas, limiting fire size (Remy et al., 2023).

Despite these correlations between climatic variability and changes in fire activity, conclusions about the effects of changes in climatic conditions on changes in fire activity should be made with extreme caution. Uncertainties still exist about the Fennoscandian climate during the Holocene, and what factors played a role in the determination thereof. While temperature reconstructions over the whole of Fennoscandia have been made (Seppä et al., 2009), no similar region-wide reconstruction for precipitation or moisture content could be found. Instead, multiple different proxies such as *Spaghnum spp*. spores and lake-level fluctuations are used to reflect moisture and precipitation in palaeoecological and fire-history reconstructions (Bradshaw et al., 2010; Remy et al., 2023).

3.1.2 Vegetation

Vegetation serves as a fuel source that is needed to sustain fires after ignition. When vegetation is widely available and dry, it can effectively be burned in a fire. However, under wet conditions, or when little vegetation is available, vegetation can also inhibit fire activity

(Marlon, 2020). For example, Ohlson et al. (2011) saw that moist coastal regions showed less biomass burning than drier inland regions.

Moreover, different vegetation types can have different effects on fire regimes, by having functional traits that affect flammability rates and the fuel type. Therefore, changes in vegetation type can also impact fire regimes (Clear et al., 2013).

The dominant tree species in boreal forests in Fennoscandia react differently to fires (Figure 3). *P. sylvestris* is a species that is able to resist fires relatively well through its thick bark and its fast recovery after fires. It grows best on xeric, nutrient-poor soils. Because *P. sylvestris* lacks low-hanging branches, most fires in *P. sylvestris*-dominated forests are relatively frequent surface fires that seldomly spread to the crown (de Groot et al., 2013; Feurdean et al., 2017; Remy et al., 2023). Contradictory, *P. abies,* which grows mostly in wet environments, completely lacks traits that allow the species to recover after fires. Additionally, its branching structure and flammable needles promote severe, stand-replacing crown fires during dry periods, by providing a ladder fuel structure that allows fire to move into the crown (de Groot et al., 2013; Feurdean et al., 2017; Remy et al., 2023; Rogers et al., 2015).

Ohlson et al. (2011) saw that the establishment of *P. abies* correlates to a decrease in wildfire activity. Although climate was one of the drivers that they identified as a cause of decreasing wildfire activity, they also saw a correlation between the amount of *P. abies* pollen and the amount of charcoal. A possible explanation for the decreased fire activity seen by Ohlson et al. (2011) is that the establishment of *P. abies* caused a cooler and wetter microclimate, and also causes denser forest stands. Another study found that the after the establishment of *P. abies,* the fire return interval decreased from 150 to 510 years (Clear et al., 2015). It is however unclear whether the establishment of *P. abies* is caused by a lower fire frequency, or if the trees themselves cause this decrease in fire frequency (Clear et al., 2015; Kuosmanen et al., 2014; Ohlson et al., 2011).

Similarly to *P. abies, P. sylvestris* establishment shows a complex relationship with fire activity. Increasing fire activity was shown to happen at the same time as an increase in *P. sylvestris* pollen was found (Brown & Giesecke, 2014). In this case too, the direction of the effect remains unknown.

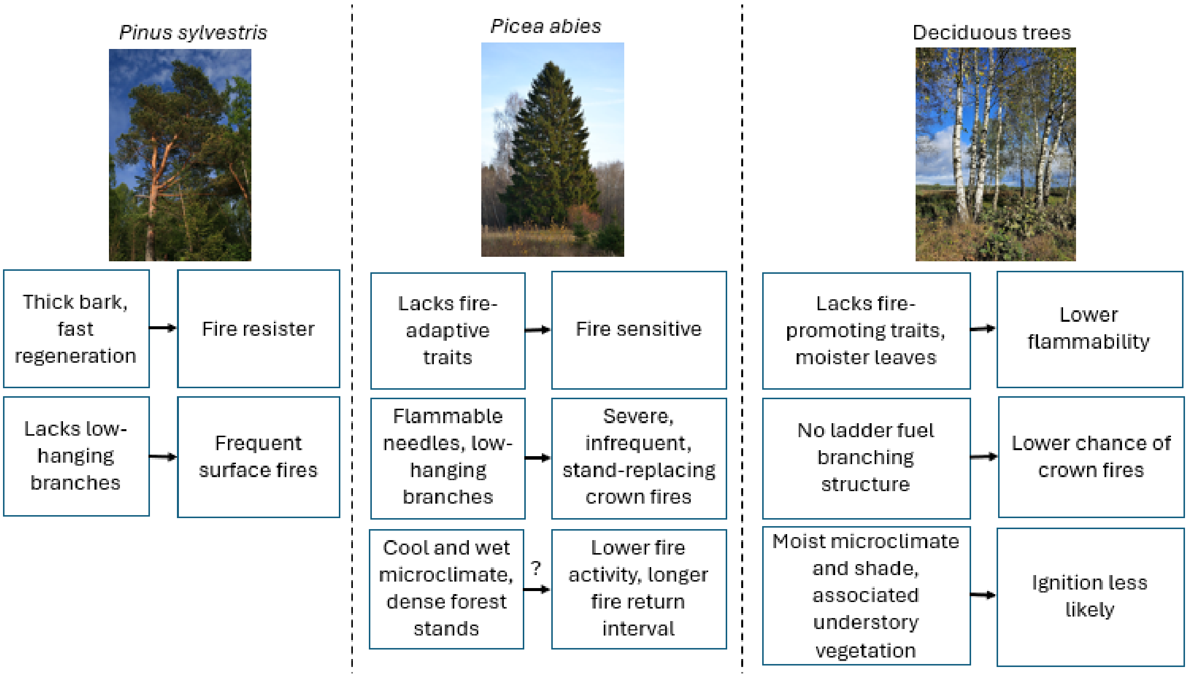


Figure 3: Different traits of P. sylvestris, P. abies and deciduous trees that result in them reacting to fires differently. For each species (group), the boxes on the left indicate a specific trait and the boxes on the right indicate the result of the trait. '?' = the hypothetical relationship proposed by Ohlson et al. (2011). Pictures taken from (Delcey, 2012; Leidus, 2011; Ruwe Berk (Betula Pendula)*, n.d.).*

Deciduous trees also react differently to fires than coniferous species do (Figure 3). Deciduous species lack fire-promoting traits such as high resin content, and contain less flammable leaves. They also do not have the same branching structure as conifers, lowering the chance of fires moving into the crown layer. Lastly, deciduous trees provide a moister microclimate and shade, which makes ignition less likely (Feurdean et al., 2017; Rogers et al., 2015).

3.2 Changes in wildfire regimes in time and space

Wildfire activity in boreal Fennoscandia was variable throughout the Holocene, responding to changes in climate, vegetation and human activity. Figure 4 shows the general pattern of biomass burning (BB) in Fennoscandia during the Holocene (Molinari et al., 2020). The uncertainty of the reconstruction decreases through time, with the later Holocene generally showing less uncertainty than the earlier parts of the Holocene. In the most recent part of the Holocene, the uncertainty increases again. Caution should therefore be taken when interpreting this trend. Thus, only the general trend is described here.

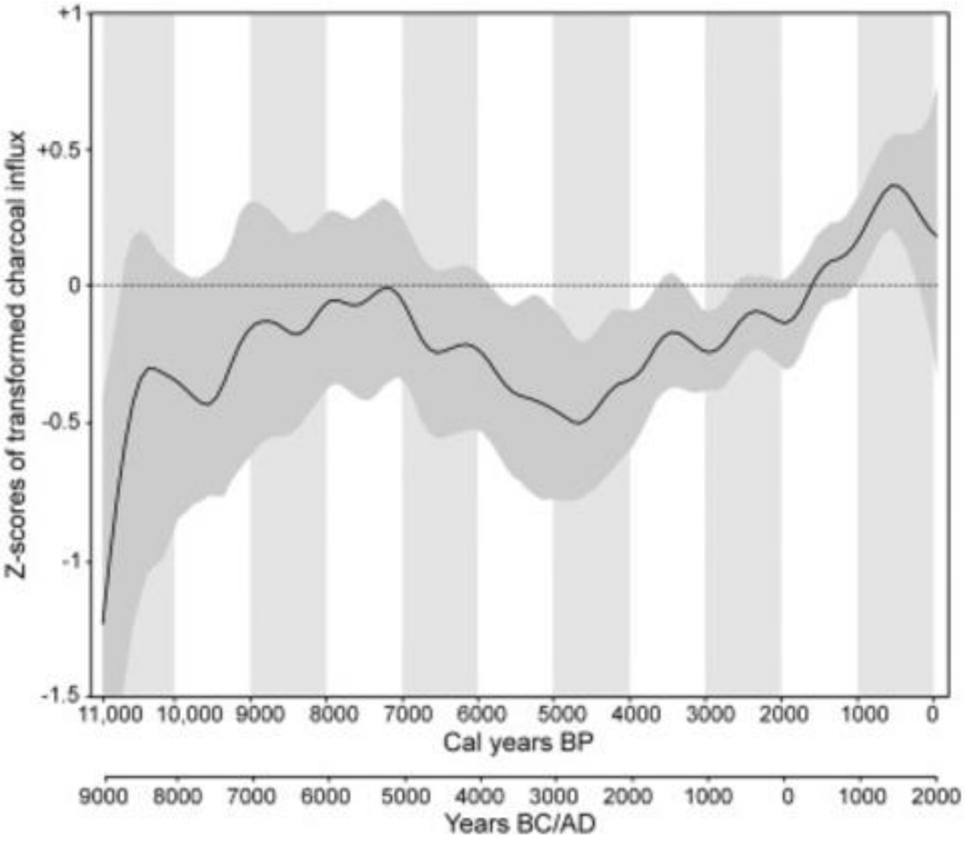
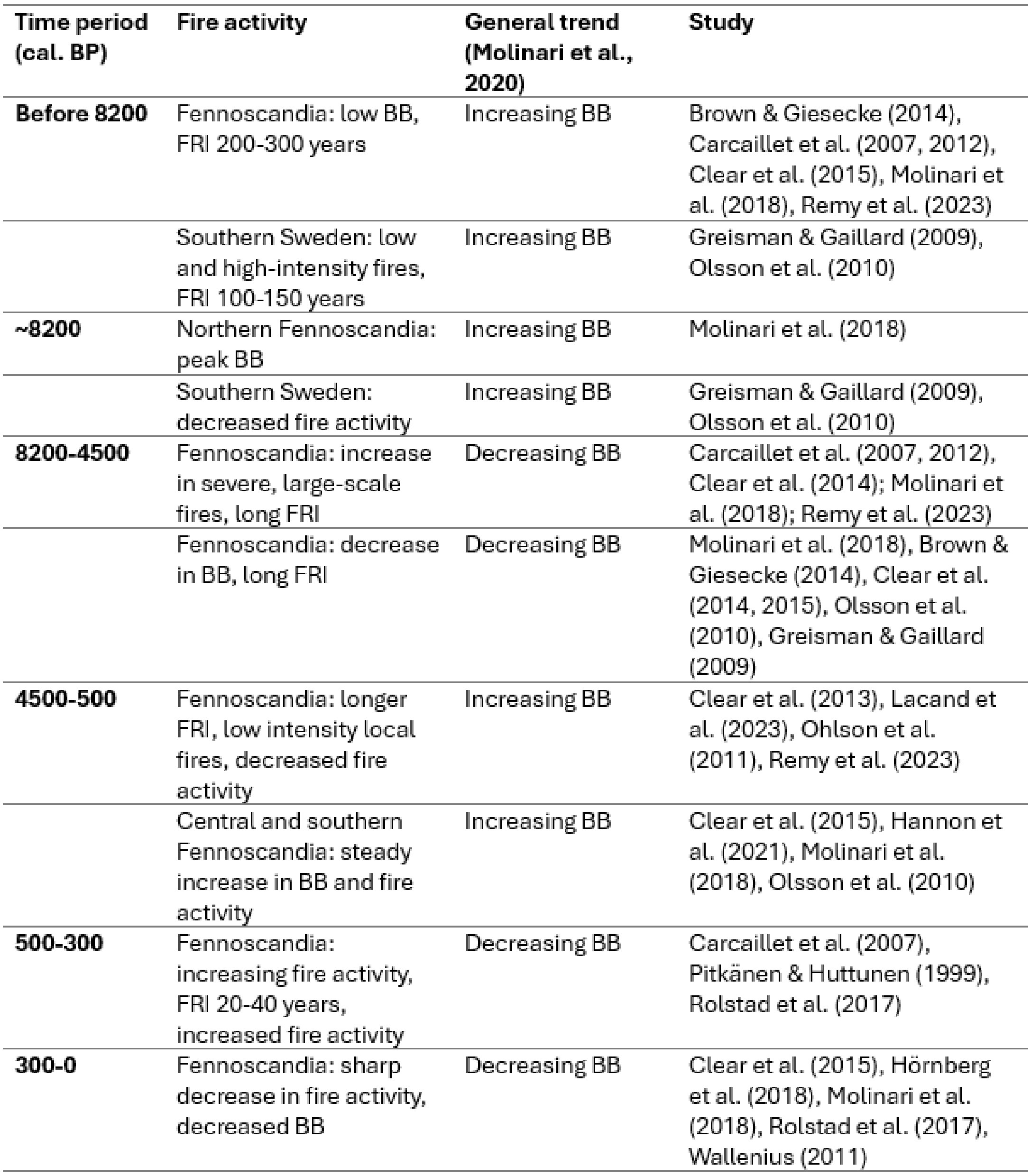


Figure 4: fire activity in Fennoscandia throughout the Holocene, taken from 69 sedimentary charcoal records (Molinari et al., 2020). The black line indicates the overall trend of biomass burning (BB). Grey shadowing indicates 95% CI. The overall trend indicates an increase in BB until about 7000 cal. BP, a decrease in BB from 7000 until 4500 cal. BP, an increase from 4500 to 500 cal. BP, after which a decrease in fire activity is indicated.

The overall trend shows an increase in BB during the early Holocene, and a decrease during the mid-Holocene. An increase in BB is shown from ~4500 cal. BP until ~500 cal. BP, after which BB decreases again. This last increase in BB roughly coincides with the increase in temperature in Fennoscandia from 5000 cal. BP until the present day that was observed by Seppä et al. (2009), indicating that increases in temperature and increases in BB may be related to each other.

Early in the Holocene, fire activity was low in northern Fennoscandia, with low amounts of BB and fire-return intervals (FRIs) having a long duration (200-300 years; table 3) (Brown & Giesecke, 2014; Carcaillet et al., 2007; Clear et al., 2015; Molinari et al., 2018; Remy et al., 2023). Carcaillet et al. (2012) note that fires may have spread over a large surface area in northern Sweden, so wildfires were probably occurring on a regional scale. Fire activity was different in southern Fennoscandia during this period (Greisman & Gaillard, 2009; Olsson et al., 2010). While fires in the early Holocene were probably not very intense and relatively small, they were more frequent than in northern Fennoscandia (FRI 100-150 years). Following this period of relatively low fire activity, fire activity became more variable, with periods of both low and high fire activity being recorded between 10500 and 9500 cal. BP, while high fire activity is shown on a local scale between 9500 and 8500 cal. BP (Greisman & Gaillard, 2009; Olsson et al., 2010).

Table 1: A general overview of fire activity throughout the Holocene. Indicated are time period, the corresponding fire activity, the general trend as reconstructed by Molinari et al. (2020) and the corresponding studies.



Time period (cal. BP)	Fire activity	General trend (Molinari et al., 2020)	Study
Before 8200	Fennoscandia: low BB, FRI 200-300 years	Increasing BB	Brown & Giesecke (2014), Carcaillet et al. (2007, 2012), Clear et al. (2015), Molinari et al. (2018), Remy et al. (2023)
	Southern Sweden: low and high-intensity fires, FRI 100-150 years	Increasing BB	Greisman & Gaillard (2009), Olsson et al. (2010)
~8200	Northern Fennoscandia: peak BB	Increasing BB	Molinari et al. (2018)
	Southern Sweden: decreased fire activity	Increasing BB	Greisman & Gaillard (2009), Olsson et al. (2010)
8200-4500	Fennoscandia: increase in severe, large-scale fires, long FRI	Decreasing BB	Carcaillet et al. (2007, 2012), Clear et al. (2014); Molinari et al. (2018); Remy et al. (2023)
	Fennoscandia: decrease in BB, long FRI	Decreasing BB	Molinari et al. (2018), Brown & Giesecke (2014), Clear et al. (2014, 2015), Olsson et al. (2010), Greisman & Gaillard (2009)
4500-500	Fennoscandia: longer FRI, low intensity local fires, decreased fire activity	Increasing BB	Clear et al. (2013), Lacand et al. (2023), Ohlson et al. (2011), Remy et al. (2023)
	Central and southern Fennoscandia: steady increase in BB and fire activity	Increasing BB	Clear et al. (2015), Hannon et al. (2021), Molinari et al. (2018), Olsson et al. (2010)
500-300	Fennoscandia: increasing fire activity, FRI 20-40 years, increased fire activity	Decreasing BB	Carcaillet et al. (2007), Pitkänen & Huttunen (1999), Rolstad et al. (2017)
300-0	Fennoscandia: sharp decrease in fire activity, decreased BB	Decreasing BB	Clear et al. (2015), Hörnberg et al. (2018), Molinari et al. (2018), Rolstad et al. (2017), Wallenius (2011)

During the earlier Holocene, climate likely played a role in determining fire activity in Fennoscandia. Cooler and moister climatic conditions have been reconstructed for this time in northern Fennoscandia, while warm and dry conditions have been reconstructed for southern Fennoscandia. These climatic conditions have been related to the fire activity in the respective regions (Clear et al., 2014, 2015; Greisman & Gaillard, 2009; Molinari et al., 2013, 2018; Olsson et al., 2010; Remy et al., 2023). This variation in climatic conditions could partly explain the differences between northern and southern Fennoscandia. However, the lower fire activity in northern Fennoscandia could also be due to there being fewer natural ignitions of fires in this region as a result of fewer lightning strikes and a relatively wet landscape (Carcaillet et al., 2007; Granström, 1993; Larjavaara et al., 2005). Furthermore, the sea-surface temperature of the North Atlantic Ocean could be related to fire activity in Northern Scandinavia. Lower sea surface temperatures would lead to shifts in air circulation, which in turn negatively impact precipitation and thereby increase fire activity in Northern Scandinavia (Drobyshev et al., 2016). Increased fuel load is suggested to have led to increasing BB during the early Holocene in Fennoscandia (Clear et al., 2014, 2015).

Multiple studies in southern Sweden found decreases in fire activity that correspond roughly to the 8.2 ka cal. BP event, a period of abrupt cooling (Greisman & Gaillard, 2009; Olsson et al., 2010; Seppä et al., 2009). Interestingly, northern Fennoscandia experienced peak BB around 8000 cal. BP, while showing a decrease from 7500-5500 cal. BP (Molinari et al., 2018).

During the mid Holocene, fire activity in Fennoscandia as a whole is generally higher, coinciding with the Holocene Thermal Maximum. Fire frequency increased, with medium to large scale surface fires occurring throughout Fennoscandia, and BB increasing as well (Carcaillet et al., 2007, 2012; Clear et al., 2014; Molinari et al., 2013; Remy et al., 2023). Between 6500 and 4700 cal. BP, an increase in severe, large scale fires is seen. These fires were, however, rather infrequent, with fire-return intervals probably having spanned 250 years (Remy et al., 2023). This result of increased fire activity is not surprising, since climatic conditions (warm and dry) would have been favourable for wildfires to occur. The infrequent nature of the fires is, however, unexpected. The present vegetation composition could not be linked to this long FRI, suggesting that the cause of this pattern may be a climatic factor, such as a lower frequency of lightning strikes.

Despite many studies seeing an increase in fire activity with the climatic conditions during the HTM, some studies find the opposite, which is consistent with the general decreasing trend (Figure 4; Molinari et al., 2020). Molinari et al. (2018) find that BB decreased in northern Fennoscandia between 7500-5500 cal. BP and saw a steady decrease after 8700 cal. BP in central Fennoscandia. This is also reflected in the low fire activity and long time between fires in central and southern Sweden (FRI>350 years) (Brown & Giesecke, 2014; Olsson et al., 2010), and long FRIs in southern Finland, which were approximately 500 years between 4500 and 3500 cal. BP (Clear et al., 2015). Additionally, Clear et al. (2014) found that many sites in Finland experienced lower fire activity during this period, even though climatic conditions were favourable for wildfires during this period, a pattern that was also found for central Sweden by Brown & Giesecke (2014).

Possible explanations for this pattern of low fire activity during a period that was conducive to fires are higher moisture levels in southern Sweden (Greisman & Gaillard, 2009), as well as warmer conditions that would have been favourable for a vegetation composition with a higher amount of deciduous species (Brown & Giesecke, 2014). This second hypothesis was supported by a study in the Baltic region, where a pattern of increased broadleaf vegetation was seen during the HTM as well (Feurdean et al., 2017). Moreover, fire events may be very site-specific and depend on local influences of topography, vegetation, climate and elevation (Kuosmanen et al., 2014; Molinari et al., 2013). This could explain why local patterns of fire cannot be explained by regional climatic trends.

From ~4500 cal. BP to ~500 cal. BP, fire activity generally increases in Fennoscandia (Figure 4), with a higher fire frequency and more BB occurring (Clear et al., 2014, 2015; Hannon et al., 2021; Molinari et al., 2020; Remy et al., 2023). Olsson et al. (2010) saw increasing fire activity between 4000 and 2500 cal. BP in one location, while fire activity was low in a nearby location, once again implying the importance of local conditions. This pattern of increasing fire activity is surprising, since climatic conditions became less favourable for fires during the late Holocene (Seppä et al., 2009). Therefore, it is highly probable that fires were driven by another variable during this period at locations with increasing fire activity. Brown & Giesecke (2014) were able to correlate increasing fire activity in the late Holocene to increases in *P. sylvestris* abundance, so vegetation composition may have played a role at more sites.

Despite this general increase in BB, there are also studies that show relatively low fire activity for the late Holocene. A decrease in fire activity is noted by Ohlson et al. (2011) from 4500 cal. BP onwards, while low-frequency and low-intensity fires were noted in southern Finland between 5000 and 2000 cal. BP (Clear et al., 2013). These shifts in fire activity can be linked to the climatic conditions in the late Holocene (Seppä et al., 2009), as well as shifts in vegetation composition that would have led to moister microclimates (Ohlson et al., 2011). Lacand et al. (2023) see a decrease in fire frequency on the regional scale from 4000 cal. BP. They were unable to relate this change in fire frequency to climatic variables, and instead explain this pattern by variations in altitude and the resulting change in vegetation composition and fuel availability.

Over the course of the last 2000 years, fire activity in northern Finland was lower, except during the Medieval Warm Period (~1000 cal. BP), which was a period of slightly higher fire activity and higher fire frequency, though severity of the fires did not change (Lacand et al., 2023; Remy et al., 2023). This pattern suggests that climate may have been an important driver of fires during this period. In southern Finland, fire activity was higher from 2000 cal. BP onwards, which may be linked to the higher abundance of *P. sylvestris* in the area during this time (Clear et al., 2013).

The general decrease in BB over the last 500 years (Figure 4) coincides with the Little Ice Age, so the lower temperatures during this period may have played a role in the decreased BB during this period. During the Little Ice Age (300 cal. BP), fire intervals between years with large fire activity increased in length (Drobyshev et al., 2014).

In southern Norway, fire activity was low before 1625 AD, with some large but very seldomly occurring fires having been shown. In the period from 1625-1800 AD, fire activity was higher with small and frequent fires occurring. No recent fires were recorded. FRIs fell between 60-100 years before 1625 and decreased to 20-40 years after 1625 (Rolstad et al., 2017). Correlating increases in charcoal were found from ~400 cal. BP in eastern Finland, suggesting increasing fire activity during the late Holocene (Pitkänen & Huttunen, 1999). Due to the correlation with the Little Ice Age, one would expect to see lower fire activity due to the cooler conditions. This implies that another factor may have driven fire activity during this period instead, a view that is supported by Olsson et al. (2010).

During the 18th and 19th century, Carcaillet et al. (2007) see an increase in fire activity, contrasting with the very long fire-return intervals they found before that. From the 19th century onwards, fire activity sharply decreased over Fennoscandia, with a clear decline visible over the last 100 years (Clear et al., 2015; Hörnberg et al., 2018; Wallenius, 2011).

4. The influence of human activities on wildfire regimes in boreal forests in Fennoscandia

4.1 Human activities and their effects on boreal forests

During the Holocene, humans developed into a dominant species that started affecting land-cover by practices such as agriculture (Zapolska et al., 2023). It is likely that northern boreal forests have been inhabited and used for their resources by humans for millennia, as some of the oldest settlements found in northern Fennoscandia are between 8000 and 10000 years old (Josefsson et al., 2009). Additionally, archaeological evidence shows that the native people of Fennoscandia, the Sami, probably have been living in northern Fennoscandian forests and using them for a long time, for example for reindeer grazing (Josefsson et al., 2010).

It is unlikely that high-intensity activities such as large-scale land clearance have taken place in northern Fennoscandia. Nevertheless, humans probably still affected the forests in this region. Forest composition and structure was likely affected by lower intensity activities such as tree felling on a small scale. Younger forest stands with higher *Betula* abundance and a lower abundance of old trees are located at sites where repeated felling of trees has taken place (Josefsson et al., 2009, 2010). Additionally, the keeping of domesticated reindeer may have affected ground vegetation and its composition through grazing and trampling. The regeneration of *Betula* and *P. sylvestris* may also have been positively affected by these processes (Josefsson et al., 2010).

Human impact on forests was likely higher in southern Fennoscandia, where slash-and-burn agriculture was practiced. Slash-and-burn agriculture was used widely in Fennoscandia during the Holocene, until more modern agricultural practices and the availability of other livelihoods decreased its use (Bradshaw et al., 2010; Clear et al., 2014; Molinari et al., 2018). With this practice, pieces of forest are cut and subsequently burned to make the area suitable for crop cultivation (Čugunovs et al., 2017). Slash-and-burn agriculture can be inferred from the palaeoecological record by the coinciding change in the charcoal record and the shift in the pollen assemblage which starts showing pollen of agricultural indicator species such as cereals (Bradshaw et al., 2010; Brown & Giesecke, 2014; Molinari et al., 2005; Olsson et al., 2010). Sometimes, the practice of slash-and-burn agriculture is related to a decrease in species diversity in forests (Kuosmanen et al., 2016). Archaeological findings from southern Finland suggest that slash-and-burn agriculture may have been practiced here around 3000 cal. BP already (Clear et al., 2015). In southern Sweden, slash-and-burn agriculture was probably practiced even earlier, around 4000 cal. BP (Olsson et al., 2010).

Since the 18th century, forestry has been the dominant human activity taking place in boreal forests in Fennoscandia, as it is an economically viable industry. In Fennoscandia, forestry is intensive in character, as harvesting is mostly done by clearcutting (Kuuluvainen & Gauthier, 2018). This results in younger forest stands with mainly monocultures of *P. sylvestris* and *P. abies*, and few old forests scattered across the landscape. The monotonous landscape that results from the intensive forest management in Fennoscandia results in less diverse forests and large homogeneity in the landscape, which increases vulnerability to disturbance agents (Huuskonen et al., 2021; Kuuluvainen & Gauthier, 2018).

4.2 Effects of human activity on wildfire regimes

Human influence on wildfire regimes is most prevalent later on in the Holocene, and can mostly be excluded as having had impact on fire regimes in Fennoscandia during the early and mid Holocene (Clear et al., 2014, 2015; Molinari et al., 2013, 2018). Changes in fire activity during the late Holocene in Fennoscandia that cannot be attributed to climate change or changes in vegetation are often related to changes in land-use, such as slash-and-burn agriculture and management for forestry, which did take place in this period (Brown & Giesecke, 2014; Clear et al., 2013, 2015; Rolstad et al., 2017).

Human activity can have a multitude of effects on fire regimes (Figure 5). Though hunter-gatherer communities seem to have had limited impact on fire regimes and vegetation, fire frequency and the amount of small-scale fires often increased when humans start using practices such as slash-and-burn in Fennoscandia (Molinari et al., 2005; Stivrins et al., 2019). For example, Rolstad et al. (2017) found FRIs of 60-100 years before humans settled their study area in Norway around 1625 AD, while these intervals were 20-40 years in the period after 1625. In Sweden, fire return intervals of 20 years were noted while slash-and-burn agriculture was being practised (Olsson et al., 2010).

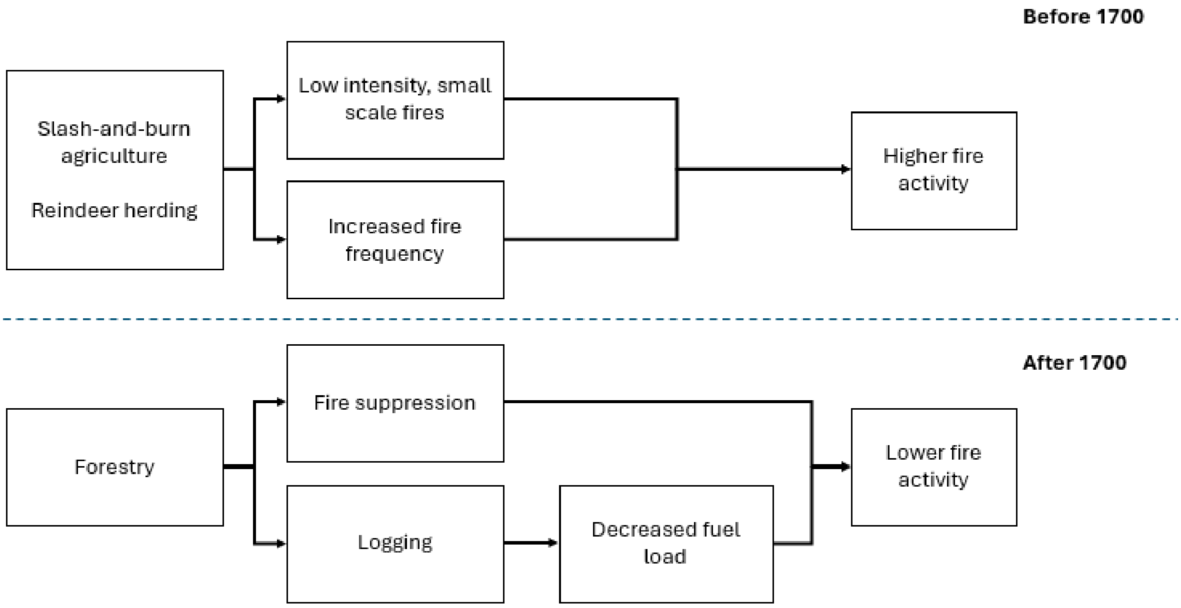


Figure 5: The dominant human activities in boreal Fennoscandia throughout the Holocene and their effects on fire regimes.

For most of northern Fennoscandia, human influence can be excluded as a factor that has impacted wildfire regimes during the Holocene, though humans have probably influenced the fire regime majorly in this region from the 18th century onwards (Carcaillet et al., 2007). However, Hörnberg et al. (2018) propose that fire regimes in pine-lichen forests in northern Sweden were altered by the Sami for the creation of suitable winter grazing areas for reindeer from 2000 cal. BP onwards already. The combination of pollen indicators and microscopic charcoal indicate fire intervals variating between 40-80 years during this period, while they varied between 125-250 years before human presence was indicated in the study (Hörnberg et al., 2018). Humans were already using these forests, including for the keeping of domesticated reindeer (Josefsson et al., 2010), and therefore this type of land-use may indeed have impacted fire regimes in the region.

While the use of slash-and-burn agriculture and its effect on fire regimes can be traced back to ~4000 cal. BP, other researchers have found that human activities only started affecting the fire regime around 1600 AD (400 cal. BP) in remote areas in Norway (Rolstad et al., 2017), which indicates that the influence of human activities on fire regimes may be very local. From the 1600s onwards, increasing fire activity in northern Sweden could not be explained by climate, suggesting that human activity was the cause of this change in fire regime (Niklasson & Granström, 2000). Olsson et al. (2010) indicate that human activity was likely the main driver for changing fire regimes during the late Holocene at their study site in southern Sweden, since climate and vegetation could not be linked to the changes in fire regimes.

Human activity can also affect the timing of fire occurrence during the season. Dendrochronological studies can in some cases indicate whether a fire was ignited by natural causes or humans by looking at the timing of a fire during the season. However, interpretations should be made carefully, since differences in seasonality of fire are not definitive proof of human impact (Granström & Niklasson, 2007). Despite that, Rolstad et al. (2017) did find a small change in the fire occurrence during the season, with fires earlier during the season likely being caused by human activities, due to most natural fires occurring later in the season when there are more lightning strikes.

From the 1700s onwards, there is a decrease in fire activity and biomass burning in Fennoscandia. This trend can be explained by the decline of traditional forms of land-use like slash-and-burn agriculture, and the subsequent increase of forestry as a land-use type (Molinari et al., 2018). The prominence of the forestry industry resulted in fire suppression policies being made and management to protect the forest plantations from wildfire, which decreased fire activity in Fennoscandian forests (Bradshaw et al., 2010; Brown & Giesecke, 2014; Hörnberg et al., 2018; Molinari et al., 2018; Olsson et al., 2010; Rolstad et al., 2017). Logging by itself could also decrease fire activity, as it leaves a low-density forest with a decreased fuel load (Rolstad et al., 2017).

Thus, forestry has a direct inhibitory effect on fire activity in Fennoscandia. However, fire suppression leads to fuel upbuild, which can lead to more severe, large-scale fires occurring when conditions are favourable (Stephens et al., 2014). Indirectly, through this increased fire risk, forestry and its associated practices could therefore be a driver for higher fire activity in the future. The intensive management of boreal forests in Fennoscandia affects forest composition and structure, which may in turn influence fire risk in these forests, due to the species-specific traits with regard to flammability (Figure 3).

Generally, there is a strong correlation between humans entering an area and changes in fire regimes occurring. Nevertheless, a clear indication of human activity and presence in an area is needed to clearly connect changing wildfire regimes and human activity to each other. Unless archaeological evidence is present from nearby sites, it is extremely difficult to connect shifts in fire regimes to human activity with certainty (Marlon, 2020).

5. Challenges and future directions

Three important drivers of wildfires can be identified in Fennoscandia: climate, vegetation (fuel) and human activity (Figure 6). The wildfire regimes in Fennoscandia have been clearly impacted by human activity during the late Holocene. Though human activity can be excluded as a driver of wildfires during earlier parts of the Holocene, the disentangling of climate and vegetation as drivers of wildfire activity remains complex, due to the complex interactions between all three drivers (Figure 6).

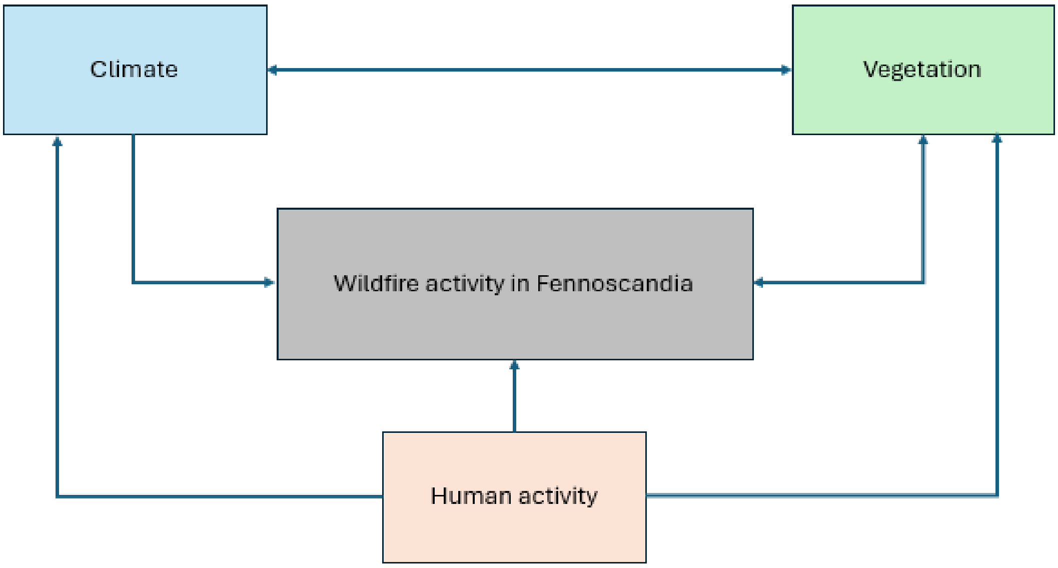


Figure 6: The three important drivers of wildfire activity and their relations to each other.

Climate in northern Fennoscandia is projected to be warmer, with changing precipitation amounts and extreme weather events also being likely consequences of climate change (Kivinen et al., 2017). With climatic conditions becoming warmer and drier for longer times in the future, conditions will be favourable for wildfire activity, and a risk of large, severe wildfires are exists because of this (Gaboriau et al., 2020; Marlon, 2020; Remy et al., 2023).

However, interpretations with regard to climate as a driver need to be made with caution, as climate does only affect wildfire activity directly, but also has the potential to influence vegetation composition, thereby indirectly influencing the wildfire regime as well (Figure 7) (Molinari et al., 2020; Remy et al., 2023). If conditions become warmer and wetter in Fennoscandia, deciduous species might expand their range northwards into the boreal zone. The presence of deciduous species might limit fire activity, due to the absence of fire-promoting traits (Feurdean et al., 2017; Molinari et al., 2020). Moreover, climate change could result in more open forests in the boreal zone, which are more sensitive to wildfires due to the availability of fuel and the lack of fire-inhibiting microclimate conditions (Rotbarth et al., 2025). More research on the interplay between climatic factors and vegetation in establishing and changing fire regimes is necessary to uncover the primary drivers of changing fire regimes in past and future conditions.

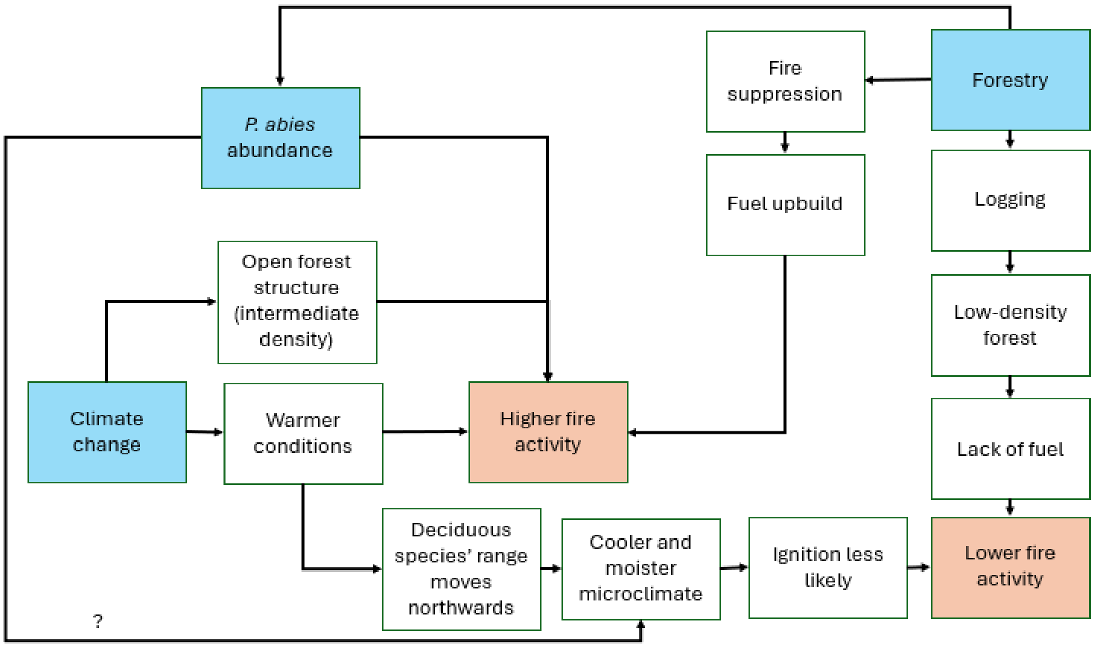


Figure 7: Relationships between climate change, vegetation and forestry and their possible effects on fire activity. Blue boxes indicate the main drivers, orange boxes indicate the possible outcomes. ? = the possible relationship outlined by Ohlson et al. (2011). Data from: (Clear et al., 2013; Feurdean et al., 2017; Kitenberga et al., 2019; Ohlson et al., 2011; Rolstad et al., 2017; Rotbarth et al., 2025).

A prime example of the complicated interplay between vegetation, climate and wildfires is the relationship between *P. abies* and the wildfire regime in Fennoscandia during the Holocene. The workings of the interaction between *P. abies* and wildfires in Fennoscandia are complex and thus require further investigation. Research on the interaction between *P. abies* and wildfires in Fennoscandia is especially relevant due to the species' high abundance in forests in the region, and its potential to cause severe and large-scale fires when climatic conditions are favourable in the future (Clear et al., 2013). The risk of these sort of fires occurring may be strengthened by current land management and the resulting fuel upbuild.

Because of the ability to affect large areas and the destructiveness of large wildfires, as well as the economic value of timber, fire suppression policies have been widely implemented, and fire suppression is now the main human action that affects wildfire regimes in Fennoscandia (Stephens et al., 2014; Wallenius, 2011). As fire is also an important ecological disturbance agent that positively affects biodiversity and forest structure (Kuuluvainen & Gauthier, 2018), and due to the risks of increased fuel loads, there have been calls for changes in policy and fire management, such as prescribed burning (Kitenberga et al., 2019; Marlon, 2020). Palaeoecological research could help with the determination of what kind of management is appropriate for an area or landscape, including the appropriate burning intervals.

During the course of the writing of this review, few motivations on the choice of site were found. Though some studies (e.g. Clear et al., 2013) reconstruct fire regimes with the explicit goal of providing baseline conditions for conservation and management of an area, most studies seem more descriptive and do not provide a motivation for their choice of study site. If palaeoecological studies are to be used for the planning of (conservation) management, the choice of study site should be better motivated.

For local management solutions, studies on the local patterns of fires can provide valuable information, as these studies also look into the local environmental conditions, which are indicated to play a role in the determination of a fire regime (Kuosmanen et al., 2014; Molinari et al., 2013). However, for regional reconstructions of fire regimes, it may be far more valuable to look at comparable sites over larger areas. Meta-analyses that compile results from comparable sites may provide valuable results when attempting to provide recommendations for management that can be applied at large scale.

Since studies that use multiple proxies for the reconstruction of fire show promising results (Edvardsson et al., 2022; Stivrins et al., 2019), it is proposed here that multi-proxy approaches such as those that integrate dendro-chronological and palaeoecological data can be a valuable tool in providing a complementary picture of past ecosystem dynamics and fire histories. The same can be said for the integration of other proxies, such as those for climate reconstruction. A multi-proxy assessment of moisture and precipitation throughout the Holocene in Fennoscandia may be a valuable tool for not only climate reconstructions in Fennoscandia, but as an explanatory source for fluctuations in fire activity as well, since a correlation seems to exist between precipitation amounts and fire activity (Aakala et al., 2018). Currently, one of the largest challenges with the reconstruction of fire regimes is the disentangling of different drivers. This calls for a multi-disciplinary approach that uses the reconstruction of historical fires, archaeological evidence and vegetation and climate reconstructions. When the main drivers of changing fire regimes are known, management can be applied and adjusted in order to limit the ecological and societal damage that wildfires cause.

6. Conclusion

Here, literature about wildfire regimes in Fennoscandian boreal forests during the Holocene was reviewed. Several different methods for the reconstruction of fire histories have been discussed, as well as the main trends in wildfire regime change throughout the Holocene along with the main drivers. Lastly, future directions for research were discussed.

The different methods for the reconstruction of fire histories all have different properties, advantages and disadvantages. Depending on the objectives of a study, the most appropriate method should be chosen. In case fire regimes from before human interventions with the landscape need to be reconstructed, palaeoecological reconstruction is the only suitable method. By combining methods for fire reconstruction, a complementary picture of fire histories might be gained.

Wildfire regimes in Fennoscandia were variable throughout the Holocene, with periods of low and high fire activity occurring in different parts of Fennoscandia. Fire activity can often be correlated to changes in climate and vegetation. Human activities only played a significant role in the determination of fire regimes during the late Holocene, through activities such as slash-and-burn agriculture and forestry.

Connecting changes in fire regimes to different drivers is complex, due to the interactions between climate, vegetation and human activities. In order to provide recommendations for the management of Fennoscandian forests and fires in Fennoscandia, multi-proxy approaches into climate and fire history reconstructions may be valuable. Additionally, a holistic approach that incorporates archaeology, climate, vegetation and fire regimes may be a valuable tool that can help with the disentangling of the different drivers of wildfire regimes in Fennoscandia.

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I declare that this writing assignment was made without the use of generative AI. It is therefore an original report that represents my own work. Where the ideas of others have been used, proper citation has been used.