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Holocene fire in Fennoscandia and Denmark

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Abstract. Natural disturbance dynamics, such as fire, have a fundamental control on forest composition and structure. Knowledge of fire history and the dominant drivers of fire are becoming increasingly important for conservation and management practice. Temporal and spatial variability in biomass burning is examined here using 170 charcoal and 15 fire scar records collated throughout Fennoscandia and Denmark. The changing fire regime is discussed in relation to local biogeographical controls, regional climatic change, anthropogenic land use and fire suppression. The region has experienced episodic variability in the dominant drivers of biomass burning throughout the Holocene, creating a frequently changing fire regime. Early Holocene biomass burning appears to be driven by fuel availability. Increased continentality during the mid-Holocene Thermal Maximum coincides with an increase in fire. The mid–late Holocene front-like spread of *Picea abies* (Norway spruce) and cooler, wetter climatic conditions reduce local biomass burning before the onset of intensified anthropogenic land use, and the late Holocene increase in anthropogenic activity created artificially high records of biomass burning that overshadowed the natural fire signal. An economic shift from extensive subsistence land use to agriculture and forestry as well as active fire suppression has reduced regional biomass burning. However, it is proposed that without anthropogenic fire suppression, the underlying natural fire signal would remain low because of the now widespread dominance of *P. abies*.

Additional keywords: biomass burning, climate change, fire suppression, slash and burn.

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Introduction

Heavily managed forests and active fire suppression have created an ecosystem almost free of fire throughout Fennoscandia and Denmark (Zackrisson 1977; Wallenius 2011). The absence of fire from the landscape not only affects natural forest regeneration (Ruokolainen and Salo 2006) but also reduces floral and faunal biodiversity and threatens the survival of red-listed species such as saproxylic beetles that are reliant on the regular occurrence of forest fire (Lindbladh *et al.* 2003). This absence of fire from the Fennoscandian Boreal ecosystem is thought to have contributed to the widespread dominance of *Picea abies* and subsequent decline in deciduous species (Bjune *et al.* 2009) with *P. abies* becoming the most abundant tree species in northern European forests and emerging as a new boreal forest keystone species (Seppä *et al.* 2009). Fire has not always been so rare throughout Fennoscandia and Denmark: fire scars record a significantly more intensive fire regime in the recent past (e.g. Niklasson and Granström 2000; Power *et al.* 2013; Storaunet *et al.* 2013). Fire scars are valuable for understanding past human fire activity (Neolithic to present day slash and burn activity). However, fire scar records rarely exceed 600 years of age in Fennoscandia (Wallenius *et al.* 2007) and do not pre-date the time of significant anthropogenic influence.

The anthropogenic fire signal recorded in fire scars gives an artificially high perception of the historical fire frequency regime that dilutes the natural fire frequency signal in Fennoscandia and Denmark. By contrast, charcoal series record fire history on a palaeoecological timescale, which is far beyond the temporal capability of fire scars and pre-dates significant anthropogenic disturbance (Clear *et al.* 2013), with macroscopic charcoal recording local fires with high spatial precision (Ohlson and Tryterud 2000; Higuera *et al.* 2007). It is only because of palaeoecological data on biomass burning that we can understand the influence of natural drivers of fire. Even with minimal anthropogenic disturbance it remains difficult to disentangle the complex interactions of natural drivers of biomass burning: climate variability, vegetation type and fuel availability (Molinari *et al.* 2013).

The aim of this paper is to combine available charcoal and fire scar records from Fennoscandia and Denmark to explore spatial and temporal heterogeneity and variability in biomass burning. We aim to identify the changing dominant drivers and controls of fire throughout the early, mid- and late Holocene.

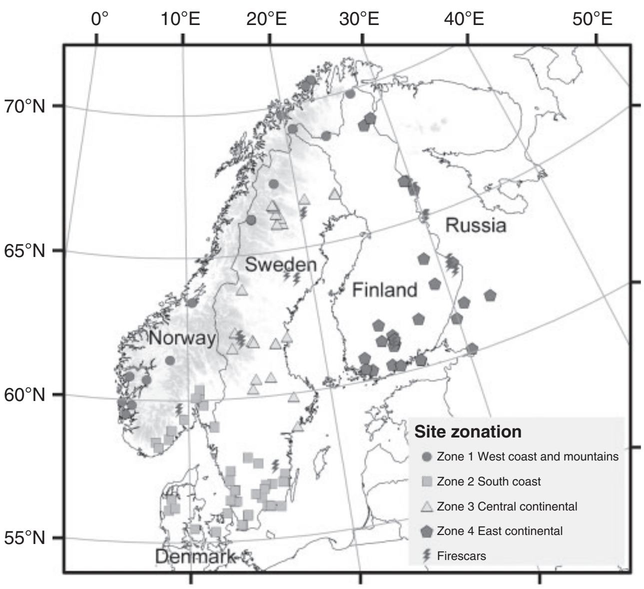

Fig. 1. Charcoal and fire scar data for 143 individual sites (185 data series) located throughout Fennoscandia and Denmark. The charcoal data are divided into four geographical regions: Zone 1 (west coast and mountains) consisting of the western coast of Norway and Scandes Mountains; Zone 2 (south coast) consisting of southern Scandinavian regions including Denmark, south-west Norway and Sweden around the Skagerak and Kattegat Strait; Zone 3 (central continental) comprising sites in central Sweden; Zone 4 (east continental) consisting of sites in eastern Fennoscandia including Finland and Russian Karelia. Fire scar records are denoted separately.

Materials and methods

Data collection

Charcoal and fire scar data were collated for 143 sites in Fennoscandia and Denmark between latitudes 55°12′19″–70°42′0″N and longitudes 5°19′4″–32°44′39″E (Fig. 1). Where available, both macroscopic and microscopic charcoal records from an individual site were included in the analysis, along with subsequent analyses. A total of 170 charcoal datasets and 15 fire scar records were included in the analysis. Data sources included (1) raw charcoal data and charcoal influx calculations provided directly by the original researcher, (2) charcoal records available from the European Pollen Database (EPD) (http://www.europeanpollendatabase.net, accessed June 2013; Fyfe *et al.* 2009) and (3) digitised data from published articles in peer-reviewed journals. Published data were digitised using Data Mugger version 1.1 (K. Welsh, unpubl. data). A standard linear interpolation age depth model was applied using Clam (Blaauw 2010) to sites with available depth data. Where depth data were not available, charcoal values were digitised directly against age and thus relied on the published, pre-calculated age depth calculations. Raw data obtained directly from other researchers also consisted of pre-calculated age depth curves. Dating controls on sedimentary charcoal records vary including accelerator mass spectrometry (AMS) ^{14}C dates, ^{210}Pb dating, varve counts and cross-correlation of vegetation with nearby dated sites. Fire scar chronologies were pre-determined by the original researchers using dendrochronological techniques. All ages were converted to calibrated years before present (hereafter cal years BP, where 0 cal years BP = 1950 AD), with all-time series constrained between −60 and 13 240 cal years BP (2010 AD–11 290 BC). To include as many data as possible, the charcoal dataset was gathered from sites spanning a wide range of depositional environments including lakes, bogs, mires and forest hollows. Sites have unique depositional features relating to individual site location and biogeography (e.g. site type, elevation, topography and surrounding vegetation type). Site specific information is available in the Supplementary material.

Spatial and temporal division

All of the sites were spatially sub-divided into four geographical regions based on their present day climate and continentality. Zone 1 consisted of the west coast of Norway and Scandes Mountains; Zone 2 consisted of southern Scandinavian regions including Denmark, south-west Norway and Sweden around the Skagerak and Kattegat Straits; Zone 3 central continental sites comprised sites in central Sweden and Zone 4 sites were in eastern Fennoscandia, including Finland and Russian Karelia (Fig. 1). To compare time periods with distinctive charcoal records, 100-year charcoal averages were calculated, and a stratigraphically constrained cluster analysis (CONISS) was implemented in TILIA (Grimm 1987), and identified six time periods: (1) >10 000 cal years BP; (2) 10 000–7800 cal years BP; (3) 7800–5500 cal years BP; (4) 5500–3000 cal years BP; (5) 3000–700 cal years BP and (6) 700–−60 cal years BP.

Data standardisation and analysis

All charcoal data were standardised using the basic standardisation method ($n \div$ max), where n is each charcoal abundance value and max is the maximum charcoal abundance recorded within each site. This method of standardisation causes some loss in the magnitude of data variance, but is essential for data comparison between sites. For each individual site the standardised mean value (μ) was calculated for each time period (t) and compared to the mean value of the previous time period (μt_{prev}). Any increase (positive) or decrease (negative) in the charcoal abundance was calculated ($\mu t - \mu t_{prev}$) to determine the temporal rate of change within any given site. The significance of any rate of change was calculated using a Mann–Whitney U test, given the non-normal distribution of the data, with the significance value to accept the null hypothesis (H_0) set at both 5% ($P < 0.05$) and 1% ($P < 0.01$). The Mann–Whitney U test results comparing the mean charcoal value of each period (μt) with the mean charcoal value of the previous period (μt_{prev}) were plotted using ArcMap10 (ESRI 2011) on five time series maps (excluding >10 000 cal years BP) of Fennoscandia and Denmark (Fig. 2). Graduated triangles were plotted for two significance levels: $P < 0.01$ and $P < 0.05$ for both an increase and decrease in mean charcoal abundance relative to the mean of the previous period. Sites that recorded non-significant increase or decrease in charcoal abundance were denoted with circles. To be represented on a map, a site required available data in both the present and previous period. Percentage calculations for the number of sites that record significant ($P < 0.01$ and $P < 0.05$) and non-significant ($P \geq 0.05$) increase (positive) or decrease (negative) in charcoal abundance were calculated for ($\mu t - \mu t_{prev}$) and are included in Table 1.

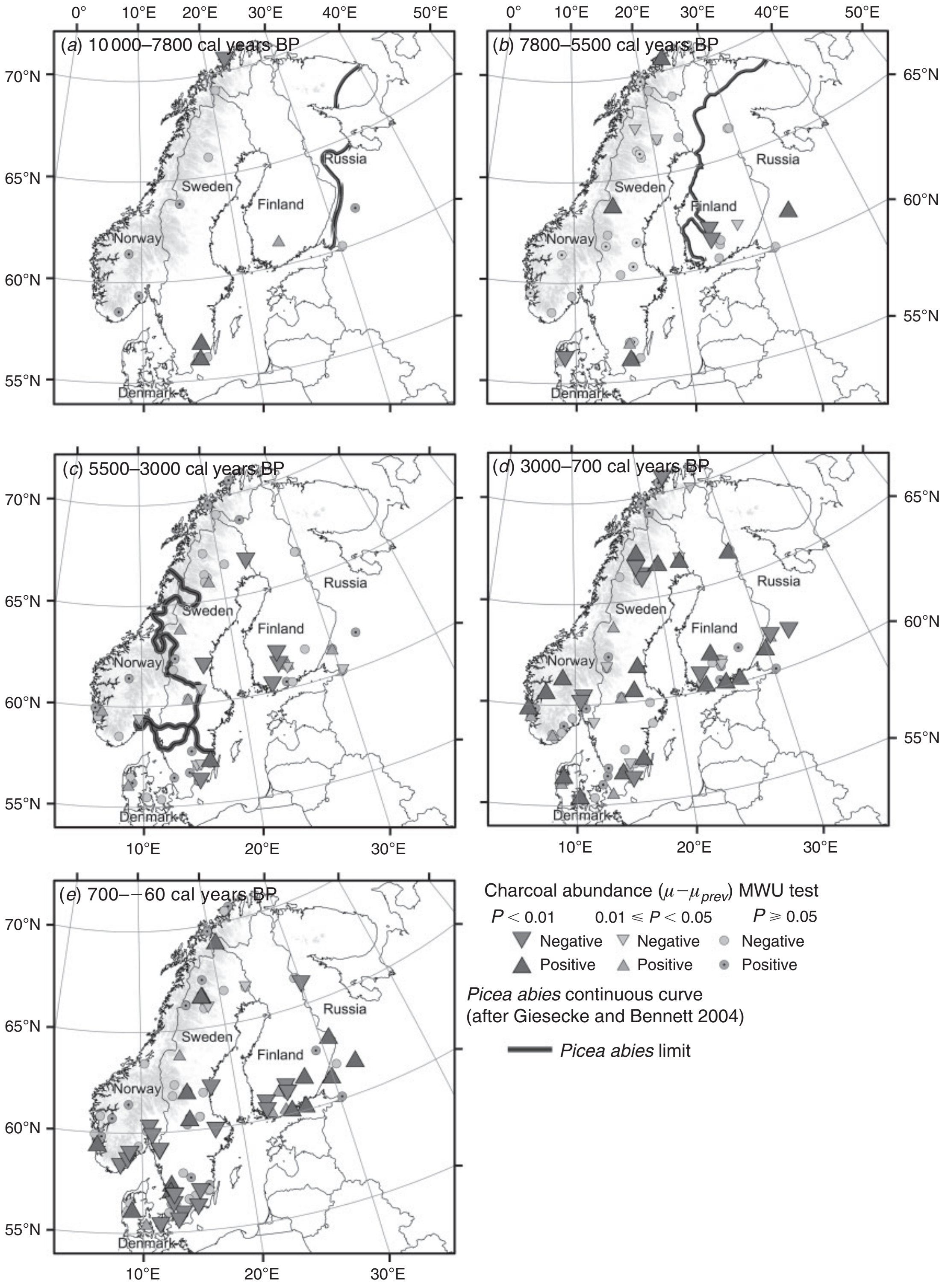

Fig. 2. Five time series maps: (*a*) 10 000–7800 cal years BP; (*b*) 7800–5500 cal years BP; (*c*) 5500–3000 cal years BP; (*d*) 3000–700 cal years BP; and (*e*) 700––60 cal years BP show the rate of change in sedimentary charcoal abundance compared to the previous period ($\mu t - \mu t_{prev}$). Any increase or decrease in charcoal abundance is recorded at three significance levels ($P < 0.01$, $P < 0.05$ and $P \geq 0.05$) calculated by the Mann–Whitney U Test. The extent of the continuous curve of *Picea abies* is displayed after Giesecke and Bennett (2004).

Table 1. Results of Mann–Whitney U Test and percentage calculations of number of sites that record a relative increase or decrease in charcoal abundance compared to the previous period

$\mu t - \mu t_{prev}$ (cal years BP)	Total number of sites	Charcoal abundance (positive): Mann–Whitney U Test			Percentage of sites			Charcoal abundance (negative): Mann–Whitney-U Test			Percentage of sites		
		$P < 0.01$	$P < 0.05$	$P \geq 0.05$	% (all)	% (sig)	% sig sites positive	$P < 0.01$	$P < 0.05$	$P \geq 0.05$	% (all)	% (sig)	% sig sites negative
10 000–7800	16	2	1	6	56	19	75	1	0	6	44	6	25
7800–5500	49	3	4	20	55	14	58	3	2	17	45	10	42
5500–3000	81	1	8	26	43	11	41	6	7	33	57	16	59
3000–700	115	21	14	34	60	30	63	9	12	25	40	18	37
700–−60	145	19	5	36	41	16	44	25	5	55	59	21	56

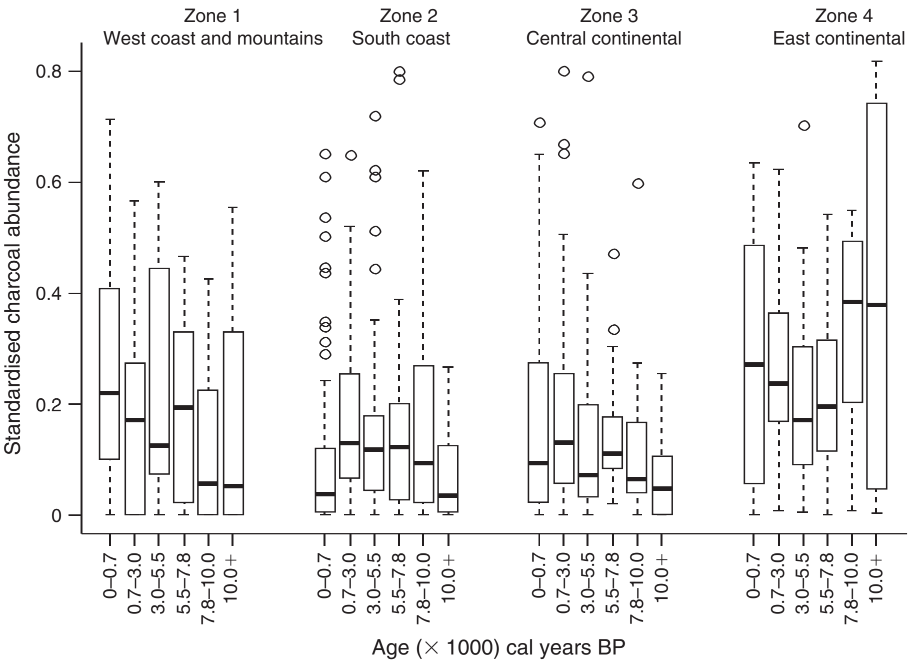

Fig. 3. Box plots of standardised charcoal abundance for each site divided into four geographical regions over six periods. The box plots display median charcoal values, minimum and maximum values, 25th and 75th percentiles, and outliers.

The spatial and temporal distribution of charcoal abundance was analysed using box plot transformations in R (R Development Core Team, 2010) for the four pre-determined geographical regions over the six periods (Fig. 3). The 100-year average values calculated for the time series maps were used to estimate charcoal abundance variation within each geographical region previously identified for the last (a) 1000 cal years BP and (b) 10 000 cal years BP (Fig. 4).

Fire scar records and charcoal abundance data were combined to estimate the timing of any decline in fire or fire suppression throughout Fennoscandia and Denmark (Fig. 5). The date at which the last fire was recorded was used to determine the timing of a decline in fire and assigned to one of the following categories: (1) no fire suppression; (2) fire suppression since 150 cal years BP (post-1800 AD) or (3) fire suppression before 150 cal years BP (pre-1800 AD).

Results

Fire activity over the past 10 000 years was investigated based on 185 records, including 170 macroscopic and microscopic sedimentary charcoal series and 15 fire scars datasets. These records represent 143 different site locations across Fennoscandia and Denmark. The data from the 170 macroscopic and microscopic charcoal records are presented in five time series maps (Fig. 2) and include the position of the spreading front of *P. abies* in Fennoscandia (after Giesecke and Bennett 2004). Temporal resolution of sites ranges from between a few hundred years to thousands of years with relatively few records available between 10 000 and 7800 cal years BP and with an increase in site abundance for each period as we approach the present day. The spatial distribution of sites is irregular throughout the study area with data concentrated in areas along

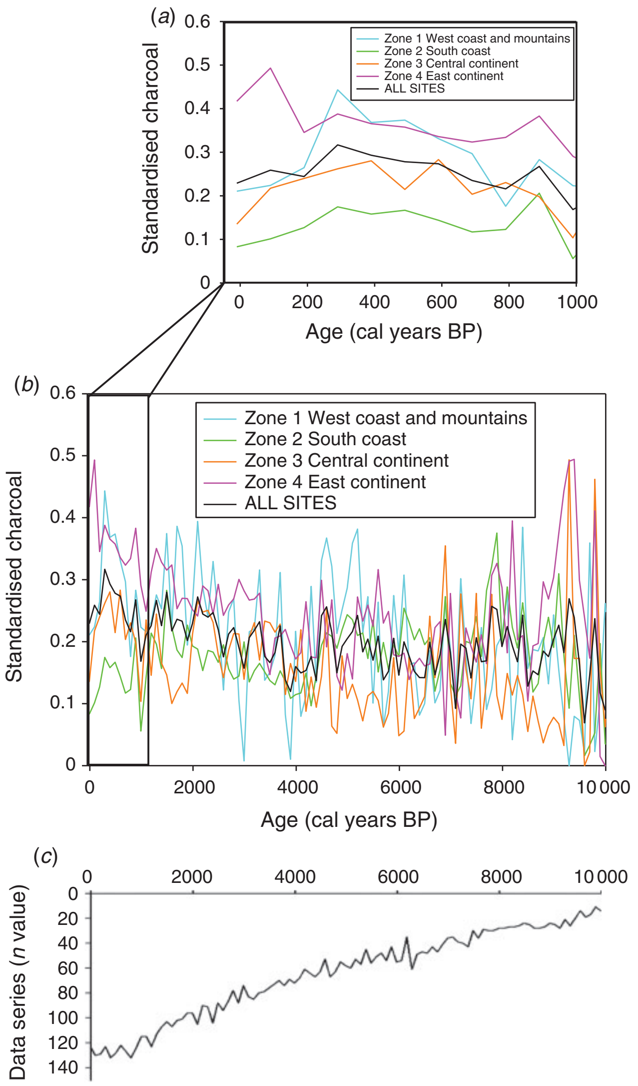

Fig. 4. Standardised average charcoal abundance for periods: (*a*) 1000 cal years BP; and (*b*) 10 000 cal years BP at 100-year intervals for four geographical regions as well as the overall average charcoal abundance for all sites in Fennoscandia and Denmark. The number of sites included in the analysis is displayed in (*c*).

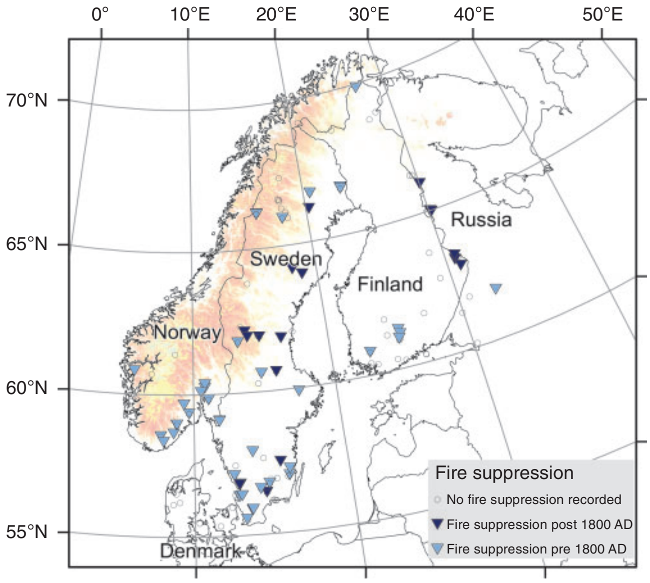

Fig. 5. Fire suppression denoted by the last recorded date of fire at three time intervals: (1) no fire suppression recorded; (2) fire suppression recorded post-1800 AD and (3) fire suppression recorded pre-1800 AD.

the southern coasts of Fennoscandia and Denmark. There are relatively few study sites in northern Finland and Russia and along the Norwegian coast. For this reason the data should be interpreted with caution. However, these maps provide a valuable insight into the temporal and spatial variability in palaeofire records throughout Fennoscandia and Denmark.

10 000–7800 cal years BP

There are relatively few sites ($n = 16$) with sedimentary charcoal records pre-dating 10 000 cal years BP. These sites are concentrated in western and southern areas of Fennoscandia with no data available for Denmark (Fig. 2*a*). In total 56% of sites recorded an increase in charcoal abundance compared to the pre-10 000 cal years BP. Also 25% of all sites recorded a significant variance ($P < 0.05$) in charcoal abundance, with 75% of these sites recording a significant increase in charcoal abundance (Table 1). This indicates an overall increase in burning compared to pre-10 000 cal years BP in southern Norway, southern and central Sweden and southern Finland. Sites that recorded a decrease in charcoal abundance compared to pre-10 000 cal years BP are located in Russia, northern Norway and in central and southern Sweden. Median charcoal abundance values are generally low for both pre-10 000 cal years BP and 10 000–7 800 cal years BP, with the exception of Zone 4, which records the highest overall median charcoal values compared to any other region for any period (Fig. 3). All zones recorded an increase in median charcoal abundance between pre-10 000 cal years BP and 10 000–7800 cal years BP. The mean charcoal curve (Fig. 4) is highly variable during 10 000–7800 cal years BP, probably because of the insufficient number of sites available, and therefore these data are interpreted with caution. Peaks in mean charcoal abundance are recorded at 9800 and 9300 cal years BP, driven by an increase in charcoal abundance in Regions 3 and 4, at 8400 cal years BP driven by an increase in average charcoal abundance in Zones 1 and 2, and at 7800 cal years BP because of an increase in average charcoal abundance in Zones 2 and 4.

7800–5500 cal years BP

Sedimentary charcoal datasets ($n = 49$) are more abundant and widespread (Fig. 2*b*) compared to the previous period, with 55% of sites recording an increase in charcoal abundance. In total 24% of all sites recorded significant variance ($P < 0.01$), with 58% of significant sites recording an increase in charcoal abundance (Table 1). Sites characterised by a significant increase in charcoal abundance are generally located in a band spanning from southern Sweden to north-eastern Norway, with the exception of one site in Russia. In contrast, there is a general distribution of sites with a decrease in charcoal abundance in

Denmark and Finland. Zones 1, 2 and 3 recorded an increase in median charcoal abundance compared to the previous period (Fig. 3), whereas during this period a sharp decline in charcoal abundance is registered in Zone 4. The mean charcoal curve records one peak in abundance values at *c*. 6900 cal years BP, driven by consecutive peaks in Zones 1, 2 and 3 (Fig. 4).

5500–3000 cal years BP

It is during this time period that the first overall decline in charcoal abundance is recorded, with 57% of sites ($n = 81$) observing a reduction in charcoal values. In total 27% of sites recorded a significant variance and of these sites, 59% recorded a decline in charcoal abundance (Table 1). The sites characterised by the most significant decline ($P < 0.01$) are located in eastern Sweden and western Finland (Fig. 2*c*). All zones recorded a decline in median charcoal abundance (Fig. 3). There are four peaks in mean charcoal abundance recorded during this period (Fig. 4): 5200 cal years BP, driven by a peak in charcoal in Zones 1 and 4; 4500–4400 cal years BP with peaks in Zones 1, 3 and 4; 3700 cal years BP, driven by Zone 1 and 3300 cal years BP, driven by Zones 1 and 4.

3000–700 cal years BP

In total 60% of sites ($n = 115$) recorded an increase in charcoal abundance compared to the previous period (Table 1). There are 56 sites (48% of sites) with a significant variance and of these, 63% recorded an increase in charcoal abundance. This is the period of most significant increase recorded throughout Fennoscandia and Denmark, with all four zones experiencing an increase in median charcoal abundance (Fig. 3). The sites that recorded a significant decrease in charcoal abundance are generally clustered around the southern coastal areas of Fennoscandia and Denmark, with some isolated sites in northern areas of Norway and Sweden (Fig. 2*d*). The mean curve (Fig. 4) records peaks in charcoal abundance at 2100 and 1500 cal years BP, driven by an increase in charcoal abundance in Zones 1, 3 and 4; and at 1300 cal years BP with peaks in Zones 1 and 4.

700–−60 cal years BP

Since 700 cal years BP, the largest number of datasets ($n = 145$) recorded an overall decline in the charcoal abundance, with 59% of sites showing a reduction in charcoal compared to the previous period (Table 1). In total 37% of sites recorded significant variance, and 56% of these recorded a significant decrease in charcoal abundance. This widespread decline is most notable in a band along the southern coasts of Norway, Sweden and Finland that extends north along eastern Sweden (Fig. 2*e*). However, this reduction is not uniform throughout the research area: a significant increase in charcoal abundance is recorded in eastern Fennoscandia, central and western Sweden and some isolated sites in Norway and Denmark. Box plot observations are divided during this period, with Zones 2 and 3 recording a decline in median charcoal abundance, whereas Zones 1 and 4 recorded an increase (Fig. 3). The mean charcoal abundance curve (Fig. 4) peaks at levels higher than any previous period between 400 and 300 cal years BP, driven by all four zones. There is a uniform decline in average charcoal abundance, with Zone 2 recording a decrease in charcoal abundance from *c*. 400 cal years BP followed by a decline in charcoal abundance in Zones 2 and 3 around 300 cal years BP. A decline in mean charcoal abundance in Zone 4 is not recorded until 100 cal years BP (Fig. 4). This overall decline in charcoal abundance is evident when observing fire absence pre- and post-150 cal years BP (Fig. 5). A clear cessation of fire is recorded in 52 charcoal sites and 15 fire scar sites throughout Fennoscandia and Denmark. All fire scar sites record a decline in fire post-1800 AD, whereas over half of the charcoal series record fire suppression pre-1800 AD. Sites indicating an earlier (pre-1800 AD) fire absence are generally located in the southern regions of Fennoscandia, with the exception of a few sites in central and northern Sweden, whereas sites recording a later (post-1800 AD) absence of fire are concentrated in central and northern regions of Sweden, Finland and Russia.

Discussion

Charcoal (macroscopic and microscopic) and fire scar data give insight into Holocene temporal and spatial variability in biomass burning. The time series, determined through CONISS analysis, correspond to changes in the broad-scale distribution of charcoal in Fennoscandia that may be attributable to changes in the dominant drivers of biomass burning (see Marlon *et al.* 2013; Molinari *et al.* 2013). The fire history of Fennoscandia and Denmark can be roughly divided into two stages: the early–mid-Holocene natural fire signal, where fuel availability, climate variability and vegetation type are the likely dominant drivers of biomass burning; and the mid–late Holocene anthropogenic fire regime, with human induced ignition and subsequent fire suppression.

Climate, vegetation and fuel availability

Early Holocene warming lead to the retreat of the Weichselian ice margin and a gradual northward and centralised deglaciation of Scandinavia (Lundqvist 1986). This deglaciation enabled expansion of plant distributions with the development of tundra vegetation dominated by herbs (e.g. *Artemisia* spp. and Chenopodiaceae), grasses and sedges with scattered birch stands and intermittent phases of pine–birch forest development (Björck and Möller 1987). This post-glacial vegetation expansion and increase in fuel availability appears to drive the early Holocene increase in biomass burning (Fig. 2*a*). The retreating ice margin reached the Norwegian coast *c*. 15 000–13 000 cal years BP (Andersen 1979), southern Sweden approx. 13 500 cal years BP (Berglund 1979) and southern Finland around 13 000 cal years BP (Lunkka *et al.* 2004), enabling earlier vegetation development and potentially an earlier increase in biomass burning compared to the central Fennoscandian sites. This early forest succession and consequent earlier peak in charcoal abundance would account for the few sites that record a decline in biomass burning since 10 000 cal years BP. The coastal and mountain distribution of sites, in particular sites that record a decline in biomass burning, are supporting evidence of a multidomed late glacial ice sheet suggesting mountain areas of Norway and Sweden were ice free by the late Weichselian (Paus *et al.* 2006). The last remnants of the ice sheet most likely melted by 8500 cal years BP in central Scandinavia (Andersen 1980; Lundqvist 1986), explaining the absence of early Holocene sites in this region. Although the early Holocene experienced rapid climatic warming, pollen-inferred temperature reconstruction indicates mean July temperatures were still low (~11.0°C) and annual precipitation was high (~600–800 mm; Seppä and Birks 2001). This, coupled with minimal anthropogenic disturbance can explain the general trend of lower-than-average biomass burning during the early Holocene.

The mid-Holocene thermal maximum (HTM) is well documented throughout Scandinavia (Rosén *et al.* 2001; Seppä and Birks 2001; Davis *et al.* 2003) and is characterised by warm, dry climatic conditions. The timing of the HTM varies, usually between 6000 and 7000 cal years BP (Davis *et al.* 2003) and coincides with an increase in continentality recorded in areas east of the Scandes Mountains (Giesecke *et al.* 2008). These continental climate conditions could account for the general increase in biomass burning throughout central Fennoscandia and in Russia (Fig. 2*b*). Interestingly, Swedish and Finnish sites experience a striking difference in regional biomass burning during this period, with 90% of Finnish sites recording a decline in charcoal abundance, suggesting a factor other than climate and continentality as a possible driver of regional biomass burning.

The reasons for the absence of *P. abies* in the early Holocene, post-glacial Fennoscandian forest development are poorly understood (Bradshaw *et al.* 2000), with vegetation models failing to identify the reason behind the late expansion of *P. abies* in Scandinavia (Miller *et al.* 2008). There was a mid–late Holocene expansion of *P. abies* on a broad front moving from east to west into Finland and northern Scandinavia, and then south and west towards its present-day limits (Giesecke and Bennett 2004), with some early Holocene population outliers developing as far west as the Scandes Mountains (Kullman 2001; Giesecke and Bennett 2004). The expanding front of *P. abies* has been traced onto the time series map (Fig. 2) after (Giesecke and Bennett 2004). The map shows the east-to-west spread of the beginning of the continuous curve of *P. abies* in the pollen records. Fire appears to decrease in sites as *P. abies* becomes regionally established in Finland (7800–5500 cal years BP) and in Sweden (5500–3000 cal years BP). This negative correlation between *P. abies* and fire has been well documented for Fennoscandia, with both the spread of *P. abies* being held responsible for a reduction in fire (Ohlson *et al.* 2011), and a decrease in fire being blamed for the subsequent spread of *P. abies* (Bjune *et al.* 2009). Here, our compilation indicates that the change in fire regime occurs once *P. abies* is regionally established. Clear *et al.* (2013) record a similar change in the fire regime linked to fuel type: local fire frequency declines with a shift from a mixed deciduous forest to a predominantly coniferous forest. It should also be considered that *c.* 5500 cal years BP climatic conditions shifted to become predominantly cooler and wetter than the HTM period (Seppä and Birks 2001). These conditions would also favour a reduction in charcoal abundance and cannot be excluded as possible drivers of mid-Holocene biomass burning. After 3000 cal years BP intensified anthropogenic disturbance of the fire regime makes the *P. abies*–climate–fire signal even more difficult to decipher.

Anthropogenic ignition and suppression

A mid–late Holocene increase in biomass burning (Fig. 2*d*) with poor regional coherency suggests an increase in the local-scale control of fire by humans. Prior to 3500 cal years BP, the human population was largely controlled by environmental factors (Tallavaara and Seppä 2012). The establishment and expansion of agriculture enabled population growth, and human influence is estimated as the strongest driver of forest compositional change (Reitalu *et al.* 2013). The anthropogenic use of fire intensified in conjunction with slash-and-burn activity driven by swidden cultivation and animal husbandry (e.g. Lagerås 1996; Alenius *et al.* 2008; D'Anjou *et al.* 2012). The intensification of slash-and-burn activity *c.* 1000 cal years BP corresponds to the expansion of permanent cultivation and the establishment of permanent village communities (Lagerås 1996; Taavitsainen *et al.* 1998; Alenius *et al.* 2013). The sustained increase in biomass burning during the mid–late Holocene is most likely the result of intensive anthropogenic land use that controlled biomass burning until it peaked at *c.* 300 cal years BP. The subsequent pre-industrial decline in fire recorded throughout Scandinavia (excluding Finland and Russia) coincides with an economic and cultural transition from traditional livelihoods, such as slash and burn, to modern agriculture and forestry (Wallenius 2011). Intensive commercial forestry operations beginning in the late 1800s is also associated with a reduction in anthropogenic use of fire (Granström and Niklasson 2008). The delay in fire suppression in the east continental region suggests a later economic and cultural transition. It is not until the twentieth century Industrial era (*c.* 100 cal years BP) that there is an overall decline in fire through Fennoscandia and Denmark.

The cause of the late Holocene decline in biomass burning

The mid-Holocene decline in biomass burning preceded the onset of increased anthropogenic activity and can potentially be linked to the spread of *P. abies* in Fennoscandia. The subsequent anthropogenic-induced increase in biomass burning created an artificially high record of fire that overshadowed the natural signal. The late Holocene decline in anthropogenic use of fire as well as active fire suppression reduced biomass burning. However, it is likely that without active fire suppression, the natural fire frequency would have remained low because of the widespread dominance of *P. abies*.

This paper highlights the importance of palaeoecological knowledge and how seemingly unprecedented events can be placed within a long-term perspective (Whitlock 2004). Using only short-term ecological data provides a modern yet 'short-sighted' view of past environmental change. We should not only look back at the recent past (i.e. when the fire signal was artificially high due to anthropogenic land use), but further back in time to the natural fire signal before significant anthropogenic activity (Clear *et al.* 2013). It is likely that without an increase in anthropogenic biomass burning, natural biomass burning would have continued to decline with the increase in dominance of *P. abies*.

Acknowledgements

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