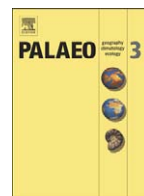




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A continuous record of fire covering the last 10,500 calendar years from southern Sweden – The role of climate and human activities[☆]

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ABSTRACT

A high-resolution, continuous 10,500 cal. yrs-long macroscopic charcoal record from a peat and lake sediment deposit at Storasjö, in the hemiboreal vegetation zone of southern Sweden, is presented. This record was compared with the microscopic charcoal record from the same core, and tentatively correlated with the macroscopic and microscopic charcoal records from another site (Stavsåkra), situated 30 km West of Storasjö. The charcoal records are also compared with regional climate proxy records with the aim to separate climate – from human-induced fire activity. The results suggest that the major signal of both microscopic and macroscopic charcoal records represents local fire history. The best record of local fire history was obtained from the continuous macroscopic charcoal analysis. A tentative correlation of the charcoal records between the sites indicates that most fire episodes of the early and middle Holocene are probably of regional character. Both sites exhibit three major phases of high fire activity 1) 8700–8300 BC, 2) 7250 BC to ca. 4000 BC, and 3) 750 BC to the 19th century. These three phases are separated by periods with lower or very low fire activity. This general trend is in good agreement with the pattern emerging for Europe from the analysis of the recently developed global charcoal database. Fire appears to have been controlled by climate during the early and middle Holocene and by humans during the late Holocene. Warmer and drier climate during the early and middle Holocene caused frequent and intensive fires, which suggests that natural fire activity might increase under predicted future climate scenarios. The results also suggest that fire was an important disturbance factor in the hemiboreal vegetation zone of Sweden and played an important role in the forest dynamics and characteristics of the flora and fauna of the region.

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1. Introduction

Global warming is expected to cause more fires as a result of an increase in drought, wind and lightning in certain regions of the world (e.g. Overpeck et al., 1990). This assumption is mainly based on past records of climate-induced changes in fire frequency and intensity. Such changes can be studied over a variety of temporal scales using records of charcoal in lake sediments or peat deposits (e.g. Power et al., 2008). However, full understanding of the effects of climate change on fire activity at the regional to local spatial scale, and the consequences on vegetation and fauna, still requires detailed reconstructions of fire history over the last millennia in many parts of the world.

There is relatively little research on long-term fire history covering the entire Holocene in Europe compared to America (e.g. Long et al., 1998; Carcaillet and Richard, 2000; Millsbaugh et al., 2000; Paduano et al., 2003; Marlon et al., 2006; Whitlock et al., 2007) and Australia (e.g. Black and Mooney, 2006). Finland has the longest tradition of fire studies in Europe (e.g. Tolonen, 1978; Huttunen 1980; Pitkänen and Huttunen, 1999; Pitkänen et al., 1999a,b, 2001, 2002). The study by Clark et al. (1989) was the first entire Holocene fire record from central Europe. More recent studies were performed in the Southern Alps (e.g. Tinner et al., 1999; Tinner et al., 2006; Colombaroli et al., 2008). While studies in America and Australia discuss the fire-climate relationships (e.g. Harrison and Dodson, 1993; Haberle and Ledru, 2001; Black and Mooney, 2006), few European investigations correlate fire history with climate change, while many studies discuss human activity as a cause of fire in the past (e.g. Clark et al., 1989; Innes and Blackford, 2003; Mouillot and Field, 2005; Froyd, 2006). Tinner et al. (1999) suggested that increased fire in the Alps for the period 7000–5000 cal yr BP resulted from the combined effects of intensified land-use activities and

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centennial-scale shifts to warmer and drier climatic conditions. A comprehensive discussion and synthesis of the long-term climate forcing on past fire activity is found in Power et al. (2008). Charcoal records in Europe indicate fire activity greater than present during the early Holocene (6500–4500 BC) and the late Holocene (1000 BC–AD 1500), and fire activity lower than present during the middle Holocene (4500–1000 BC). Fires during the late Holocene in Europe and western Asia are generally explained by the use of fire as a tool for deforestation during the Bronze Age and Iron Age. In the Northern Hemisphere, increased seasonality and biomass may have regulated the early Holocene fire regimes, whereas decreased seasonality, coupled with increased human activity, were important regulators of fire during the late Holocene (Power et al., 2008).

Except from the detailed studies in eastern Finland (e.g. Pitkänen et al., 2001, 2002), the Holocene long-term fire history of European boreal and hemiboreal forests is still poorly known for the early and middle Holocene. Fire-scar studies covering the last ca. 200–600 years (Lehtonen et al., 1996; Lehtonen and Huttunen, 1997; Niklasson and Drakenberg, 2001; Niklasson et al., 2002; Wäglind, 2004) show that human activities have been a major cause of ignition in Fennoscandia. Information on human-induced fire activity in southern Sweden during the late Holocene is found in the studies by Björkman (1996), Lagerås (1996, 2000), Niklasson et al. (2002), and Lindbladh et al. (2003, 2008). The fire history of the last 7000 years was documented by microscopic charcoal analysis at a few sites in southernmost Sweden, and it was suggested that fire played a significant role in the transformation from a wooded to a more open landscape during the middle Holocene, and also contributed to the maintenance of landscape openness through time (Berglund et al., 1991). The first study of fire activity covering the entire Holocene in southern Sweden

is that of Stavsåkra (Fig. 1; Greisman and Gaillard, 2009; Olsson and Lemdahl, 2009; Greisman et al., submitted for publication). The fire history was compared to vegetation and to climate proxy records from the same region, and it was concluded that changes in fire activity were probably climate-induced during the early and middle Holocene, and human-induced during the last ca. 3000 calendar years.

In this paper we present a high-resolution charcoal record from a sediment and peat stratigraphy at Storasjö, southern Sweden (Fig. 1), covering the last 10,500 calendar years. It is compared with the record from Stavsåkra, situated 30 km W of Storasjö, and with regional climate proxy data in order to disentangle regional from local fire episodes, and to separate climate from human-induced fire activity. Moreover, we compare results based on microscopic and macroscopic charcoal analysis performed on pollen slides and plant macrofossil sieve residues, respectively, with the results from the quantification of macroscopic charcoal using image analysis (Mooney and Radford, 2001; Mooney and Black, 2003).

2. Study region and sites description

The sites Storasjö (56° 56' N, 15° 16' E; 255 m a.s.l.) and Stavsåkra (57° 01' N, 14° 48' E; 187 m a.s.l.) are located in the central part of the province of Småland, southern Sweden, within the hemiboreal vegetation zone (Ahti et al., 1968) (Fig. 1). Gravelly till deposits with an abundance of large boulders cover granite bedrock at Storasjö, whereas Stavsåkra is characterised by silty-sandy till deposits on similar bedrock (Daniel, 1994). The study region, including Storasjö and Stavsåkra, is dominated by locally indigenous but planted spruce (*Picea alba*) and pine (*Pinus sylvestris*) forests, often growing together with birch (*Betula pubescens* and *B. pendula*).

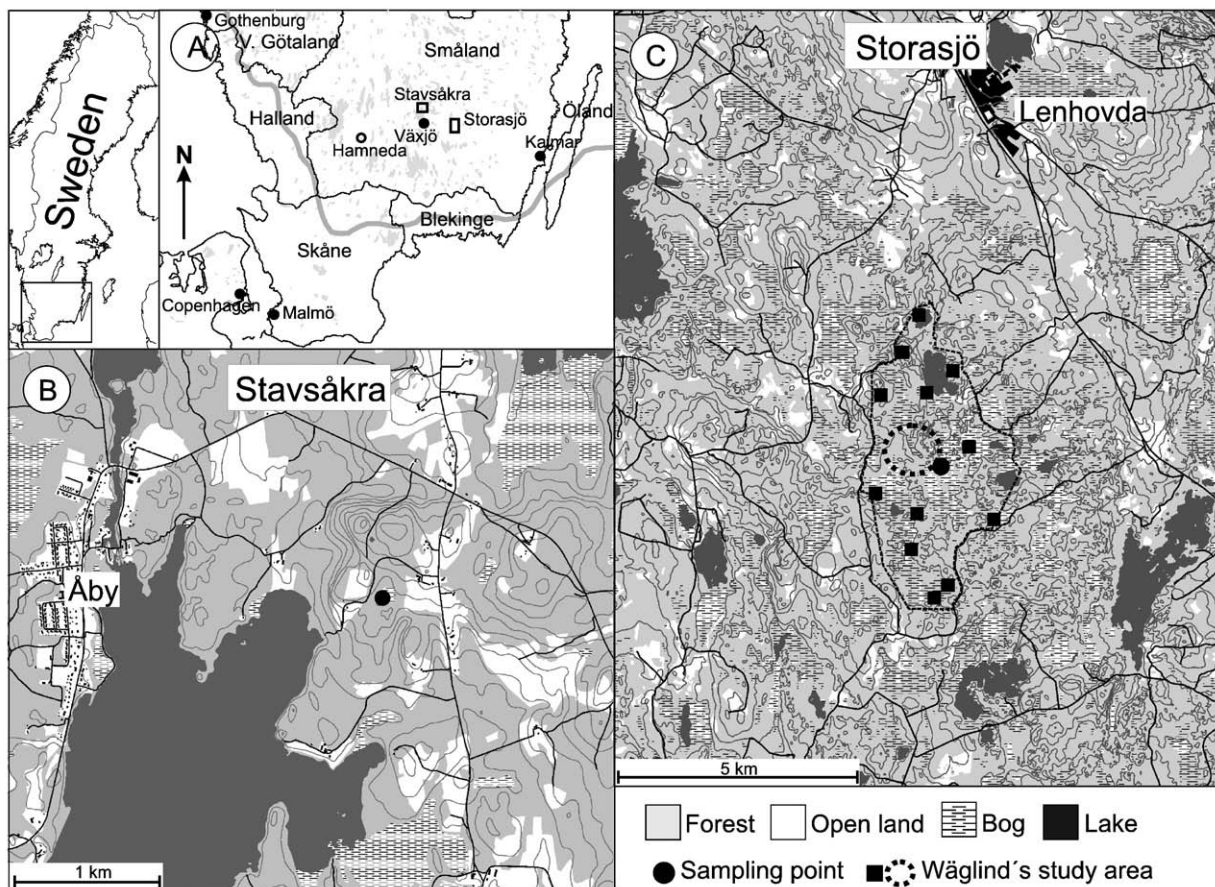


Fig. 1. Location of the two study areas in southern Sweden (A) and of the coring sites at Stavsåkra (B) and Storasjö (C). The location of the site at Hamneda (Lagerås, 2000) is also indicated in map A. The squares around the Storasjö coring site and the dashed circle represent Wäglind's (2004) study sites. Elevation contours are drawn at 5 m intervals.

The dominant wind direction in the contemporary environment is south-western to western (SMHI, 2008). During the period 1961–1990, the mean annual, July and January temperatures were 6 °C, 15 °C and – 3 °C, respectively. The mean annual precipitation is 680 mm at Storasjö, and 651 mm at Stavsåkra (Alexandersson and Eggertsson-Karlström, 2001). The lightning ignition frequency in the area during the period 1944–1975 was 120–150 ignitions · ha⁻¹ · yr⁻¹ (Granström, 1993).

At Storasjö, the cores were taken at the southern extremity of a very narrow, elongated ca. 50 m broad and 500 m long (ca. 2.5 ha) bog (Daniel, 2002; Fig. 1). The Storasjö area is dominated by *Pinus sylvestris*, but *Picea abies* and *Betula pubescens* also occur as important components of the vegetation, while broad-leaved trees are rare. The bog vegetation is dominated by *Sphagnum*, *Eriophorum vaginatum*, and Ericaceae species. In the contemporary environment cultivated fields and pastures occur only beyond 2 km of the coring point (Fig. 1). The small bog at Stavsåkra (ca. 2 ha) is overgrown by *Pinus sylvestris* and *Betula pubescens* with a field layer of Ericaceae. It is surrounded by planted *Picea* with some open grazed areas (Fig. 1).

3. Materials and methods

3.1. Lithostratigraphy and chronology

At both sites, sampling was carried out where the lithostratigraphy appeared to be best represented in the basin, and where charcoal layers were clearly visible. A Russian peat sampler (100 × 10 cm) was used to collect overlapping cores of the entire stratigraphy. The lithostratigraphies of the sampled cores from the two sites are described in Table 1.

The chronologies used to plot charcoal records against time scales were based on age/depth models presented in Olsson and Lemdahl (in preparation) and Greisman (2009). These models combine the general linear line-fitting by weighted least squares (Storasjö 15–140 cm; Stavsåkra 26–190 cm), and the line-fitting by Bernshtein polynomial (Storasjö 160–330; Stavsåkra 190–280 cm) as implemented by psimpoll v. 4.25 (Bennett, 2005). A few outlier dates (three for Storasjö, and two for Stavsåkra) were rejected before establishing the models (Fig. 2). For this paper, age/depth curves were also estimated using a Bayesian approach developed by Lanos (2004) in order to check whether the selected chronologies were included in the confidence envelope of the Bayesian estimated age/depth curves and, therefore, reliable for temporal correlation of the records between

the two sites. The Bayesian approach makes it possible to estimate a mean age–depth curve with its confidence envelope that interpolates the data and takes into account all the uncertainties coming from the calibrated radiocarbon dates, the errors on depth measurements (mostly small), and the curve itself (through unknown global variance) (Lanos, 2004). The calculation is carried out using MCMC techniques (Metropolis–Hastings algorithm) (Gilks et al., 1997). 50,000 iterations were needed to get the estimation on the curve and the global variance (Fig. 2). The latter provides some insight on the uncertainty of the age of a given depth. The standard deviation obtained is ± 8–9 cm in average. The selected chronologies are included in the confidence envelope of the Bayesian estimated age/depth curve (Fig. 2). All dates below are given in calibrated years BC/AD.

3.2. Macroscopic charcoal analysis

The fire history was inferred from records of microscopic and macroscopic charcoal, charred plant remains, and remains of pyrophilous beetles at both sites (Olsson and Lemdahl, 2009, in preparation; Olsson, 2009; Greisman and Gaillard, 2009). Larger charcoal fragments (≥ 1 mm) were taxonomically identified using wood anatomy characteristics (Schweingruber, 1982) (Table 2).

The macroscopic charcoal record from Stavsåkra is based on estimates of charcoal abundance in the captured material after washing the samples through a sieve with mesh size 0.25 mm. Samples were taken continuously as 5–10 cm thick sections and soaked in 10% NaOH for 24 h. The amount of macroscopic charcoal fragments was then estimated and is presented in Figs. 4 and 5.

At Storasjö, macroscopic charcoal was analysed using oxidation, wet sieving and image analysis. This method allows long, high resolution charcoal records to be obtained with relatively little effort (e.g. Black and Mooney, 2006; Mooney and Maltby, 2006; Black et al., 2007). 325 contiguous 2 cm³ – samples of peat or lake sediment were extracted from the core every centimetre. They were then dispersed in 30 ml of 5% sodium hypochlorite (bleach) for 24 h to remove the pigment from organic matter, and washed through a 0.25 mm sieve. The material was photographed in a Petri dish on a light board (Gepe slimlight 2003) using a Nikon d70s DSLR-camera. The area (mm² of charcoal · cm⁻³) was measured, and the abundance of charcoal (no. of particles · cm⁻³) was calculated using the image analysis software Scion Image for Windows version 4.0.3.2 (downloaded 2007-08-21 from www.scioncorp.com). Both area and abundance of charcoal

Table 1
Lithostratigraphy of the studied sequences at Storasjö and Stavsåkra.

Depth (cm)	Age cal. yrs. (AD/BC)	Layer description
<i>Stavsåkra</i>		
0–27.5	AD 2000–1550	Low humified <i>Sphagnum</i> peat
27.5–70	AD 1550–1200 BC	High humified <i>Sphagnum</i> peat with a thick charcoal layer at 45 cm
70–115	1200–3400 BC	High humified <i>Carex</i> – <i>Sphagnum</i> peat with wood remains and a thick charcoal layer at the upper boundary (70 cm)
115–190	3400–7720 BC	Wood carr peat (<i>Carex</i> –wood peat) with a thick charcoal layer at 150 cm and several thinner charcoal layers of which three particularly distinct ones at ca. 120,135 and 180 cm
190–240	7720–8450 BC	Carr peat (<i>Carex</i> – <i>Eriophorum</i> peat)
240–270	8450–8570 BC	<i>Phragmites</i> peat with <i>Carex</i> and <i>Equisetum</i>
270–280	8570–8600 BC	Coarse detritus gyttja with <i>Potamogeton</i> and <i>Nymphaea alba</i> seeds
<i>Storasjö</i>		
0–5	AD 2006–1930	Dark brown <i>Carex</i> – <i>Sphagnum</i> peat, high humified. Lower boundary relatively sharp (5 mm).
5–30	AD 1930–1450	Light brown <i>Carex</i> – <i>Sphagnum</i> peat, high humified. Lower boundary progressive (20 mm).
30–52	AD 1450–500	Light brown sedge (<i>Carex</i>) peat, humified. Lower boundary relatively sharp (5 mm).
52–213	AD 500–7240 BC	Light brown carr peat/wood carr peat with few wood pieces, humified. Lower boundary progressive (10 mm). 15 distinct charcoal levels of which a very thick one (163–170 cm)
213–247	7240–7880 BC	Blackish brown carr peat with <i>Eriophorum</i> rhizomes. Lower boundary progressive (20 mm).
247–270	7880–8300 BC	<i>Phragmites</i> (reed) peat with <i>Phragmites</i> rhizomes. Lower boundary progressive (30 mm).
270–295	8300–8640 BC	Greenish brown coarse detritus gyttja. Lower boundary relatively sharp (5 mm)
295–315	8640–8800 BC	Light brown fine detritus gyttja. Lower boundary relatively sharp (5 mm).
315–325	8800–8900 BC	Light brownish grey clay gyttja, sandy at the bottom (324–325 cm). Charcoal layer: 321–323 cm.

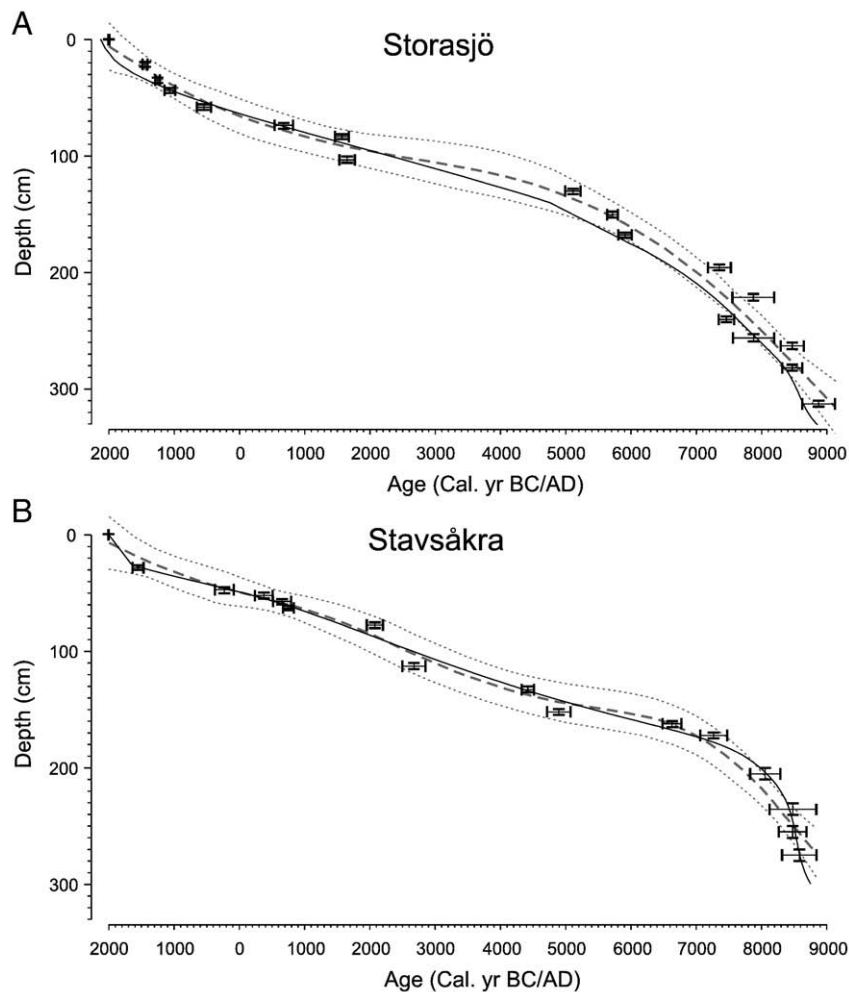


Fig. 2. Age/depth models of the two studied sequences at Storasjö and Stavsåkra. The age/depth models presented as unbroken lines were used to establish the chronologies adopted in this paper. Alternative age/depth models estimated using a Bayesian approach are shown as dashed lines, and their confidence envelop as dotted lines (see text on chronology for more explanations).

were measured, however as the correlation between these two parameters was high (Pearson's $r = 0.901$) the results are presented as number of charcoal particles/cm³ (CHAR) only.

To estimate the number of fire events at Storasjö, the charcoal accumulation rate (CHAR, number of charcoal particles · cm⁻² · yr⁻¹, Fig. 3E) was calculated using the computer program CharAnalysis (Higuera et al., 2008). The program interpolates the actual charcoal counts, sample volume, and sample depths by using the median sample resolution before calculating CHAR. The median sample resolution in the record of Storasjö is 31 years. No transformations were used. In CharAnalysis, CHAR is composed of two components, $C_{\text{background}}$ and C_{peak} . The background component illustrates low-frequency trends reflecting changes in the rates of charcoal production, secondary transport, sediment mixing, and sediment sampling (Higuera et al., 2008). It also correlates well with long distance transport from the entire charcoal source area (Higuera et al., 2007). The peak component is the high-frequency variations representing the local fire events/episodes, in the study area. $C_{\text{background}}$ was estimated with Lowess smoother, robust to outliers, with a 1800-yr window width. The C_{peak} component was calculated as residuals, i.e. $C_{\text{background}}$ was subtracted from $C_{\text{interpolated}}$. The threshold value separating fire related from non-fire related variability in the peak component was set at the 95th percentile of a Gaussian mixture model. CHARs, identified fire episodes marked with +, fire return interval (FRI, number of years between fire events), and fire frequency (number of fires · 750 yr⁻¹) are plotted as a function of time (see Fig. 3E, F, G).

3.3. Pollen and microscopic charcoal analysis

One cm³ of material was sampled at 2 to 10 cm intervals. The samples were prepared for pollen analysis according to Berglund and Ralska-Jasiewiczowa (1986). After treatment with NaOH, the samples were washed through a 160 µm sieve mesh. The microscopic charcoal particles ($\geq 10 \mu\text{m} < 160 \mu\text{m}$) were counted simultaneously with pollen and spores (Greisman and Gaillard, 2009; Greisman, 2009), and are presented as a percentage of the sum of terrestrial pollen and charcoal particles, and as microscopic charcoal accumulation rates (micro CHAR) (Fig. 3C, D; Fig. 4). The results of the pollen analysis were presented in Greisman and Gaillard (2009) and Greisman (2009).

In this paper, plant nomenclature follows Flora Europaea (Tutin et al., 1967–2001), and pollen taxonomy the established rules for the European Pollen Database (<http://www.europeanpollendatabase.net/>).

4. Results

4.1. Microscopic and macroscopic charcoal analyses

4.1.1. Storasjö

The macroscopic CHAR record can be subdivided into seven zones (Cz 1–7). They are described below, together with the related characteristics of the microscopic charcoal record, the occurrence of saproxylic and pyrophilous beetles, and charred plant remains (Fig. 3). Saproxylic beetles are confined to trees and dead wood, and

Table 2

Identified macroscopic charcoal fragments from the studied sequences at Storasjö and Stavsåkra.

Depth (cm)	Age cal. yrs. (AD/BC)	Species (number of fragments)
<i>Stavsåkra</i>		
70–75	1200–1450 BC	<i>Quercus</i> sp. (11) <i>Pinus sylvestris</i> (1)
67–76	1050–1500 BC	<i>Pinus sylvestris</i> (1 very large piece, partly carbonized)
160–165	6100–6450 BC	<i>Pinus sylvestris</i> (6) with very narrow annual rings
<i>Storasjö</i>		
23.4–28.0	AD 1500–1650	Ericaceae cf. <i>Vaccinium/Empetrum</i> (4)
28.0–32.6	AD 1350–1500	Leaf of Ericaceae cf. <i>Vaccinium oxycocum</i> (4) Dicotyledonous wood undiff. (2) Ericaceae cf. <i>Vaccinium/Empetrum</i> spp. (2)
56.0–60.5	AD 25–280	<i>Pinus sylvestris</i> (10; 4 large, 6 small fragments) Coniferous tree undiff. (1) <i>Salix</i> sp. (3)
100.5–105.5	2500–2800 BC	Ericaceae cf. <i>Vaccinium</i> sp. (?) <i>Pinus sylvestris</i> (7) Coniferous tree undiff. (3) <i>Betula</i> sp. (1) <i>Salix</i> sp. (1) Herb monocotyledon undiff. (1) Herb undiff. (1)
128.0–132.5	4200–4450 BC	<i>Pinus sylvestris</i> (5; 3 large, 2 small fragments) Coniferous tree undiff. (1 young twig) <i>Betula</i> sp. (4) Herbs undiff. (3) Herb monocotyledon undiff. (2) Broad-leaved wood undiff. (6 small fragments)
289.0–294.0	8525–8600 BC	<i>Pinus sylvestris</i> (13)

may be indicative of the availability of fuel in the woods. Pyrophilous beetles are dependent on a regional continuity of fires and are favoured by habitats created by fire, probably because of the lack of competition from other species and/or the availability of specific food substrates that appear only after a fire (Wikars, 1997). The identified macroscopic CHAR peaks are referred to as “fire events”. However, these “events” may correspond to more than one fire. A tentative correlation of the fire “events” identified in the microscopic and macroscopic charcoal records (numbered from 1 to 23) is shown in Fig. 3.

4.1.1.1. Cz 1 (8925–8100 BC). The macroscopic CHAR exhibits five fire “events” (episode 1) clustered between 8700 and 8300 BC. Fire frequency is high, ca. six fire “events” per 750 yrs – period (average FRI: ca. 100 years). There is only one peak of microscopic charcoal (1) ca. 8925 BC. Otherwise the micro-charcoal values are generally low. Saproxylic beetles occur regularly from ca. 8750 BC, and the pyrophilous beetle *Orthotomicus suturalis* is present at one level. Charred remains of Ericaceae are present at a few levels.

4.1.1.2. Cz 2 (8100–7250 BC). During these 850 years there are no peaks of macroscopic CHAR, but only small amounts of charcoal not exceeding the “background level”. The microscopic CHAR and charcoal % maintain very low values as in Cz 1. Saproxylic beetles occur regularly and charred plant remains are rare.

4.1.1.3. Cz 3 (7250–6200 BC). The macroscopic CHAR indicates five fire “events” (2–6), relatively evenly separated through time. The mean FRI is ca. 200 yrs, and fire frequency increases to 3–4 fire “events” per 750 yrs period. The microscopic charcoal % and CHAR exhibit high values (40–60%; 500–750 particles cm⁻²·yr⁻¹) with three small peaks (2, 3–4, 5). The increases in macroscopic and microscopic charcoal are synchronous (ca. 7250 BC). Saproxylic beetles are present at the beginning and in the last part of the zone. Charred remains

of Ericaceae, *Carex* and *Pinus* occur in the first half of the zone, and correlate with the first 3 fire events in the macroscopic CHAR record.

4.1.1.4. Cz 4 (6200–5625 BC). This period of 575 years is characterised by very low values of macroscopic CHAR, not exceeding the “background level”; no fire event is recorded. In contrast, there is an increase in microscopic charcoal % (ca. 40–75%) and microscopic CHAR (ca. 700 to 2000 particles cm⁻² yr⁻¹). Saproxylic beetles and charred remains of Ericaceae, *Carex* and *Pinus* are present.

4.1.1.5. Cz 5 (5625–1850 BC). This zone starts with the most pronounced peak of macroscopic CHAR (7) of the sequence. After this “event”, there are nine peaks or fire “events” (8–15) relatively evenly distributed through time. Moreover, the highest value in each peak decreases in two steps through the zone, between 5500 and 5000 BC and between 4000 and 3500 BC. The mean FRI is 377 years; however, the time interval between the most distinct eight peaks is close to 500 yrs. The microscopic charcoal % and CHARs exhibit a similar pattern, with four major peaks (7, 8, 9, 10–11) between 5500 and 4000 BC, and four minor peaks (12, 13, 14, 15) with significantly lower values between 3500 and 2000 BC. Saproxylic beetles are present through the entire zone, while pyrophilous species occur only in the uppermost level analysed. Charred remains of *Empetrum nigrum* were found in most levels, while charred remains of *Carex* and *Pinus* occurred at a few levels, mainly at the beginning of the zone.

4.1.1.6. Cz 6 (1850 BC–AD 250). Cz 6 is characterised by a periodicity of fire “events” comparable to that of Cz 5, but the macroscopic CHAR peak values are only just above the “background” values. During this long period of 2100 years, three fire “events” (16–18) are recorded. The record of microscopic charcoal CHAR shows a single clear peak (18) at ca. 500 BC. Slightly higher values are also found at ca. 1500 AD (16), 1000 AD (17) and around the time of Christ’s birth. The latter peak is not recorded as a fire “episode” in the macroscopic CHAR record as the values are just below the level of C_{background}. A few charred remains of *Empetrum nigrum*, *Vaccinium*, and *Pinus* were found in most analysed levels, as well as pyrophilous and saproxylic beetles.

4.1.1.7. Cz 7 (AD 250–present). This zone differs from Cz 5 and Cz 6 by the irregular periodicity of the macroscopic CHAR peaks. There is a first “isolated” fire “event” (19) at ca. AD 400 followed by a period of ca. 700 years without macroscopic CHAR peaks. In contrast, from ca. AD 1100, six fire “events” (20, 21, 22 (two peaks) and 23 (two peaks)) with short time intervals between them were identified. Fire frequency increases rapidly from ca. one to five fires per 750 yrs period, while FRI decreases from 1000 yrs to ca. 100–150 yrs, i.e. to values comparable to those of zone Cz 1. The microscopic charcoal % and CHAR exhibit four distinct peaks (19–23); the first and second peaks appear to be synchronous with the fire “event” at ca. 1500 BC (19) and the first (20) of the high frequency fire events from ca. AD 1100, respectively. The two last peaks of microscopic charcoal (22, 23) might correlate with the highest values of macroscopic CHAR of the groups of peaks 22 and 23. Pyrophilous beetles occur at one level only and saproxylic beetles are represented at the beginning and the end of the zone. Charred plant remains were recorded at the level of the fire “event” around 1500 BC (*Vaccinium* and *Pinus*) and during the period with frequent fires (*Empetrum nigrum*, *Vaccinium*, and *Pinus*).

4.1.2. Stavsåkra

The results of the charcoal (Greisman and Gaillard, 2009; Greisman, 2009), and the insect analyses (Olsson and Lemdahl, 2009) have been described and discussed in detail previously and are summarised here. The sequence can be subdivided into four major zones, Ch 1–Ch 4 (Fig. 4).

4.1.2.1. Ch 1 (8600–4250 BC). This zone is characterised by 1) peaks of microscopic charcoal % and CHAR at intervals of ca. 500 years or less

Storasjö

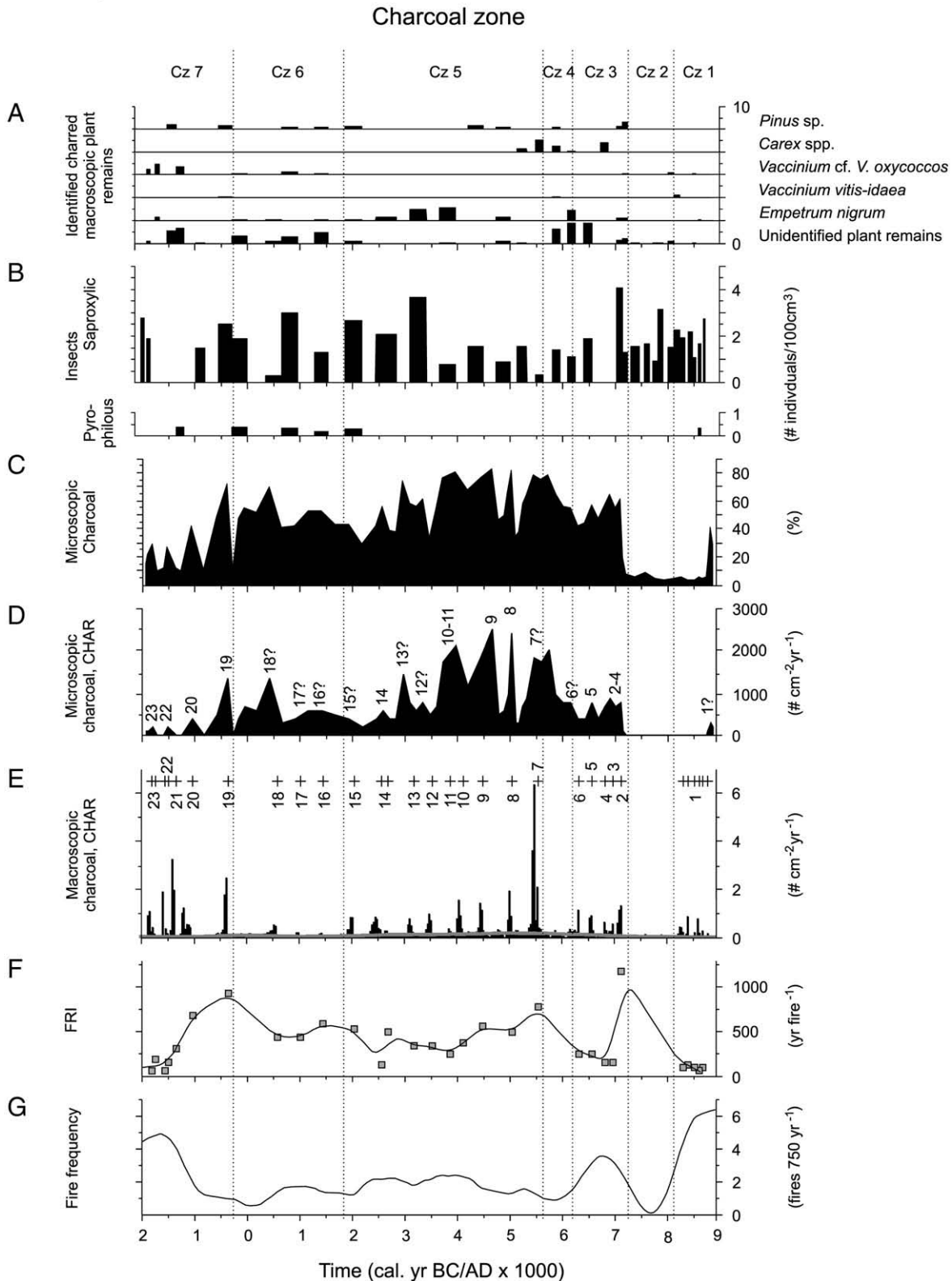


Fig. 3. Results from charcoal analyses of the lake-sediment and peat sequence of Storasjö. A. Identified charred macroscopic plant remains. Note: the thickness of the bars does not represent sample thickness; samples were taken continuously as 5–10 cm thick sections. B. Saproxylic and pyrophilous Coleoptera species in number of individuals per 100 cm². C. Microscopic charcoal counted on pollen slides expressed as percentages. D. Microscopic charcoal counted on pollen slides expressed as accumulation rates. E. Macroscopic charcoal expressed as accumulation rates (CHAR) and CHAR peaks (indicated by +) F. Fire return interval (FRI) in number of years between fires. G. Fire frequency in number of fires per 750 yrs-interval. A tentative correlation between the peaks of macroscopic and microscopic charcoal is shown by numbering assumed synchronous episodes/peaks from 1 to 23.

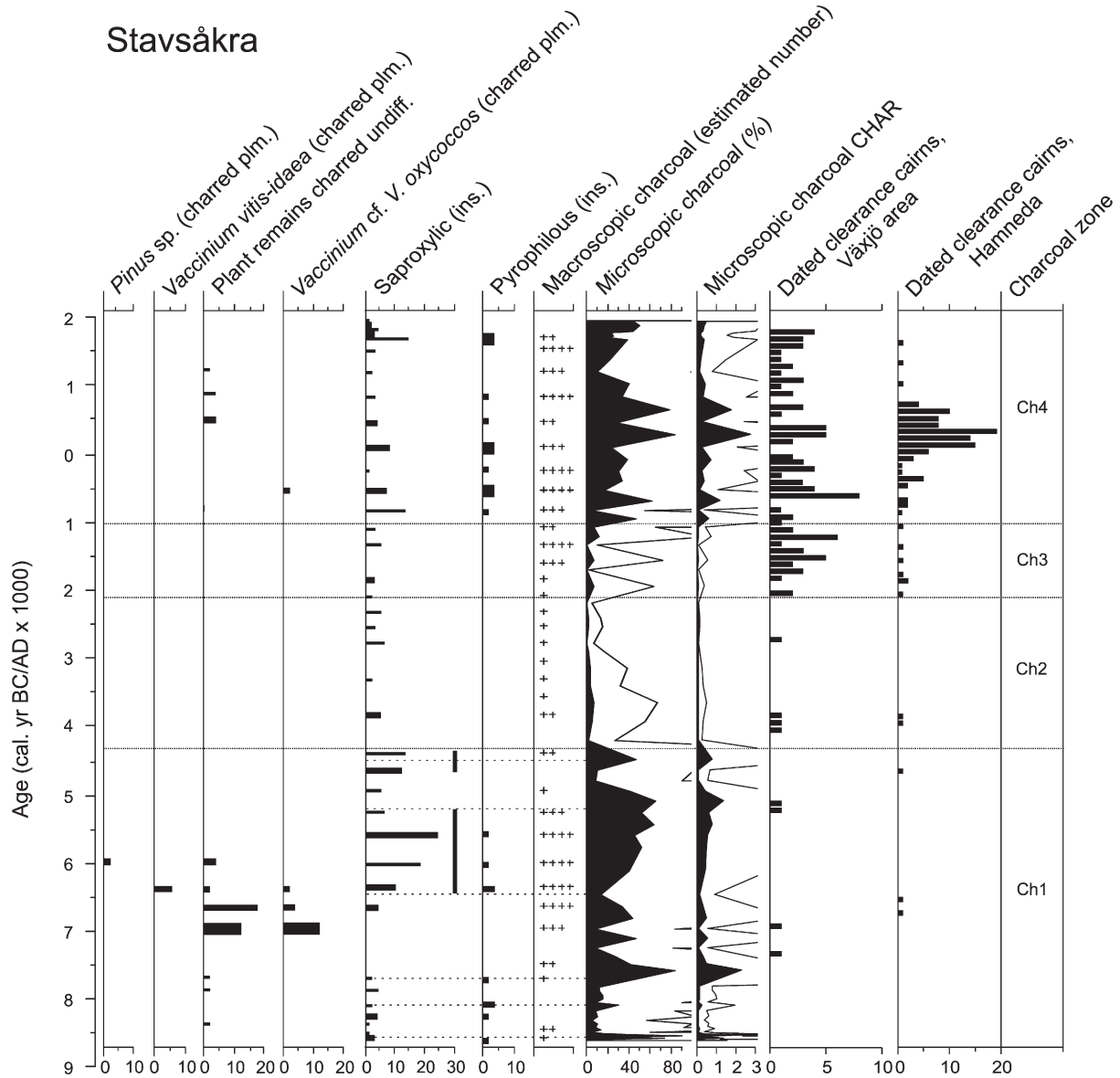


Fig. 4. Charred plant macrofossil remains (number per 100 ml) and charcoal records from Stavsåkra. Note: the thickness of the bars does not represent sample thickness; samples were taken continuously as 5–10 cm thick sections. The number of macroscopic charcoal fragments in the sieve residues was estimated: +, 0–10; ++, 10–100; +++, 100–1000; +++++, >1000. The microscopic charcoal is expressed in percentages and accumulation rates (CHAR; scale: $1 = 10^3 \cdot \text{cm}^{-2} \cdot \text{yr}^{-1}$). The number of dated clearance cairns for 100 years intervals in the Växjö area (Skoglund, 2005) and at Hamneda (Lagerås, 2000) (Fig. 1) is also shown for comparison. The synchronicity of the occurrence of pyrophilous insect species and high values of macroscopic and microscopic charcoal during the early and middle Holocene is indicated by dashed lines.

between 8600 and 6750 BC, 2) a period of high values ca. 6250–5000 BC, and 3) a last peak at ca. 4500 BC. Except between 6750 and 7500 BC, the high values of microscopic charcoal correlate with high values of macroscopic charcoal, and the occurrence of pyrophilous beetles. Charred plant remains are found in particular during the periods 8400–7700 BC and 7000–6000 BC.

4.1.2.2. Ch 2 (4250–2100 BC). This zone is characterised by very low values of microscopic and macroscopic charcoal.

4.1.2.3. Ch 3 (2100–1000 BC). The microscopic charcoal record (% and CHAR) exhibits three peaks of low values. The amount of macroscopic charcoal increases from 1500 BC. From 2000 BC, there is a continuous record of dated clearance cairns from the Växjö area and Hamneda (Fig. 1).

4.1.2.4. Ch 4 (1000 BC–present). The values of microscopic charcoal exhibit a series of nine peaks, with four major peaks of CHAR at

900 BC, 750 BC, AD 250 and AD 600. Particularly low values of microscopic CHAR at ca. AD 1200 correlate with an absence of pyrophilous beetles. There is a continuous record of dated clearance cairns from the Växjö area and, from ca. AD 0 to 600, a period with a particularly high number of dated clearance cairns from Hamneda.

4.1.3. Identified charcoal fragments

The identified charcoal fragments are presented in Table 2. The oldest early Holocene fragments (Storasjö ca. 8500 BC; Stavsåkra ca. 6300 BC) are from *Pinus sylvestris*. The middle Holocene charcoals at Storasjö (ca. 4300 and 2650 BC) are dominated by fragments of *P. sylvestris*, accompanied by *Betula* spp., *Salix* spp. and herbs. There are no identified charcoals from those periods at Stavsåkra. During the late Holocene, a dominance of fragments of *Quercus* spp. was found at Stavsåkra at a level dated to 1200–1450 BC with one fragment of *P. sylvestris*. A large piece of partly carbonised *Pinus sylvestris* was found at a level dated to 1050–1500 BC. At Storasjö, *P. sylvestris* is dominant

at AD 25–280 with some *Salix* spp. and Ericaceae. Fragments of Ericaceae (cf. *Vaccinium oxycoccos*, and cf. *Vaccinium/Empetrum*) characterise the upper levels dated to AD 1350–1500 (with fragments of Dicotyledonous wood) and AD 1500–1650.

4.2. Vegetation history and human impact inferred from pollen analysis

The pollen diagrams from Storasjö and Stavsåkra are published in Greisman and Gaillard (2009) and Greisman (2009). Below, we briefly summarize the vegetation and human-impact history at the two sites and focus on the vegetation types in which ignition might have occurred, i.e., woods and heaths.

Pinus and *Betula* were the dominant trees around 8500 BC at both sites. There is indication of the occurrence of open patches and/or a relatively open structure of the forest at that time. *Corylus* established locally ca. 8450 BC at Stavsåkra. In contrast, an early establishment of *Corylus* is not confirmed at Storasjö (Greisman, 2009). For ca. 750 years (ca. 8450–7700 BC), the site at Stavsåkra was surrounded by woods of *Pinus*, *Betula*, *Corylus*, and *Salix*. By ca. 7500 BC, *Pinus*, *Ulmus*, *Salix* and *Calluna* decreased, while *Alnus*, *Quercus* and *Tilia* established, and *Betula* and *Corylus* increased. At Storasjö, *Corylus* established ca. 7100 BC. Competition between *Pinus* and broadleaved trees was likely during the early Holocene at both sites, but *Pinus* maintained an important presence until ca. 5500 BC. *Pinus*, *Calluna*, *Empetrum* and *Vaccinium* decreased from ca. 5500 BC to reach low values at Stavsåkra ca. 4800 BC. Between 4500 and 2800 BC, the area around Stavsåkra was characterised by broadleaved woods with some pine woods. At Storasjö, *Pinus* was still an important component of the forest through the middle Holocene until AD 500.

The history of human activities from Late Neolithic through the Bronze Age and Iron Age is comparable between the two sites, except that the centres of activity were situated at a longer distance from the study site at Storasjö than at Stavsåkra (Greisman, 2009). At Stavsåkra, evidence of forest clearance (*Quercus* and *Tilia* in particular) ca. 2200 BC and 1500 BC agrees with the records of Late Neolithic and Early Bronze Age monuments, respectively (e.g. Skoglund, 2005). A third episode of forest clearance is dated to 850 BC (Late Bronze Age). Both areas might have been used for extensive grazing during those periods. Grazing favoured *Calluna* from 750 BC at Stavsåkra and 600 BC at Storasjö. However, the Storasjö area was probably characterised by grazing in *Pinus* dominated woods, while open *Calluna* heaths expanded at Stavsåkra from the Early Medieval time and particularly in the 18th–19th centuries. Whether *Fagus sylvatica* established locally remains an open question for both sites. *Picea* established locally at ca. AD 1000 at both sites, but it was not common until ca. AD 1700 when the climate deterioration of the Little Ice Age might have favoured its expansion at the expense of broad-leaved trees (Giesecke, 2004; Miller et al., 2008). It was planted at the end of the 19th century and during the 20th century as in most parts of the province of Småland and large parts of southern Sweden south of Stockholm.

5. Discussion

5.1. Methodological issues and interpretation of the charcoal record

Charcoal layers in peat stratigraphies are indisputable evidence of *in situ* fires next to the lake basin or the bog (Pitkänen et al., 2001). According to most studies on charcoal dispersal and deposition, larger and heavier charcoal fragments settle closer to the fire edge and represent local fires, while smaller, lighter particles may be transported over long distances and, therefore, indicate regional fire events (e.g. Patterson et al., 1987; Whitlock and Millspaugh, 1996; Clark et al., 1998; Long et al., 1998; Tinner et al., 1998; Blackford, 2000; Ohlson and Tryterud, 2000; Carcaillet et al., 2001; Gardner and Whitlock, 2001). Blackford (2000) found that particles <20 µm were most reliable as indicators of regional background charcoal, while

particles >125 µm were representative of local fires. Millspaugh and Whitlock (1995), Clark et al. (1998), and Froyd (2006) suggested that particles >120–125 µm were the most useful to reconstruct fire events. Tinner et al. (1998) and Duffin et al. (2008) recommended using charcoal >50 µm to reconstruct local fire history.

All peaks of macroscopic CHAR from Storasjö ascribed to local fire “events” (1 to 23 in Fig. 3) are found in the microscopic charcoal record as well. Similarly, all periods with high values of microscopic charcoal at Stavsåkra are also characterised by high estimates of macroscopic charcoal abundance. These results suggest that the microscopic fraction (≥ 10 –<160 µm) represents a mixture of local and regional fire signals, while the fraction ≥ 250 µm probably represents mainly local fire events. Moreover, because the records of macroscopic and microscopic charcoal at our study sites show comparable peaks (Figs. 3 and 4) through the entire Holocene, we propose that the charcoal signal at these sites is essentially local. Most of the time intervals between fire “events” at Storasjö are characterised by relatively high values of microscopic charcoal % and CHAR. The latter indicates that there may be a relatively high “background level” of microscopic charcoal coming from long distance and representing regional fire events. Moreover, it is known that charcoal deposition may peak several years after the maximum of forest fires, which may blur the detailed fire record (e.g. Whitlock and Millspaugh, 1996; Tinner et al., 1998).

In spite of a relatively large number of studies aimed to calibrate charcoal records against known fire events in middle- to high-latitude regions, the charcoal source area and the effect of lake/basin size on source area is still not well understood (Duffin et al., 2008). Peters and Higuera (2007) developed a particle dispersal model to calculate the potential charcoal source area (PCSA) for several classes of fires. The simulated PCSAs suggest that the variability in airborne charcoal deposition to a lake, and the patterns of charcoal deposition in both time and space, depend on the source-area to fire-size ratio, and on the size and location of fires in the PCSA. The simulations show that if a 100-ha fire originates within a small PCSA, the charcoal deposition will almost always cover the entire PCSA, resulting in charcoal peaks equal to one. Therefore, multiple 100-ha fires would create a nearly binary pattern of airborne charcoal deposition through time, i.e. with peaks when there is a fire in the source area and no charcoal otherwise. With larger PCSAs, the simulations show that the number of potential locations of 100-ha fires within the PCSA increases, which would result in greater variability in airborne charcoal deposition due to location alone, because fires close to a lake deposit more charcoal than fires far from a lake. A larger PCSA also allows for more fires of varying sizes to occur within the source area, creating further variability in charcoal deposition through time.

Peters and Higuera (2007) propose that boreal-forest PCSAs are likely larger than those assumed earlier (e.g. Carcaillet et al., 2001; Lynch et al., 2004), because sediment charcoal records from boreal forests often lack binary patterns of charcoal deposition. However, the macroscopic charcoal record from Storasjö exhibits a clear binary pattern, which implies that, when the deposition basin is very small, in our case not exceeding 2.5 ha, the PCSA is probably relatively small. The theoretical results of Peters and Higuera (2007) also suggest that macroscopic charcoal, even though strongly biased towards short distances, may travel many kilometres, which is consistent with dispersal data from uncontrolled fires (e.g. Whitlock and Millspaugh, 1996; Pisaric, 2002; Hallett et al., 2003; Tinner et al., 2006).

It has been recommended to use charcoal accumulation rates (CHAR) rather than percentages for the interpretation of the charcoal record in terms of fire history (e.g. Whitlock and Larsen, 2001). In the present study, we use the CHAR records of both microscopic and macroscopic charcoals to infer fire activity. The concept of a “fire regime” usually include parameters such as fire intensity, fire strength/depth in the humus layer, frequency and spatial size (Conedera et al., 2009). In the following discussion we refer to “fire activity” following the definition of Power et al. (2008). However, we

also discuss “fire regimes” at a century to millennial temporal scale, a “fire regime” being in that case defined by the frequency of major fire episodes (including one to several “fire events”) despite the fact that the time resolution of the analyses is not high enough to allow inference of detailed fire frequencies at decadal scales. Peaks of CHARs, i.e. fire “events” in the result description above, may represent either times of frequent fires or a single fire event. Our work probably best describes fire frequency, defined by a certain time interval between fire “events” (or episodes of several events). It should be stressed that the methods do not allow objective conclusions about fire intensity.

5.2. What plants did burn?

Charred plant remains such as leaves, needles and twigs (Figs. 3 and 4), and identified charred wood pieces (Table 2) give clues on what plants were burning at the two study sites. *Pinus* was obviously the tree species that burnt most at both sites through the major part of the Holocene (8600–200 BC). *Betula* and *Salix* were also probably common among trees and larger shrubs burning during the Holocene; the two genera are recorded as charcoal fragments during the middle and late Holocene at Storås. Moreover, *Quercus* did burn at Stavsåkra during the late Holocene as indicated by charcoal pieces dated to 1200–1450 BC. The latter finding suggests that *Quercus* might have burnt at both sites during the time when it was most common, ca. 2250–750 BC. Charred leaves of Ericaceae were relatively common in the peat deposits of the early Holocene at Stavsåkra and most of the Holocene at Storås. These species were growing in the pine wood shrub layer (*Empetrum nigrum*, *Vaccinium myrtillus*, *V. uliginosum* and *V. vitis-idaea*) or on the bog (in particular *Vaccinium oxycoccos*). They may have been the plants that burnt most during the last 500 years at Storås. There are very few charcoal fragments of coniferous and deciduous trees during the last 500 years at both sites. Charred seeds of *Carex* and some charcoal fragments of herbs (mainly monocotyledon, possibly grasses) were also found at Storås during the middle Holocene.

5.3. A correlation between the fire histories at Storås and Stavsåkra

An attempt to correlate the charcoal records from Storås and Stavsåkra is presented in Fig. 5 (B, C). In this context it is important to stress the uncertainties related to chronologies established on series of ^{14}C dates. The chronologies based on Bayesian statistics have the advantage to provide estimated envelopes of ages for the analysed peat levels, which makes it possible to evaluate possible correlations between sites. For example in our case, the age of 6200 BC might date the levels 138 to 172 cm at Stavsåkra (mean 155 cm), and the levels 155–180 cm at Storås (mean 167 cm). Similarly, the age of 7500 BC might date the levels 175 to 207 cm at Stavsåkra (mean 191 cm), and the levels 211–234 cm at Storås (mean 222 cm). It also implies that a peat level cannot be dated more precisely than \pm ca. 200–500 years. Therefore, discrepancies between the sites in terms of ages of certain characteristic features of the charcoal record might be due to these dating uncertainties that have to be taken into account in the discussion.

There are indications of fire at both sites around 8500 BC. The low values of microscopic CHAR suggest that the fires either were not widespread in the region, or were not particularly intense. The macroscopic CHARs from Storås indicate a relatively high fire frequency of ca. one fire per 100–150 years, which is comparable to the potential fire frequency in the area today. Between ca. 8500 BC and 7200 BC at Storås and around ca. 7600 BC at Stavsåkra, the fire activity was low, as indicated by very low values or absence of both microscopic and macroscopic charcoals at the sites. At ca. 7100 BC at Storås and ca. 7500 BC at Stavsåkra, a rapid increase in macroscopic and microscopic CHAR marks the start of a long period characterised by frequent episodes of high fire activity. The time discrepancy between

the two sites might be due to dating uncertainties (see above). According to the Bayesian models (Fig. 2), the level corresponding to the increase in charcoal may date to 7300 ± 200 BC at Storås, and 7500 ± 300 BC at Stavsåkra. These ages are overlapping and, therefore, we assume that these changes are synchronous.

Between ca. 7400 BC and 2000 BC, the charcoal record of Storås is characterised by a sequence of charcoal peaks at strikingly regular time intervals. We propose that the peaks of microscopic charcoal at Stavsåkra dated to ca. 7100 and 6750 BC might be synchronous to the peaks of macroscopic charcoal at Storås ca. 6800–6600 and 6300 BC, respectively, and that the low charcoal values at Stavsåkra at ca. 6500 BC might correlate with the time without peaks of macroscopic charcoal at Storås around 6000 BC (Fig. 5B and C). The discrepancies in age between the two sites during this time period are also included in the age interval obtained from the Bayesian age/depth models (Fig. 2).

There is an obvious discrepancy between the two sites from 4500 BC, as the CHARs are very low at Stavsåkra from 4400 to 1000 BC, while they still have relatively high values at Storås, though they gradually decrease between 4500 and 2500 BC, a trend that is also seen in the low values at Stavsåkra. A possible explanation to the difference in the amount of charcoal might be found in the tree species composition prevailing during that period at the two sites. From ca. 4500 BC, the relationship *Pinus*/broad-leaved trees is higher at Storås than at Stavsåkra (Greisman, 2009). The higher abundance of pine at Storås may explain higher fire activity during that time.

From ca. 2000 BC until present the charcoal records are very different between the two sites, which may be explained by differences in land use. Between 2000 and 500 BC, the macroscopic CHARs at Storås indicate very low fire activity, while both microscopic CHARs and macroscopic charcoal estimated amounts at Stavsåkra show a progressive increase in values, with two peaks between 1000 and 500 BC. The relatively high CHARs of microscopic charcoal at Storås between 2000 and 500 BC suggest that, even though it probably burned very little around the site, fires may have been common in the region during this period. The insect record at Storås (Fig. 3B) is characterised by the occurrence of species depending on forest fires from ca. 2000 BC to AD 1200. It suggests that there were still local fires. The only possible synchronicities between the two sites during the late Holocene are the low fire activity between ca. 500 BC to AD 250, and the relatively high fire activity ca. 500 AD. The latter might be due to comparable trends in human activities in the entire study region during this time period.

5.4. Natural or human-induced fires?

Natural ignition due to lightning varies significantly geographically. Lightning is more frequent in south-eastern than in south-western and northern Sweden (Granström, 1993). In the contemporary environment, there are 2–3 lightning-induced fires per 100 km² and per decade in south-eastern Sweden, and 5–25% of the forest fires are caused by lightning, with the remainder due to human activities (e.g. Niklasson and Nilsson, 2005, and references herein).

In an attempt to disentangle the climate from human activity as causes of forest fires in the past, Greisman and Gaillard (2009) and Greisman (2009) compared the fire history at Stavsåkra with climate proxy records from southern Sweden and southern Norway, and with land-use history as inferred from the pollen records and archaeology. Here, we compare the climate data with the fire histories at both Stavsåkra and Storås (Fig. 5A–C). As in Greisman and Gaillard (2009), we use the compilation of climate proxy records of Hammarlund et al. (2003), complemented here by the pollen-inferred temperature curve from Lake Flarken (Seppä et al., 2005) (Fig. 5A). The best climate data for the early Holocene in the region are the records of lake-level changes in southern Sweden (e.g. Digerfeldt, 1988; Gaillard and Digerfeldt, 1991). The climate characteristics inferred from changes in the oxygen isotope presented in Fig. 5A

are most reliable from ca. 7000 BC. The absence of any isotopic enrichment prior to ca. 7000 BC is tentatively explained by Hammarlund et al. (2003) as a consequence from the proximity of the study site to the Preboreal sea during early Holocene. The coastal setting probably decreased the regional groundwater gradient, which may have impeded any lake-level lowering and reduction of lake volume. By ca. 7000 BC, the influence of these environmental conditions on the hydrological balance of the lake had ceased.

The existence of a water-body at both Stavsåkra and Storasjö during the early Holocene, and its gradual in-filling during the period of fire activity described above may be the result from a climate change towards drier conditions from ca. 8700 BC. A time of generally dry climatic conditions ca. 9500–8500 BC (e.g. Digerfeldt, 1988; Gaillard and Digerfeldt, 1991) (Fig. 5A) concurs with a large number of climate proxy records from the Northern Hemisphere indicating that the warmest summer temperatures of the Holocene occurred at that time (e.g. Snowball et al., 2004). Drier climatic conditions around 9500–8500 BC in southern Sweden likely caused frequent fires in the region as a whole. There are finds of insect species dependant on fires at one level dated to ca. 8500–8600 BC at Storasjö, which indicates that there was a regional continuity of fires (Olsson and Lemdahl, in preparation).

The macroscopic CHARs at Storasjö suggest that fire episodes (including several individual fires) had a frequency of ca. 200 years from 7400 BC to ca. 6500 BC, and a somewhat lower frequency of 300–500 yrs (FRI = 377 yrs) between ca. 5500 and 2000 BC, with the lowest CHARs between 3500 and 2000 BC. Such fire intervals can be compared to 50–110 years intervals that were common in forests of northern Sweden during the last centuries (Zackrisson, 1977; Granström et al., 1995; Niklasson and Granström, 2000). Long fire intervals are usually characteristic of natural fires, while short fire intervals are often related to human-induced fires (e.g. Niklasson and Nilsson, 2005). We assume that the fire intervals found at Storasjö during the middle Holocene are characteristic of natural fires during that period. The middle Holocene is characterised by a relatively high amount of charred plant remains from *Pinus*, *Carex* spp., *Vaccinium oxycoccos*, and *Empetrum nigrum* indicating that fires influenced the local forest.

Nevertheless, there are a number of particular changes during the middle Holocene that needs to be further discussed. A period with relatively low fire activity around 6000 BC corresponds with a period of generally high lake levels in southern Sweden ca. 6850–5550 BC interpreted in terms of increased humidity (e.g. Gaillard and Digerfeldt, 1991; Harrison and Digerfeldt, 1993). It is tempting to compare the low values in macroscopic and microscopic charcoals at both sites ca. 6300–6000 BC with the widely recognized “8200 BP cool event” (ca. 6200 BC) identified in the Greenland ice cores (e.g. Alley et al., 1993). This event is particularly well registered in the pollen and charcoal record of Stavsåkra (Greisman and Gaillard, 2009).

The high level of fire activity at both sites ca. 5500 and 5000 BC corresponds to dry climatic conditions in the region (Hammarlund et al., 2003). A marked decrease to very low charcoal-inferred fire activity at ca. 4700 BC at Stavsåkra was compared to a short period of lower values in $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ at Lake Igelsjön (Hammarlund et al., 2003), and ascribed to a brief period of increased precipitation and lowered summer temperature (Greisman and Gaillard, 2009). There is also a period of lower fire activity between 5000 and 4500 BC at Storasjö, but it belongs to a series of time intervals with low fire activity starting before 5000 BP and continuing until 2000 BC. Therefore, correlation between low fire activity and short episodes of climate cooling should be further tested.

Hammarlund et al. (2003) proposed that a rise in groundwater due to an increase in precipitation occurred relatively rapidly, within a few 100 years, shortly after 2050 BC, and argued that a critical climatic threshold for the Northern Hemisphere was passed around 2000 BC. The abrupt decrease in fire activity after 2000 BC at Storasjö, and the low activity until ca. 500 BC might be a result of that rapid change towards significantly more humid and cooler conditions. Jessen et al.

(2005) described an unstable period already from 2600 BC spanning until 1450 BC, with temperature decreases and an increase in precipitation. Temperatures may have decreased (Seppä et al., 2005) and humidity increased (Digerfeldt, 1988; Gaillard and Digerfeldt 1991) even earlier, from ca. 4000 BC (Fig. 5A), which might explain the lower values of microscopic and macroscopic charcoals at Storasjö from that time, and the distinct period of very low fire activity at Stavsåkra ca. 4000 to 2000 BC (Fig. 5B and 5C).

Human activity appears to have had a significant impact on the regional landscape from ca. 2000 BC as indicated by the concentrations of dated clearance cairns (Fig. 4) in the areas of Växjö and Hamneda south of Stavsåkra (Fig. 1) (Skoglund, 2005; 2007; Lagerås, 2000). From that time onwards, human impact may have played a major role in the fire history of the region, and disentangling the effect of climate from that of human activities becomes problematic. For the last 2000 years, the temperature curve for the Northern Hemisphere established by Moberg et al. (2005) show two major climatic changes, the “Medieval Warm Period” with higher temperatures during the interval AD 1000–1200, and the “Little Ice Age” from ca. AD 1300 with the lowest temperatures of the last 2000 years ca. AD 1500–1700. These climate changes cannot be correlated to any contemporary changes in the fire records from the two study sites. From ca. 900 BC at Stavsåkra and ca. 600 BC at Storasjö, the role of human activities may override an eventual effect of climate change on fire activity at the sites.

The pollen records and archaeological data suggest that the forests at Stavsåkra were cleared from ca. 2000 BC. Wood was needed for building purposes, and open areas for more intensive grazing during Late Neolithic and Early Bronze Age (Skoglund, 2005; 2007). Grazing and the use of fire favoured *Calluna* at both sites from 750 BC at Stavsåkra, and 600 BC at Storasjö. Open *Calluna* heaths expanded at Stavsåkra particularly AD 250–750 and in the 18th–19th centuries (Greisman, 2009; Greisman et al., submitted for publication). The expansion of *Calluna* heaths AD 250–750 (Early Iron Age) can be compared with the high numbers of dated clearance cairns at Hamneda, indicating that land-use might have been particularly intensive in central Småland during that period. At Storasjö, the forests of pine were probably used for grazing by cattle and burned regularly to improve the quality of the fodder from at least AD 1100, as has been demonstrated by Wäglind (2004) for the time period AD 1400–1800. *Pinus* was the major tree burning in AD 25–280, while Ericaceae cf. *Vaccinium/Empetrum*, and *V. oxycoccos* dominate the macroscopic charcoal record during the 14th to 17th centuries. The latter may indicate a change in the human-induced fire regime sometime between AD 280 and 1350, most probably in early Medieval time, ca. AD 1000. Wäglind (2004) identified very high fire frequencies from between AD 1407 and 1793. The average time interval between fires was 22 years. Fire intervals of ca. 20 years have been found in several similar studies in southern Sweden (Niklasson and Drakenberg, 2001). In the heath areas of southwestern Sweden, the fire frequency is higher, with ca. one fire per 10 years (Granström et al., 1995; Arnell et al., 2002). The detailed tree-ring dating at Storasjö also showed that most fires (80%) during the 17th and 18th centuries took place in early summer, i.e. before the period of growth (dormant season, i.e. before mid-June) (Wäglind, 2004). Moreover, the individual fires were shown to be spatially small. These characteristics were interpreted as indicating anthropogenic, intentional fires to improve the quality of the grazing land. Natural fires would occur less frequently, later in the season (mid-June–August) (Granström, 1993), and cover larger areas (Niklasson and Granström, 2000). The last fire dated by dendrochronology in the Storasjö area occurred AD 1793 and seems to mark the end of a period with high fire frequency (Wäglind, 2004). The sudden change from very frequent fires to complete absence of fires in the 18th–19th centuries is a consequent trend found in Sweden (Zackrisson, 1977; Niklasson and Granström, 2000; Niklasson and Drakenberg, 2001; Niklasson, 2002; Lindbladh et al., 2003).

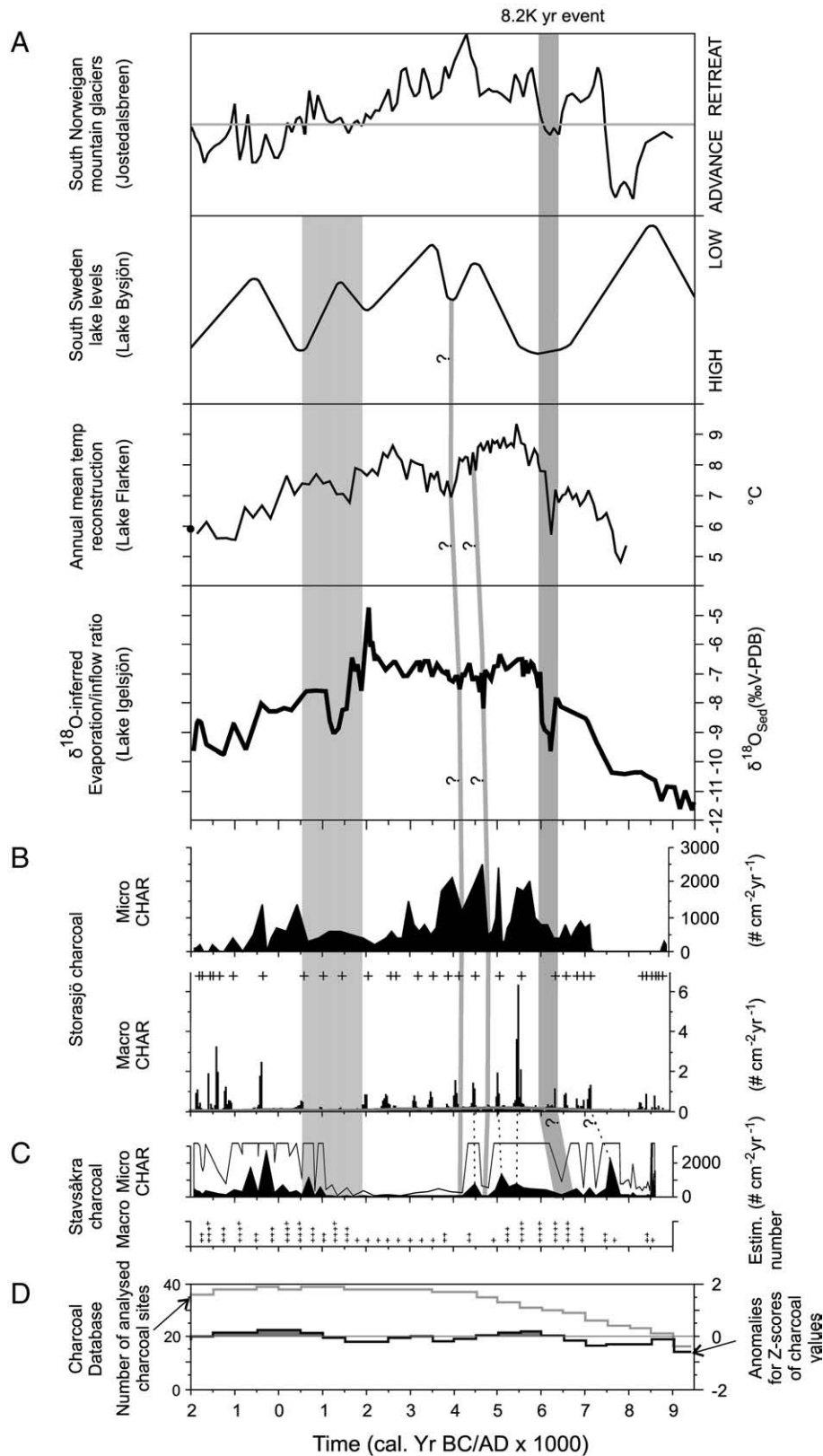


Fig. 5. Comparison between climate proxies from southern Scandinavia (A) with the charcoal records (accumulation rates, CHAR) at Storasjö (B) and Stavsåkra (C). For scales see caption of Fig. 4. $\delta^{18}\text{O}$ -inferred evaporation/inflow ratio, lake-level changes (Digerfeldt, 1988) and mountain glaciers fluctuations (Nesje et al., 2001) are presented as in Hammarlund et al. (2003), with the addition of the pollen-based annual temperature reconstruction from Seppä et al. (2005). The tentative correlations between the charcoal records from Storasjö and Stavsåkra are shown with dashed lines, and between the charcoal records and the climate proxies by grey bands.

The recent fire history described by Wäglind (2004) is visible in the charcoal record from the peat bog. It is represented by a series of more or less high values of macroscopic charcoal and fire identified CHAR peaks from ca. AD 1400 to recent times (Fig. 3). According to Wäglind's study, fire events occurred on average once every 22 years which implies that each of the five CHAR peaks represent more than one fire. We assume that the fire episode (macroscopic and microscopic charcoal) dated to ca. AD 1000–1250 may belong to a similar, human-induced fire regime. The human-induced fires of the Late Neolithic, Bronze Age and Iron Age seem to be less frequent than fires during the early Middle Ages.

6. Conclusions

Charcoal analyses at two small sites in the hemiboreal vegetation zone of Sweden show that the major signal of both microscopic and macroscopic charcoal records represents local fire history. However, the microscopic charcoal (fraction ≥ 10 – <160 μm in this study) probably also includes a significant signal from fires at a regional scale. The most economical and simplest record of local fire history was obtained from the macroscopic charcoal analysis performed using image analysis (Mooney and Radford, 2001; Mooney and Black, 2003). An attempt at correlating the charcoal records between the sites indicate that many fire episodes of the early and middle Holocene are probably of regional character. Both sites exhibit three major phases of high fire activity and more or less frequent fire episodes around 8500 BC, between ca. 7350 BC and ca. 4000 BC, and from ca. 750 BC. These phases are separated by longer periods with lower or very low fire activity. This general trend of fire history over the entire Holocene is in good agreement with the pattern emerging for Europe from the analysis of the recently developed global charcoal database (Power et al., 2008) (Fig. 5D). The latter shows higher fire activity than present 6000–5000 BC and 1000 BC–AD 500. Moreover an increase in fire activity is indicated during the intervals 9000–8500 BC, 7000–6000 BC, and 2000–500 BC.

The middle Holocene (ca. 5000 to 2000 BC) fire regime is characterised by long time intervals between fire episodes, while the early Holocene (8500–5500 BC) fire regime exhibits very irregular fire frequencies. The latter might be explained by the unstable character of the climate until ca. 5500 BC, followed by a period of comparatively more stable climatic conditions until 2000 BC (Hammarlund et al., 2003; Seppä et al., 2005) (Fig. 5). The more irregular character of the CHAR record from ca. 2000 BC is tentatively interpreted as a consequence of human-induced fire from that time on, which is supported by the archaeological data from the study region and around our study sites (Skoglund, 2005, 2007; Lagerås, 2000).

These results demonstrate that fire was a very important disturbance factor in the past, and that it was controlled by climate during the early and middle Holocene, and primarily by human activities until recently (19th century). Warmer and drier climate during the early and middle Holocene appears to have resulted in periods characterised by frequent fires, which suggests that natural fire activity might increase in the hemiboreal vegetation zone of Sweden under global warming conditions. This study also shows that *Pinus sylvestris* was the major tree species that burned, followed by *Betula*, *Salix*, and *Quercus*. Therefore, areas characterised by natural or planted pine forests in the study area might be at larger risk than broad-leaved forests. However, one should not underestimate the potential vulnerability of broad-leaved forests on well-drained soils in cases where dead wood is abundant.

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