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Woody vegetation, fuel and fire track the melting of the Scandinavian ice-sheet before 9500 cal yr BP

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ABSTRACT

New studies indicate the presence of early Holocene ice-free areas far north in Scandinavia. Post-glacial fire and vegetation were investigated based on sedimentary charcoal and pollen from two small lakes in northern Sweden. Accumulation of organic sediment started around 10,900 and 9200 cal yr BP, showing that both lake valleys were ice-free extremely early given their northerly location. Fire events started after 9600 cal yr BP and became less common around the '8.2-ka event'. Woody vegetation provided fuel that contributed to fires. The first vegetation in our pollen record consisted of *Hippophae*, *Dryas*, grasses and sedges. Subsequently broadleaved trees (*Betula*, *Salix*) increased in abundance and later *Pinus*, *Alnus*, ferns and *Lycopodium* characterized the vegetation. Pollen from *Larix*, *Picea* and *Malus* were also found. The change in vegetation composition was synchronous with the decrease in lake-water pH in the region, indicating ecosystem-scale processes; this occurred during a period of net global and regional warming. The changes in fire frequency and vegetation appear independent of regional trends in precipitation. The reconstructed fire history and vegetation support the scenario of early ice-free areas far north in Scandinavia during early Holocene warming, creating favorable conditions for woody plants and wildfires.

Introduction

It is generally thought that fire cannot occur in periglacial areas, although fuel is present in the form of dwarf shrubs and small or prostrate trees at the southern limit of the tundra. Fires spread within shrubby-tundra (Landhäusser and Wein, 1993), but the fire cycle is extremely long (Payette et al., 1989). Future global warming is likely to support more fires in the tundra (Hu et al., 2010) and the northern boreal forests (Balzter et al., 2007; Girardin and Sauchin, 2008; Bergeron et al., 2010) with a great impact on climate and carbon cycling (Mack et al., 2011). There is evidence of fire in northern Alaska during the early post-glacial period, linked to the establishment of woody plants (Higuera et al., 2008). The drought and the presence of fuel are the key-factors triggering fires. Fuel quality is crucial for fires in cold boreal ecosystems (Hu et al., 2006) and their functional analogues (Blarquez and Carcaillet, 2010). There are various climate stressors in boreal regions: precipitation controls the spatial variability of fire occurrences (Girardin et al., 2009), whereas temperature has a great effect on the general trend (Girardin and Mudelsee, 2008). Precipitation and temperatures may control fire-season length (Wotton and Flannigan, 1993; Balzter et al., 2007) but in the past, this was also controlled by changes in solar insolation (Hély et al., 2010). Insolation was greatest between 14,000 and 8000 cal yr BP (Berger and Loutre, 1991), i.e. during the deglaciation period in northern Scandinavia. Hence, a drier early Holocene climate with higher insolation could have provided conditions that encouraged fire, if there was an established fuel source.

The classic view of northern Scandinavia is that the area was covered by ice until ca. 9000 cal yr BP (Denton and Hughes, 1981; Boulton et al., 1985). With postglacial warming, southern Sweden was partly ice-free 16,000 yr ago (Backéus, 1999). Plants started to migrate into the south of the peninsula from ca. 13,000 cal yr BP (Huntley and Birks, 1983; Paus, 1995; Berglund et al., 1996). The northern Scandinavia, including the mountains, would have been the last areas to become ice-free ca. 9000 cal yr BP (Lundqvist, 1994) despite the short '8200 cal yr BP event' (Alley and Agustsdottir, 2005; Ellison et al., 2006).

However, studies have reported evidence, based on pollen, macrofossil data and DNA, contradicting this view and indicating ice-free conditions before 11,000 cal yr BP far north in Scandinavia. In Norway, coastal areas had a sparse vegetation cover as far back as 20,000 cal yr BP (Alm, 1993) and tree macrofossils of *Betula* cf. *pubescens* have been found in samples from ca. 20,000 cal yr BP (Kullman, 2006) that is supported by DNA analyses (Parducci et al.,

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2012). The glacial ice sheet would have been multi-domed (Dahl et al., 1997), possibly with ice-free deserts in central Norway by 16,000 cal yr BP (Paus et al., 2006). In the mountains of central Sweden, *Betula* sp., *Pinus sylvestris* and *Picea abies* were present 16,800, 13,800 and 13,000 cal yr BP, respectively (Kullman, 2000, 2002, 2008). Farther north, trees were established ca. 9500 cal yr BP (Hörnberg et al., 2006; Barnekow et al., 2008; Oberg and Kullman, 2011).

Hence, during the postglacial period, there were complex spatial patterns of ice-free areas and plant occurrences in northern Scandinavia. A re-examination of some pollen occurrences, e.g. *Picea* and *Larix*, as suggested by Segerström and von Stedingk (2003) and Paus (2010), would, therefore, be valuable for taxa that were formerly considered to be present in the record as a result of long-distance transport from the south or the east (e.g. Hafsten, 1992; Berglund et al., 1996). Instead, we must consider whether such pollen came from small local populations. If this was the case, tree establishment in northern Scandinavia during the late glacial period probably occurred first at medium and high altitudes that became ice-free earlier than the surrounding lowlands (Kullman and Kjällgren, 2006). In this case, tree establishment would have kept pace with rapid shifts in climate. All this information highlights the importance of cryptic glacial refugia for species survival on *nunataks*, in periglacial areas, and for immigration patterns (Stewart and Lister, 2001; Bennett and Provan, 2008; Holderegger and Thiel-Egenter, 2009).

We hypothesize that ice-free areas during the early Holocene in northern Sweden were favorable for a postglacial woody vegetation, which could have promoted fires when the environment was sufficiently dry, notably triggered by orbital forcing (maximum insolation). We aimed to identify postglacial fire patterns and vegetation composition from sedimentary charcoal and pollen, respectively, from two small lakes situated in adjacent valleys in the northern Swedish mountains. The patterns of pollen occurrence were used to elucidate plant dynamics that could have supported the known fire history. Finally, the fire-vegetation history was analyzed in the light of regional ecological processes (lake pH) and climate features (precipitation, temperature, insolation).

Material and methods

Study sites

The two small lakes, Lake Raigejegge (66°09′17 N–18°12′31 E; size ca. 0.4 ha) and Lake Lattok (65°57′25 N–18°20′42 E; size ca. 1.1 ha) are situated in adjacent valleys 23 km apart in the Arjeplog area of northern Sweden (Fig. 1). The valleys are characterized by moraine deposits on the slopes or higher elevations and, scattered sand deposits at lower elevations. The valley bottoms are intersected by open mires, lake and forests. The lakes were chosen because of their small sizes and small catchment areas, and the sediments were assumed to include charcoal and pollen reflecting mainly local fire and vegetation history (Jacobson and Bradshaw, 1981; Sugita, 1994; Broström et al., 2005). They are also similar with respect to their maximum water depth (Zmax = 5.1 m), sediment thickness (ca. 1.5 m), aspect (south), and elevation (480 m asl on till, with sandy glacio-fluvial material dominating in the valley bottoms). For the period 1961–1990 in Arjeplog, the mean annual temperature was −0.5°C, mean temperatures in January and July were −13.9°C and 13.0°C, respectively, and mean annual precipitation was 554 mm (Anonymous, 2000). In both valleys, the present-day vegetation is dominated by pine (*P. sylvestris*) with scattered spruce (*P. abies*), white birch (*B. pubescens*), aspen poplar (*Populus tremula*), and goat willow (*Salix caprea*). The understorey

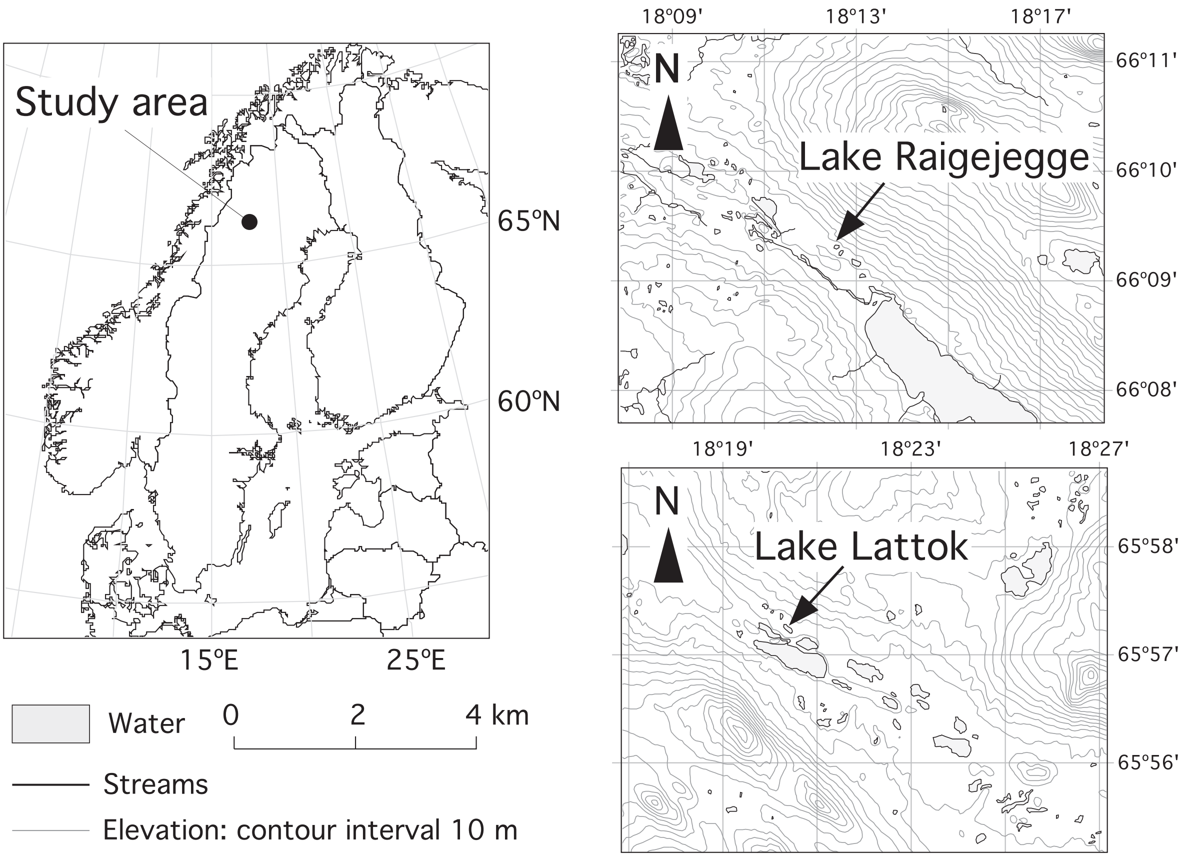

Figure 1. Map of Sweden with the study area marked; the samples were collected from Lake Raigejegge (top) and Lake Lattok (bottom).

consists of dwarf shrubs (*Calluna vulgaris*, *Vaccinium myrtillus*, *Vaccinium uliginosum*, *Vaccinium vitis-idaea*).

Along the Ipmatis valley containing Lake Raigejegge, abundant archeological evidences of Mesolithic settlements (oldest available date: 9890–9835 cal yr BP) have been found (Bergman et al., 2003; Olofsson, 2003; Bergman et al., 2004; Bergman and Zackrisson, 2007), but these peoples did not use fire as a tool to open up vegetation (Hörnberg et al., 2006) and the occasional anthropogenic fires did not affect the regional fire pattern (Carcaillet et al., 2007). Mesolithic finds are totally lacking in the valley containing Lake Lattok (I. Bergman, pers. obs.).

The area of Arjeplog is hilly, situated at several tens of kilometers from the tall Scandes mountains. However, some hills in the Arjeplog surroundings are tall enough depicting treeless vegetation >700 m asl near their summits (e.g. the Galtispuouda mountain at ca. 12 and 25 km from the Lakes Raigejegge and Lattok, respectively). But the modern upper treeline in generally continuous in the Scandes mountain situated at about 70–80 km west-northwest from the study sites.

Core sampling and dating

The sampling took place during winter making use of the lakes' ice cover. All sediment cores were collected using a Russian corer (Jowsey, 1966; ø = 4 cm, length = 50 cm). All cores were taken from the deepest part of both lakes. Two parallel cores from the bottom 50 cm of sediment were collected from each lake. In this study, we expected that these bottom 50 cm samples would effectively cover the postglacial period. Because the lakes are situated rather close to each other (23 km apart) and at the same elevation (480 m asl), it seemed likely that they became free of the Weichselian ice sheet at approximately the same time.

The cores were correlated according to depth measurements; in Lake Raigejegge both cores included the glacial clay at the bottom. However, in Lake Lattok only the core intended for pollen analysis included the glacial clay; 2 cm of sediment was lacking from the core intended for charcoal analysis. Although the complete core sequences were analyzed for charcoal (Carcaillet et al., 2007), only results covering the first few centimeters above the glacial clay from both lakes are discussed in the present study, which focuses on the early postglacial millennia. For the pollen analysis, the first 30 cm of sediment above the glacial clay was used from both lakes. This sampling design was based on results from a previous study in the area (Hörnberg et al., 2006) that allowed us to focus on the pioneer vegetation.

The cores from each lake were cut in half lengthwise. From the first half, samples for AMS radiocarbon dating were extracted from: the transition between organic sediment and glacial clay at 150 cm; the highest level analyzed for pollen at 120 cm; and, between these, at levels where marked changes in the pollen percentages were recorded. Five and four levels were extracted for radiocarbon dating from the Lake Raigejegge and Lake Lattok cores, respectively. Only terrestrial macrofossils were dated, and the samples were processed by AMS at the Ångström laboratory (Uppsala, Sweden). The ^{14}C measurements were calibrated against dendrochronological years using the CALIB program (Stuiver and Reimer, 1993) and reported as the intercept with a 2σ range (details in Carcaillet et al., 2007).

Charcoal analysis and fire reconstruction

One cubic centimeter every 0.5 cm was sampled. The procedure for measuring charcoal abundance was that described by Carcaillet et al. (2001). Briefly, the samples were first soaked in NaP_2O_4 solution (3%) for a minimum of 2 days, then sieved through a tissue-mesh (160 μm). The remaining particles were bleached in a 10% water solution of sodium hypochlorite (NaOCl) to distinguish charcoal from dark organic matter. The area of each charcoal fragment was estimated microscopically (×40). Charcoal measurements are reported as charcoal area concentration ($mm^2\ cm^{-3}$). The age–depth model determined from radiocarbon dating was applied to the charcoal series to estimate the charcoal accumulation rate (CHAR; $mm^2\ cm^{-2}\ yr^{-1}$), from which the fire history was inferred.

The fire reconstruction approach was described by Carcaillet et al. (2007) and the method is summarized here. The initial series were transformed into series with a constant time resolution (20 yr). The sieved-charcoal series were derived from data relating to particles that accumulated during fire years (charcoal peaks) and those that accumulated during non-fire years due to re-deposition within the lake catchments or basins. The process employed to estimate fire events through the sedimentary sequence was, thus, based on the decomposition of the charcoal series (Clark and Royall, 1996; Carcaillet et al., 2001). A threshold was applied to the residual peaks to isolate those that were most likely to correspond to the accumulation of charcoal during fire years. All calculations were carried out using the CHARSTER software (Gavin et al., 2006).

Pollen analysis

In the cores used for pollen analysis, the bottom 30 cm of sediment above the glacial clay was sampled. A 1 cm^3 sample of sediment was excised every 0.5 cm and prepared by acetolysis, using a standard method (without HF treatment) as described by Moore et al. (1991). The samples were stained with safranine and mounted in glycerine on microscope slides. Pollen was counted at a magnification of ×400 except for critical examinations when a magnification of ×1000 was used. A minimum of 500 terrestrial pollen grains were counted at each level and percentages were calculated based on the total terrestrial pollen sum. The key by Moore et al. (1991) was used for pollen identification together with a reference pollen collection from the Department of Forest Ecology and Management (Swedish University of Agricultural Sciences, Umeå).

Results

The gyttja accumulation started in Lake Lattok around 11,000 cal yr BP. At Raigejegge, the organic sediments started to accumulate by 9300 cal yr BP.

Charcoal and fire history

The mean time resolution was of similar order of magnitude in the lakes: 29 and 34 yr sample^{-1} in Lake Lattok and Lake Raigejegge, respectively. The charcoal series show values ranging from 0.000 to 0.044 $mm^2\ cm^{-2}\ yr^{-1}$ for Lake Lattok and from 0.000 to 0.032 $mm^2\ cm^{-2}\ yr^{-1}$ for Lake Raigejegge (Fig. 2). The patterns exhibited by the charcoal series are similar, showing several peaks and background values that are lower than 0.01 $mm^2\ cm^{-2}\ yr^{-1}$ in both lakes (Fig. 2). The fire reconstruction indicates that there was an initial period without fires lasting ca. 500 yr at Lattok and ca. 40 yr at Raigejegge from the onset of gyttja sedimentation. The first charcoal influx peak, which clearly marks the first fire near Lake Lattok, is identified in the record at 9660 cal yr BP, and at 8990 cal yr BP in Lake Raigejegge (Fig. 2). The reconstructed mean fire return interval (mFRI ± sd) was 272 ± 186 yr (SE = 48 yr, [60–640 yr], n = 13) in the Lake Lattok valley and 360 ± 359 yr (SE = 127 yr, [40–1040 yr], n = 7) in the Lake Raigejegge valley if the interval before the first fire was not included. This first interval in each series represents the fire-free interval since the onset of gyttja deposition. No marked differences were found between mFRI (Student-*t* test for unpaired data with unequal variance: $p = 0.30$; ddf = 7), suggesting that the sites had a similar mFRI history. Five fire dates are similar in the two records (max. δt = 90 yr) and might not represent different events given the uncertainties associated with the radiocarbon dating, the computation of the age model and the sampling resolution.

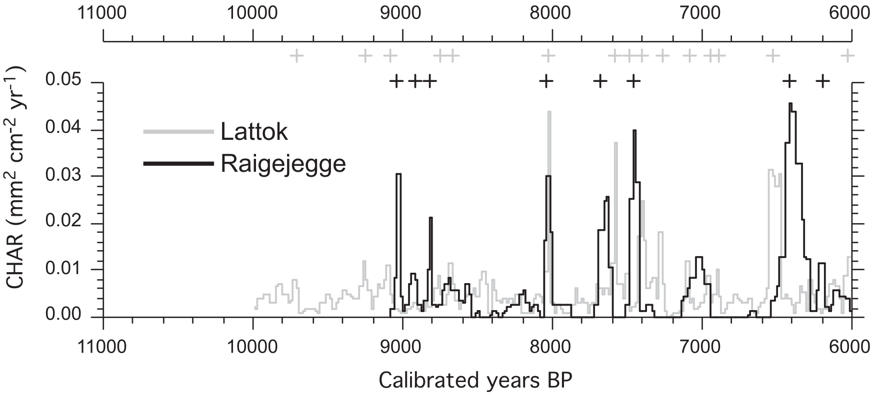

Figure 2. Charcoal influx series ($mm^2\ cm^{-2}\ yr^{-1}$) for Lake Lattok and Lake Raigejegge before 6000 cal yr BP. Crosses (+) indicate timing of the reconstructed fires.

All fires occurred after 9660 cal yr BP (Fig. 2) with periods of shorter fire intervals around 9250–8600 cal yr BP (Lattok and Raigejegge), and 7500–6900 cal yr BP (Lattok). It is possible that there may have been small-size or low-severity fires before 9710 cal yr BP at Lattok given that a background charcoal presence was observed in the sediments. However, the very low levels of charcoal ($<0.01\ mm^2\ cm^{-2}\ yr^{-1}$) prevent the reconstruction of fire events before 9660 cal yr BP. Interestingly, both sites experienced an isolated fire event at 8030–8040 cal yr BP during a long period without fires (Fig. 2), towards the end of the 8.2-ka climate event, which lasted about 400 yr (Alley et al., 1997).

Palynology and vegetation history

Both pollen diagrams are characterized by the same general vegetation composition and succession, although the accumulation of gyttja started considerably earlier in Lake Lattok (Figs. 3a, b). Both diagrams cover ca. 2000 yr but the Lake Lattok diagram covers the period between 10,900 and 8700 cal yr BP and, the Lake Raigejegge diagram the period between 9300 and 7400 cal yr BP (Fig. 2). Because the focus of this study is the fire-vegetation history and because of the very little pollen variation, the diagrams have not been divided into pollen assemblage zones.

Lake Lattok, vegetation dynamics, ca. 10,900–8700 cal yr BP

In the record, the arboreal pollen (AP) is initially dominated by *Betula* (Fig. 3a). Subsequently, the percentages of *Pinus*, *Alnus* and *Ulmus* pollen increase, and scattered occurrences of *Populus* are recorded. Two occurrences of pollen from cf. *Malus* (at least Maloidea pollen) and *Larix*, and one from *Picea* are also recorded.

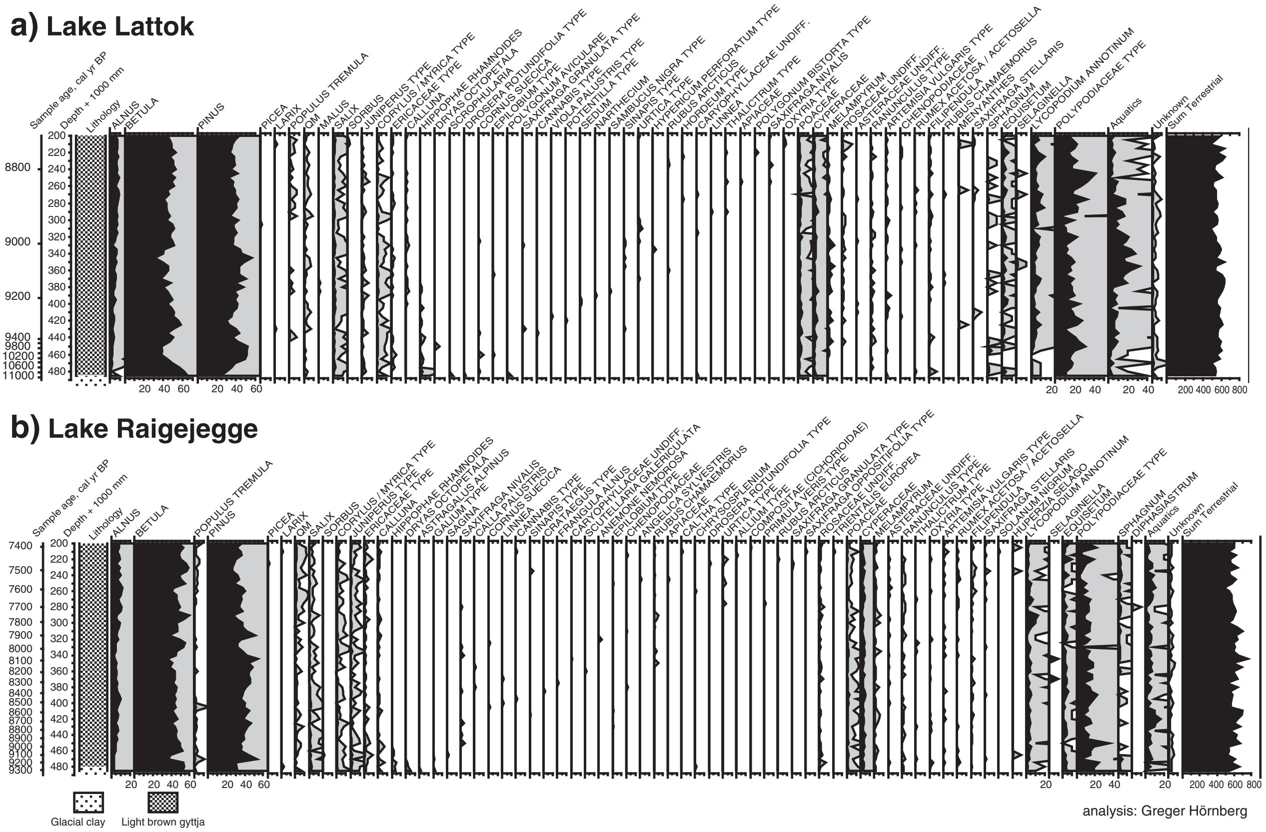

Figure 3. Pollen percentage diagrams from Lake Lattok (a) and Lake Raigejegge (b). From the left: calibrated ^{14}C ages (cal yr BP), lithology, and pollen and spores presented as percentages (black fields) and per mil (grey fields, exaggeration).

Among the non-arboreal pollen (NAP), from shrubs and dwarf-shrubs, *Hippophae* is recorded initially but not higher in the profile, while *Salix* and *Myrica*/*Corylus*-type are present throughout. Pollen of *Juniperus* and, Ericaceae including *Calluna* are observed within several levels. Among herbaceous taxa, pollen of, among others, *Scrophularia*, *Drosera*, *Polygonum aviculare* and *Dryas* are recorded at the bottom of the profile. Subsequently, pollen from other herbs like *Sinapis*, *Epilobium* and *Urtica* occurs, and closer to the top of the profile pollen from a large *Hordeum*-type grass and *Thalictrum* are recorded. The *Hordeum*-type includes many problematic wild grasses, not only the cultivated *Hordeum* (Moore et al., 1991; Joly et al., 2007). Poaceae, and Cyperaceae are recorded continuously, and *Melampyrum*, *Ranunculus*, *Artemisia*, Rosaceae and *Filipendula* occur at many levels. Pollen from aquatic plants also occurs continuously, with a slight increase after ca. 9100 cal yr BP. Of the spores present, Polypodiaceae are recorded at similar percentages at all levels, and spores from *Lycopodium* and *Equisetum* are observed at most levels.

Lake Raigejegge, vegetation dynamics, ca. 9200–7400 cal yr BP

Betula and *Pinus* pollen co-dominate the AP sum, and the *Alnus* percentages remain constant over the 1800-yr-long sequence (Fig. 3b). *Populus* is observed at low percentages with an increase after ca. 7700 cal yr BP. A few scattered pollen grains of *Larix* and *Picea* are also found. Among NAP taxa, *Hippophae*, *Dryas*, *Sagina* and *Astragalus alpinus* occur initially but they soon disappear. Subsequently pollen from *Saxifraga nivalis*, *Linnea*, *Epilobium* and Chenopodiaceae are recorded, and at the top of the profile *Urtica* occurs. Poaceae and Cyperaceae are recorded continuously, and *Salix*, *Myrica*/*Corylus*, *Juniperus*, *Calluna*, Ericaceae, Asteraceae, *Artemisia*, *Filipendula*, *Melampyrum*, *Ranunculus* and Rosaceae are observed at most levels. Spores from Polypodiaceae are recorded at all levels. Spores of *Lycopodium* and *Equisetum* and pollen from aquatic plants occur continuously.

Discussion

Pollen and charcoal records indicate that woody vegetation invaded the area immediately after the ice disappeared and, reveal that fires began to occur soon after. The speed of woodland establishment underlines the fact that trees were already present in the Ipmatis valley or surroundings during the period of deglaciation, and that the postglacial succession that began ca. 10,800 cal yr BP did not involve a pure tundra phase, a process already observed in other boreal regions (Lundqvist, 1969; Richard, 1980; Genries et al., 2012). At most, the first decades and centuries were characterized by open plant assemblages. In the following paragraphs we discuss the relationship between vegetation and fire, then we address the climatic and ecological framework of this post-glacial history.

Pattern of fire history

The first fire event is indicated ca. 9710 cal yr BP around Lake Lattok (Fig. 2). However, the main period for fires occurred between 9250 and 8600 cal yr BP, when six fires cumulated at both lakes resulted in a relatively short FRI with mean values <200 yr (Fig. 2). Subsequently the FRI increased to intervals >200 yr in both valleys during the period 8600–7500 cal yr BP, and decreased again between 7500 and 6900 cal yr BP in the Lattok valley only. The pattern of fire return intervals was not markedly different in the valley of Lake Raigejegge and the valley of Lake Lattok. Furthermore, the dates of events are very similar for five fires ($30<\delta t<90$ yr). The Lake Lattok series appears a little delayed compared to the Lake Raigejegge series (Fig. 2), but a small shift in the age–depth model or the uncertainty with the ^{14}C measurements and the sampling of sediment could easily account for this apparent delay. The two histories probably record synchronous fires. This observed resemblance of fire history (five fires) during the postglacial in the two lakes situated 23 km apart suggests that some fires spread over very large areas, amounting to several tens to hundreds of square kilometers or that different fires spread between the two valleys during very close years characterized by similar fire-climate. Fuel (vegetation) and climate are the most likely factors affecting this pattern of fire history.

Fire and vegetation development

Vegetation composition and dynamics in the two valleys, inferred from the pollen data, were very similar (Figs. 3a, b), and followed the same general succession as found by Hörnberg et al. (2006): initially *Betula*, *Salix*, *Hippophae*, grasses and sedges characterized vegetation together with a scattering of different alpine herbs. Here, it seems that the presence of *Hippophae* together with other nitrogen fixing species – such as free-living cyanobacteria and possibly the feathermoss–cyanobacteria complex (DeLuca et al., 2002) – were vital for the initial nutrient build up in the humus that, in turn, facilitated the establishment of non nitrogen-fixing plants. The slow build up of nitrogen in the humus by nitrogen fixation during the postglacial is important and may partly explain the time lag in tree establishment discussed by e.g. Paus (1995, 2010). Nitrogen fixation by bacteria results in natural soil acidification because of the release of H$^+$. Interestingly, reconstructions undertaken by Bigler et al. (2003) have suggested acidification of lake waters during this same early Holocene period of *Hippophae* abundance, with a rapid kinetic during the first decades (Fig. 4b). This acidification could have been caused by the pioneer vegetation that included *Hippophae*. A denser tree canopy subsequently replaced the initial open vegetation and other herb species became common in the field layer, a primary succession that is clearly similar in the two valleys. Surprisingly, this acidification of lake water in the region occurred during a period with a very short FRI (Fig. 4d), which should contribute to sustaining high pH values by releasing cations. However, we also know that the charcoal produced by fire facilitates the nitrification (DeLuca et al., 2006) that is a source of H$^+$. Nitrogen-fixing species and the nitrification facilitated by the presence of charcoal created by fires might explain the observed decrease in pH up to 8400 cal yr BP.

In Lake Lattok accumulation of organic sediment started earlier than in Lake Raigejegge. Around Lake Lattok the first woody vegetation was probably open *Betula* woodland with *Salix* and *Hippophae*, and a field layer characterized by ericaceous species, grasses, sedges, ferns, *Ranunculus* and *Dryas*. The pollen records indicate that the woody vegetation had already established in the area when the lake became deglaciated and started to accumulate organic material, i.e. before 10,900 cal yr BP. After 10,900 cal yr BP, *Betula* and *Pinus* were co-dominant and *Alnus* was also present. Herbs like *Sinapis*, Rosaceae, grasses, sedges, ferns and *Lycopodium* species characterized the field layer. Because enough fuel was present, the first fire occurred ca. 9700 cal yr BP. However, no pollen changes are recorded in association with this first fire, indicating that it was not severe enough to transform a vegetation dominated by resprouting species (*Betula*, *Salix*). There is no co-occurrence of fire-dependant taxa evident in the vegetation (i.e. *Epilobium*), or an increase in the abundance of herbs and birch that generally follow fires. However, the higher percentages of shrubs associated with fires between 9200 and 8900 cal yr BP suggest that fire acted on the vegetation to promote shrub growth (Fig. 4a). The presence of *Hippophae*, *Salix* and *Dryas* at least until ca. 9100 cal yr BP, indicates that the vegetation was fairly open, probably exhibiting rather low productivity and thereby resulting in a slow build up of fuel. This underlines the resilience of the initial vegetation to the first fires, and the fact that fire can sometimes alter the vegetation, but not significantly. This question of the vegetation stability in the face of fires and its effect on fire intervals has also been highlighted for eastern boreal Canadian forests (Carcaillet et al., 2010), as well as for subalpine

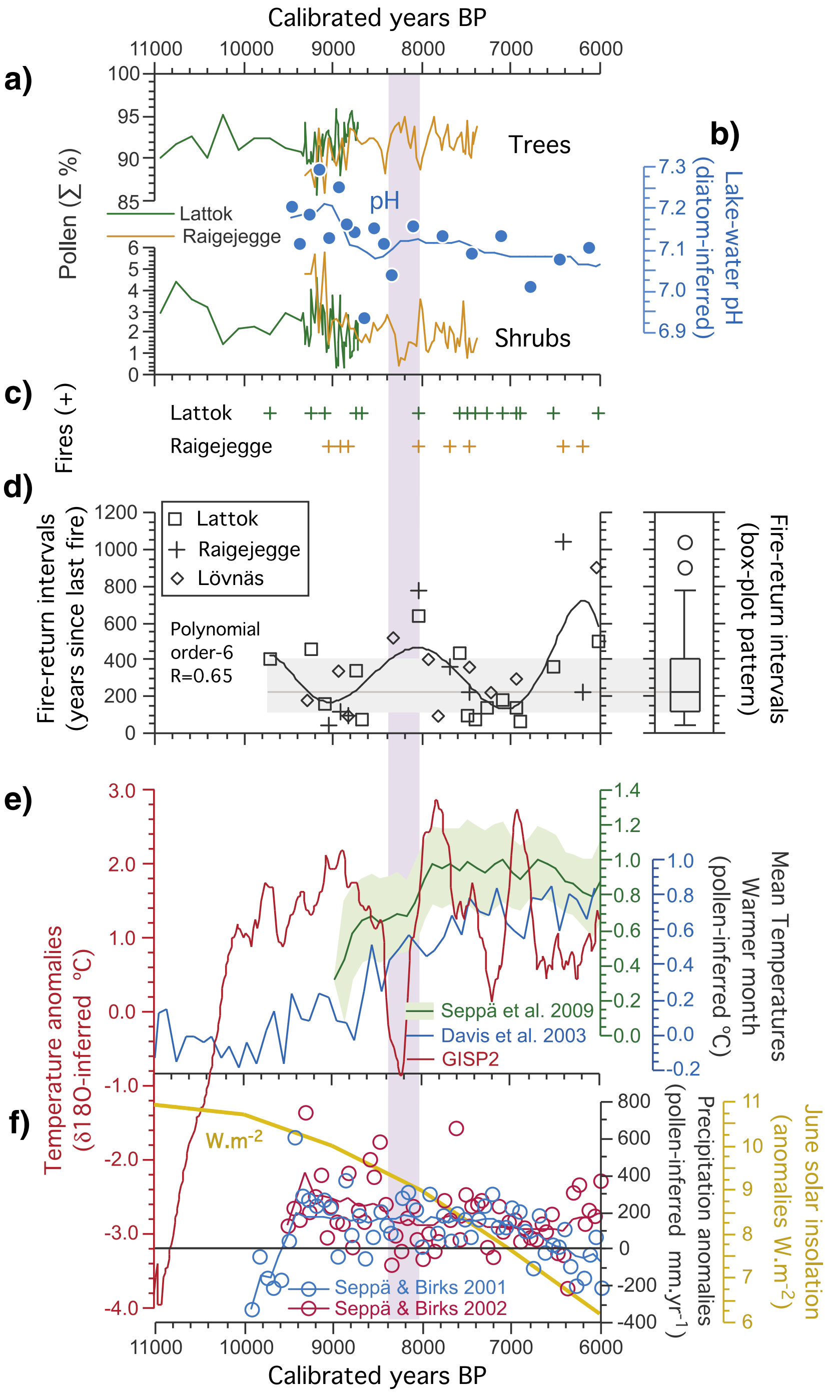

Figure 4. Synthesis of vegetation, fire, lake pH and climate history from 11,000 to 6000 cal yr BP in northern Scandinavia. (a) Sum of pollen percentages of trees (*Pinus*, *Betula*, *Populus*, *Picea*, *Larix*) and of shrubs (*Alnus*, *Salix*, *Hippophae*, Ericaceae) for Lake Lattok (green) and L. Raigejegge (orange). (b) pH inferred from diatoms (Bigler et al., 2003). (c) Reconstruction of fire events (+) at Lattok (green) and Raigejegge (orange). (d) Regional pattern of return fire intervals. The curve derived from a sixth-order polynomial, illustrates the fire return interval history. On the right: box-plot distribution of the cumulated fire intervals, showing the median (grey horizontal line), the 2nd and the 3rd quartiles, the two standard deviations (vertical bar) and the outlier values (open circles). (e,f) Climate changes in boundary conditions affecting northern Europe (all reconstructions are calculated as difference from today): insolation anomalies (W m^{-2}, 60°N, June values; Berger and Loutre, 1991), the northern-hemisphere temperature anomalies inferred from δ^{18}O (GISP2; Alley, 2000), temperature anomalies for the warmest month inferred from pollen for northeastern Europe (blue curve: Davis et al., 2003) and Scandinavia (green curve with 95% confidence interval: modified from Seppä et al., 2009); precipitation reconstruction for Scandinavia inferred from pollen (Seppä and Birks, 2001, 2002). The purple vertical line corresponds to the 8.2 ka event, clearly indicated by the GISP2 curve.
Panel d is modified from Carcaillet et al., 2007.

forests (Genries et al., 2009); vegetation appears to be resilient up to a particular threshold of fire (Blarquez and Carcaillet, 2010).

When organic sediment started to accumulate in Lake Raigejegge, open *Betula*–*Pinus* forests had already become established in the area, with *Alnus* probably present on wetter sites. *Salix*, *Myrica*, *Juniperus* and *Hippophae* dominated the shrub pollen and dwarf shrubs including ericaceous species, along with and *Dryas*, occurred in the field layer together with grasses, sedges and ferns. There was a temporary decrease in *Betula*, grasses, ferns and *Juniperus* ca. 9100 cal BP. The tree layer continued to be rather open but subsequently *Dryas* and *Hippophae* disappeared, and the forest floor vegetation was characterized by herbs, grasses and ferns. At ca. 8000 cal yr BP, changes in the vegetation were characterized by a rise in *Betula*, and a decrease in *Pinus*, *Salix*, grasses and ferns. This change occurred during the period when there were long intervals between fires in the region after the establishment of the vegetation (Fig. 4d). Indeed, the vegetation changed from 9000 to 8000 cal yr BP in tandem with the increase in fire interval. Interestingly this assumed single fire event is represented by a large-magnitude peak in both lakes (Fig. 2), suggesting that this fire was severe (Clark et al., 1996), i.e. the fire area was extremely large or the burn depth significant. After ca. 8000 cal yr BP, the amount of *Populus*, *Juniperus* and Ericaceae increased just after the co-occurrence of fires at both Lattok and Raigejegge, and grasses decreased indicating that the *Betula*–*Pinus* forest became denser.

Climate, fuel and fire

The period between 11,000 and 9000 cal yr BP was characterized by a global increase in annual temperature (Alley, 2000). In Scandinavia, the mean annual temperatures peaked between 8000 and 6000 cal yr BP with values around 0.7–1.2°C above those recorded today (Bigler et al., 2003; Seppä et al., 2009; Fig. 4e). The fire number increased during this warmer period and thus seems sensitive to summer temperatures, which reached their maximum between 8000 and 7000 cal yr BP. Surprisingly, this period was characterized by rather stable vegetation: little pollen fluctuation could be linked to fire events in the Raigejegge pollen record. This observation indicates that the early subarctic–boreal ecosystem was already adapted to fire. We cannot rule out the possibility that pollen assemblages represent more than the local vegetation (Broström et al., 2005), but the small size of the lake (0.4 ha) supports the contention that the pollen would be dominated by that from the surrounding stand and locality, and that this sensitivity of vegetation to disturbances is significant (Koff et al., 2000). A poor link between vegetation and fire would be the case especially if the first fires were low-intensity ground fires that did not kill trees and for which there was limited fuel. Indeed, it has been shown that low-intensity fires are poorly represented in sedimentary charcoal (Higuera et al., 2005), probably due to the restricted burn depth.

To summarize, fires and the woody vegetation expanded in northern Sweden as soon as the glacier retreated as a result of the warming climate. The summer solar insolation (Fig. 4f) was higher than today, thus favoring the spread of fire fed by the dry fuel within ecosystems containing enough pine, birch and shrubs. The fluctuation in the regional fire-return interval (Fig. 4d) appears to be linked neither to vegetation fluctuation (Fig. 4a) nor to reconstructed temperatures (Fig. 4e). Reconstructed annual precipitation levels (Fig. 4f) do not support a causal process that would have controlled the fire history. The two periods of short fire-return intervals (9200–8600 and 7500–6800 cal yr BP) occurred during the wetter early Holocene. The direct link between fire and long-term climate proxies remains difficult to assess, but may be mostly under the control of temperature. However, the mean FRI fluctuated more between 10,000 and 6000 cal yr BP than any reconstructed climate parameters (Seppä and Birks, 2001; Bigler et al., 2003; Larocque and Hall, 2004; Seppä et al., 2009), suggesting that long-term pluri-annual components are certainly less efficient than inter-annual variability in precipitation or temperature for explaining the fire history.

Interestingly, the 8200 cal yr BP period (the “8.2 ka event”) is well represented by the GISP2 reconstructed temperatures (Fig. 4e), which fell during a period of long fire-intervals lasting ~800 yr and that include the ~400 yr of the 8.2 ka event (Alley et al., 1997). At the end of the 8.2 ka event, fires occurred at both sites (Fig. 4d); this may have been the result of plant mortality producing fuel that allowed fires to spread. Indeed, tree pollen was less abundant at the end of the 8.2 ka event (8000 cal yr BP), and shrub pollen increased (Fig. 4a). Thus, the abrupt drop in North-Atlantic temperatures may have finally killed trees, promoting open woodlands containing dead plant material, eventually favoring fires when ignition occurred.

Surprising taxa

In both valleys there were some interesting pollen taxa; e.g. in the Lattok valley, two occurrences of cf. *Malus* and two of *Hordeum*-type pollen were recorded. The *Malus* occurrence probably originated from long-distance pollen dispersal or from a strictly local occurrence of wild apple. But it could also be an abnormal pollen grain of *Sorbus*. Although findings from Poland have indicated the use of *Malus* during the early Mesolithic (Bienek and Litynska-Zajac, 2001), it seems unlikely that wild-apple trees grew in the Lattok valley and no subfossil macro-remains have been recorded so far in the archeological dwellings from the region (Bergman et al., 2003; Olofsson, 2003; Bergman et al., 2004). The *Hordeum*-type pollen probably originated from a wild grass (O'Connell, 1987; Kalis et al., 2003), e.g. *Elymus* or some other large wild grass growing on sandy sediments. The same pollen type was also found previously further west in the Lake Raigejegge valley (Hörnberg et al., 2006). The occurrences of *Picea* pollen that have been interpreted in the past as long-distance transport may, however, represent local occurrences in both valleys. Because a large number of macrofossils from *Picea* have been convincingly dated, it is now accepted that *Picea* was present in small populations in the Scandinavian mountains during the early Holocene (Kullman, 2002; Oberg and Kullman, 2011). The same goes for *Larix* although few remains were discovered (Kullman, 1998; Oberg and Kullman, 2011). *Larix* disappeared from Scandinavia later during the Holocene (Kullman, 2008). Because pollen grains of *Larix* are dispersed very poorly (Simak, 1979), the presence of larch pollen should indicate a local population (Paus, 2010). However, more fossil evidences are needed to confirm the local occurrence of all unexpected taxa in the region of Arjeplog under the Arctic Circle. Indeed, the findings of Kullman and collaborators came from area up to 300 km further south.

Conclusions

Although northern Sweden is generally considered to have been entirely glaciated, a plant cover already existed between 11,000 and 9000 cal yr BP and this included woody species some of which were trees. Fires started to occur around 9700 cal yr BP. This process happened during a period of global and regional warming, with strong summer insolation that could have caused dead biomass to dry out and become suitable fuel. The climate drivers of fire remain obscure because mFRI fluctuated but not synchronously with temperature or precipitation. Boreal vegetation was already adapted to fires, although little of the fluctuation in shrub abundance seems linked to fires. The fire and the vegetation records co-vary, with lake-pH changes suggesting ecosystem processes at the scale of the catchment areas maybe trough the nitrogen fixation and nitrification process. Fuel build-up had a crucial impact on fire history during this periglacial period.

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