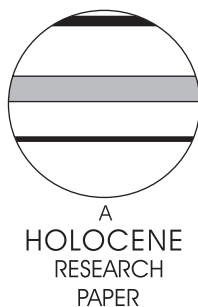


# The macroscopic charcoal record in forested boreal peatlands in southeast Norway

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**Abstract:** We present a spatial and quantitative analysis of the macroscopic charcoal record in 11 forested peat basins in a boreal forest landscape in southeast Norway. The areas of the basins ranged from 200 to 6400 m<sup>2</sup> and our study is based on 247 peat sequences that were sampled from randomly selected positions. In total we found 1228 charcoal layers in these peat sequences, which altogether had a length of 551 m. The number of charcoal layers per sequence ranged from 0 to 31 and the average number of charcoal layers per sequence was  $3.9 \pm 0.3$  SE, giving a mean fire frequency of one per 475 years. The average charcoal layer contained 170 charcoal particles > 0.28 mm per 10 cm<sup>2</sup>, of which 30 were > 1 mm. Peat sequences that totally lacked macroscopic charcoal were found at all sites. Nonetheless, all sites have burned recurrently during the Holocene, since at least one sequence from each site had seven or more charcoal layers. Neither the number of layers nor particle size decreased with increasing distance to the surrounding forests, indicating an *in situ* charcoal production and deposition. The charcoal record was characterized by a striking spatial variability. Geostatistical analyses revealed a strong spatial structuring on fine scales, i.e. c. 0.25–1.5 m, but there was no evidence for spatial structuring at between-site scales, demonstrating that the sites have idiosyncratic fire histories. The rate of charcoal deposition was greater for the period prior to establishment of *Picea abies* than for the post-establishment period.

**Key words:** Black carbon, charcoal layer, charred particles, fire frequency, forest fire, spruce forest, Norway, Holocene.

## Introduction

Recurring wildfires are important determinants of biodiversity and ecosystem processes in boreal forest landscapes (Bonan and Shugart, 1989; Zackrisson *et al.*, 1996; Amiro *et al.*, 2001) and much work has been devoted to documenting past fires in order to understand the disturbance dynamics and the history of boreal forests (eg, Zackrisson, 1977; Bradshaw *et al.*, 1997; Stocks *et al.*, 2004). Spatial patterns of past fires in a Holocene time-perspective are nonetheless rather poorly known. This lack of knowledge is attributable to three main reasons. First, stratigraphic records of microscopic charcoal particles, usually varying in size from 5 to 50 µm, which have been widely and successfully used to document temporal patterns in past fire events (Berglund, 1986), do not explain detailed spatial patterns because their

presence in a stratigraphy may originate from a nearby local fire source as well as from a distant, regional source (Tolonen, 1986; Clark, 1988). Second, tree-ring chronologies, which have the potential to resolve detailed spatial patterns of past fires (Niklasson and Granström, 2000), generally cover far too short timespans to be applicable to a Holocene time perspective. This is exemplified by the two 'supra-long' tree ring chronologies from northern Europe (Eronen *et al.*, 2002; Grudd *et al.* 2002), neither of which reveal past fire patterns. Third, stratigraphic records of macroscopic charcoal particles, which provide indisputable evidence for the occurrence of local fires (Whitlock and Millspaugh, 1996; Clark *et al.*, 1998; Gardner and Whitlock, 2001), have usually been based on the analysis of one single peat core sequence supposed to be representative for a given forest site (eg, Hörnberg *et al.*, 1995; Ohlson and Tryterud, 1999; Hellberg *et al.*, 2003). Such a single-sequence approach is, however, insufficient to reveal spatial patterns in past fires and reconstruct realistic long-term fire histories.

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The 'basin-based' approach of Pitkänen *et al.* (2001), by which macroscopic charcoal layers are surveyed at different points in small peat deposits surrounded by forests, has shown promising results for reconstruction of Holocene forest fire histories. By this approach, Pitkänen *et al.* (2002, 2003a) were able to reconstruct local fire histories covering the entire Holocene by the use of some few study points along short transects (3 to 8 m long) in small mire basins. So far, however, little is generally known about spatial variability in the macroscopic charcoal record. For example, it is not known to what extent, and on which spatial scales, the charcoal banding patterns could be expected to vary among core sequences sampled close to each other within a single site. However, recent results from experimental forest fires give strong evidence for a patchy and spatially highly variable deposition of charcoal particles  $\geq 0.5$  mm (Clark *et al.*, 1998; Ohlson and Tryterud, 2000). We therefore hypothesize that the patchy deposition of charcoal should be reflected in high spatial variability in the macroscopic charcoal record.

Presupposing a considerable spatial variability in the charcoal record, previous studies based upon analysis of a single core sequence per site are likely to have overestimated the occurrence of historically fire-free forest stands because lack of macroscopic charcoal in a single sequence can then not be confidently extrapolated to the surrounding area (see, eg, Hörnberg *et al.*, 1995; Ohlson *et al.*, 1997; Ohlson and Tryterud, 1999; Pitkänen *et al.*, 2003b). Because the presence of charcoal particles  $> 2$  mm can be used to distinguish between fire-prone and fire-free areas with high spatial precision (Ohlson and Tryterud, 2000), spatially precise patterns of past fires over millennial timespans might, however, be revealed with metre-scale precision by studying a large number of core sequences sampled to capture the variation within, as well as among, different sites.

In the present study, we have used a 'basin-based' approach to obtain a spatially precise and long-term fire history for an entire boreal forest landscape, covering most of the Holocene. This is accomplished by detailed analysis of the macroscopic charcoal record in no less than 247 peat sequences from 11 peat basins representing forests sites of different size and topographic positions. The studied forest landscape is dominated by Norway spruce (*Picea abies* (L.) Karst.). All study sites were swamp forests, which typically are species-rich islands in an otherwise rather species-poor boreal forest landscape (Hörnberg *et al.*, 1998). Interestingly, each of our study sites has been shown to have a plant species composition with a unique component, which could not be explained by present-day environmental conditions (Økland *et al.*, 2003). Økland *et al.* (2003) suggested that this uniqueness in species composition might be due to an individualistic accumulation of species in each swamp forest, which in turn may be due to forest-specific and unique fire disturbance histories.

The present study has four main aims: (1) to document on which spatial scales the Holocene macroscopic charcoal record varies within and among boreal forested peat basins; (2) to elucidate the potential of the macroscopic charcoal record as a source for reconstruction of realistic long-term forest fire histories; (3) to discuss methodological considerations of peat sequence sampling strategies and the interpretation of charcoal banding patterns; and (4) briefly to explore the relationship between establishment by Norway spruce and occurrence of forest fires by comparing pre- and postestablishment charcoal depositions in the peat basins.

## Materials and methods

### Study area and study sites

The study was carried out in SE Norway, within the Østmarka Nature Reserve (59°50' N, 11°02' E) located c. 20 km SE of Oslo. Østmarka is characterized by a rather broken landscape relief with relative heights of 50 to 150 m and there is a marked S–N direction of hills and valleys. Coniferous forests dominated by Norway spruce (*Picea abies* (L.) Karst.) or Scots pine (*Pinus sylvestris* L.) form a matrix in which small lakes, mires and swamp forests occur interspersed. The climate is slightly suboceanic with annual mean temperature and precipitation of c. 4°C and 800 mm, respectively. Based upon an initial survey of 57 spruce swamp forests in the central parts of the reserve, 11 were selected for this study to be representative for the variation in peat basin area (Table 1) and environmental conditions. Distances between selected sites ranged from 80 to 2340 m and Økland *et al.* (2001, 2003) give detailed information on patterns of variation in plant species composition and environmental conditions.

### Sampling of peat

A baseline was placed along the long axis of each peat basin. Transverse lines, three to eight per peat basin in proportion to the length of the baseline, were randomly placed along the baseline. In total, 52 transverse lines were used. Along the transverse lines, a total of 133 sampling point positions were placed randomly. In addition, 17 positions were selected by a stratified random sampling procedure to ensure representation in the material of spring horizons, inlets and outlets, which were assumed to represent variation along ecologically important gradients. Vegetation data collected from these sampling points have been analysed by Økland *et al.* (2001, 2003). In order to address more fine-scaled spatial patterns in the charcoal record, four complementary sampling points were located at fixed positions, 25 and 75 cm off every fifth basic sampling position, in opposite directions (Figure 1), giving a total of 270 sampling points. However, because of tree stumps or other physical obstacles in the peat, it was only possible to obtain complete peat sequences (from the peat surface down into the underlying mineral soil) at 247 points. A Russian peat corer (Jowsey, 1966) with a diameter of 50 mm was used to collect the complete peat sequences. The number of peat sequences sampled per peat basin ranged from 10 to 37 (Table 1). Sampling was performed in 1998. Every sampling point was geo-referenced with accuracy sufficient for calculated between-point distances to be within  $\pm 1\%$  off true distances.

### Analysis of the macroscopic charcoal record

Immediately after excavation each peat core was carefully searched for macroscopic charcoal layers, of which the vertical positions (depth below the surface) and layer-widths were recorded. The black charcoal contrasted well against the typically brown colour of the fresh, non-oxidized peat and all parts of the peat sequences assessed to contain charcoal were collected for further laboratory analysis. In the laboratory, a slice of the peat sequence (thickness c. 1 cm), with the charcoal layer in the centre, was boiled for 10–15 min in 10% NaOH solution to partially digest and bleach the organic material. The suspension was filtered through a net with a mesh size of 0.28 mm. Water was added and charcoal particles were searched for and identified under a stereomicroscope (see Hörnberg *et al.*, 1995). Of the 1305 charcoal layers collected in the field and analysed this way, 87 did not contain any charcoal. Slices of peat in which no charcoal was observed in

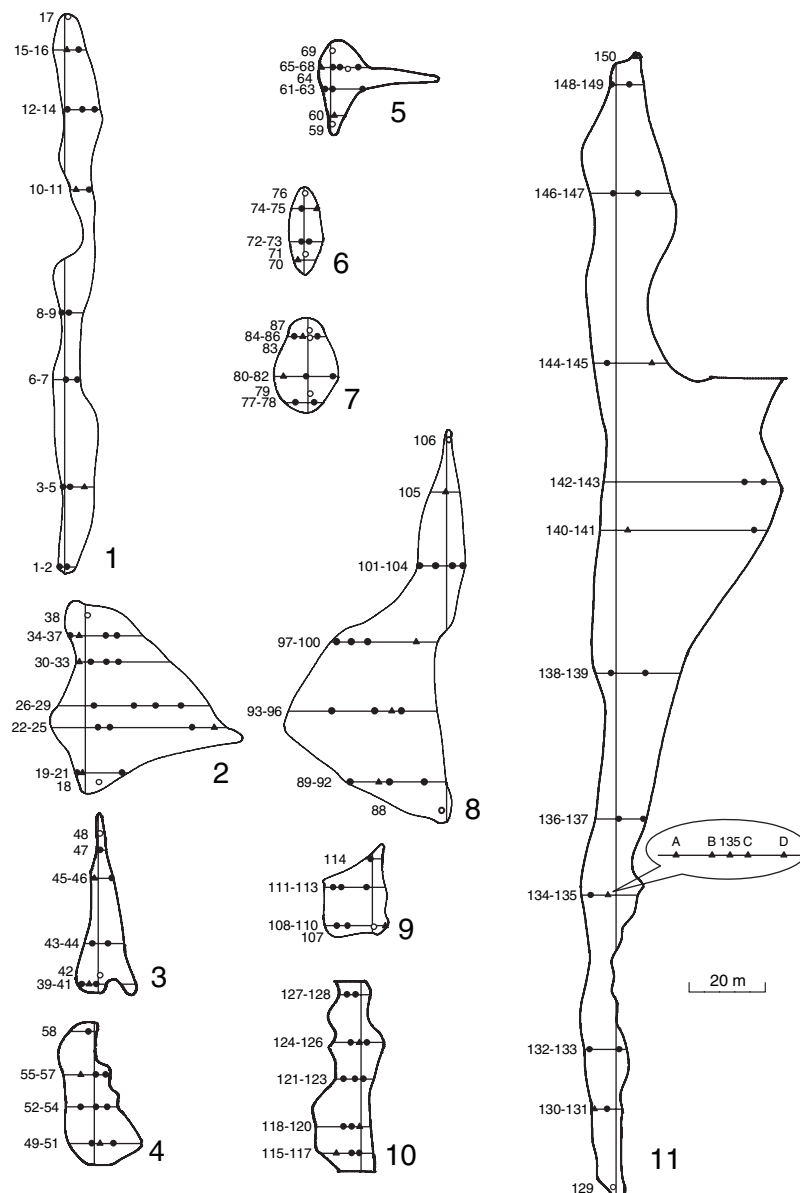
**Table 1** Peat basin characteristics and number of peat sequences sampled

Site	Altitude (m a.s.l.)	Area (ha)	Max peat depth (m)	Average peat depth (m)	<sup>14</sup> C age <sup>a</sup> (yr BP)	Lab. ref.	Number of peat sequences
1	245	1.2	3.7	2.3	8945 ± 175	T-13996	24
2	260	1.4	7.0	2.6	9100 ± 215	T-13997	37
3	265	0.4	0.7	0.6	2990 ± 110	T-13998	18
4	270	0.5	1.1	0.9	2980 ± 105	T-13999	17
5	235	0.4	1.1	0.7	2420 ± 115	T-14000	14
6	225	0.2	1.6	1.0	5040 ± 115	T-14001	13
7	235	0.3	1.8	1.3	6595 ± 105	T-14002	17
8	230	1.8	4.1	2.7	8920 ± 145	T-14003	34
9	255	0.3	0.7	0.6	3900 ± 100	T-14004	10
10	210	0.5	8.0	4.9	7990 ± 135	T-14005	26
11	230	6.4	6.4	2.8	7750 ± 135	T-14006	37

<sup>a</sup>Age refers to <sup>14</sup>C age of the deepest sediment in each basin, ie, an estimate of the onset of peat accumulation.

the field have also been analysed in the laboratory to check if macroscopic charcoal was overlooked. Meen (1998) found small amounts of macroscopic charcoal in only 4% of 657

slices (1 cm thick) that were assessed not to contain charcoal in the field. This confirms a reliable, although slightly conservative, identification of macroscopic charcoal in the field, since



**Figure 1** The studied peat basins and positions of sampling points for peat sequences. Randomly located basic sampling points along transverse lines (●); sampling points located by a stratified random procedure (○); complementary sampling points located at fixed positions, 25 and 75 cm off every fifth basic sampling position (▲). Note that the scale is different in the insert showing the complementary sampling points A, B, C and D at fixed positions off every fifth basic sampling point. See Materials and methods for further information

some very thin or sparse charcoal layers may have been overlooked.

All charcoal particles were sorted and counted in a gridded petri dish under a stereomicroscope. The particles were sorted into six size classes according to the length of their longest axis, ie, 0.28–0.5, 0.5–1, 1–2, 2–4, 4–8 and > 8 mm. A pilot study revealed that an acceptable accuracy of the size frequency distribution of charcoal could be achieved by counting a subset of grid squares. Charcoal particles  $\geq 0.5$  mm were therefore counted in 52 (fixed) of 140 squares, while particles in the smallest size class were counted in 5 of 140 squares. Charcoal particles > 4 mm were stored for radiocarbon dating and later use.

### Recording of explanatory variables

Two charcoal explanatory variables were recorded: (1) total number of charcoal layers in each peat core (range = 0–31; recorded for all 247 peat cores) and (2) depth from the peat surface to the uppermost charcoal layer (range = 7–330.5 cm; recorded for all 207 peat cores in which at least one charcoal layer was found). In addition, the following three environmental explanatory variables were recorded for all 150 vegetation sampling points: (1) distance to mineral soil (range = 0–16.3 m), the shortest horizontal distance from a sampling point to solid mineral ground (not covered with peat); (2) peat depth (range = 0–790 cm), the depth (length) of each peat sequence from peat surface to mineral soil; (3) median distance from the peat surface to the water table (range = 1.1–39.4 cm) in the growing season of 1998 (see Økland *et al.*, 2001). Two swamp-forest variables were calculated ( $n = 11$ ): Total area of each peat basin (range = 0.02–0.64 ha) and altitude above sea level (range = 210–270 m).

### Statistical analysis and spatial structure

Kendall's rank correlation coefficients  $\tau$  (Kendall, 1938) were calculated between selected pairs of explanatory variables, including swamp-forest means for the charcoal variables and swamp-forest variables, by use of SPSS/PC+, Version 8.0 (Norusis, 1997).

All charcoal and environmental explanatory variables had strongly right-skewed frequency distributions, indicating heteroscedasticity (Sokal and Rohlf, 1995). For analyses of spatial structure, homogeneity of variances (homoscedasticity) was achieved for each variable by finding the parameter  $c$  of the transformation formula  $\ln(x+c)$  that resulted in a transformed variable with zero skewness. Transformed variables were expressed on a 0–1 scale prior to analyses (Økland *et al.*, 2001, 2003).

The spatial structure of charcoal variables (and, for comparison, selected environmental explanatory variables) was evaluated from standardized empirical semi-variograms (Palmer, 1988; Rossi *et al.*, 1992), obtained by R software (Anonymous, 2005) Version 2.1.0, library geoR Version 1.5–6 (Ribeiro and Diggle, 2005). The range of distances between observation points was divided into 14 lag classes ( $f$ ) for charcoal and 10 for environmental explanatory variables, each class with geometrical midpoint  $2^{f-3.5}$  and upper limit  $2^{f-3}$  m (0.25, 0.5, ..., 2048 m):

$$\gamma(f) = 0.5 \times N_f^{-1} \times \left[ \sum_{\text{all } j, 1: 2^{f-4} < d_{j,1} \leq 2^{f-3}} (x_j - x_1)^2 \right] / \text{var } X \quad (1)$$

where  $N_f$  is the number of observation pairs in the lag class  $f$ ,  $d_{j,1}$  is the distance between pairs of observations  $j$  and 1 with observed values  $x_j$  and  $x_1$ , respectively, for the variable in question, and 0.5 is a scaling factor that adjusts the estimated semi-variance to the same scale as the sample variance ( $\text{var } X$  is

the sample variance of the variable). Envelopes for each standardized semi-variance value were obtained by permutation using the `variog.mc.env` function of `geoR` by which data values were randomly allocated to spatial locations  $n = 999$  times and new variograms calculated on each permutation. The envelopes represent for each lag the minimum and maximum of the semi-variance values for the simulated data. Because no absolute criterion exists for assessment of the strength and range (ie, upper limit of spatial structuring; cf. Palmer, 1988) of spatially dependent variation, inference about spatial structure, notably the existence of a range, was based upon inspection of the variation of  $\gamma$  (see Økland *et al.*, 2001).

### $^{14}\text{C}$ dating and estimation of fire frequency and fire rotation period

Conventional radiocarbon dating of the deepest peat in each site was performed at the Radiological Dating Laboratory at The Norwegian University of Science and Technology to determine the start of peat accumulation. In addition, eight selected individual charcoal particles representing seven peat sequences from site 2 were accelerator dated (AMS) at the Ångström Laboratory in Uppsala. All dates are presented as  $^{14}\text{C}$  age (yr BP).

Two different approaches were used to provide rough estimates of fire frequency. (1) For site 2, the age of a selected charcoal particle was divided by the number of charcoal layer positioned above the vertical position of the dated particle in a given peat sequence. (2) The  $^{14}\text{C}$  age of the deepest peat at each site was divided by the maximum number of charcoal layers in peat sequences from this site. Both approaches provide conservative estimates because subsequent fires may have consumed charcoal layers and/or some layers may have been lost by decomposition of peat (Pitkänen *et al.*, 2002).

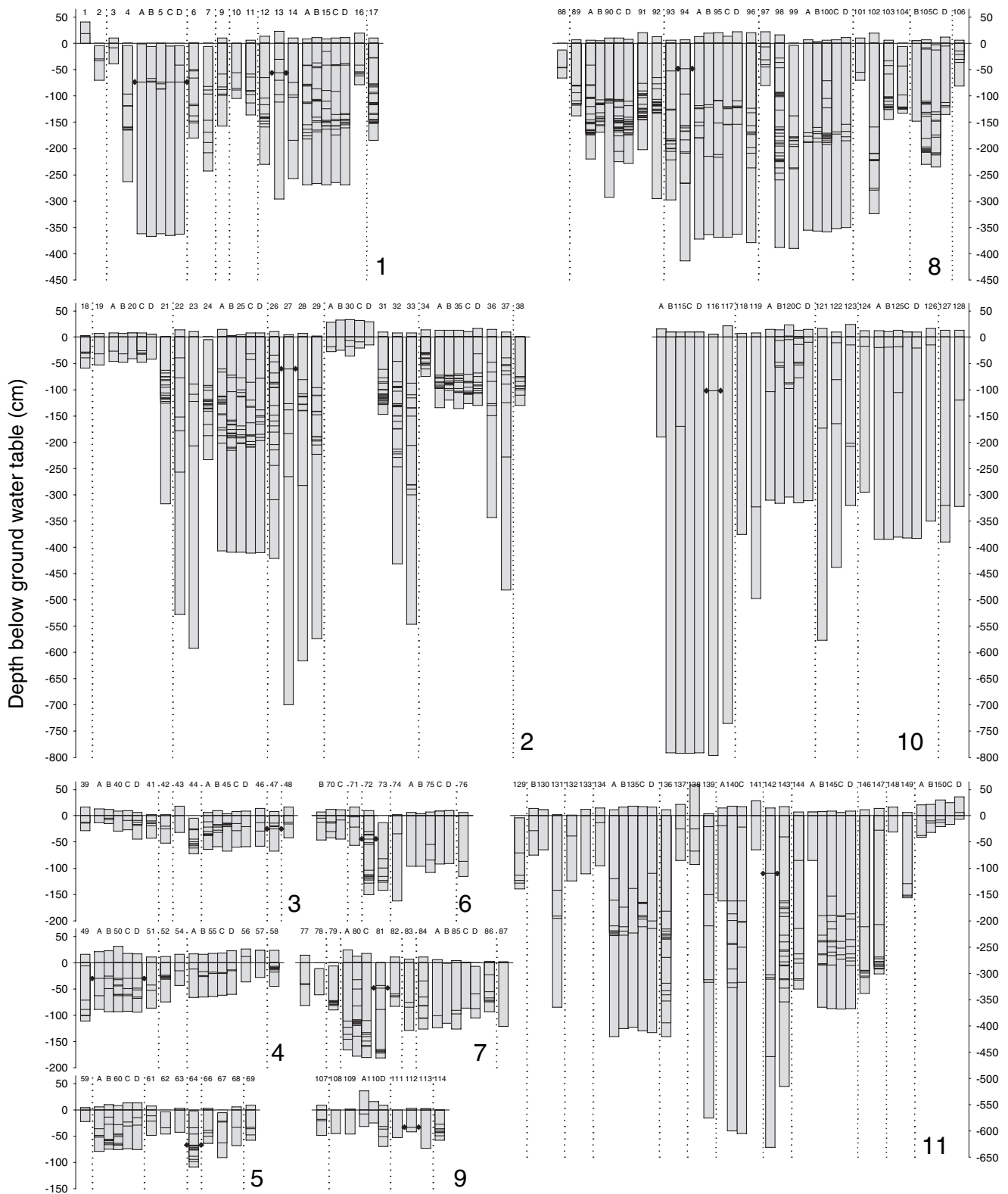
Fire rotation period, ie, the mean number of years required for an area equivalent in size to the actual sampling site to be affected by fire (Heinselman, 1973), was estimated for each site by dividing the  $^{14}\text{C}$  age of the deepest peat with the mean number of charcoal layers in the peat sequences from this site. This estimate is less accurate than the fire frequency estimates since it depends much on the spatial arrangement of sampling points and the occurrence of past fires.

### Establishment by Norway spruce and rate of charcoal deposition

Pollen analysis by standard methods (Berglund and Ralska-Jasiewiczowa, 1986) was used to define pre- and post-spruce sections in a subset of 20 peat sequences selected to represent the deepest parts of each peat basin. The average rate of charcoal deposition before and after spruce establishment was calculated by use of the age of the deepest dated peat in each basin (Table 1) and the dated immigration of Norway spruce, ie, 1700  $^{14}\text{C}$  year BP (see Hafsten, 1992). Two measures of deposition rates were calculated, ie, the average rate of macroscopic charcoal particle deposition per 10 cm<sup>2</sup> and year, and the average number of charcoal layers per year. Spruce was defined as having established when the relative proportion of spruce pollen was > 2% of the sum of pine and spruce pollen (Hafsten, 1992). A minimum of 200 pine and spruce pollen were counted in each sample. The significance of the differences in average pre- and post-spruce charcoal deposition rates (both for particles and layers) were tested using paired  $t$  tests (Sokal and Rohlf, 1995).

### Illustrations of charcoal layering patterns

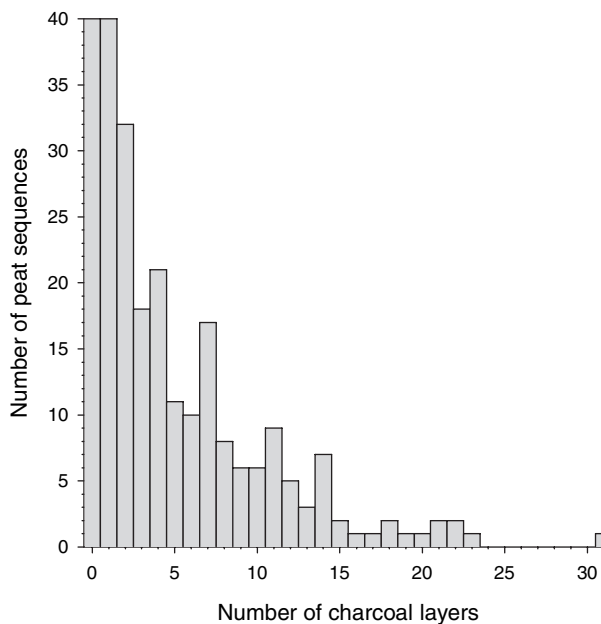
Standardized illustrations of charcoal layering patterns were produced for each peat basin (see Figure 2). All peat sequences



**Figure 2** Schematic illustration of the stratigraphy of charcoal layers in 11 forested peat basins. Numbers on peat sequences refer to the sampling point in Figure 1. Peat sequences grouped together and labelled with A, B, C and D refer to the complementary sampling points at fixed positions, see Figure 1. Vertical broken lines define peat sequences sampled along the same transverse line. The local establishment of *Picea abies* about 1700 <sup>14</sup>C-yr BP is indicated by ◆—◆ in a subset of 20 peat sequences. The median depth to the groundwater table in 1998 was used as a horizontal reference level to show the surface topography of the peatland. Note that the resolution of the illustrations makes some charcoal layers seemingly appear as one layer while in fact being made up by separate layers

in Figure 2 are labelled according to the sampling points shown in Figure 1 and it is thus possible to locate the spatial position of each sequence in each peat basin. The median depth to the groundwater table in 1998 was used as a horizontal reference level to depict the surface topography of the peat-

land. Note that the resolution of the illustrations makes some charcoal layers seemingly appear as one layer while in fact being made up by two separate layers. The spruce immigration level is indicated by ◆—◆ in the subset of 20 peat sequences selected to represent the deepest parts of each



**Figure 3** Frequency distribution for number of charcoal layers among the 247 investigated peat sequences

peat basin. This level was not extended horizontally to include sequences in which pollen analysis was not carried out, because of uncertainties due to local variation in peat accumulation rates.

## Results

### Charcoal record and site characteristics

In total, 1228 charcoal layers were found in the 247 peat sequences and the average number of layers per sequence was  $4.9 (\pm 0.3 \text{ SE})$ . The maximum number of charcoal layers found in one sequence was 31 (site 8) and the frequency distribution for number of charcoal layers was characteristically right-skewed (Figure 3).

The number of charcoal layers per peat sequence varied considerably among sites (Figure 2); the mean number ranged from 1.4 (site 9) to 9.4 (site 8) and the median number ranged from 0 (site 9) to 9 (site 2). Also the average number of charcoal layers per metre peat sequence varied considerably among the sites, from 0.3 (site 10) to 4.8 (site 3). Tables 2 and 3 give further site-specific information on the charcoal layers. Peat sequences that totally lacked macroscopic charcoal occurred in all sites. In fact, 16% of the sequences lacked macroscopic charcoal and a substantial proportion of the sequences contained only one or two charcoal layers (Figure 2). Nevertheless, sequences with seven or more charcoal layers were found in all sites (Table 3).

The number of macroscopic charcoal particles per volume unit of peat varied greatly among sites as well as among peat sequences within a single site. For example, the average number of particles per  $\text{cm}^3$  of peat ranged from 0.1 at site 10 to 1.8 at site 1 (Table 2) and the total number of particles in a sequence could vary from 0 to 6673 in one site (Table 3). An average charcoal layer contained *c.* 170 macroscopic charcoal particles of which 30 were larger than 1 mm in diameter (Table 4).

With increasing swamp forest area both the total number of charcoal layers per peat sequence (Kendall's  $\tau = 0.509$ ,  $P = 0.029$ ,  $n = 11$ ) and the depth to the first charcoal layer increased ( $\tau = 0.561$ ,  $P = 0.016$ ,  $n = 11$ ). There was also a significant positive relationship between the number of

charcoal layers and the depth to the uppermost charcoal layer (Kendall's  $\tau = 0.191$ ,  $P < 0.001$ ,  $n = 207$ ). None of the charcoal variables was significantly related to altitude (Kendall's  $\tau = 0.075$ ,  $P > 0.1$ ,  $n = 11$ ).

The two environmental explanatory variables Distance to mineral soil and Peat depth were strongly correlated (Kendall's  $\tau = 0.420$ ,  $P < 0.001$ ,  $n = 150$ ), as expected because peat-basin depths naturally increase from the periphery to the centre. Both charcoal variables were strongly and, notably, positively correlated with Distance to mineral soil (Number of charcoal layers: Kendall's  $\tau = 0.171$ ,  $P = 0.002$ ,  $n = 147$ ; Depth to uppermost charcoal layer: Kendall's  $\tau = 0.318$ ,  $P < 0.001$ ,  $n = 127$ ) and Peat depth (Number of charcoal layers: Kendall's  $\tau = 0.326$ ,  $P < 0.001$ ,  $n = 147$ ; Depth to uppermost charcoal layer: Kendall's  $\tau = 0.483$ ,  $P < 0.001$ ,  $n = 127$ ). Median depth to the water-table was uncorrelated with charcoal as well as other environmental explanatory variables (Kendall's  $\tau < 0.025$ ,  $P > 0.5$ ,  $n = 127-150$ ).

Relationships between the two charcoal variables and the environmental explanatory variables were markedly site-specific. For five out of six combinations of a charcoal variable and an environmental explanatory variable, both significantly positive and significantly negative correlations were observed among the sites. This indicated that relationships between the occurrence of macroscopic charcoal and peat basin characteristics such as area, peat depth, position of the ground water level relative to peat surface, and altitude above sea level could not be generalized over the investigated sites.

### Spatial structure

The standardized semi-variograms for the two charcoal variables were very similar; both variables had spatial structure at several scales (Figure 4), very strong up to *c.* 1.5–3 m (lag-classes 1 and 2 in Figure 4 with upper limits 2 and 4 m), and moderate to strong up to *c.* 25–50 m (lag-classes 5 and 6 with upper limits 32–64 m). None of the environmental explanatory variables had patterns of spatial structure exactly similar to those obtained for the charcoal variables; many had ranges of spatial structuring between 50 and 200 m (lag-classes 6–8 in Figure 4 with upper limits 64–256 m; ie, at between swamp-forest scales). This is exemplified by Peat depth (Figure 4) but indicated also for Depth to the water-table (not shown).

Even though the charcoal variables were spatially structured at several scales, the macroscopic charcoal record was characterized by considerable within-site variation, also on very fine spatial scales. This is clearly illustrated by variation in banding patterns among the five peat sequences that were sampled close to each other at every fifth sampling plot, see for example sequences 60A–D from site 5 and sequences 105A–D from site 8 (Figure 2). On the other hand, the charcoal-banding patterns for five neighbouring points in space could also be fairly similar, as shown by sequences 35A–D (Figure 2). Altogether, our results indicate that the macroscopic charcoal record in boreal forested peatlands is highly individualistic and unpredictable, even down to very fine scales.

### Fire frequency and fire rotation period

The striking spatial variation in the macroscopic charcoal record was reflected in high variability of fire frequency estimates. For example, based on the number of charcoal layers positioned above the dated charcoal particles in site 2, fire frequency in this site ranged from one in 415 to one in 3095 years, with an average of one fire in 1504 years (Table 5). The average fire frequency over all sites was one fire in 475 years, with a noticeable variation among sites; from 220 years in site 5 to 1141 years in site 10 (Table 6). Note that the two methods

**Table 2** Peat sequence and charcoal characteristics for the forested peatland sites

Characteristic	Site										
	1	2	3	4	5	6	7	8	9	10	11
Investigated peat sequences (no.)	24	37	18	17	14	13	17	34	10	26	37
Total length of peat sequences (m)	55.5	97.2	10.0	15.3	10.1	13.3	21.4	92.2	5.7	129	101
Total charcoal layers (no.)	153	303	51	52	47	27	60	321	14	36	164
Charcoal layers per metre peat (no.)	3.1	3.9	4.8	3.4	4.0	2.0	2.7	3.9	2.2	0.3	1.6
Charcoal particles per cm <sup>3</sup> peat (no.)	1.8	1.5	1.1	0.8	0.3	0.3	0.2	0.6	0.6	0.1	0.4
Largest charcoal particle (mm)	20	20	18	13	10	16	10	17	12	20	24

**Table 3** Number of charcoal layers and macroscopic charcoal particles per peat sequence

Site	<i>n</i>	Charcoal layers					Charcoal particles				
		Min	Max	Median	Mean	SE	Min	Max	Median	Mean	SE
1	24	0	22	5	6.4	1.1	0	6673	1441	2159	413
2	37	0	22	9	8.1	1.0	0	6322	1647	1971	267
3	18	0	8	2	2.8	0.5	0	1455	245	375	94
4	17	0	7	2	3.1	0.5	0	773	88	139	22
5	14	0	11	3	3.4	0.9	0	525	109	151	41
6	13	0	13	1	2.1	1.0	0	1942	20	212	147
7	17	0	11	2	3.5	0.8	0	495	126	182	41
8	34	0	31	7	9.4	1.2	0	3482	736	870	127
9	10	0	7	0	1.4	0.7	0	1709	0	227	168
10	26	0	7	1	1.4	0.3	0	812	65	153	45
11	37	0	19	3	4.4	0.7	0	3782	405	755	153

used to estimate average fire frequency gave quite different results for site 2, ie, one fire in 1504 versus one fire in 413 years (Table 6). This difference depends on the spatial variation in the charcoal record and that the lowest estimate was calculated from the maximum number of charcoal layers present.

The average fire rotation period (over all sites; total area = 13.4 ha) was 1886 years, ranging among sites from 700 to 5700 years (Table 4).

### Spruce establishment and charcoal concentrations

The average deposition rate for macroscopic charcoal particles was significantly greater for the period prior to establishment of Norway spruce than for the postestablishment period. Also the average deposition rate of charcoal layers was greater prior to, than after spruce establishment (Table 7). Despite a clear tendency for higher pre-establishment values for the charcoal variables, the spatial variation was large, both prior to and after establishment of Norway spruce. This is exemplified by neighbouring peat sequences 5A–D in site 1 (Figure 2) that were completely different with respect to occurrence of macroscopic charcoal in pre- and post-spruce sections.

## Discussion

### Spatial variation in charcoal layer patterns

Our results clearly show that the studied forested peatlands are characterized by strong spatial variation in charcoal layer patterns, both on broader and finer spatial scales. The fact that complete horizontal alignment of charcoal layers across a peat basin is not observed in any site, and that 16% of the peat sequences lack macroscopic charcoal (Figure 2), indicate a very patchy fire pattern in which considerable areas remain unburned at each fire event. Estimates of mean fire size over the sites corroborate a very patchy pattern since mean fire size was small and ranged from 0.03 (site 6) to 1.5 ha (site 11) among the sites. Most likely, this pattern is brought about by

prevalence of low-intensity fires that advance across the peatlands in an irregular way so that each fire event only affects a small proportion of a peatland area. We hypothesize that the causal explanation for this patchy pattern is the spatial variability of surface peat topography, which in turn is related to moisture levels and, importantly, the distribution of woody plants that are the main sources of potential forest fire fuel and charcoal (Økland *et al.*, 2001). This hypothesis is strongly supported by semi-variance patterns obtained for number of charcoal layers for which the strong spatial structuring on the finest scales (0.25–1.5 m) closely resembles the patterns obtained for surface peat topography (depth to the water-table as recorded for 0.25 m × 0.25 m vegetation subplots) by Økland *et al.* (2001).

Differences in number of charcoal layers on broader spatial scales within sites are also indicated in the material, eg, by the loss of spatial structure at 25–50 m distances between sampling points. One example is site 6, where only two charcoal layers are found in the northern part (a mean of 0.3 charcoal layers per peat sequence) while 25 layers are found in the southern part (a mean of 4.2 charcoal layers per sequence). We are convinced that the variation at this spatial scale is to some extent linked to variation in hydrology, which shows variation at similar, within-site spatial scales (Økland *et al.*, 2001).

The geostatistical analyses give no evidence for spatial structuring of number of charcoal layers at between-site scales (ie, beyond interpoint distances of *c.* 50 m). This means that the number of charcoal layers compared in any two peat basins is not related to the distance between the basins. This result parallels the lack of distance decay of floristic similarity for ecologically similar sites (cf. Nekola and White, 1999) observed for the studied swamp-forests (Økland *et al.*, 2003), indicating that the swamp-forest sites have idiosyncratic fire histories as well as individualistic species accumulation histories.

All peat basins do, however, display examples of horizontally aligned charcoal layers in neighbouring sequences that almost certainly have originated from the same fire event. Typical

**Table 4** Size and number of charcoal particles per 10 cm<sup>2</sup> charcoal layer in boreal forested peatlands

Particle size-class (mm)	Median	Mean	SE	Range	CV (%)
0.28–0.5	21	56.3	2.5	0–926	160
0.5–1	49	80.1	2.7	0–911	117
1–2	14	25.3	0.9	0–333	132
2–4	2	5.2	0.3	0–132	177
4–8	0	0.7	0.1	0–23	272
> 8	0	0.1	0.0	0–6	409

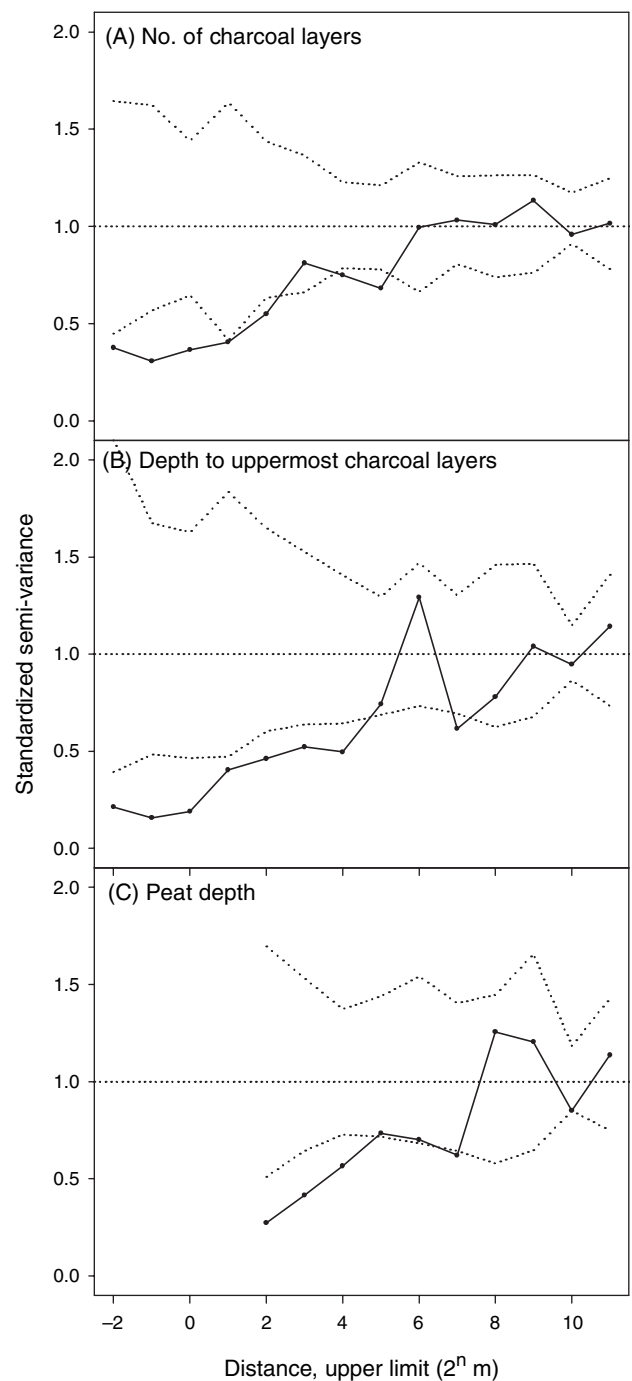
**Table 5** Age of selected charcoal particles and estimates of fire frequency. All sequences and particles are from site 2. The dated particles were > 4 mm in diameter

Peat sequence	Depth (cm)	<sup>14</sup> C age (yr BP)	Lab. ref.	Charcoal layers above the dated particle	Fire frequency (year)
35D	48	415 ± 65	TUa-2344	0	415
35B	96	4015 ± 60	TUa-2345	3	1338
35B	86	3095 ± 65	TUa-2346	0	3095
34	37	2675 ± 55	TUa-2348	0	2675
29	207	6305 ± 70	TUa-2349	7	901
25C	217	8035 ± 105	TUa-2350	10	804
22	266	6950 ± 85	TUa-2351	4	1738
37	64	2125 ± 65	TUa-2449	2	1062

examples are the pattern in site 8 where several charcoal layers in sequences 98 to 100D show horizontal alignment, and the characteristic charcoal layer appearing in the upper part of sequences 122 to 126 in site 10 (Figure 2). In some sites (eg, 3, 4 and 8), the apparently corresponding charcoal layers occur at variable depths, seemingly dependent on the underground topography, with layers positioned deeper below the peat surface in long sequences compared with short sequences. Presupposing a concave surface of the peat basin, such a banding pattern may result by synchronous initiation of peat accumulation in different parts of a peat basin, giving rise to a 'paludification system' according to Korhola (1995). In line with this explanation, the many charcoal layers seemingly making up consistent patterns but being placed at different depths, eg, in swamp-forest localities 2, 3, 4, 7 and 8, may well have originated from the same fires. However, age–depth relationships in boreal peatlands are known to be highly variable (Økland and Ohlson, 1998; Clymo *et al.*, 1998) and charcoal at a given depth may differ considerably in age within one single peat basin, as was the case in site 2 (Table 5). This highlights the need for, and importance of, multiple datings (a notorious bottle-neck for economical as well as methodological reasons) in order to provide high-resolution data on the history of forest fires. In this context, the use of established pollen marker levels may be helpful (Pitkänen *et al.*, 2002, 2003a,b).

### Fire history and impact

The high proportion of peat sequences that lack charcoal or contain few charcoal layers indicates that fire has played a rather subordinate role in the forested peatlands we studied. Actually, the estimated fire frequency intervals and fire rotation periods are among the longest ever recorded for boreal forests and clearly contrast the widely accepted view that European boreal forests typically have burned at a mean



**Figure 4** Standardized semi-variograms for (A) number of charcoal layers ( $n = 247$ ), (B) depth to uppermost charcoal layer ( $n = 207$ ), and (C) peat depth ( $n = 150$ ). Labels on the abscissa indicate upper limit of lag classes, expressed as  $2^n$  m. Envelopes represent the minimum and maximum of standardized semi-variances obtained for 999 permutations of the data on the spatial locations

interval of 50–120 years with a fire rotation of 75–200 years (eg, Zackrisson, 1977; Niklasson and Granström, 2000). However, the sporadic occurrence of fires in the Østmarka Nature Reserve corroborates results from long-term studies in Finland, Sweden and Norway, indicating that fire was generally rare in spruce swamp sites during the Holocene (Hörnberg *et al.*, 1995; Tryterud, 2003; Pitkänen *et al.*, 2003b). The results from the present study are, nevertheless, fundamentally different from those of Hörnberg *et al.* (1995) and Pitkänen *et al.* (2003b), who claim virtual absence of fires in some sites (three out of ten sites and in two out of three sites, respectively). Evidently, fire has struck all our sites at several

**Table 6** Fire frequency and fire rotation period (year) in each site calculated from  $^{14}\text{C}$  peat age and the maximum and mean number of charcoal layers found per peat basin (see Tables 1, 4 and 5 for data on area,  $^{14}\text{C}$  age and charcoal layers, respectively)

Site	Frequency	Rotation
1	407	1398
2	413	1123
3	374	1067
4	427	964
5	220	712
6	388	2400
7	600	1884
8	288	949
9	557	2785
10	1141	5707
11	408	1761

occasions during the Holocene. In this context, it is important to recall that Hörnberg *et al.* (1995) and Pitkänen *et al.* (2003b) analysed one single peat sequence per site. Given that the probability of obtaining a charcoal-free sequence (the proportion of sequences without charcoal) is 16% in our present study, we find it likely that more, or all, of the spruce swamp sites studied by Hörnberg *et al.* (1995) and Pitkänen *et al.* (2003b) actually have burned locally during the Holocene. Interestingly, the 16% proportion of sequences that lacked charcoal in our study accords very well with Ohlson and Tryterud (2000) who found that the probability that a charcoal-trap in a burnt forest area would lack macroscopic charcoal was approximately 14%. It is, nonetheless, beyond all doubt that forested spruce mire sites are little affected by recurring forest fires as compared with other boreal forests in a Holocene time perspective. This means that the forest structure and dynamics are mainly determined by factors other than broad-scale fire disturbance, which in turn has important implications for the management of these forests (Ohlson and Tryterud, 1999; Pitkänen *et al.*, 2003b). Nevertheless, the fire events may have had considerable impact on development of these ecosystems, as well as their species composition (Økland *et al.*, 2003).

### ***In situ* fires**

The counting and sorting of charcoal particles performed as part of our study allow us to compare the number of particles in the charcoal layers with estimates of charcoal production and deposition by forest fires. Such a comparison clearly shows that the number of particles and their size distribution in a charcoal layer (Table 4) generally match, or even exceed, the number and size of particles trapped inside burned areas during forest fire events (see Ohlson and Tryterud, 2000). It is thus reasonable to believe that the macroscopic charcoal record in our study sites has originated from peatland fires *in situ*. But because post-fire transport of charcoal from forests surrounding a lake can continue for several years after a fire (Whitlock and Millsaugh, 1996) we can not, at the outset, rule out that some of the charcoal in the peat basins studied may originate from fires in the surrounding forests on mineral soil. However,

if *ex situ* fires contribute substantially to deposition of charcoal in peat basins, both charcoal particle abundance and number of charcoal layers is expected to decrease significantly with increasing distance to the mineral soil. Since we found no such relationship, rather the opposite, we conclude that the macroscopic charcoal in the peat basins studied results principally from *in situ* peatland fires and that the central parts of the peatlands in this study, including also the largest sites (sites 2, 8 and 9), have provided both fuel and reasonable burning conditions during a substantial part of their Holocene history.

The general lack of charcoal in the deepest parts of the peat basins studied (Figure 2), which are typically composed of *Carex* and *Phragmites* peat, is likely to be due to blocking of fire by the peatlands in their early developmental stages when they were open and wet. However, an absence of large charcoal particles must be carefully interpreted because fire detection depends strongly on fire severity (Higuera *et al.*, 2005). Moreover, other types of fuel than wood may have burned, which results in a lack of charcoal in spite of the presence of fire since wooded fuel is a prerequisite for charcoal production. In the present study, a combination of small amounts of fuel, fuel that produced no charcoal (ie, mosses and sedges) and low fire intensity most likely explain the lack of macroscopic charcoal in the deepest parts of the peat, since the relationship between fuel accumulation and fuel consumption is the key determinant of charred-particle production (Clark *et al.*, 1998). Moreover, the ability of a peat basin to record forest fires in the form of visible charcoal layers is dependent on the vegetation and hydrology of the basin (Pitkänen *et al.*, 2003b). Consequently, differences in charcoal layers within as well as among our sites can, to a certain extent, be ascribed to different hydrological conditions.

### **Local establishment of *Picea abies* and occurrence of fire**

Our result that local establishment of spruce is associated with reduced deposition rate of charcoal particles (Table 5) is consistent with the known fire ecology of *Picea abies* (Zackrisson, 1977; Sannikov and Goldammer, 1996; Linder *et al.*, 1997). A key question in this context is whether *P. abies* established because of decreasing fire impact or the establishment of spruce caused fires to decrease. Arguments for the former hypothesis are the well-established links between climate change and continental-scale distribution and abundance of species as well as forest fires (Stocks *et al.*, 1998; Grissino-Mayer and Swetnam, 2000) and that the regional spread of *P. abies* in Scandinavia has been described as a migrating front closely tracking the changing area of suitable climates (Bradshaw and Lindbladh, 2005). However, the prevailing forest disturbance regime affects the establishment and survival of tree species by providing regeneration sites and, selectively, by removing established individuals (Overpeck *et al.*, 1990). Since fire disturbance has not been generally important in the spruce swamps studied (very low fire frequencies and long fire rotation periods), we believe that the local establishment of *P. abies* was determined by factors other than fire, and that spruce establishment actually may

**Table 7** Macroscopic charcoal values (mean  $\pm$  1 SE) in forested peatlands before and after establishment of Norway spruce *Picea abies*

Charcoal variable	Before establishment	After establishment	<i>P</i> (one tailed)
Rate of particle deposition ( $10 \text{ cm}^{-2} \times 1000 \text{ yr}^{-1}$ )	164 $\pm$ 43	42 $\pm$ 18	0.008
Charcoal layers ( $1000 \text{ yr}^{-1}$ )	1.6 $\pm$ 0.6	0.4 $\pm$ 0.1	0.047

Number of peat sequences = 20.

have made the swamps burn less frequently because of vegetation change caused by the shady local climate that is typical of *P. abies* forests (see Tryterud, 2003). Moreover, anthropogenic alteration of the disturbance regime has catalysed the spread of the late Holocene migrant *P. abies* in Europe (Bradshaw and Lindbladh, 2005) and we argue that there is a need for more knowledge on the inter-relationships between human land use, local establishment of *P. abies* and occurrence of fire.

## Conclusions

The results of the present study of charcoal layers in 247 peat sequences from 11 forested peat basins suggest that we should revise our understanding of how fires have affected boreal swamp forests. Most importantly, our results demonstrate fine-scaled patterns of fire impact and indicate that all investigated forests exhibit traces of fires, and also that all contain patches in which no previous fire can be traced. Thus, sound conclusions about fire-free refugia in forests require a much larger data set than is normally provided, and such conclusions can definitively not be drawn from single peat sequences. Forest fire frequencies in forested peatlands are lower than in comparable forests on mineral soils, and were further lowered after the establishment of *Picea abies*. We find few clear relationships between local charcoal patterns and ecological conditions, but our results confirm the view that hydrology is an important determinant of fire occurrence and fire behaviour in peatlands. Although fire frequencies are low, boreal swamp forests have been exposed to fires a sufficiently large number of times for fire to play an important role in their ecology and development.

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