Ruuhijärvi, 1976; Korhola, 1992; Ikonen, 1993; Seppä, 1996). The succession of peatlands together with environmental and climatic changes and plant tissue remains have been more rarely analysed.

Using multiproxy data with several methods of dating we examined two different types of peatlands, a fen and a bog, in the same region for (1) peat and carbon accumulation during the Holocene, (2) relationships between peat chemistry and vegetation, and (3) main changes in the surrounding forest vegetation. We also discuss whether the changes in peat development were related to large-scale climatic changes or regulated by local or regional factors.

Material and methods

Study area

The study area is located about 60 km NE of Tampere in southern Finland. The area belongs to the southern boreal coniferous forest zone (Ahti *et al.*, 1968) and to the raised bog region (Ruuhijärvi, 1983). Mean annual precipitation in the area is 709 mm, and mean annual temperature is +2.9 °C. The minerotrophic Konilampi mire (the fen site), which forms the northern part of the Hanhisuo mire complex (61°48′N, 24°17′E, 155 m a.s.l.), is located between the esker Vatiharju and the lake Hanhijärvi. The first ditches were made in the early 1940s, until the mire was drained for forestry purposes in 1955. In the 1960s, the site type was a tall sedge pine fen (*sensu* Laine and Vasander, 1996). In 1994, the fen site was dominated by a stand of pine (*P. sylvestris*) with some spruce (*P. abies*) and birches (*Betula pubescens* and *B. pendula*). The field layer vegetation consisted of dwarf shrubs, namely *Ledum palustre*, *Vaccinium uliginosum*, *Vaccinium myrtillus* and *Betula nana* (Jauhiainen *et al.*, 2002). Nomenclature follows Hämet-Ahti *et al.* (1998) for vascular plants, Koponen *et al.* (1977) for bryophytes and Ahti (1993) for lichens.

The Viheriäisenneva mire, the bog site (61°51′N, 24°14′E, 160 m a.s.l.), is located about 10 km north from the studied fen. Some drainage ditches appear on 1946 aerial photographs, although the mire was drained for forestry purposes in 1963. The site was a nearly treeless ombrotrophic low-sedge bog with some *Sphagnum fuscum* hummocks when afforested in 1966 (Sarkkola and Päivänen, 2001). The vegetation in 1994 consisted of pine seedlings (*P. sylvestris* and *P. contorta*) and the field layer vegetation comprised *Calluna vulgaris*, *Empetrum nigrum* and *V. uliginosum* (Jauhiainen *et al.*, 2002). The bottom layer was densely covered by *Cladonia* spp. and some ombrotrophic *Sphagna*.

Sampling

Cores were taken in autumn 1994 and 1997. An auger of 8.3 × 8.4 × 100 cm was used down to a depth of 100 cm. Below that depth, samples were collected from two adjacent boreholes using a Russian peat sampler of 5 × 50 cm (Jowsey, 1966). Cores for physical and chemical analyses of peat were taken in both years. The results for the upper 50 cm are the averages of 12 samples, whereas one core per year was taken from deeper peat. The cores for pollen, plant tissue remains and radiocarbon dates were taken in 1994 only. The degree of decay was estimated in the field with von Post's (1922) 10-grade scale (H1-10). The distance from the coring point to mineral soil was about 100 m at the fen site, and about 500 m at the bog site.

Cores for physicochemical analysis were cut in the field into 10 cm pieces between 0 and 100 cm depth, and into 12.5 cm pieces for the rest of the peat profile. Pieces were packed into plastic bags. The cores for vegetation and radiocarbon analyses were placed in 50 cm long gutters and wrapped in plastic for undisturbed transport. The samples were stored in a cold room (5 °C) until the day of subsampling. Laboratory analyses were completed during the following winter.

Physicochemical analysis of peat

Bulk density (BD) was determined after drying samples at 105°C to constant mass, after which they were milled. Organic matter content was determined from the 1994 samples as the percentage of loss-on-ignition (LOI) by igniting subsamples at 550°C for two hours. Carbon (C) and nitrogen (N) concentrations were analysed from the subsamples at each depth with a LECO CHN-600 analyser. Acidity (as pH) was measured from $CaCl_2$ (0.01 M) suspension (1:2.5 v/v) of peat. Mineral element concentrations (Ca, Mg, Fe, Al, K, P) were measured with an ICP analyser after HNO_3-H_2SO_4-$HClO_4$ digestion at 200°C at an internationally certified laboratory of Finnish Forest Research Institute, Vantaa Research Center. The detection limits for elements (ppm) were: Al (0.16), Fe (0.015), P (0.15), Ca (0.001), Mg (0.001) and Mn (0.004).

The long-term rate of carbon accumulation (LORCA), g m^{-2} yr^{-1}, was calculated by dividing the accumulated mass of C in the whole profile by the age (cal. BP) of the basal peat. Calculations are based on the measured BD and the percentage of C in each sample. The C accumulation was calculated also for slices according to the dated horizons starting from the basal peat.

Vegetation analysis and ^{14}C dating

Due to higher accumulation rates, the total profile length was longer for the bog than the fen. Accordingly, subsamples of 1 cm^3 were taken at every 5 cm intervals from the core of the fen site, and at every 10 cm from the core of the bog site. Samples were prepared using the method of Fægri and Iversen (1964) for pollen analysis. Two tablets of *Lycopodium* (Stockmarr, 1972) were added to each sample, which enabled us to estimate pollen concentrations. A minimum of 300 arboreal pollen grains were counted from each sample. Pollen and spore percentages for different species were calculated from the sum of total pollen (AP + NAP) excluding aquatic plants. Charcoal particles larger than 10 µm were tallied.

Percentages of humification and plant tissue remains were examined from subsamples of 10 cm^3 taken at intervals of 25 cm in the Mire Research Laboratory of the Karelian Research Centre in Petrozavodsk, Russia. Humification was determined by microscoping subsamples with a magnification of ×140. The percentage of dark, decomposed organic matter represented the value of humification (Minkina and Varligin, 1939). The humification value (R, Razlochenie = decay) is comparable to von Post's values, so that R values less than 5% are equivalent to von Post's H1, R values of 15–20% are equivalent to H4, and R values of 55–65% correspond to H9. Plant remains were examined using the method of Korotkina (1939). Samples were washed with warm tapwater through a sieve of 250 µm mesh size in order to remove amorphous material. Several microscopic slides were made from the residue by placing plant tissue fragments in pure glycerine. The slides were surveyed under a high-power microscope and all plant fragments were identified and listed. The surveying continued as long as new taxa were being found. In *Sphagnum* peat, usually four slides were enough. Relative percentages of each species were calculated and presented in plant tissue remains diagrams, together with the values of humification.

Radiocarbon dates were determined at 50 cm intervals for the peat profiles of both mires at the Helsinki University Radiocarbon Dating Laboratory. After mechanical separation

Table 1 Radiocarbon dating for the fen and the bog

Fen site lab. no.	Depth (cm)	Conventional ^{14}C (yr BP)	$\delta^{13}C$	Cal. yr BP
Hel-3458	45–50	3220 ± 100	– 29.1	3346–3566
Hel-3459	95–100	4170 ± 110	– 29.0	4544–4817
Hel-3460	145–150	5030 ± 100	– 29.3	5671–5882
Hel-3461	195–200	6430 ± 100	– 29.3	7262–7424
Hel-3462	225–230	8130 ± 160	– 28.7	8793–9289
Bog site				
Hel-3863	45–50	680 ± 90	– 22.8	571–699
Hel-3864	95–100	1470 ± 100	– 22.2	1303–1487
Hel-3865	145–150	3480 ± 120	– 25.8	3602–3907
Hel-3904	195–200	4220 ± 120	– 25.1	4583–4911
Hel-3905	245–250	4640 ± 110	– 28.6	5129–5496
Hel-3867	295–300	6070 ± 110	– 27.3	6796–7106
Hel-3869	345–350	7280 ± 130	– 26.7	7982–8235
Hel-3870	395–400	8490 ± 130	– 26.6	9327–9622
Hel-3871	425–430	9110 ± 120	– 27.1	10132–10438

of rootlets, the AAA (acid-alkali-acid)-treatment was applied. All results were corrected for isotopic fractionation based on the $\delta^{13}C$ values (Table 1). The calibration of radiocarbon ages is based on the INTCAL98 calibration data set (Stuiver *et al.*, 1998), and the CAL25 calibration program (van der Plicht, 1998) was used. The median values of calibrated ages together with the 1 sigma interval are given in Table 1. All dates used in the text are ^{14}C years BP. The calculations for the LORCA were made using the years of cal. BP.

Results

Peat and carbon accumulation during the Holocene

Fen

Paludification of the fen site started at 8130 ± 160 BP uncalibrated years (Table 1 and Figure 1). The mean rate for the vertical peat increment was 0.28 mm yr^{-1}. The increment was slow during the first 1700 years of peat development (0.18 mm yr^{-1}). A high increment rate (0.58 mm yr^{-1}) occurred between 5000 and 4000 BP, whereas the increment was slow again (0.16 mm yr^{-1}) for the upper 50 cm of peat (Figure 1).

The LORCA for the fen site was 11.1 g m^{-2} yr^{-1}. The bottommost 30 cm and the uppermost 50 cm had C accumulation rates of 6.6 and 9.6 g m^{-2} yr^{-1}, respectively (Table 2). Both these sections also showed high BD (Figure 2). The accumulation rate exceeded 15 g C m^{-2} yr^{-1} during the Subboreal period, between 5000 and 3000 BP, i.e., at the depth 150–50 cm (Table 2).

Bog

Paludification of the bog site started at 9110 ± 120 BP (Table 1 and Figure 1). The peat accumulated at an average rate of 0.47 mm yr^{-1}. However, there was about 1000 years of higher increment rate between 4640 ± 100 and 3480 ± 120 BP. During the first 400 years of this period, the increment rate was 1.19 mm yr^{-1}, and 0.68 mm yr^{-1} during the following 700 years (Figure 1).

The LORCA for the whole profile was 13.2 g m^{-2} yr^{-1}. Carbon accumulated at its lowest rate of 6.1 g m^{-2} yr^{-1} during the period between 3480 and 1470 BP (150–100 cm) and at its highest rate of 21.1 g m^{-2} yr^{-1} at the upper 50 cm surface peat, which represents the time period since 680 BP to the present day (Table 2).

Physical and chemical stratigraphy

Fen

Two different measurements, in 1994 and 1997, show the same large-scale changes during peat development (Figure 2). The concentrations for Al, P, Mg, Mn and C and N contents show fairly small changes in the stratigraphy between the two years, whereas fairly large changes occurred in Fe and Ca concentrations in the catotelm (Figure 2).

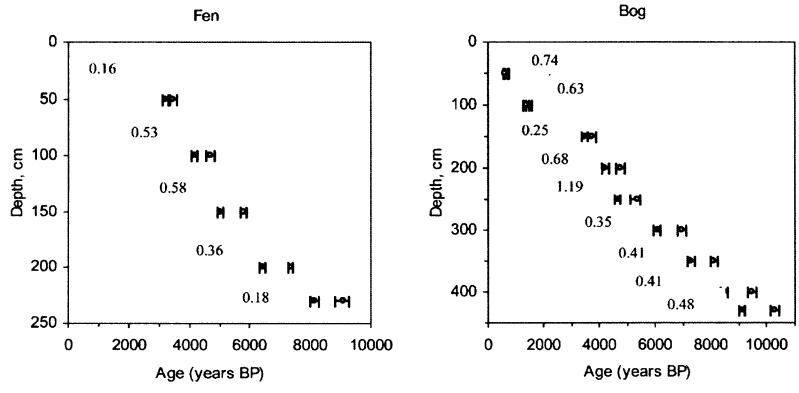

Figure 1 Relationship between peat depth and age for the fen and bog sites. Filled circles with ± error bars represent uncalibrated years BP. Open circles with error bars of 1 sigma interval represent calibrated years BP. The values represent the peat accumulation rates (mm yr^{-1}) during the development of mires.

Table 2 Carbon accumulation rates for each 50 cm slice according to calibrated ^{14}C year BP for the fen and the bog (LORCA, g $m^{-2} yr^{-1}$)

Depth (cm)	Fen	Bog
0–50	9.6	21.1
50–100	15.3	18.4
100–150	15.6	6.1
150–200	12.9	11.3
200–(230)250	6.6	19.5
250–300		9.7
300–350		16.4
350–400		16.1
400–430		18.1

The deepest sample is influenced by the mineral bottom as indicated by BD and C and N contents (Figure 2). The bottommost peat, below 200 cm, was well decomposed having high bulk density (BD). Thereafter the BD remained almost the same (70–80 g dm^{-3}) up to 50 cm depth. The organic matter content (LOI) increased abruptly above the mineral bottom, and remained high (85.1–98.8%) throughout the stratigraphy (Figure 3). A small decrease in LOI occurred at around 4300 BP (110 cm). The peat became more acid and nutrient-poor from the bottom towards the surface of the peat (Figure 2). The pH of 3.6 measured for bottom peat decreased to 2.8 at the surface.

The most remarkable changes occurred in the Fe concentration, which decreased from 13 mg g^{-1} to 2 mg g^{-1} during the peat development. Remarkable differences in concentra-

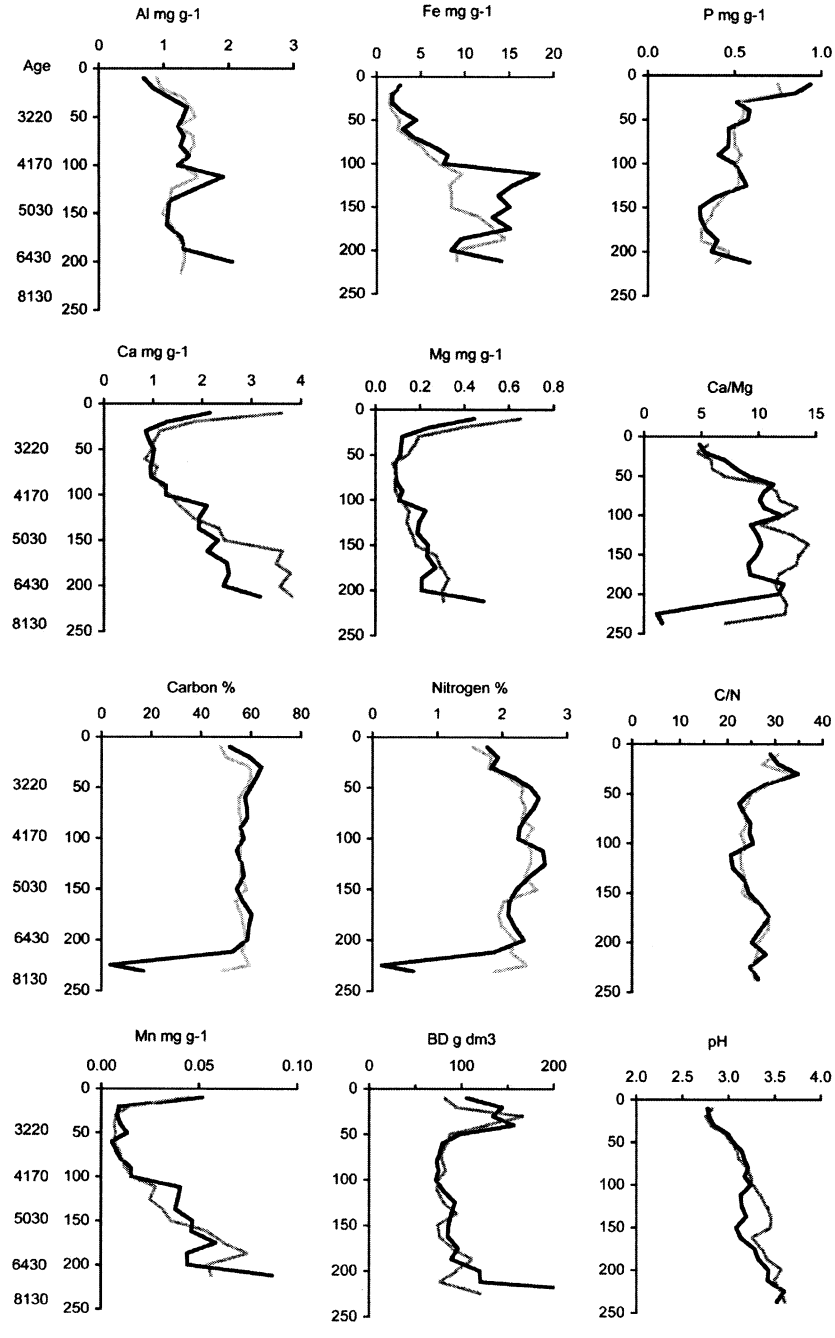

Figure 2 Physicochemical properties of peat in relation to depth (cm) and age (^{14}C) at the fen site. Black line = year 1994; grey line = year 1997.

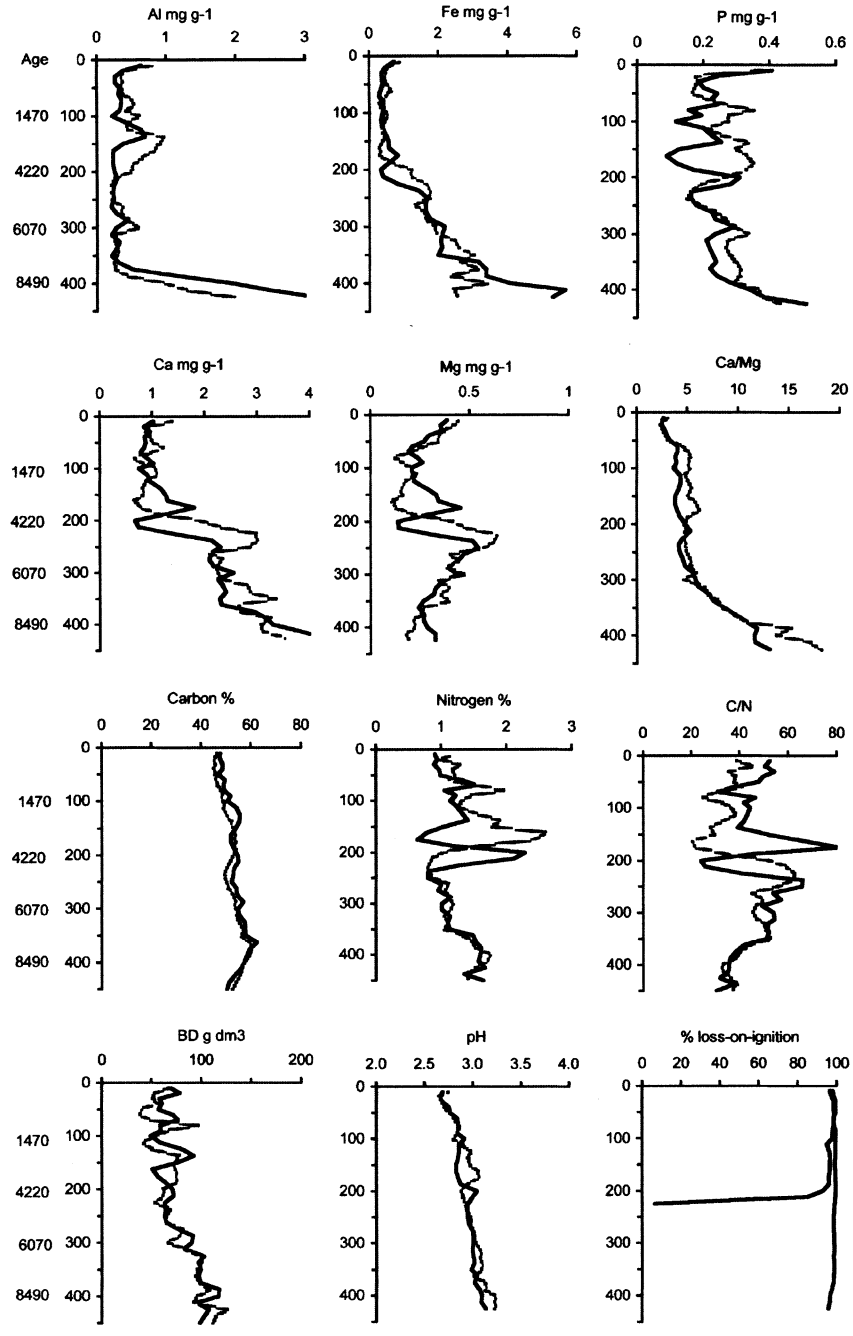

Figure 3 Physicochemical properties of peat in relation to depth (cm) and age (^{14}C) at the bog site, and organic matter content (LOI) of both mires. Black line = year 1994; grey line = year 1997.

tions also occurred between the years. The concentrations of the 1994 samples were much higher at the depth between 170 and 110 cm, representing the time period between 5600 and 4300 BP, than those for the same depth for the 1997 samples. The highest Fe (18 mg g^{-1}) was measured in 1994 for the sample at 110 cm depth (4300 BP). The concentrations of Al and P also were higher at the same depth, especially in 1994.

The Ca concentrations differed considerably between the years at the depth of 220–150 cm, representing the age between 8000 and 5000 BP. The Ca, Mg and Mn concentrations showed a decreasing trend during peat development until the depth of 50 cm, but reached very low levels already at 4200 BP (100 cm).

The C content for the early peat between 8100 and 5600 BP (230–170 cm) and in the upper 50 cm peat was about 60% or more, whereas for the peat between it was below 60%. The N content, on the contrary, was lower (less than 2.4%) for the early peat and for the upper 50 cm peat, but exceeded 2.4% at the period between 5000 and 3200 BP (170–50 cm). These resulted in three stages for C/N ratio. The first stage was between 8130 and 5600 (230–170 cm), the second stage was between 5600 and 3220 BP (170–50 cm) and the third was for the upper 50 cm of peat, having the C/N ratios of 25–30, 20–25 and 25–35, respectively (Figure 2).

The upper 50 cm differed from the rest of the peat. The BD increased from 80 to about 160 g dm^{-3}. The concentrations of Al and Fe decreased, and P, Ca, Mg and Mn increased at, or above, 50 cm depth (Figure 2). The K was measurable only for the 20 cm surface peat and is not shown in the diagrams.

Bog

Little variation (93.6–99.6%) occurred in organic matter content throughout the stratigraphy, as described by % loss-on-ignition (Figure 3). Little variation also occurred in C content, which decreased gradually since 7500 **BP (360 cm)** from 60 to 42% (Figure 3). Otherwise the chemostratigraphical data of the bog can be divided into three stages of development during a period of about 9000 years. The first stage, i.e., almost the first half of peat development between 9110 and 4640 BP (430–250 cm), is characterized by a gradual change in concentrations. During the second stage of about 900 years, between 4600 and 3500 BP (250–150 cm), the element concentrations and N content oscillated greatly. The third stage represents the last 3500 years of development (Figure 3). Drainage did not cause changes in the surface chemostratigraphy.

The deepest samples were influenced by the mineral bottom, as seen clearly for example in Al, P and Fe concentrations (Figure 3). The BD decreased from 110 to 60 g dm^{-3} during the first half of peat development (Figure 3) and ranged thereafter between 40 and 80 g dm^{-3}. There was no noticeable change in BD due to drainage. The peat at the bog site was slightly more acidic throughout the profile than the peat at the fen. The pH decreased from 3.2 in the bottom peat to 2.7 in the surface peat (Figure 3), differing very little from the corresponding change of the fen site.

The concentrations of Fe and Ca, the N content and Ca/Mg ratio decreased gradually during the first half of peat development, while the Mg concentration and C/N ratio increased (Figure 3). During this gradually changing trend there were, however, some more changes between 7500 and 7200 BP (360–350 cm) (Figure 3).

During the period between 4600 and 3500 BP (250–150 cm), the Fe concentration decreased from almost 2 mg g^{-1} to a level below 0.5 mg g^{-1}, where it stayed for the rest of the peat development. The Al concentration first increased but then decreased, and also remained at a level below 0.5 mg g^{-1}. The greatest oscillation occurred in the concentrations of Ca (0.8–3 mg g^{-1}) and Mg (0.1–0.6 mg g^{-1}) as well as N content (0.6–2.7%) and C/N ratio (20–80), for both sampling years. For the rest of the peat development, Ca remained at a level of about 1 mg g^{-1}, Mg about 0.3 mg g^{-1} and N content about 1%. The P concentration oscillated since 4600 BP (250 cm); however, the level of the concentration was low (0.1–0.4 mg g^{-1}). Thus the last, third period is characterized by decreased concentrations of elements Fe, Ca and Mg. There was no clear compaction of surface peat due to drainage at the bog site.

Botanical composition of the peat profiles

Fen

The early peat at the fen site was composed primarily of tissue remains of reeds (*Phragmites australis*), birch (*Betula pubescens*) and aquatic plants, such as *Equisetum fluviatile* and *Menyanthes trifoliata* (Figure 4). The early peat was well humified, in von Post scale H6-7 (R 40%). The site remained wet for a relatively long time, as indicated by *Phragmites* remains, which were still present at the time when *Betula* became dominant. Tissue remains of *Betula* reached 80% of the total after about 2000 years of peatland development at 6400 BP (200 cm), at which point the peat became slightly less humified (H6). Sedges (*C. lasiocarpa*, *C. limosa* and *C. rostrata*) became dominant around 4800 BP (140 cm), indicating that the wooded mire changed to an open sedge fen. Since then, *Carex* remained the main peat-forming genus, along with *M. trifoliata* and some *Scheuchzeria palustris*. The topmost 50 cm was well humified peat with tissue remains of *Betula* and *Pinus*.

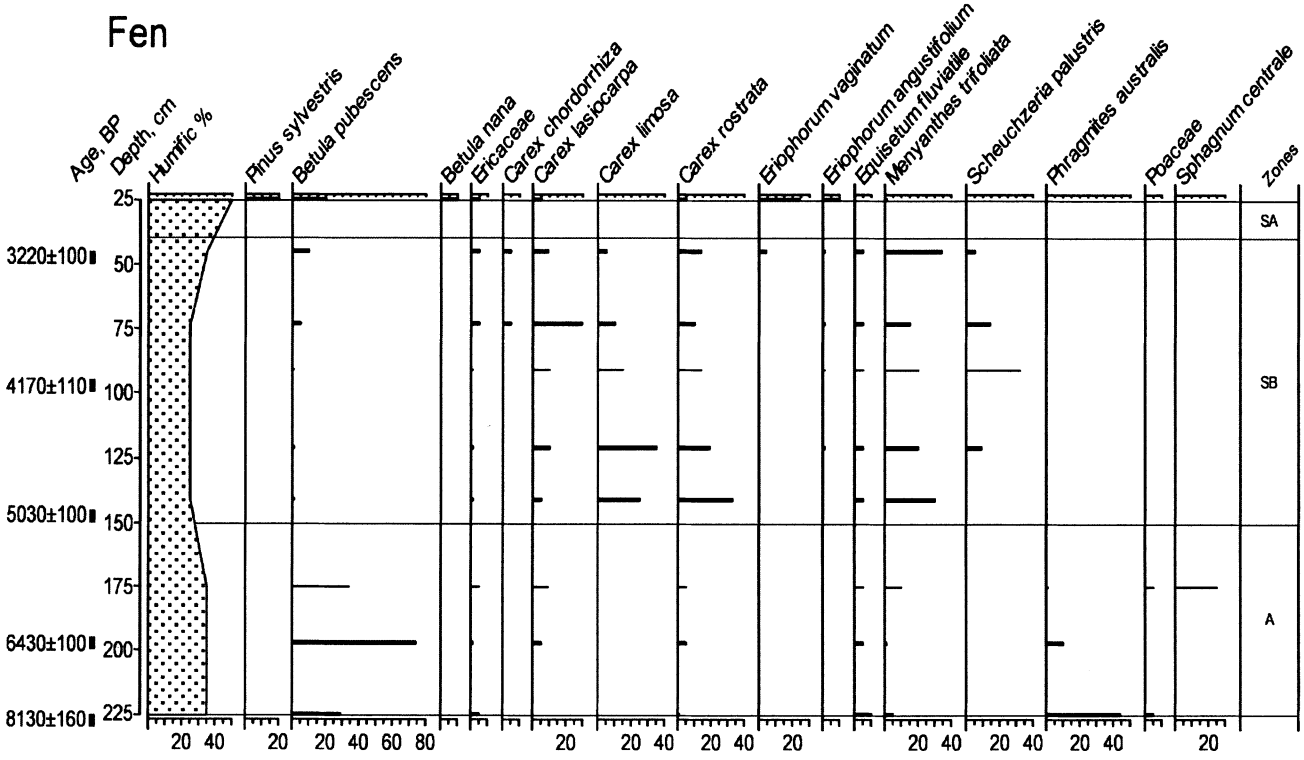

Figure 4 Humification percentage (R%), and relative percentage of plant tissue remains of different species in peat profile at the fen site. The chronozones are SA = Subatlantic, SB = Subboreal, A = Atlantic, B = Boreal. Chronozone lines represent ^{14}C years BP and have been drawn according to Donner *et al.* (1978).

Bog

The field stratigraphy investigation showed that the bottommost peat (435–430 cm) was very poorly humified (H2) *Bryales-Phragmites* peat, with some mineral matter in it. Within the next 10 cm, *Bryales* disappeared while woody *Carex* remains increased. This formed the dated basal peat. Thereafter *Carex* spp. became dominant and were the main peat-forming species for about 2000 years, between 9100 and 7200 BP (425–350 cm), (Figure 5). The peat consisted of the remains of *Carex lasiocarpa*, *C. limosa* and *C. rostrata* with some *Eriophorum angustifolium*, *Equisetum fluviatile* and *M. trifoliata*, indicating that the mire was a wet sedge fen at the beginning of its development. About 7200 BP (350 cm depth), these species disappeared and were replaced by *Eriophorum vaginatum* and some *Sphagnum* species. This, and the appearance of Ericaceous shrubs, suggest that the mire started to change into a wet ombrotrophic bog. Between 6600 and 4600 BP (320–250 cm), *S. fuscum* increased from 10% to over 30%, while *Eriophorum* decreased from its maximum of 60% to 10% and remained at about that level until the present day. The *S. fuscum* stage lasted until 2300 BP (120 cm). The peat of the *Sphagnum* stage was light coloured and poorly decomposed with 15% of humification (H4 in von Post). The surface peat since the *S. fuscum* stage had more hollows, as indicated by *S. balticum*, *S. magellanicum*, *S. majus* and *S. papillosum*. Drainage made the uppermost 10 cm of peat drier and the surface became covered by lichens, mostly *Cladonia* and *Cladina* species.

Pollen stratigraphy

The same main trends with the early occurrence of *Betula* and *Pinus*, followed by *Alnus* at about 8000 BP can be found in the arboreal pollen (AP) diagrams of both mires (Figures 6 and 7). Further, the period of deciduous trees (*Ulmus*, *Corylus* and *Tilia*) started around 6000 BP, and lasted about 1500 years. The deciduous trees started to decline when *Picea* colonized the area around 4600 BP. Coniferous forests became dominant about 1000 years later, at 3500 BP.

Pollen of field layer species (NAP) showed the same differences as plant tissue remains analysis. Sedge pollen (*Cyperaceae*) was abundant at the fen site until 3200 BP, whereas at the bog site it had decreased to less than 5% already around 6000 BP. Also Poaceae, Polypodiaceae and Ericaceae were more abundant at the fen than at the bog.

Discussion

Peat and carbon accumulation

Fen

Climate and landscape were favourable for peat formation before 9000 years BP in the study area, as indicated by our dated basal peat results, which agree with those of Tolonen *et al.* (1979) from a mire nearby. When paludification starts, the transition zone between the mineral substrate and the organic peat soil often remains thin (Korhola, 1992). At both studied mires, the organic matter content exceeded 90% in less than 10 cm. Peatlands in Finland have been measured to grow vertically at a rate of 0.2 to 4.0 mm yr^{-1} (Korhola and Tolonen, 1996). Our fen site grew at an average rate of 0.28 mm yr^{-1}. However, different stages clearly occurred in peat accumulation during development, as found also by Belyea and Warner (1996). The basal and the uppermost peat were well-decomposed woody peat and accumulated at much lower rates than peat between them. In addition, the basal peat was fed with nutrient- and oxygen-rich water from the esker nearby, providing good conditions for decomposers resulting in well-humified peat. The uppermost peat has been influenced by drainage, which has caused clearly compacted and well-decomposed peat. Minkkinen *et al.* (1999) reported that the surface peat in minerotrophic mires subsides 20–28 cm during a 30-year drainage period. If our fen site had continued its accumulation at the mean rate of 0.28 mm yr^{-1} since 3220 BP, the thickness of the upper section would have been 90 cm instead of 50 cm. The BD of the compacted surface peat was 52% higher than that for the peat below. Silins and Rothwell (1998) reported an even higher increase in BD (63%) in a shorter period of drainage.

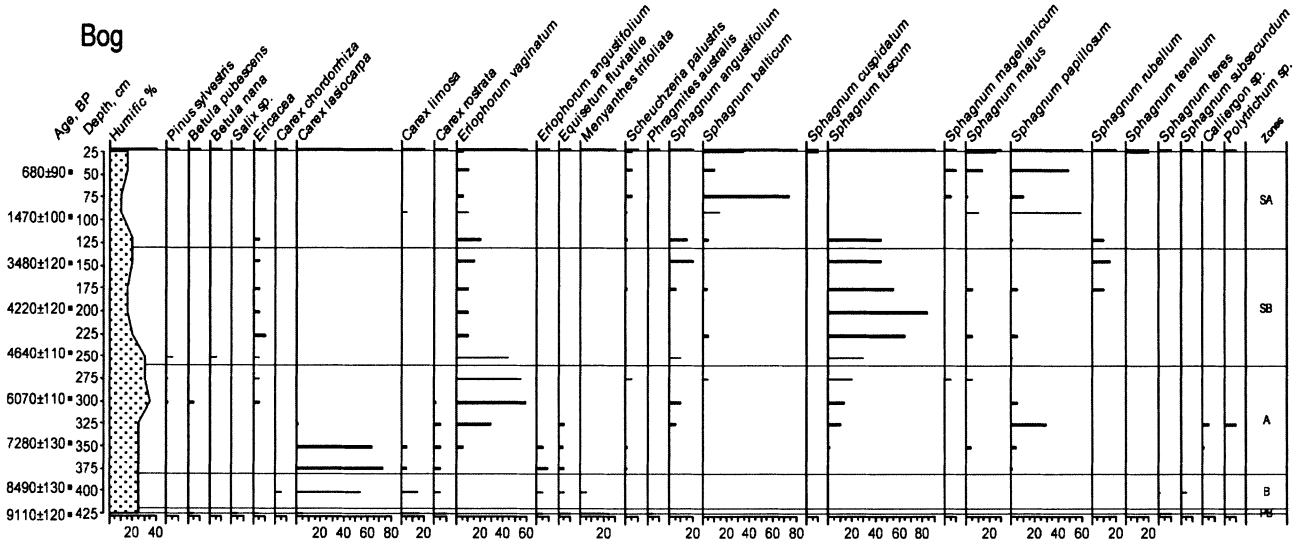

Figure 5 Humification percentage (R%), and relative percentage of plant tissue remains of different species in peat profile at the bog site. The chronozones are SA = Subatlantic, SB = Subboreal, A = Atlantic, B = Boreal, PB = Preboreal. Chronozone lines represent ^{14}C years BP and have been drawn according to Donner *et al.* (1978).

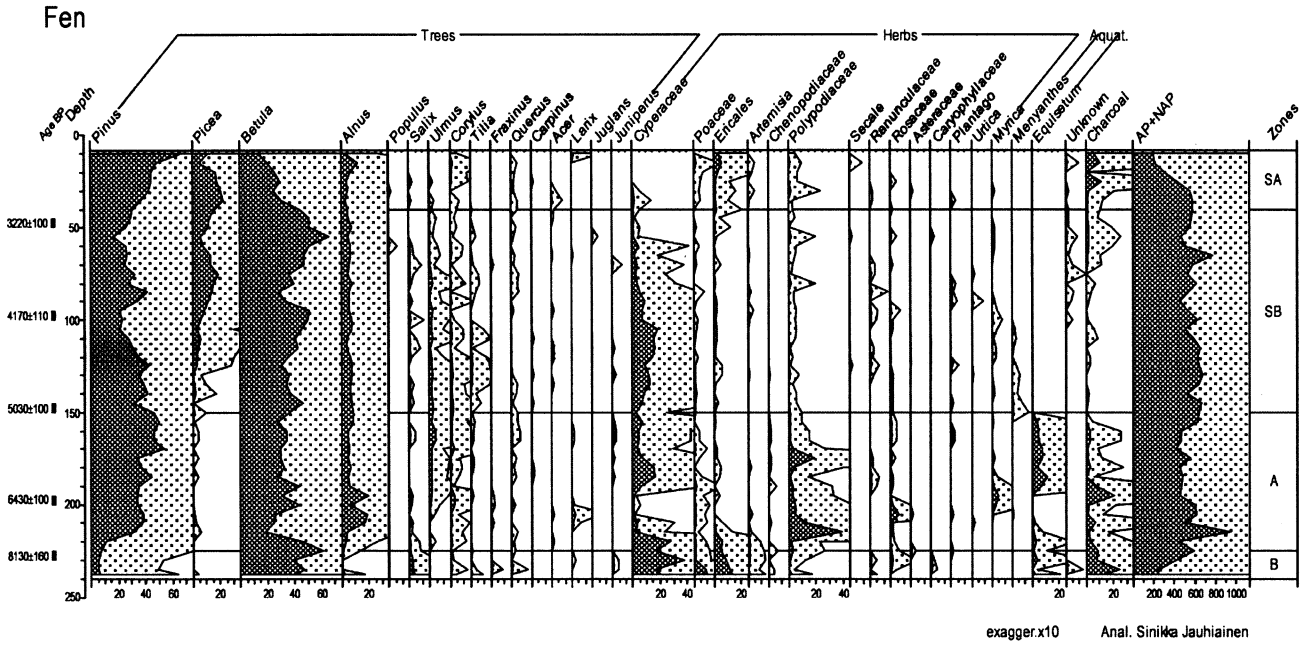

Figure 6 Relative percentage of pollen, spores and charcoal particles in peat profile at the fen site. Dark shaded curves show the relative percentage of species; light shading shows a 10-fold exaggeration. Pollen sum of AP + NAP (excluding aquatic plants) represents the total. Chronozones as in Figure 4.

Peat accumulation rate is also affected by autocompaction of the peat (Aaby and Tauber, 1975; Clymo, 1983). Our fen site showed some autocompaction, as seen from the measured BD, which slightly increased with increasing depth below the compacted drained surface.

Carbon accumulates at different rates depending on the age of the mire. Korhola (1995) and Tolonen and Turunen (1996) found that the LORCA was lower for old than for young mires. Further, they reported that the LORCA was usually lower for fens than for bogs, and lower for drained than for undrained mires (Turunen *et al.*, 2002). We measured a LORCA of 11.1 g m^{-2} yr^{-1} at the fen site, which was a little lower than the average (15.1 g m^{-2} yr^{-1}) reported by Tolonen and Turunen (1996) for fens in Finland.

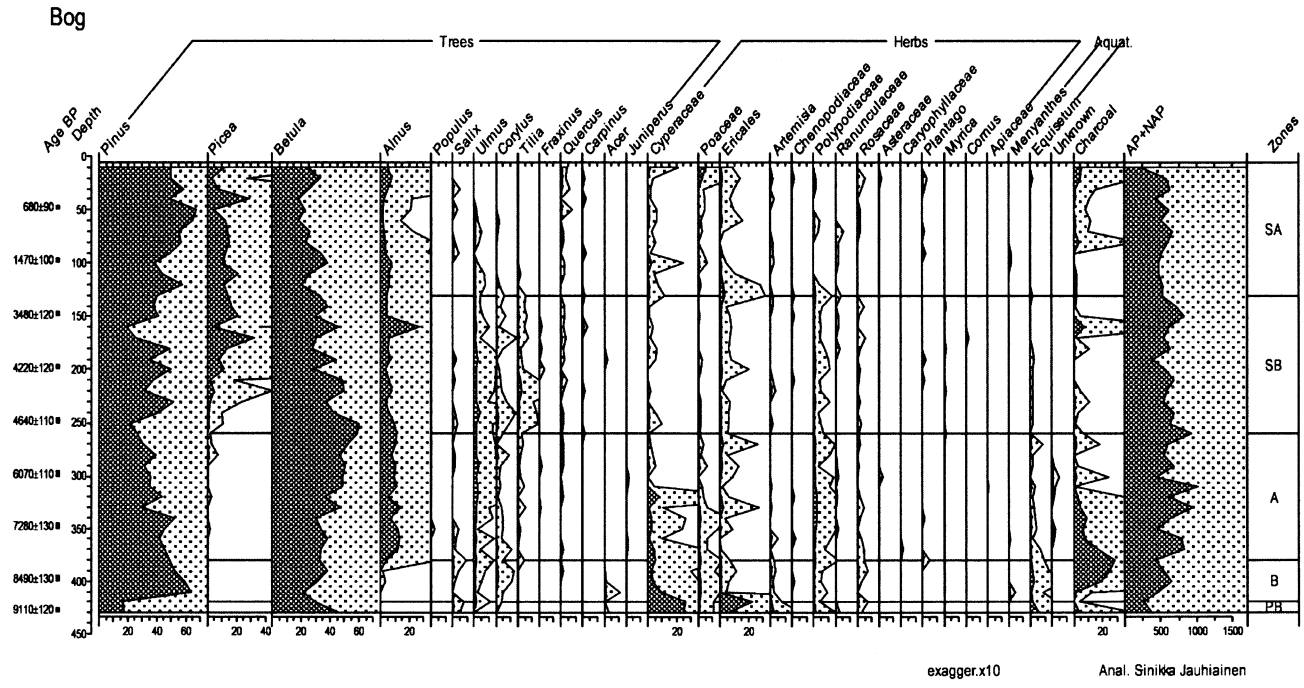

Figure 7 Relative percentage of pollen, spores and charcoal particles in peat profile at the bog site. Dark shaded curves show the relative percentage of species; light shading shows a 10-fold exaggeration. Pollen sum of AP + NAP (excluding aquatic plants) represents the total. Chronozones as in Figure 5.

The average of 50% of C has often been used in carbon accumulation calculations. This may give too high figures for C budgets. The mean rate of LORCA reported for the whole age of the peat disregards different stages of peat development. The input rate of carbon shows high variation, contrary to what was suggested earlier (Clymo, 1984). Klarqvist (2001) also found high variations in C accumulation in mires in Sweden. Factors such as species composition, decomposition rate (Tolonen and Turunen, 1996), climatic change and mire fires (Kuhry, 1994; Pitkänen *et al.*, 1999) have influenced carbon accumulation rates at different periods during peat development. Carbon accumulated at a rate of 6.6 g m^{-2} yr^{-1} in the bottommost well-decomposed woody peat of the fen. In comparison, *Carex* peat above had a much higher C accumulation rate (12–15 g m^{-2} yr^{-1}). A low C accumulation rate in the uppermost 50 cm surface peat was mostly due to drainage, and the consequent increased proportion of woody remains in peat.

Bog

The average peat accumulation rate was almost twice as fast at the bog site than at the fen site. However, variation in accumulation rate was high. This variation was due to changes in vegetation composition, mostly by alternation of hummocks and hollows, as was also found in other studies (Tolonen, 1973; Damman, 1978; Ikonen, 1993; Korhola and Tolonen, 1996). Peat formed of *Eriophorum* and *Carex* accumulated approximately at a similar rate (about 0.4 mm yr^{-1}). The humid climate during the Subboreal period favoured peat accumulation as well as the initiation of paludification (Korhola, 1995). The highest accumulation rate (1.19 mm yr^{-1}) occurred during the period between 4600 and 1800 BP when peat was composed mostly of *S. fuscum*. An increased accumulation rate with a weaker decomposition rate at this period has also been reported by Tolonen and Turunen (1996). *S. fuscum* characteristically forms a carpet of tightly packed shoots which have great capillary capacity (Lindholm and Markkula, 1984). Further, the species is the most resistant for decay (Johnson and Damman, 1991; 1993; Malmer and Wallen, 1993; Charman, 2002). The presence of uronic acids in *Sphagnum* peat act as acidifying agents (Verhoeven and Liefveld, 1997; Charman, 2002), which additionally decrease the decay rate.

Increased BD below the depth of 200 cm, i.e., during the first stage of the bog development, suggests some autocompaction of peat. Above that depth the hummocks and hollows structure created large variation in BD (Aaby, 1976) and less autocompaction. Because it is unlikely that two different cores hit exactly the same microforms, the BD also differed between the two sampling years.

The influence of drainage in the surface peat was hardly noticeable at the bog site, although a subsidence of 4–12 cm has been reported for drained ombrotrophic mires in a 30-year time period (Minkkinen *et al.*, 1999).

The carbon accumulation rate of 13.2 g m^{-2} yr^{-1} for the bog was lower than the average reported for bogs in Finland (24.0 g m^{-2} yr^{-1}; Tolonen and Turunen, 1996), but closer to that reported for Siberian mires, mostly bogs (17.2 g m^{-2} yr^{-1}; Turunen *et al.*, 2001). However, our result fell in the ranges reported in both of the referred studies, as well as for that found in Canadian *Sphagnum* mires by Kuhry and Vitt (1996). The low C accumulation rate can be explained by the age of the bog in this study (cf. Korhola, 1995; Tolonen and Turunen, 1996). The variation in C content and accumulation rates in different periods during the peat development has also been taken into consideration.

High variation was found in carbon accumulation at different periods during the bog development. Low C accumulation rates (9.7 and 6.1 g m^{-2} yr^{-1}) occurred at the climatic boundaries of Atlantic-Subboreal and Subboreal-Subatlantic. Carbon accumulated at a high rate during the period of *S. fuscum* maximum, i.e., 4600–4200 BP, in accordance with Johnson and Damman (1991). The highest C accumulation rate (21.1 g m^{-2} yr^{-1}) occurred in the uppermost 50 cm of peat in agreement with values reported for recent peats by Tolonen and Turunen (1996). Carbon accumulation since 2500 BP was favoured by increased precipitation (Eronen and Zetterberg, 1996). Under these conditions, the rate of decay decreased.

Chemostratigraphy and vegetation

Fen

Great changes occurred in element concentrations in the transition zone between the mineral bottom and the organic peat soil. The mire initiated as a nutrient-rich reed thicket as indicated by plant remains of *Phragmites australis*, *Equisetum fluviatile* and *Betula* spp. Since then, the peat chemistry was regulated by large climatic changes and local changes in the watershed. The vicinity of the esker Vatiharju plays a key role in element concentrations in the fen.

Element concentrations in vegetation do not directly determine the concentrations in peat (Malmer, 1958). The source of water and its variations during growing seasons influence the decay processes in the acrotelm (Damman, 1978; Malmer, 1986), which further regulate the input rates of chemical substances and plant remains to the catotelm (Clymo, 1978; Ingram, 1978; Damman, 1978; Malmer, 1986).

Between 8100 and 5000, i.e., during the Atlantic period, the mire developed into a more acid and low nutrient level pine fen. The concentration of Fe was high until 4300 BP (110 cm) especially in the core taken in 1994. The glasiofluvial sandy deposits of the esker were the primary source of the iron (Haavisto, 1983). Possibly, trickles of water, which were also observed at the peat surface during the restoration, transported element-rich waters to the mire causing differences in element concentrations over very small distances as seen in the differences of especially with Fe, Ca and pH between the two corings, in 1994 and 1997 (Figure 2).

During the time period of 5200–4200 BP, which includes the climatic boundary between the Atlantic and Subboreal periods, great changes occurred in peat stratigraphy. The element concentrations (Ca, Mg and Mn), which had gradually decreased, collapsed around 4500–4400 BP and remained at very low levels. The mire, which had developed under the influence of minerotrophic waters, became influenced by the ombrotrofication phenomenon (Korhola and Tolonen, 1996). Due to accumulated peat, the groundwater did not reach the peat surface, which became diluted by low-nutrient precipitation water (Damman, 1978; 1986; Malmer, 1986). The concentrations of Ca and Mg decreased approximately to the same level as they were at the bog site (Ca 1 mg g^{-1} and Mg 0.3 mg g^{-1}) at this time. The vegetation became dominated by *Carex limosa* and *C. rostrata* with some *C. lasiocarpa*, *M. trifoliata* and *Scheuchzeria palustris*, all species which indicate a very poor fen type (Malmer, 1958) and wet conditions in a mire (Heikkilä *et al.*, 2001). Simultaneously, species composition in the surrounding forests changed from deciduous to coniferous, which provided more acidic and lignin-rich litter to the nutrient cycle (Mahendrappa, 1974). The poor fen stage continued to the present day.

The upper 50 cm of peat became compacted due to drainage, as indicated by high BD. The concentrations for K, P, Ca, Mg and Mn were higher at the surface than at 50 cm depth. Drainage has been reported to induce a decrease in the concen-

trations of base cations in surface peat (Heathwaite, 1992; Laiho *et al.*, 1999). It also has been found that water from drained mires is enriched with N, P and K (Naucke *et al.*, 1993). However, several elements exist in relatively high concentrations in the biologically active surface layer and tend to decrease to lower concentrations further down the profile as found by Damman (1978), Laiho *et al.* (1999) and Jauhiainen *et al.* (2002). The occurrence of *E. vaginatum* remains in the surface peat indicates drier and disturbed conditions, possibly due to an earlier drainage period, which happened before intensive drainage for forestry purposes. The peat is also rich in woody remains (*Pinus* and *Betula*). The radiocarbon age of 3220 BP for 50 cm depth showed that the upper part of the peat should have been studied at smaller than 10 cm intervals. Large amounts of information remain undetectable when the rate of decay is high (Aaby, 1976).

Bog

Minerotrophic peat formed first at the site, similar to most of the raised bogs in Finland (Korhola and Tolonen, 1996). The remains of brown mosses and *Phragmites australis* in the first few centimetres of the transition zone between the mineral bottom and the organic peat indicate the presence of mineral-rich waters and rich fen vegetation (Malmer, 1958). The deepest samples for radiocarbon analysis and plant remains analysis were from the depth of 425–430 cm; thus the preceding thin section of poorly decomposed *Bryales-Phragmites* phase cannot be seen in the plant remain graph. The influence of minerogenous water continued until around 7200 BP, as indicated by high Ca/Mg ratio (Mörnsjö, 1968) and a high Fe concentration. Subsequently, early *Carex*-dominated mire started to develop towards a nutrient-poor *Sphagnum* mire. This, according to Seppä (1991) and Korhola (1992) indicates ombrotrofication.

During the climatic boundary between the Atlantic and Subboreal periods around 5000 BP, the major nutrients (Ca, Mg, P and N) oscillated strongly, after which they remained at very low levels and the bog vegetation became dominated by *S. fuscum* for about 2000 years. The minerotrophic *Betula-Carex*-dominated vegetation at the fen site possibly was more resistant to climatic changes than the ombrotrophic *Eriophorum-Sphagnum*-dominated vegetation at the bog site. Thus the changes in chemostratigraphy at the fen were not so distinct during this stage. Mörnsjö (1968) also reported a 'geochemical boundary' as the change from minerotrophy to ombrotrophy in southern Sweden around 4600 BP. Similar directional changes occurred also in Canadian mires in the period between 5500 and 3000 BP (Payette, 1984).

The highest N content (about 2%, Figure 3) in this study exceeds the values reported for bog peat (e.g., Malmer and Holm, 1984; Damman, 1988). The high N occurred during the period when peat was composed of weekly humified *S. fuscum* and peat accumulation rate was high. Jauhiainen *et al.* (1992) found that increased N deposition increases the length growth of *S. fuscum*. Nitrogen is enriched in actively growing parts of *Sphagnum* (Tukey, 1970), resulting in N accumulation in peat. The increased N may also be a consequence of the decomposition process, in which carbon is used as an energy source and N is immobilized by the microbial population (Malmer and Nihlgård, 1980; Malmer and Holm, 1984). An increased N content was also observed in peat deposited during the period of 1400–1000 BP, when the peat was composed of *S. balticum* and *S. papillosum*. These species might also benefit from high N content. In addition, this layer was very rich in fossils of microfauna, especially testacean amoebas (Jauhiainen, 2002). Was N immobilized by them? Unfortunately testacean amoebas were studied only to the depth of 100 cm.

During the latest 5000 years, climatic conditions became cooler and more unstable (Eronen and Zetterberg, 1996). Climatic variations affected the formation of hummocks and hollows (Aaby, 1976), whose pattern influenced the oscillating element concentrations in the peat profile, as found also in this study. Pakarinen (1978) found that the concentrations of Ca and Mg were higher in *Sphagnum* species growing on hummocks than in hollows. In contrast, higher concentrations of Al, Fe, P and N have been measured in surface peat hollows than in hummocks (Damman, 1978). The N concentrations may be 2–3 times higher in hollows than in hummocks (Damman, 1978). More hollows developed in the bog between 3500 and 1000 BP, as indicated by the presence of *E. vaginatum*, *S. balticum* and *S. papillosum* in the vegetation composition and the lower accumulation of peat with faster decay (Johnson and Damman, 1993).

Anthropogenic influences in the surface peat of the bog site have remained small. Low nutrient levels do not allow great changes in their concentrations, nor in the vegetation composition (Vasander *et al.*, 1997). Drainage made the uppermost 10 cm of peat dry and crispy, and the surface became densely covered by lichens, *Cladonia* and *Cladina* species, which is typical for ombrotrophic mires after drainage (Vasander, 1982; Laine and Vasander, 1990).

Surrounding forests

The appearance of *Betula*, *Pinus*, *Alnus* and *Picea* pollen in 9100, 8500–8100, 8100 and 4600 BP, respectively, is characteristic for peat deposits in Finland (e.g., Tolonen, 1966; Donner *et al.*, 1978; Korhola, 1992; Ikonen, 1993). The warm and humid climate of the Atlantic period favoured the growth of deciduous forests in Finland (Alhonen, 1970; Donner *et al.*, 1978; Eronen, 1990). Species such as *Ulmus*, *Tilia* and *Corylus* were flourishing, especially at the end of the period between 6000 and 5000 BP at 61° latitude (Tolonen, 1966; Tolonen and Ruuhijärvi, 1976). Large-scale climatic changes occurred at the boundary between the Atlantic and the cool Subboreal periods around 5000 BP. Deciduous trees started to decline, partly because of vegetational succession (Donner, 1972), but mostly as a consequence of climatic change. *Picea abies* spread into the area, and exceeded the 5% level in the pollen stratigraphy in 4400 BP. The forest structure changed gradually from deciduous forests to coniferous forests (Donner, 1966; Hyvärinen, 1975; Donner *et al.*, 1978; Ikonen, 1993). During the last 2000 years, climate has become cooler (Aaby, 1976; Eronen, 1990). This has favoured the growth of *Pinus*, whose pollen has increased in the latest stratigraphy.

Conclusions

The peat at the fen site accumulated at a much lower rate than at the bog. Carbon accumulated at different rates during peat development. The accumulation rate was determined by the rate of decay and species composition. The nutrient status in both mires developed towards lower nutrient levels. Followed by large-scale climatic changes, great changes occurred in peat chemistry in both mires between 4600 and 4200 BP with simultaneous change from deciduous to coniferous forests. Because minerotrophic peatlands are dependent on their watersheds, drainage influence can also clearly be seen in the physicochemical changes for the surface peat of the fen. Being dependent on precipitation, ombrotrophic peatlands react more slowly to changes in their surroundings. Thus, drainage influence was hardly noticeable in the bog stratigraphy.

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