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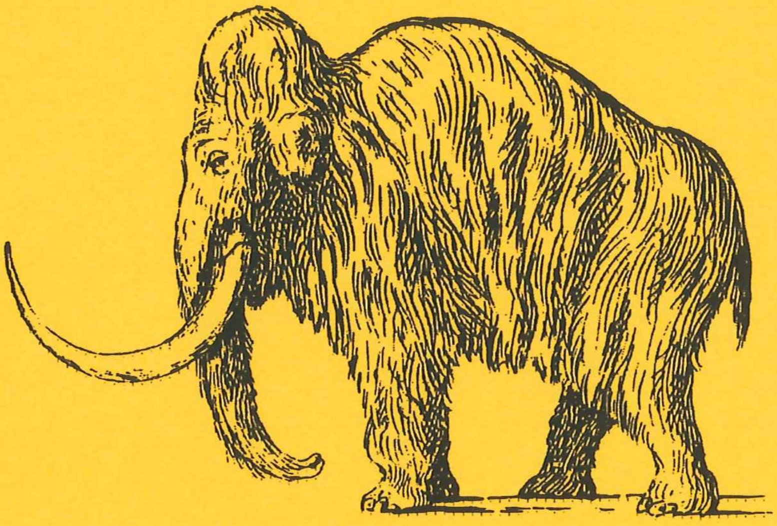

Late Holocene dune activity at Sandhammaren, southern Sweden - chronology and the role of climate, vegetation, and human impact

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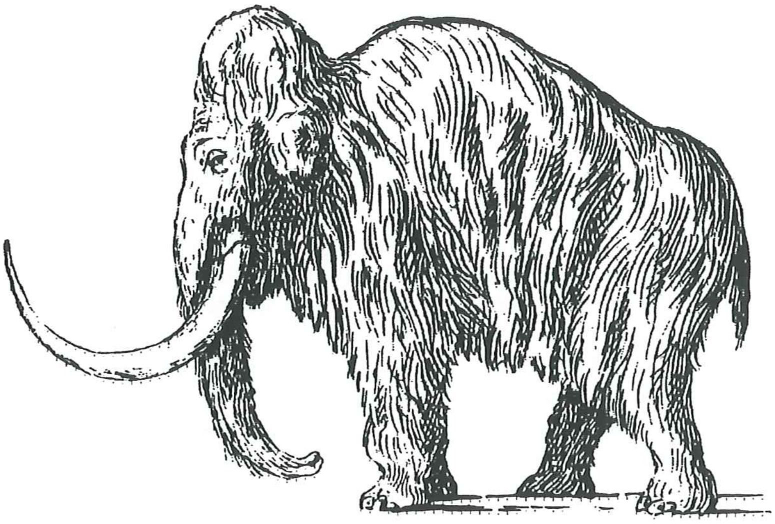

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Abstract: The palaeosoils at Sandhammaren and Skanörs ljung, southern Sweden, are located within a coastal dune landscape that developed in response to Holocene land/sea changes. These buried soils are characterised by several organic layers including pedological horizons. They were studied for fossil pollen, and soil chemistry (iron, aluminium, manganese, phosphorous, carbon, and pH) in order to appreciate the extent of leaching processes in the soils, and to understand the possible processes involved in their development, e.g. climate, vegetation history, and human impact. Macroscopic charcoals were selected from a series of levels in the soil profiles for AMS ^{14}C dating. The chemical results show that the palaeosoils have developed characteristic eluviation and illuviation zones and hence some degree of podzolisation. The soils developed under a *Calluna* heathland, with a low representation of trees. The *Calluna* heaths at Sandhammaren have been maintained by grazing and burning as part of a traditional land use which has only declined in the present century leading to woodland regeneration. The best age estimates for Late Holocene soil formation at Sandhammaren are between *c.* 2000 cal. BP (or even earlier, *c.* 2600 cal. BP) and *c.* 500 cal. BP with minor interruptions of sand drift between *c.*1800-1400 cal. BP (AD 250-550) and *c.* 900-700 cal. BP (AD 1050-1250). The most prominent dune activity took place prior to *c.* 2600 cal. BP and after *c.* 500 cal. BP (AD 1450), and probably reflect the relatively warm and dry climate conditions at the end of the Subboreal period (*c.* 4000-2600 BP), and after the Little Ice Age, from *c.* 1800 AD. The periods of minor sand drift *c.* 1800-1400 cal. BP and *c.* AD 1050-1250 may be compared with the time of low lake-levels in southern Sweden, *c.*1200-1800 BP, and the Medieval warm period, around AD 1000, respectively. Alternating periods of soil and dune formation during the Holocene have been detected in several parts of Europe and were discussed in terms of regional climate changes. This study concludes that soil formation at Sandhammaren was initiated by climatic shifts, from warm and dry to cold and wet conditions, while the maintenance of *Calluna* heaths during the period of soil formation was due to human impact. During the 18th and 19th centuries dune activity was very strong and due to a combination of climatic and human-impact factors.

Introduction

Palaeosoils are valuable archives for reconstruction of past environments. Buried soil profiles may provide information on past pedogenesis, human impact, vegetation succession, sea-level changes, dune activity, and hydrological changes.

This study is part of the project "Late glacial and Holocene dune history in southern Skåne". Previous work includes AMS ^{14}C dating and pollen analysis of a few levels at two selected sites at Sandhammaren (Gaillard *et al.* unpublished). Moreover, former investigations on the coastal dune areas of Scania have been the studies of sand vegetation by Olsson (1974), and of littoral processes and morphology of the Scanian coasts by Davidsson (1963). The present study involves high resolution soil chemistry and pollen analysis of three selected dune profiles. The aim of the research was to gather information for a better understanding of the possible causes of past dune activity, human-or climate induced.

The sites selected for the investigation are Sandhammaren and Skanörs ljung in southern Sweden. At these sites, marine sediments have accumulated in response to Holocene land/sea level changes. Sandhammaren is a large coastal dune area, whereas Skanörs ljung is affected by deflation and high dunes have never developed. The main part of the study was performed on material from Sandhammaren. In that area, the palaeosoils are characterised by several organic layers, including pedological horizons. They are of limited lateral extent, and have developed in depressions between the dune ridges. They are now covered by up to 1.2 m of aeolian sand, and a recent soil horizon. In an attempt to find a modern analogue of the ancient environment at Sandhammaren (*Calluna* heath), Skanörs ljung was selected as a site for comparison. Unfortunately, the recent soil was not well developed, but a palaeosoil was found instead. Therefore, the study of Skanörs ljung is to be regarded as a complement to the main investigation at Sandhammaren.

The present study have four major aims:

1) to obtain an absolute age for the time of formation of the different layers of palaeosoils,
2) to describe the local vegetation during the time of palaeosoil formation, and investigate whether the present oak-dominated vegetation at Sandhammaren has a long continuity back in time,
3) to appreciate the degree of maturity of the palaeosoils, i.e. the degree of leaching or podzolisation,
4) to estimate the role of climate, vegetation and human impact in past dune activity and soil formation.

Dune landscapes such as that of Sandhammaren exist in many parts of the coastal areas around the Baltic Sea, e.g. along the Polish coast. There, the dominant tree species today are beech (*Fagus sylvatica*) or pine (*Pinus sylvestris),* whereas oak (*Quercus robur*) is the common tree species at Sandhammaren. However, oak was found to be much better represented on the Polish dunes during the Holocene, between c. 3000 and 2800 years ago, e.g. Łeba Bar (Tobolski, 1980). Therefore, the modern oak woods of Sandhammaren may represent an interesting analogue of the past vegetation of Łeba Bar.

The concentration of extractable iron, aluminium, manganese and phosphorous, changes in pH, and the variation in the vertical distribution of organic material allow to appreciate the degree of soil development or podzolisation. Moreover, the concentration of phosphorous gives important information which can rule out alternative interpretations of the buried organic layers, e.g. the possible occurrence of cultural layers.

Palaeosoils in coastal dune landscapes reflect time periods with decreasing or no dune activity. They may also correspond to periods of increased average humidity and related high ground-water levels. In reverse, a lower ground-water level can be a response to decreased average humidity. A period of low ground-water level may be at the origin of reinforced dune activity, as wind erosion will be more performant in dry than in wet sand. Moreover, the vegetation cover may be altered by a drier climate, creating a more open type of landscape that will have a weaker stabilising effect on the dunes. Studies of Holocene lake-level fluctuations in southern Sweden (Gaillard and Digerfeldt, 1991) have shown that such changes have been of regional significance and, therefore, climatically induced. Correlation of the regional lake-level changes with the periods of palaeosoil formation along the coast may help to understand the possible role of climate in dune activity.

A further possible cause for dune formation is human activity, such as forest clearing, grazing and burning, all contributing to sand drift. It is known from archaeological studies that humans lived on the sandy coastal areas of southern Scania *c.* 7000-6000 years ago. Larger settlements date from the Late Neolithic time (Berglund, 1991). In the Sandhammaren area, there are also traces from the Late Iron Age (*c.* 1500 cal. BP). There, the major part of the landscape has long been a large grazing outland for the villages along the coast.

Old maps show that during the nineteenth century and the beginning of the twentieth century, the area was characterised by a sparse vegetation. Grazing and cultivation were very intensive. *Calluna* and grass heath were dominant elements in the landscape (Emanuelsson, 1993). During the eighteenth century oaks were protected by a Royal Ordinance. However, at the end of the eighteenth century the oak stands had been destroyed on the coastal sands of Sandhammaren.

Numerous buried soil profiles have been investigated in the world. This study compares the results with other parts of Europe. Periods of alternating dune/soil formation have been dated e.g. in Denmark (Christiansen & Bowman, 1986; Dalsgaard & Odgaard, unpublished), Norway (Selsing & Mejdahl, 1994), Poland (Tobolski, 1980), England (Tooley, 1990), and Ireland (Shaw & Carter, 1994; Wilson & Bateman, 1986; Wilson, 1990; Cruickshank, 1980). Such a comparison allows us to further analyse the regional significance of the palaeosoils at Sandhammaren and Skanörs ljung, and the possible role of climate.

The study areas

Site description

Sandhammaren

The investigation area at Sandhammaren (55°22’95”N/14°10’70”E) is situated at an average altitude of 5 m a.s.l. It is a marine foreland with an area of more than 1000 ha, one of the largest dune areas in Sweden (Fig. 1). The length of the coast line is about 15 km, from Löderup Beach in the south to Mälarhusen Beach in the east. The dune area has its broadest extent in the central part, where it is about 1 km wide. It is much narrower in the peripheral parts. The dune landscape is characterised by prominent dune ridges rising up to 5 m above the surroundings, and oriented in a W-E direction (Fig 1c, 2). They are often strongly affected by deflation (Davidsson, 1963).

Normally the mean annual, July, and January temperatures at Sandhammaren are 7-8°C, 16-17°C, and about 0°C, respectively. The mean annual precipitation is around 588 mm. The dominant strong wind directions are SW-W and ENE-E. In southern Sweden, the tides have no influence on the water level. The vegetation in the inner dune landscape, is largely dominated by oak and pine forests. Deflation and blowouts are characterised by a mosaic of *Calluna vulgaris* (heather) and *Cladonio-Corynephoretum* communities (Olsson, 1974). *Cladonia destricta* and *Stereocaulon condensatum* (two lichen species) are characteristic taxa of the latter community, typical of dry, non-calcareous soils on eroded aeolian sands poor in nutrient minerals. The pioneer *Cladonio-Corynephoretum* vegetation has a western oceanic distribution in middle and western Europe (Olsson, 1974). In the *Calluna vulgaris* community, oak *(Quercus robur)* regeneration is obvious,

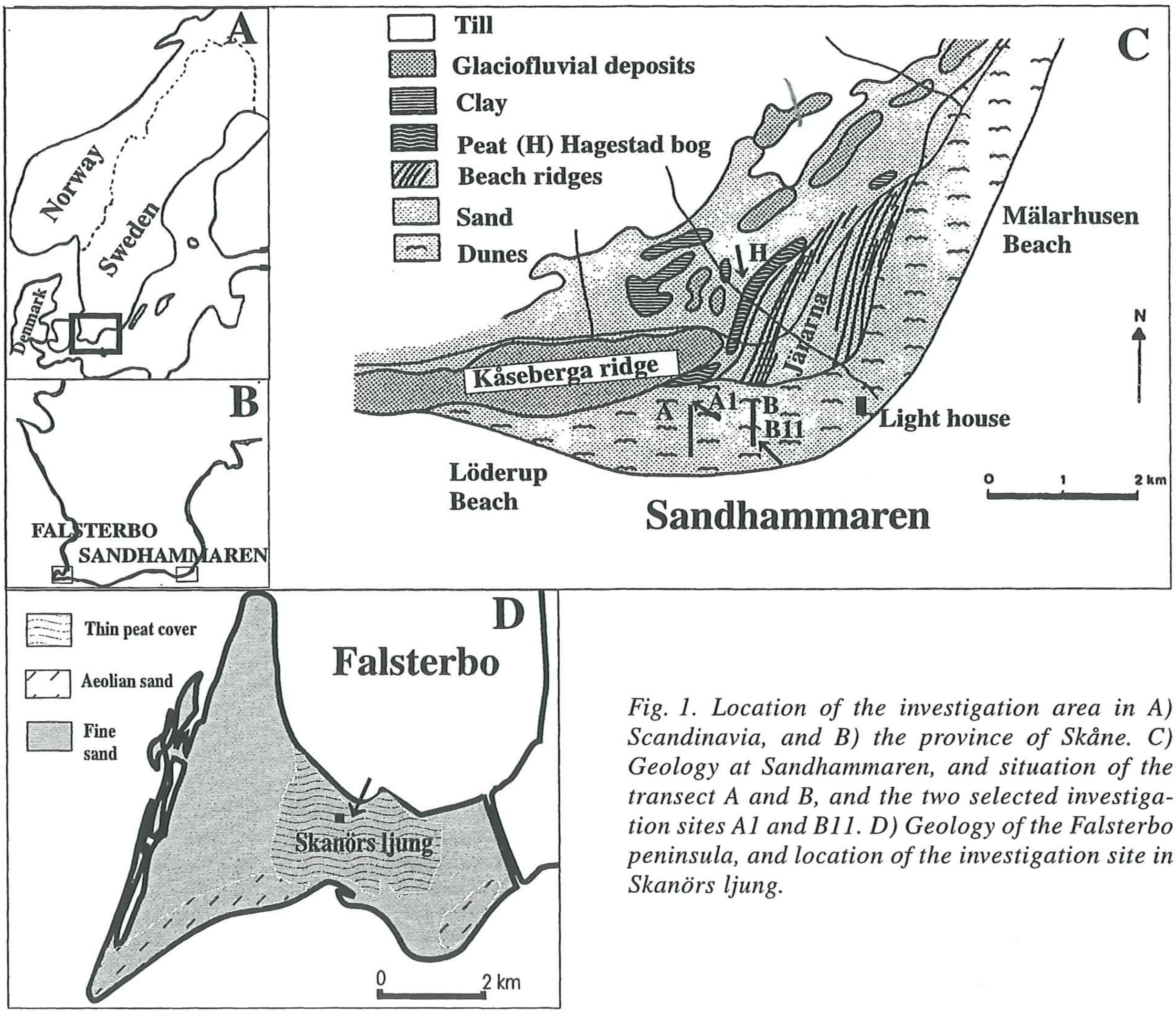

Fig. 1. Location of the investigation area in A) Scandinavia, and B) the province of Skåne. C) Geology at Sandhammaren, and situation of the transect A and B, and the two selected investigation sites A1 and B11. D) Geology of the Falsterbo peninsula, and location of the investigation site in Skanörs ljung.

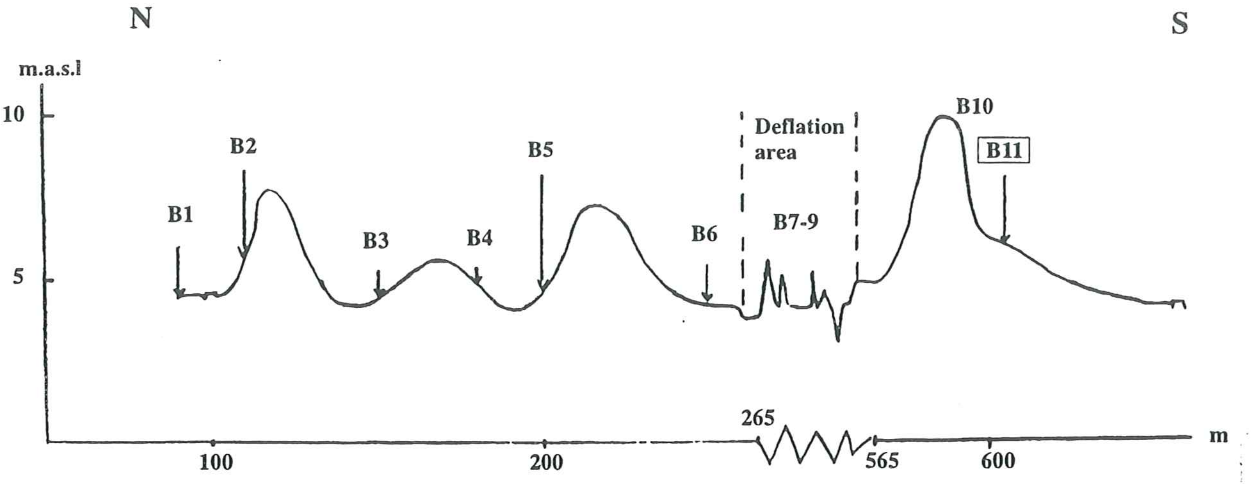

Fig. 2. Transect B (see Fig. 1C) through the dune system showing the position of the studied site B11. B1-B10 represent soil profiles investigated in an earlier survey study (Gaillard et al. unpublished).

and the heather has strongly decreased. Pine forests belong to the species-poor *Deschampsia flexuosa-Pinus sylvestris* community. *Carex arenaria* and *Vaccinum vitis-idaea* are common species in the ground vegetation of such forests (Olsson, 1974).

Skanörs ljung

The investigation area at Skanörs ljung is situated on the Falsterbo peninsula (54°24’50”N/12°54’E) (Fig. 1) at an average altitude of 5 m a.s.l. It is also a recent formation whose genesis and development fall entirely within the Holocene. The peninsula of Falsterbo is built up by a series of beach ridges connected to each other. The main part of the peninsula, about 2 m above sea level and 10 km in width, is a deflation area, and high dunes have never developed. Outside the town of Falsterbo-Skanör, lagoon lakes occur parallel to beach ridges. The development of new reefs and isolated lagoons is still active.

The temperature characteristics are the same as at Sandhammaren. The mean annual precipitation is 442 mm. The vegetation of Skanörs ljung is a wet heath dominated by *Ericion tetralicis* and *Calluna vulgaris* communities. It is surrounded by pine plantations. *Quercus robur* is rare in the area, and is confined to dry ground (Olsson, 1974).

Geology

Sandhammaren

The bedrock in the area at Sandhammaren consists of Cambro-Silurian and Mesozoic sandstones and shales (Daniel, 1986). To the South the bedrock has a thicker till cover, which gradually sinks below sea level as a pronounced moraine plain. The Kåseberga ridge is 13 km long and forms a coastal cliff with a south-east direction (Fig. 1). It consists of glaciofluvial deposits. The dune landscape is limited to the North by the Kåseberga ridge in its western part, and by a plain of beach ridges in its eastern part (“Järarna“). Most beach ridges cut through the landscape in a NNE-SSW direction. Between the coastal cliff and the beach ridges lies the Hagestad peatbog. It is divided into two parts by a 2.5 km long spit situated 7-7.5 m above sea-level. The latter formed during a longer period of constant sea level (*c.* 7000 BP), before the maximum level of the Baltic Sea during the Litorina transgression (Davidsson, 1963).

During Lateglacial time, the Kåseberga ridge was a peninsula separated from the higher situated land on the North by a narrow sea bay. The marine foreland originates from the time of the Litorina transgression. The initial shore line followed the border between the aeolian sand field and the beach ridge plain. During the course of postglacial time Kåseberga ridge was progressively abraded. The mobilised material drifted towards the west and was deposited on the lee side of the ridge. Winds from W-SW drifted the material in the opposite direction and Sandhammaren was enlarged. As the sea level was progressively lowered after the Litorina maximum, and finally approached the present level, the abrasion and the littoral drift decreased (Davidsson, 1963).

Skanörs ljung

The bedrock at Falsterbo peninsula consists of a gradually sloping chalk rock dating from the Tertiary period, Danien (Ringberg, 1975). The bedrock is covered by till, which is overlain by marine sand, including aeolian sand, and outcrops only in a few places. Generally, the thickness of the sand varies between 9 and 18 m (Davidsson, 1963).

Materials and Methods

Site selection, profile description and sampling

Sandhammaren

At Sandhammaren two profiles (A1 and B11) were selected on the basis of former surveys performed by Gaillard *et al.* (unpublished) along two parallel N-S transects A and B (Fig. 1C). The selection criteria were (1) well developed soil profiles with thick organic layers and (2) AMS ^{14}C dates of terrestrial macro remains that appeared to be reliable.

At both sites (A1 and B11), a 2.5 m deep excavation was made within a depression situated between stabilised dunes. The earlier survey of soil profiles on the two A and B transects showed that the best developed and best preserved fossil soil horizons were found where vegetation probably had the best preserving potential. Such locations are depressions, and the dunes northfacing lee sides which have lower temperatures, less insolation, and a lower evaporation rate, promoting a denser vegetation cover (Bridge & Ross, 1983).

A first soil description and subdivision of the different horizons was made in the field. In the laboratory, further classification was made, based upon the soil units used for the FAO-Unesco soil map of the world. Soil colour was assessed using Munsell Soil Colour Charts (Fig. 3).

The soils are buried by a light brownish sand (10YR 6/3) of variable thickness (80-120 cm) and a recent soil horizon. The profiles are subdivided into several horizons (Fig. 3). The upper C horizons (1) cover a transition horizon (2), with sand and lenses of organic matter. The very dark grey (10YR 3/1) organic rich layers are buried layers consisting of a mixture of organic and mineral material, and classified as buried Ah (Ahb) horizons. There are three Ahb horizons in profile B11, and two in A1. The boundaries between them and the intermediate and underlying bleached layers (buried E (Eb) horizons; 3), are distinct. The Eb horizons are dark grey (10YR 4/1), and characterised by a lower content of organic matter. They do not show the characteristic bleached colour, and are therefore poorly developed. However, because the soil profiles show evidence of illuviation and sharp boundaries to the Ahb horizons, they are considered as E horizons. Under the lowermost Eb horizon, a thick layer of sand with light spots within a dark reddish matrix occurs. The upper part of this complex (zones 4 and 5) can be classified as buried B (Bb) horizons that are enriched in

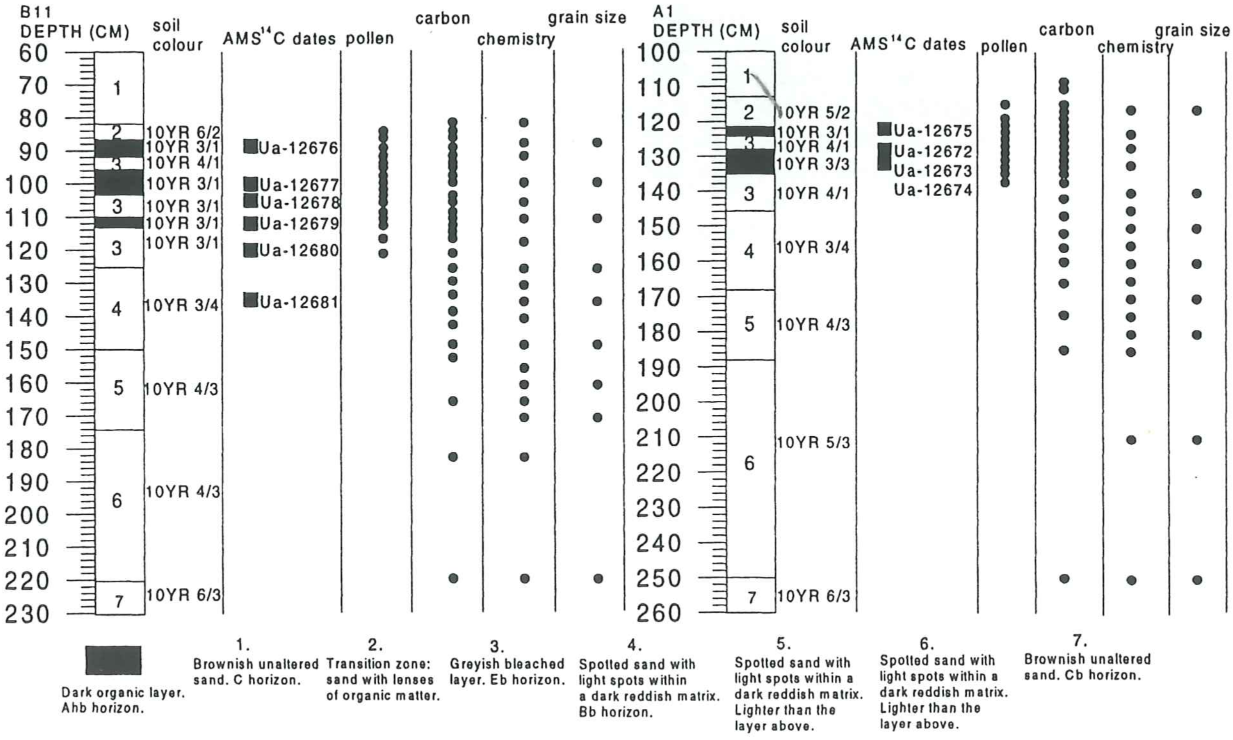

Fig. 3. Soil profiles B11 and A1 at Sandhammaren. Soil horizons and their colours, and subsampling levels for ^{14}C dating, pollen, carbon and soil chemistry analyses are indicated.

translocated oxides. Downwards the reddish colour becomes more bleached, and at the base of the profile there is brown "unaltered" sand.

Each layer and sample levels were marked and measured in centimetres below the surface. Soil samples for pollen and carbon analyses were taken at the same levels (samples for pollen were only collected in layers 2 and 3), each two centimetres from the upper transition horizon and through the Ahb and Eb horizons (Fig. 3). In the sand beneath (layers 4 and 5), the sample interval for carbon analysis was enlarged to about five centimetres. In the two bottom layers, only one sample per layer was collected. The samples for chemical and grain size analyses were collected at the same levels, one sample in each layer from the transition horizon to the lowest Bb horizon, and then each five centimetres. The samples for ^{14}C dating were collected in each Ahb horizon, and also in the second and lowest Eb horizons, as well as in an organic lense in the underlying sand of profile B11.

Skanörs ljung

At Skanörs ljung, the investigation site was chosen in a *Calluna*-dominated heath. A *c.* 50-cm deep excavation was made. In the soil profile, the ten uppermost centimetres consist of a recent root-rich Ah horizon with an underlying E horizon (Fig. 4). There is one Ahb horizon followed by an Eb horizon underneath. The sequence is overlying a relatively unaltered brownish sand. One sample per layer was collected at the same levels for all analyses. The sample for ^{14}C dating was taken in the buried Ahb horizon.

Chemical analyses

Extraction of iron (Fe), aluminium (Al), manganese (Mn), and phosphorous (P)

By measuring the concentration of secondary compounds of especially Fe and Al, the extent of leaching in a soil profile can be appreciated. The concentration is the amount of elements that has been translocated by percolating water under the weathering process. For the determination of extractable Fe, Al, Mn, and P, the samples were treated according to the citrate-bicarbonate-dithionite (CBD) method (Mehra and Jackson, 1960). Sodium dithionite ($Na_2S_2O_4$) was used for reduction, sodium bicarbonate (pH 7.3) as a buffer, and sodium citrate as a chelating or complexing agent. The samples were first dried at 105°C. Then a sample of 7.000 g was weighed on an analytical balance. Thereafter, the CBD method was applied. Finally, the concentration of Fe, Al, Mn, and P was measured with a plasmaspectrometer (ICP-AES ARL 3520). The results are expressed in mg/g dry matter, except for Mn which concentration is expressed in µg/g.

Carbon analysis

By measuring the carbon concentration in a soil profile, it is possible to quantify the organic content and its vertical distribution, which allows a more precise identification of the lithological boundaries. The samples were dried at 105°C and weighted on an analytical balance. The carbon content was measured with a Leco multiphase carbon determinator (RC-412), and is expressed in percent of dry weight.

pH analysis

pH was measured in a soil solution with a KCl-electrode (McLean, 1987). Fresh soil was used, since drying may cause erroneous pH, usually giving a reduction around 0.1-0.2 pH units (Troedsson & Nykvist, 1973). The samples were mixed with distilled water at a weight ratio 1:2. The solution was shaken for one hour, after which the mineral matter was allowed to settle. pH was measured in the supernatant. The electrode was calibrated in buffer solutions of pH 7.00 and pH 4.00 before measurement.

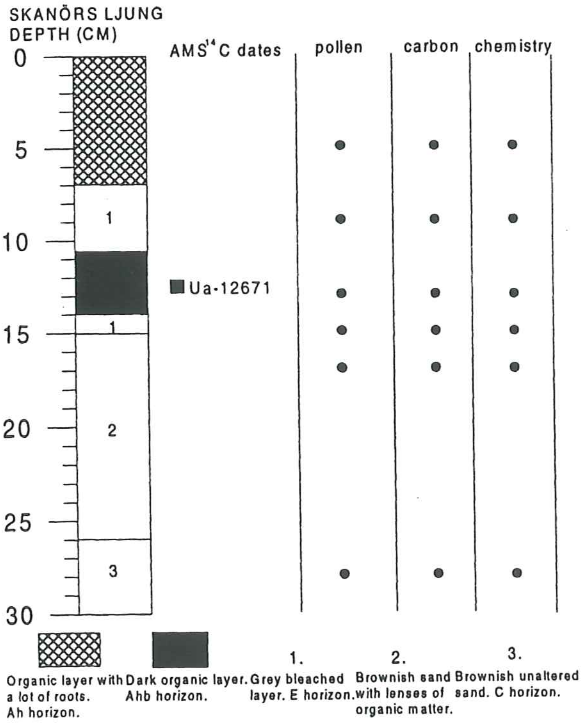

Fig. 4. Soil profile at Skanörs ljung. Soil horizons and subsampling levels for ^{14}C dating, pollen, carbon and soil chemistry analyses are indicated.

AMS ^{14}C measurements

Samples for dating were sieved with mesh widths of 0.25 and 0.5 mm. Macroscopic charcoal particles and sclerotia of *Cenococcum geophilum* were selected under a microscope. The samples were stored in clean bottles and sent to the Ångström laboratory in Uppsala for AMS (accelerator mass spectrometry) ^{14}C measurements. Using the computer program CALIB, version 3.0.3 (Stuiver & Reimer 1993) calibration of ^{14}C dates into calendar years was made. All ^{14}C dates, (including the ones obtained from the former study by Gaillard *et al.* unpublished) were calibrated into calendar years BP with 68.2 % confidence (Tables 1 and 2). The dates obtained from profile B11 are plotted on a time/depth diagram (Fig. 8).

Grain size analysis

Grain size analysis was performed on every second sample from profiles A1 and B11, since an ocular inspection showed that particle size was relatively homogenous throughout the profiles. The analysis was performed according to Talme & Almén, (1975). The sample average grain-diameter and the sediment sorting-coefficient were determined on the basis of a cumulative graph of the sieving results.

Pollen analysis

Sample volumes of 100 cm^3 were used for pollen analysis. 16 samples from B11, 14 from A1, and 6 from Skanörs ljung were prepared following conventional methods (Berglund & Ralska-Jasiewiczowa, 1986). This method includes the addition of *Lycopodium* tablets for calculation of pollen concentrations (number of pollen grains per cm^3), treatment with 10% HCl, 10% NaOH and 40% HF, acetolysis with 1 part H_2SO_4 to 9 parts $C_4H_6O_3$, and final mounting in glycerine. A Zeiss Opton microscope with 40x Zeiss fluorite objective was used for routine analysis, and a 100x Zeiss achromatic oil-immersion objective for critical analysis. A minimum of 1000 pollen grains was counted, except for samples with very low pollen concentrations. For profile A1, the results from only 11 samples are presented because of too low pollen concentrations in 3 samples. Pollen were identified using the pollen keys of Moore & Webb (1991), Reille (1992) & Erdtman *et al.* (1961), and by comparison with the reference collection at the Department of Quaternary Geology, Lund University. Results are presented in pollen diagrams drawn by using the computer program Tilia (Grimm, 1990). The calculated sum for pollen percentages includes pollen and spores from terrestrial plants (Figs. 9, 11, 12). Pollen concentrations (pollen grains per cm^3) are presented for selected taxa (Figs. 10, 13).

Results

Chemical analyses

Distribution of iron (Fe), aluminium (Al), manganese (Mn) and phosphorous (P)

Sandhammaren

The concentration values and the distribution pattern of Al and Fe in the soil profiles are very similar. Moreover, in all three profiles a fairly good correlation is seen between the carbon content, and the Fe- and Al concentrations in the Ahb and Eb horizons (Fig. 15). In profile A1 (Fig. 5), Fe and Al have low concentrations (between 0.14 and 0.30 mg/g) in the transition zone, in the Eb-horizons and in the lowermost part of the profile. Higher values are found in the Ahb-and Bb horizons. The upper Ahb horizon (120-123 cm) has a Fe and Al content of *c.* 0.34 mg/g, followed by a decrease of *c.* 35% in the Eb horizon (layer 3) beneath. The second Ahb horizon (129-135 cm) has a maximum concentration of *c.* 0.5 mg/g, with a decrease of 46 % for Fe and 48 % for Al in the underlying Eb horizon. There is a marked increase both in Al (132 %) and Fe (78 %) from the lowermost Eb horizon into the illuvial zone, which has concentrations ranging between 0.34 and 0.50 mg/g. The thickness of the Bb horizon is defined by the high values within the interval 145 cm to 180 cm (i.e. *c.* 35 cm). Within the illuvial zone some variations can be seen in both the Al and Fe curves, which are characterised by peaks at 160 cm and 180 cm. Below *c.* 180 cm Al and Fe values decrease distinctly downwards.

The P concentration also follows the horizon units. However, the values are not as well correlated to the carbon content, as Fe and Al. The concentration fluctuates between 0.11 and 0.18 mg/g in the Ahb and Eb horizons. The highest P values (*c.* 0.3 mg/g) are found within the illuvial zone. In this zone, P shows the same distinct increase as Fe and Al, and similar peak values at 180 cm and 160 cm.

The content of Mn is low (between 0.1 and 0.3 µg/g) throughout the soil profile. It shows no correlations with Al and Fe, except for the peak values in the illuvial zone at 160 cm and 180 cm, and the following decrease towards the base. In the upper part of the sequence with Ahb and Eb horizons, the pattern of the Mn curve is almost reversed compared with the other elements.

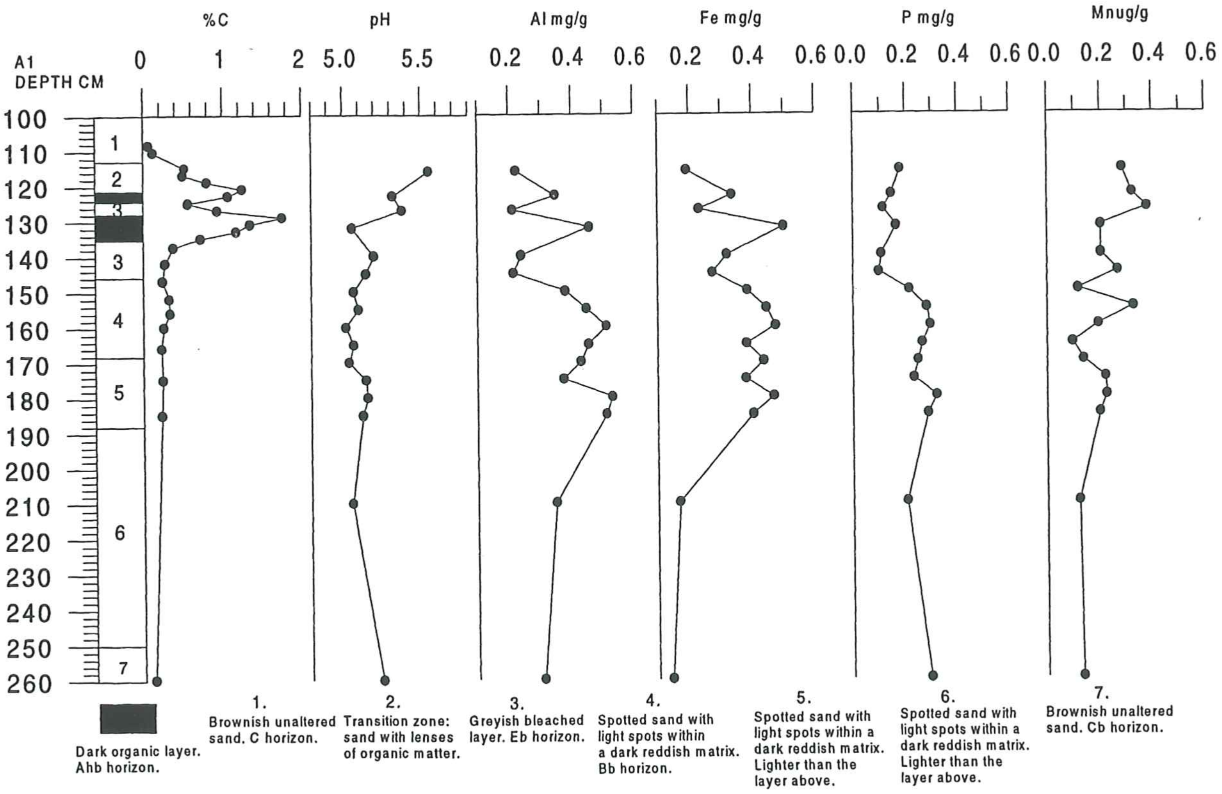

Fig. 5. Profile A1, Sandhammaren: Chemical data as a function of depth. The carbon content is expressed in percentages of dry weight. Aluminium, iron, and phosphorous are expressed in mg/g, and manganese in µg/g.

In profile B11 (Fig. 6), changes in the Al and Fe concentrations correlate with the different horizon units, as in profile A1, but the same strong correlation cannot be seen between the Fe and Al concentrations and the carbon content of the Ahb horizons. The upper Ahb horizon (88-91 cm) has the highest Fe and Al concentration, around 0.40 mg/g, while the second (96-102 cm) and the third Ahb horizon (110-114 cm) have almost equal concentrations of both Fe and Al (*c.* 0.30 mg/g and 0.26 mg/g, respectively). The first Eb horizon has values fluctuating between 0.23 mg/g and 0.30 mg/g. Even lower values are found in the second Eb horizon, which is the most leached Eb horizon. Here the concentration of Al is 0.17 mg/g and that of Fe 0.20 mg/g, which is a decrease from the overlying Ahb horizon by 44 % and 33 %, respectively. The lowermost Eb horizon exhibits no distinct decrease. A gradual increase is seen in the illuvial zone, which has Al and Fe concentrations around 0.35-0.41 mg/g. As in profile A1, two peak values (140 cm and 160 cm) occur, before concentrations eventually decrease towards the base.

The distribution of P in profile B11 has a pattern similar to the one in profile A1, with minor fluctuations between the Ahb and Eb horizons. The maximum concentration is found in the illuvial zone, and as for Al and Fe, there are two peak values at 140 cm and 160 cm, before concentrations start to decrease towards the base of the profile.

The Mn-concentrations are relatively high in the upper three samples, in comparison with profile A1. It is 9.93 µg/g in the transition zone, 4.60 µg/g in the upper Ahb horizon, and 1.04 µg/g in the upper Eb horizon. The remaining part of the profile is characterised by low values (between 0.1 µg/g and 0.4 µg/g) and shows no significant changes.

Skanörs ljung

At Skanörs ljung (Fig. 7), the interval between the analysed samples is larger. Mn was not measured because the major aimof the study was to compare the major trends in Al and Fe concentrations in a soil under a modern *Calluna* heath with those observed in the palaeosoils at Sandhammaren. Al exhibits very high concentrations, up to 2.2 mg/g. Fe and P have much lower concentrations, from just above 0 to *c.* 0.6 mg/g. Al also shows larger fluctuations between the horizons, whereas the Fe and P values are rather constant with just some minor changes in the Ahb and Eb horizons. Apart from the uppermost sample, Fe has extremely low values throughout most of the profile and also in the Ahb horizon, even though the carbon content is high. Towards the C horizon the concentration of all elements decreases.

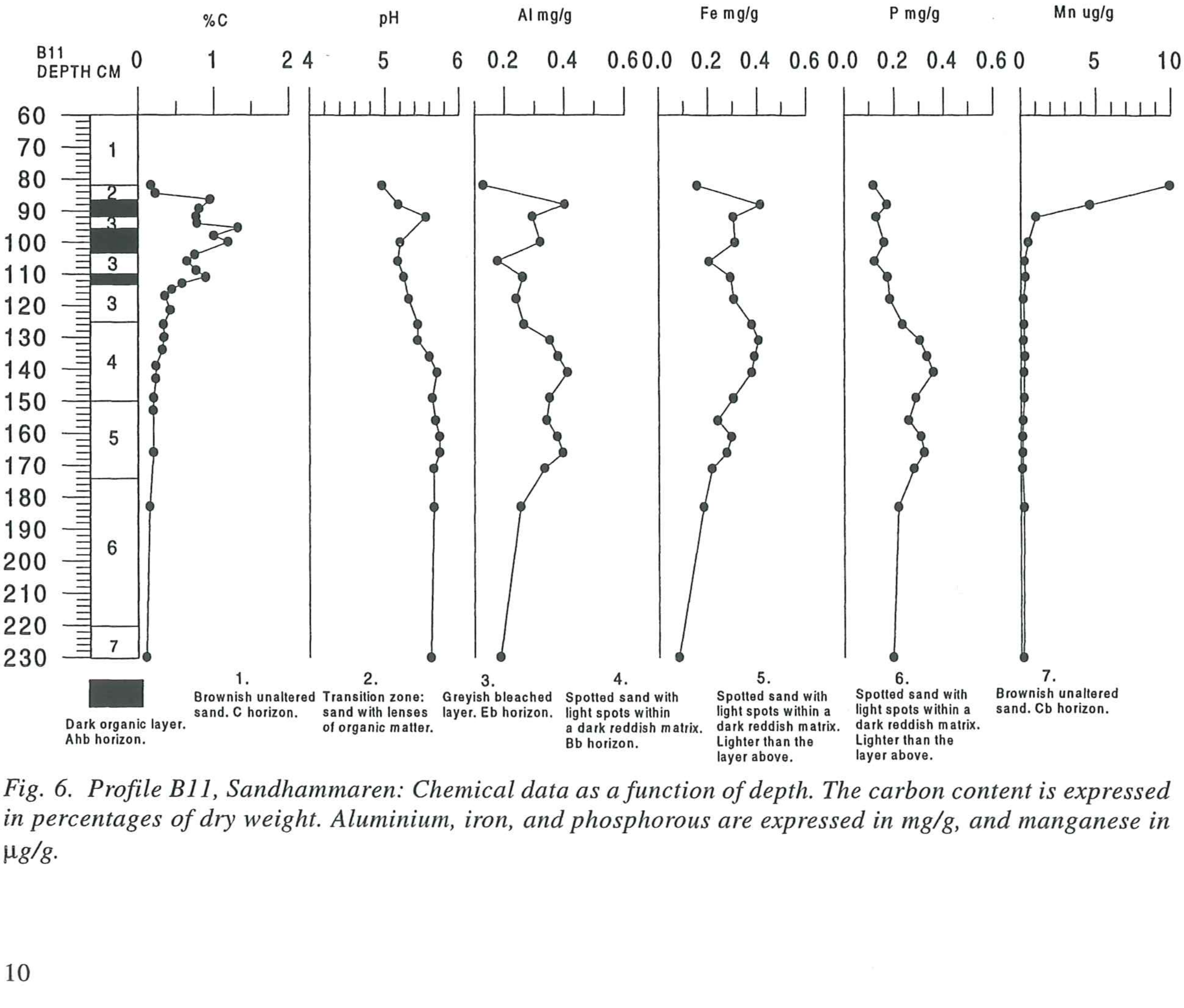

Fig. 6. Profile B11, Sandhammaren: Chemical data as a function of depth. The carbon content is expressed in percentages of dry weight. Aluminium, iron, and phosphorous are expressed in mg/g, and manganese in µg/g.

Carbon analysis

The carbon concentration in the soil profiles is in accordance with the horizon units. The buried soils show accumulation of organic material, with higher values in the Ahb horizons, and lower values in the Eb and illuvial horizons. The carbon compound in these latter samples mainly consists of charcoal. Thermal combustion of the samples from the Ahb horizons produces significant amounts of water, which indicates that the carbon compound in these samples partly consists of organic matter.

In profile A1 (Fig. 5), the carbon content in the upper and second Ahb horizon is 1.25 % and 1.75 %, respectively. The values in the Eb horizons variy between 0.4 % and 0.5 %. The remaining part of the profile has carbon values around 0.2 %. In profile B11 (Fig. 6), the carbon content in the Ahb horizons is not as high as in A1. The highest value is in the second Ahb horizon which contains 1.19 % C. The other two Ahb horizons have values around 0.8 % C. The remaining part of the profile has the same carbon content as A1, around 0.2 %.

At Skanörs ljung (Fig. 7) the carbon content is higher, with values varying between 0.2 % and 3.8 %. There is a marked increase in the Ahb horizon followed by decreasing carbon concentrations into the underlying Eb horizon.

pH analysis

The relatively high values and the depthwise variations in pH at Sandhammaren and Skanörs ljung are not "typical" of well-developed podzol profiles. In profile A1 (Fig. 5), pH ranges from 5.0 to 5.4. The upper Ahb horizon has a pH of 5.3 and is followed below by a minor increase of 0.1 pH units in the upper Eb horizon. The lowest pH, 5.0, was obtained for the second Ahb horizon, which is followed by an increase to 5.2 in the second Eb horizon. pH fluctuates in the basal part between 5.0 and 5.2, except for the bottom sample that has a slightly higher pH.

Profile B11 (Fig. 6) displays a more stable pH trend than profile A1. However, the range of variation is from pH 5.0 to pH 5.7, which is larger than that found in profile A1. A significant increase with 0.6 pH units from pH 5.0 is seen in the transition zone to the uppermost Eb horizon, which is followed by a distinct decrease to pH 5.2 in the second Ahb horizon. The remaining part of the profile, beneath the second Ahb horizon, has a trend of increasing pH towards the base, where pH stabilises around 5.7.

The soil profile at Skanörs ljung (Fig. 7) is more acid than those at Sandhammaren. The lowest value, pH 3.4, is found in the Ah horizon. pH in the Ahb horizon is still quite low, 4.0, but increases fairly rapidly with depth to 4.6 in the C horizon.

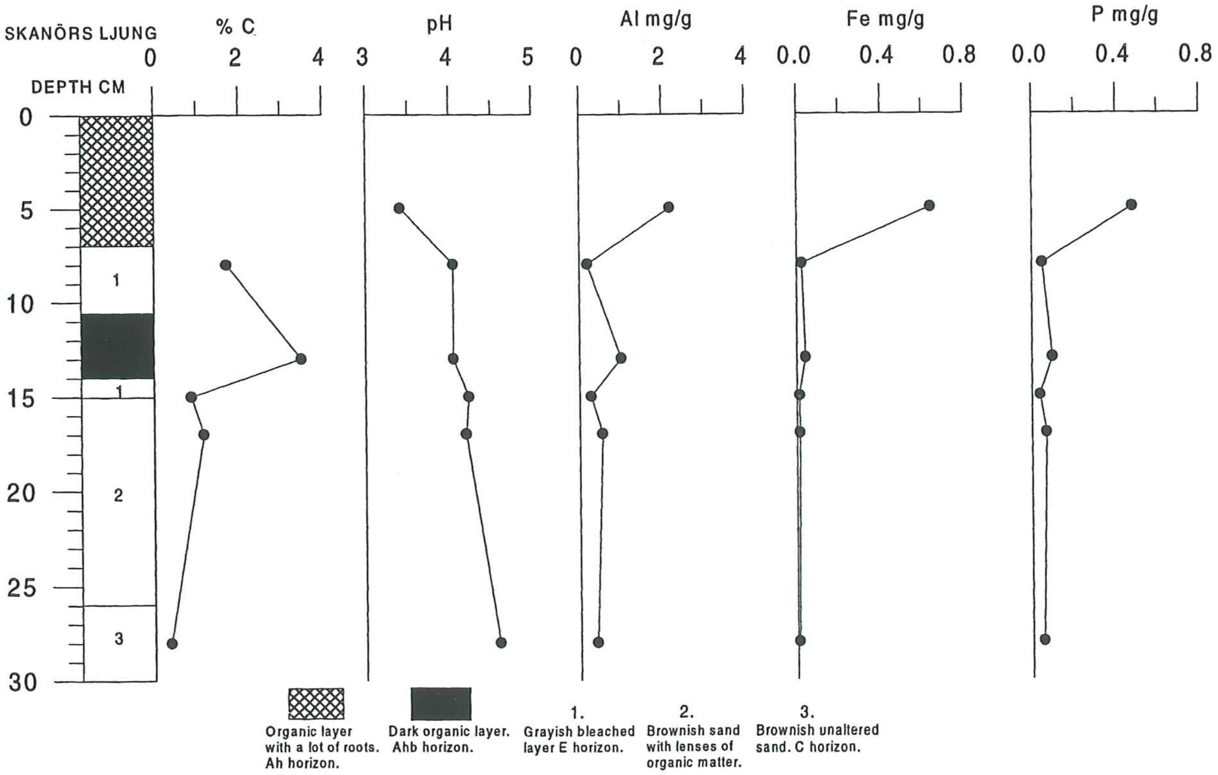

Fig. 7. Skanörs ljung: Chemical data as a function of depth. The carbon content is expressed as percentages of dry weight. Aluminium, iron, and phosphorous are expressed in mg/g.

Tab. 1. AMS ^{14}C dates from Sandhammaren (profile B11 and A1) and Skanörs ljung (present study).(Ua: Uppsala Ångström laboratory, Sweden).

SANDHAMMAREN B11				
NUMBER	DEPHT (CM)	AMS 14C DATES BP	CALIBRATED DATES BP (68.2% CONFIDENCE)	TYPE OF MATERIAL
Ua-12676	87-90	590 ± 65	590 ± 60	Charcoal. Calluna
Ua-12677	97-103	1150 ± 70	1055 ± 85	Charcoal. Calluna
Ua-12678	103-107	1675 ± 65	1565 ± 65 (0.81) 1675 ± 25 (0.19)	Charcoal. Calluna
Ua-12679	110-114	1955 ± 65	1900 ± 80	Charcoal. Calluna
Ua-12680	114-125	1550 ± 50	1450 ± 60 (0.93) 1360 ± 10 (0.07)	Charcoal. Calluna
Ua-12681	134-137	2590 ± 95	2575 ± 95 (0.64) 2745 ± 45 (0.36)	Charcoal. Calluna, Pinus
SANDHAMMAREN A1				
Ua-12672	128-135	290 ± 60	370 ± 90 (0.96) 165 ± 5 (0.02) 0 (0.02)	Cenococcum
Ua-12673	128-135	910 ± 70	825 ± 85	Calluna, fruits
Ua-12674	128-135	1275 ± 70	1205 ± 75 (0.95) 1100 ± 10 (0.05)	Charcoal. Calluna
Ua-12675	121-124	103 ± 1		Cenococcum
SKANÖRSLJUNG				
Ua-12671	13-14	1370 ± 60	1280 ± 50 (0.87) 1195 ± 15 (0.13)	

AMS ^{14}C measurements

Sandhammaren

The results of the AMS ^{14}C datings are presented in Tables 1 (this study) and 2 (former study, Gaillard *et al.* unpublished). In the present study, the six samples in profile B11 are from the organic rich Ahb horizons, and the underlying Eb horizons. Dating was performed on macroscopic charcoal particles or seeds of *Calluna vulgaris* and *Pinus sylvestris*. The four samples in profile A1 are from the Ahb horizons, with three samples from the lowest horizon. Dating was performed on various material: macroscopic charcoal particles of *Calluna vulgaris*, and sclerotia of *Cenococcum geophilum*. The single sample in Skanörs ljung is from the Ahb horizon, and dating was performed on macroscopic charcoal particles of *Calluna vulgaris*. In the former study by Gaillard *et al.* (unpublished), dating was performed on seven samples from profile B11, and a single sample from profile A1. Both sclerotia of *Cenococcum geophilum* and charcoal particles of *Calluna vulgaris* or *Pinus sylvestris*, in some cases from the same level, were dated.

In the present study, the dates for profile B11 rang between the interval 2575±95 to 590±60 calibrated years BP (cal. BP). The time/depth diagram (Fig. 8) shows a good coherency of the dates, except for one level, (120 cm), for which the age is significantly younger than for the layer above. In the study of Gaillard *et al.* (unpublished) the dates cover the time interval 2630±160 to 495±65 cal. BP. The date in the lowest Ahb horizon in profile B11 (present study), 1900±80 cal. BP (Ua-12679), agrees relatively well with the date obtained at a corresponding level in the study of Gaillard *et al.* (unpublished), i.e. 1745±135 cal. BP (Ua-2151). Moreover, the oldest dates obtained for profile B11 are fully comparable in the two studies, i.e. 2575±95 cal. BP (Ua-12681) (this study), and 2630±160 cal. BP (Ua-2152) (Gaillard *et al.* unpublished). They are both from a level situated below the lowest Ahb horizon. The dates on *Cenococcum geophilum* appears to be consequently too young when compared with the dates on charcoal particles (see profile A1, this study and profile B11, former study; Tables 1 and 2). Therefore, the dates of the upper levels in profile B11(Gaillard *et al.* unpublished; Table 2) should be considered with caution. Nevertheless, dates

Tab. 2. AMS ^{14}C dates from Sandhammaren (profile B11 and A1) (earlier study by Gaillard et al. (unpublished). (Ua: Uppsala Ångström laboratory, Sweden, UZ: University of Zürich, ETH ^{14}C laboratory, Switzerland).

SANDHAMMAREN B11				
NUMBER	DEPHT CM	AMS 14C DATES BP	CALIBRATED DATES BP (68.2% CONFIDENCE)	TYPE OF MATERIAL
Ua-2148	72-76	480 ±110	495 ± 65 (0.70) 345 ± 25 (0.18) 620 ± 20 (0.11)	Cenococcum
Ua-2149	109-111	470 ± 110	495 ± 65 (0.70) 355 ± 35 (0.25) 620 ±10 (0.05)	Cenococcum
Ua-2150	120-130	760 ± 110	710 ± 80 (0.82) 585 ± 25 (0.18)	Cenococcum
UZ-2735	120-130	965 ± 65	865 ± 75	Cenococcum
Ua-2151	120-130	1840 ± 110	1745 ± 135	Charcoal
UZ-2736	120-130	1150 ± 55	1030 ± 60 (0.90) 1120 ± 10 (0.10)	Charcoal
Ua-2152	130-150	2590 ± 120	2630 ± 160	Charcoal
SANDHAMMAREN A1				
UZ-2606		1930 ± 70	1875 ± 75 (0.89) 1765 ± 15 (0.11)	Cenococcum

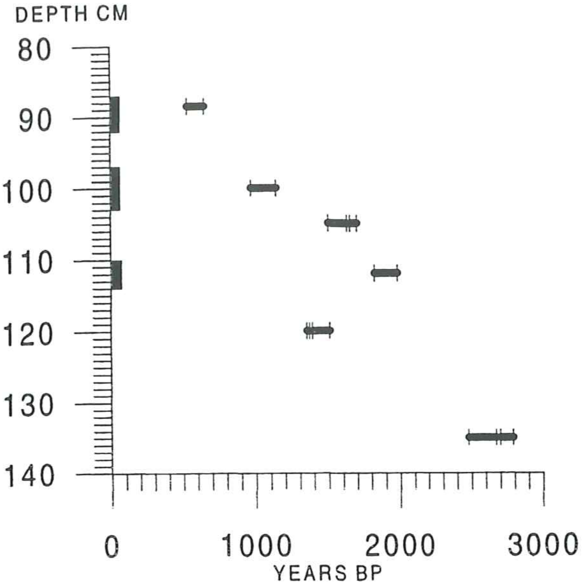

Fig. 8. Time-depth diagram for profile B11 at Sandhammaren. The organic-rich Ahb horizons are marked with black on the depth axis. A best-fit curve is not presented since variations in the accumulation rate between organic-rich (low rate) and sandy layers (high rate) are assumed. Therefore, a best-fit curve would be misleading.

from the upper Ahb horizon are comparable, 590± 60 cal. BP (Ua-12676) (this study), and 495±65 cal. BP (Ua-2148) (Gaillard *et al.* unpublished).

In profile A1, three dates were obtained from the same depth interval, 1205±75 cal. BP (Ua-12674) on charcoal of *Calluna*, 825±85 cal. BP (Ua-12673) on seeds of *Calluna*, and 370±90 cal. BP (Ua-12672) on sclerotia of *Cenococcum*. The latter date is obviously too young (see discussion above), but the two first dates may represent an approximative time interval for the deposition of the layer, i.e. between *c.* 800 and 1200 cal. BP. Moreover, a date of 1875±75 cal. BP (UZ-2606) was obtained on *Cenococcum* from a profile situated close to profile A1 (former study, Gaillard *et al.* unpublished), which extends somewhat the period of soil formation at the site. Because *Cenococcum* generally provides too young dates, the oldest organic layer of profile A1 may well be older than 1875 cal. BP.

Skanörs ljung

The single date, 1280±50 cal. BP, belongs to the same time interval as the palaeosoils of Sandhammaren. Therefore, the soil profile collected at Skanörs ljung is not a modern analogue, but rather a contemporary formation of the fossil palaeosoils at Sandhammaren.

Grain size distribution

The grain size in the soil profiles is within the interval 0.26-0.30 mm, with an average of 0.28 mm in profile B11, and 0.29 mm in profile A1. The nomenclature for the size fraction 0.2-0.6 mm is medium sand. Well sorted material is characterised by a sorting coefficient <2.5. The samples have sorting coefficients between 1.11 and 1.17. Consequently, the soil profiles consist of very well sorted medium sand. The smallest grain size and the highest sorting coefficient are found within the organic horizons. However,the differences between the horizons are relatively small. The grain size distribution in the soil profiles suggests that the sequences of sand were formed through aeolian deposition.

Pollen analysis

Pollen and spores are presented in pollen percentage and concentration diagrams (Figs. 9-13). The pollen and spores taxa are grouped into five categories, (1) trees and shrubs, (2) general apophytes (terrestrial herbs often introduced through human activity), (3) pasture and meadow apophytes, (4) arable and ruderal plants, and (5) spores. The diagrams are subdivided into local pollen assemblage zones (LPAZ). The zone boundaries, defined by more or less significant changes in the pollen spectra, correspond to the lithological subdivisions. However, for B11, the LPAZ defined in the percentage diagram differ from those in the concentration diagram. Because few samples were counted at Skanörs ljung, the results are presented as a histogram. Concentration diagrams are presented for selected taxa only for profile B11 and Skanörs ljung. These diagrams provide complementary information for a more precise interpretation of the percentage diagrams.

Sandhammaren

Profile B11: LPAZ 1: This zone is dated to a period around 2575±95 cal. BP. An increase of *Calluna* from about 25%, in the lowest Eb horizon, to nearly 80 % in the overlying Ahb horizon, characterises the zone boundary 1/2. *Pinus, Corylus,* and *Alnus* are the dominant tree taxa. There are also minor peaks of *Fraxinus* and *Quercus*. Among general apophytes, Compositae SF Cichorioideae are most common. Other well represented NAP in zone 1 are *Artemisia, Filipendula,* and *Chenopodiaceae.* The concentration diagram (Fig. 10) shows another picture of relative changes. Almost all taxa are characterised by an increase of their values at the 1/2 boundary. *Calluna* shows the largest increase, followed by *Pinus*, *Corylus,* and

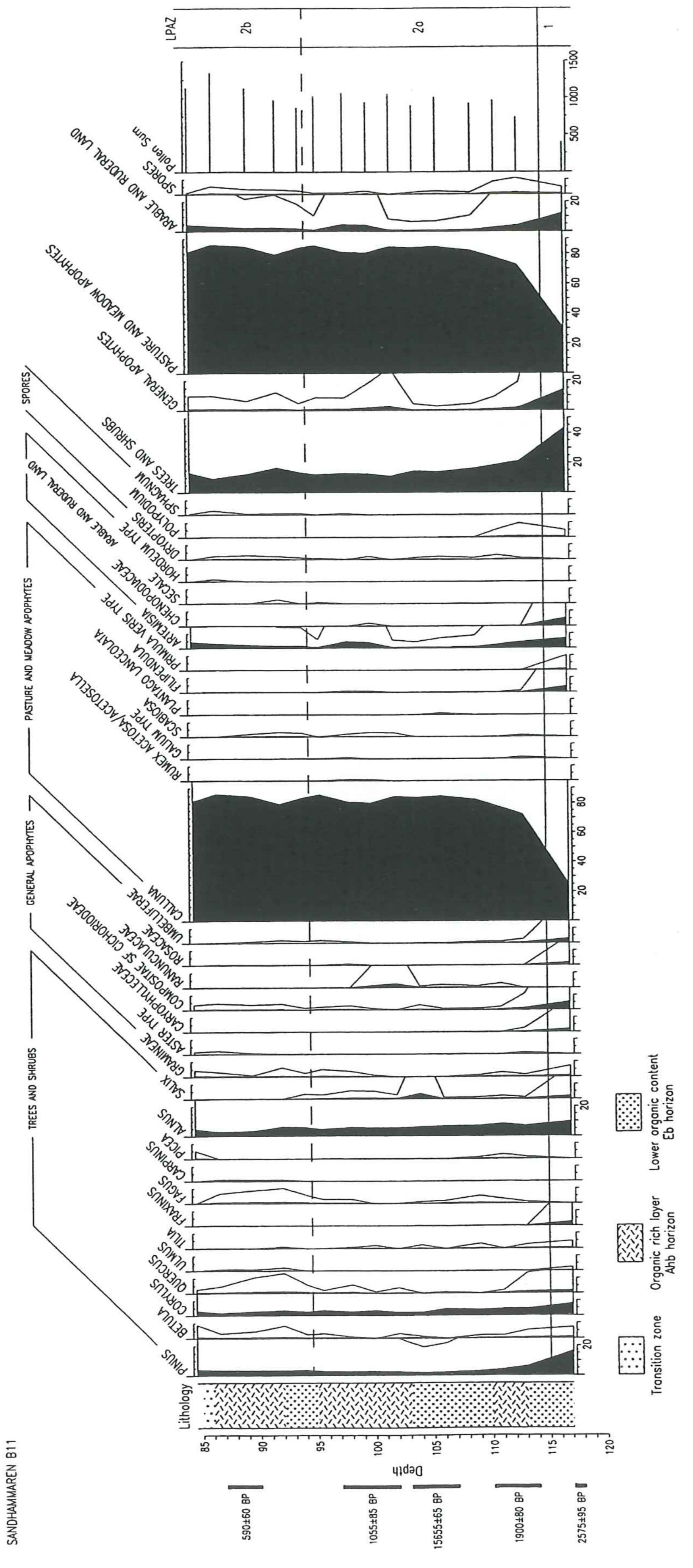

Fig. 9. Profile B11 at Sandhammaren: Pollen and spore percentage diagram.

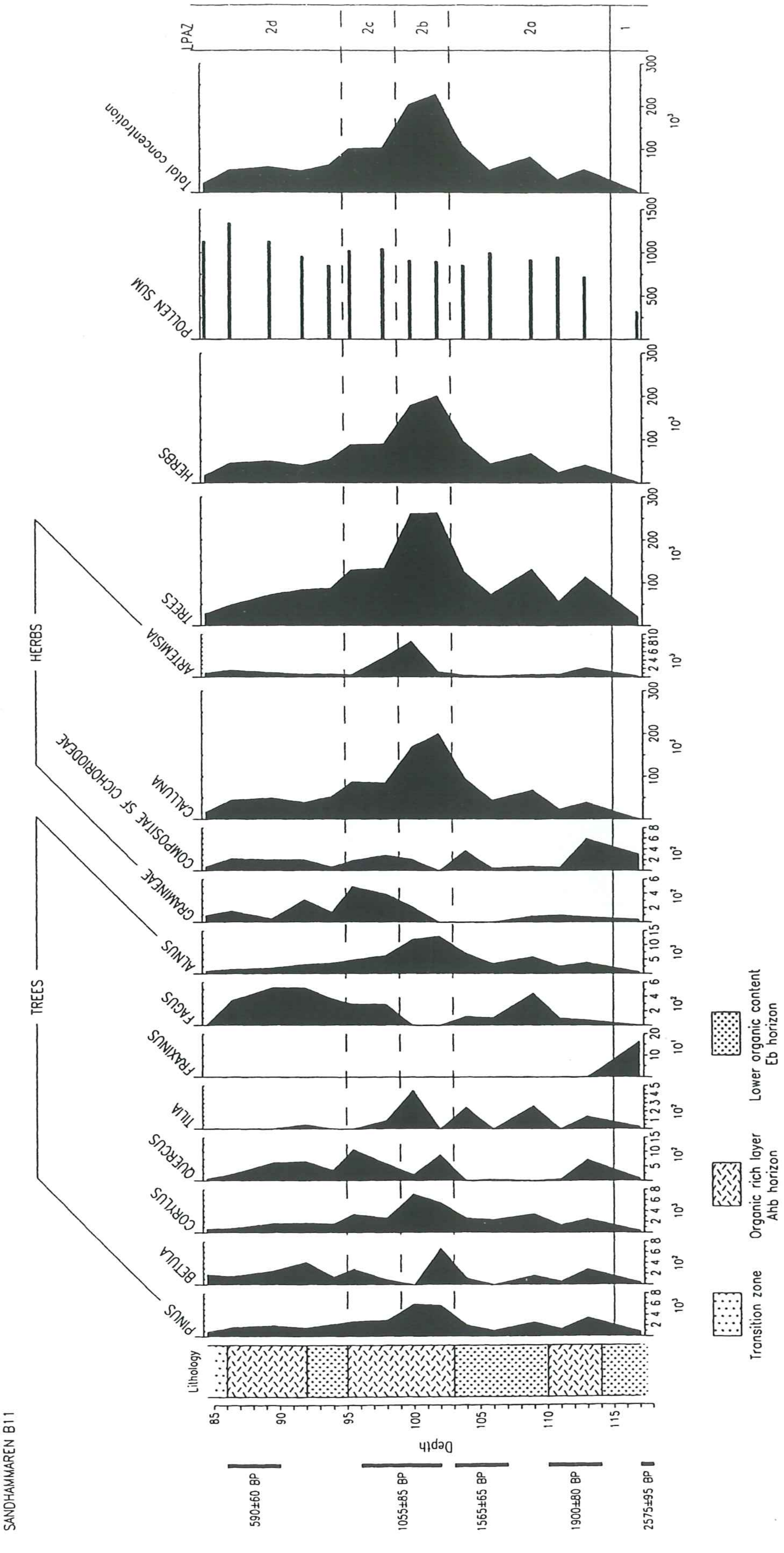

Fig. 10. *Profile B11 at Sandhammaren: Pollen concentration diagram.*

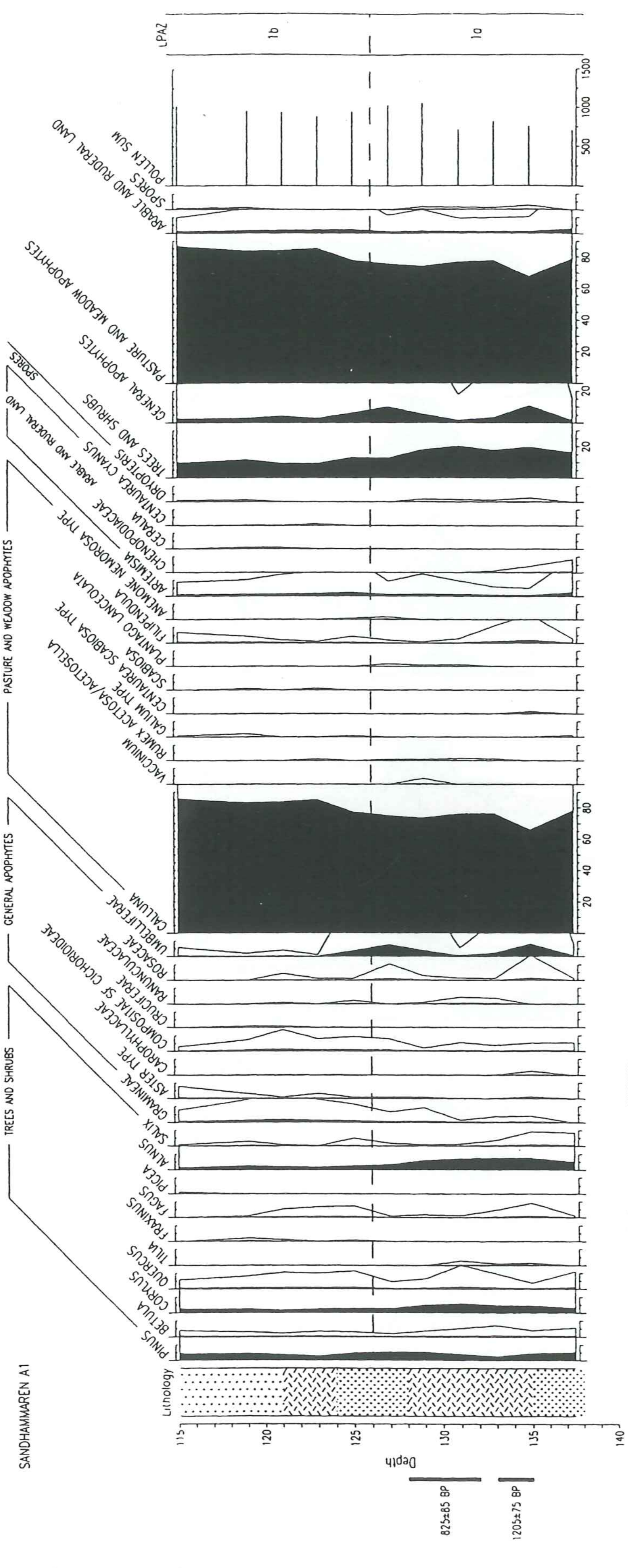

Fig. 11. Profile A1 at Sandhammaren: Pollen and spore percentage diagram.

Alnus. These results are possibly due to two complementary factors, (1) the major increase of *Calluna* produces decreases in percentages of other taxa that may be artefacts, (2) the change in accumulation rate (from high to low) between pure sand and organic sand may be at the origin of the generally very low pollen concentrations in the lower sample. Therefore, the precise vegetational changes at the zone boundary 1/2 are very difficult to infer from the pollen data. Moreover, the high values of *Pinus* and Compositae SF Cichorioideae are probably artefacts of the percentage calculation.

LPAZ 2: This zone is dated to the time interval *c*. 1900-1000 cal. BP. *Calluna* shows high pollen percentages (between 75 and 85 %) throughout the zone, whereas all other taxa have low values. The most dominant trees are *Alnus* (5-10 %), *Pinus*, and *Corylus*. The LPAZ can be subdivided into two subzones B11 2a and B11 2b, where the subzone boundary is characterised by an increase of *Quercus* and *Fagus* percentages. *Betula* and Gramineae also show a slightly increase around the subzone boundary. The higher values of *Artemisia* at the end of subzone 2a are accompanied by a slight decrease in *Calluna*. In the concentration diagram (Fig. 10), the lower part of zone 2 can be further subdivided into 3 subzones (a, b and c), zone 2b being characterised by the higher total pollen concentrations. The pollen taxa included in the peak values are *Pinus, Betula, Alnus* and *Calluna*. Even though the total concentration decrease at the subzone boundary 2b/2c, there is an indication that the increase in *Artemisia* in zone 2b corresponds to a slight decrease of *Calluna* concentration as well.

Profile A1: The pollen percentage diagram (Fig. 11) is very similar to that from profile B11, except for the bottom part. *Calluna* has high average percentages through the whole profile, and no increase of *Calluna* is registered at the base of the profile. The lowest Ahb horizon is dated to 1205±75 cal. BP. The dominant trees are *Pinus, Corylus*, and *Alnus*. The diagram can be subdivided into two subzones (A1 1a and A1 1b), where subzone 1b is characterised by a slight increase of *Quercus* and *Fagus*. Moreover, *Alnus* decreases and Gramineae increases around the subzone boundary. These characteristics are similar to those described for subzone boundary 2a/2b in the percentage diagram from B11. Therefore, the two diagrams from profile B11 and A1 can be broadly correlated. The increase in *Fagus*, also accompanied by the first occurrence of *Carpinus* in profile B11, may correspond to the regional expansion of these taxa in Scania around 1000 BP (Björkman, 1997; Gaillard *et al.* unpublished)

Skanörs ljung

Skl LPAZ 1: The percentage pollen diagram (Fig. 12) can be subdivided into 2 LPAZ. The first pollen zone is characterised by low values of *Calluna*, and high percentages of *Pinus* (*c*. 30 %), Gramineae (*c*. 30 %), and Compositae SF Cichorioideae. *Alnus, Corylus,* and *Quercus* are represented with lower values around 2-5 %. The high percentages of Gramineae and Compositae SF Cichoriodeae are probably an artefact of the percentage calculation. The concentrations of all taxa are very low, except for *Artemisia* (Fig. 13).

Skl LPAZ 2: The *Calluna* pollen percentages show a distinct increase to *c*. 40 % above the zone boundary 1/2, whereas *Pinus,* Gramineae and Compositae SF Cichorioideae are decreasing. *Corylus, Quercus* and *Alnus* keep similar values. All taxa show very low concentrations, although *Calluna* and Gramineae are characterised by a minor increase. In both the percentage and concentration diagrams, zone 2 can be subdivided into four subzones. The subzone boundary 2a/2b is defined by slight changes, i.e. an increase of *Calluna* (percentages and concentrations), and a decrease of *Pinus, Alnus*, and Gramineae (percentages). The subzone boundary 2b/2c is characterised by a decrease in *Calluna*, and an increase in Gramineae, the subzone boundary 2c/2d by an increase in *Calluna* and *Pinus* (percentages). There is a gradual increase in pollen concentration throughout the profile, each increase broadly corresponding to lithological changes. The subzone 2c at Skanörs ljung is characterised by high values of Gramineae reflecting a change in the vegetation after *c*. 1000 cal. BP. The very low total pollen concentrations throughout the profile at Skanörs ljung may also indicate a generally more open landscape in the area in the past. The upper pollen spectra at Skanörs ljung (subzone 2d) has obvious similarities with the pollen spectra from Sandhammaren (profile B11 and A1). It is characterised by the highest *Calluna* and total pollen concentrations of the profile. This may indicate that the modern vegetation at Skanörs ljung has some analogy with the past vegetation at Sandhammaren.

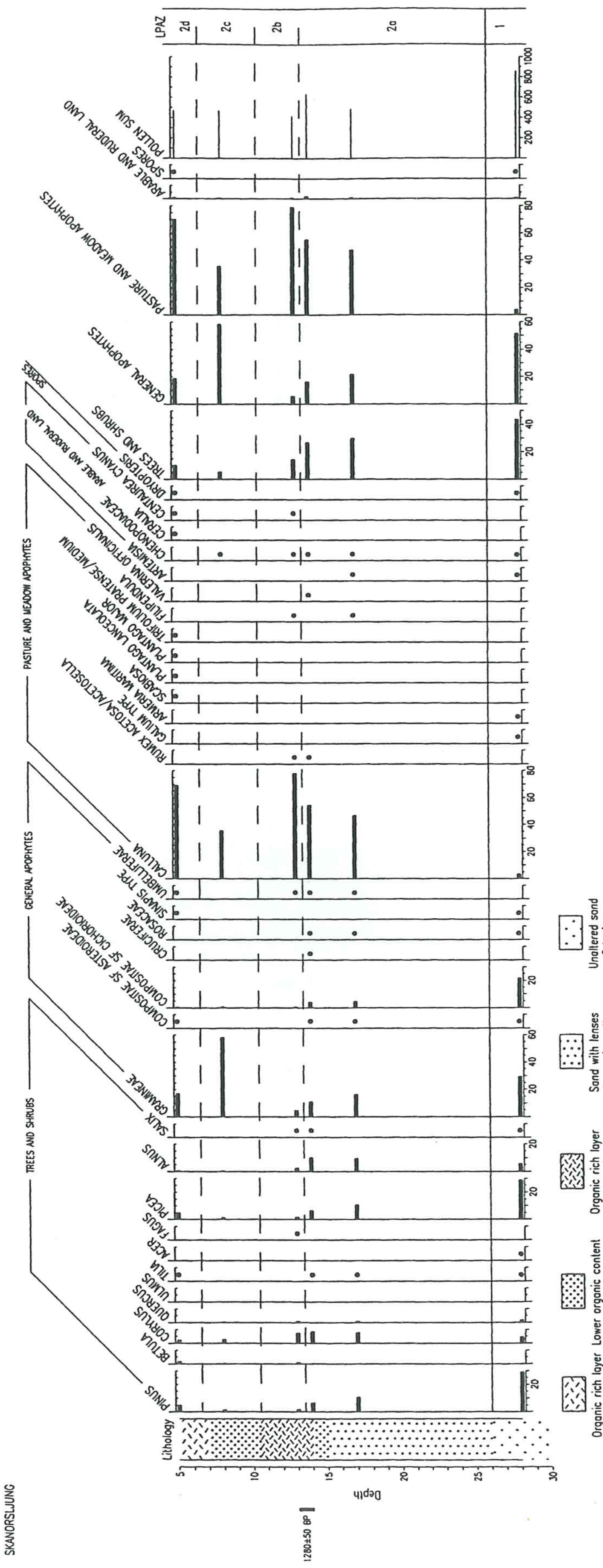

Fig. 12. Skanörs ljung: Pollen and spore percentage diagram. Taxa with pollen percentages ≤1% are represented by dots.

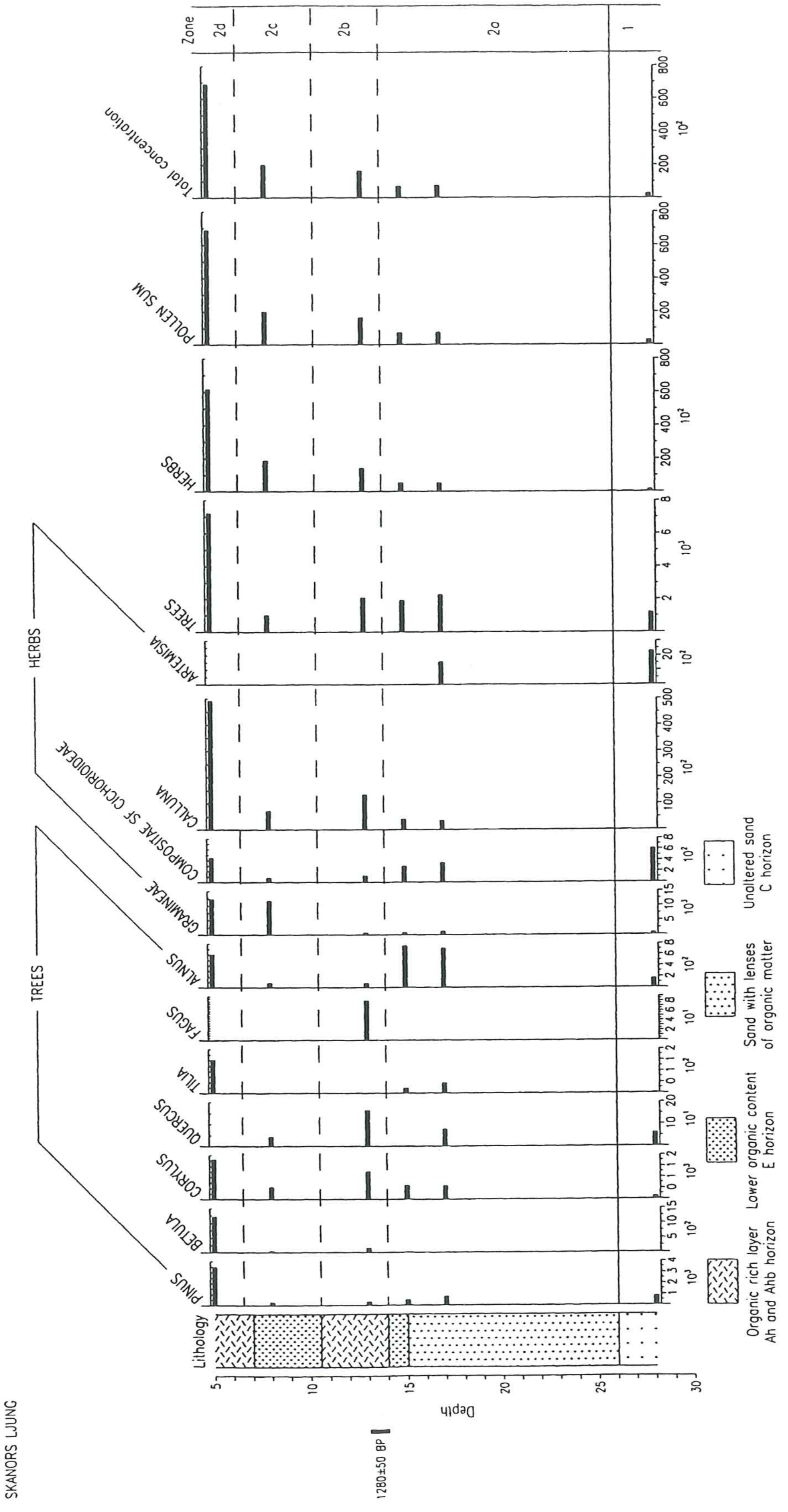

Fig. 13. Skanörs ljung: Pollen concentration diagram.

Discussion

Chronology

The best chronology was obtained for the profile B11. Thick organic layers and the occurrence of numerous macroscopic particles (primarily of *Calluna vulgaris*, but also *Pinus sylvestris*) provided a satisfactory series of ^{14}C dates. Charcoal particles appear to be more suitable for dating than sclerotia of *Cenococcum geophilum*. Translocation from overlying horizons by percolating waters may explain this phenomenon. Well sorted sand as those of Sandhammaren have a high permeability, and translocation of material would be expected. Roots and rootlets of *Calluna* may also have transported sclerotia to levels of older age than the sclerotia themselves.

Soil formation at B11 took place between c. 2600 cal. BP and 500 cal. BP. Shorter periods of reinforced sand drift and lower vegetation density (low carbon content and low pollen concentrations) occurred *c.* 1800-1400 cal. BP and 900-700 cal. BP. The age boundaries of these interval were obtained from a best fit curve of the time-depth relationship (Fig. 8). However, the Eb horizons were most probably characterised by higher accumulation rates than the Ahb horizons. This implies that the time intervals mentioned above, i.e. 400 years and 200 years respectively, are maximum estimates.

In both investigations of the profile B11, a level under the lowest Ahb horizons provided too young dates, i.e. 1450±60 cal. BP (Ua-12680) and 1030 ±60 cal. BP (UZ-2736), respectively. This can be due to the penetration of charcoals of younger age together with roots from the overlying second, thick Ahb horizon through the lower Ahb horizon, and down to the bottom Eb horizon. The same may be true for the oldest date from both profiles at B11, e.g. 2630±160 cal. BP (Ua-2152) and 2575±95 cal. BP (Ua-12681). The dated charcoals (pine) may originate from the bottom of the lowest Ahb horizon. But they may also have been in situ, and represent a time prior to the formation of the first palaeosoil. At that time dune activity was stronger. Even though, pine may have occurred in the area, and fires were probably common (occurrence of charcoals).

The ^{14}C dates obtained on *Cenococcum* from profile A1 are obviously too young (see results and Table 1), except perhaps for the oldest date

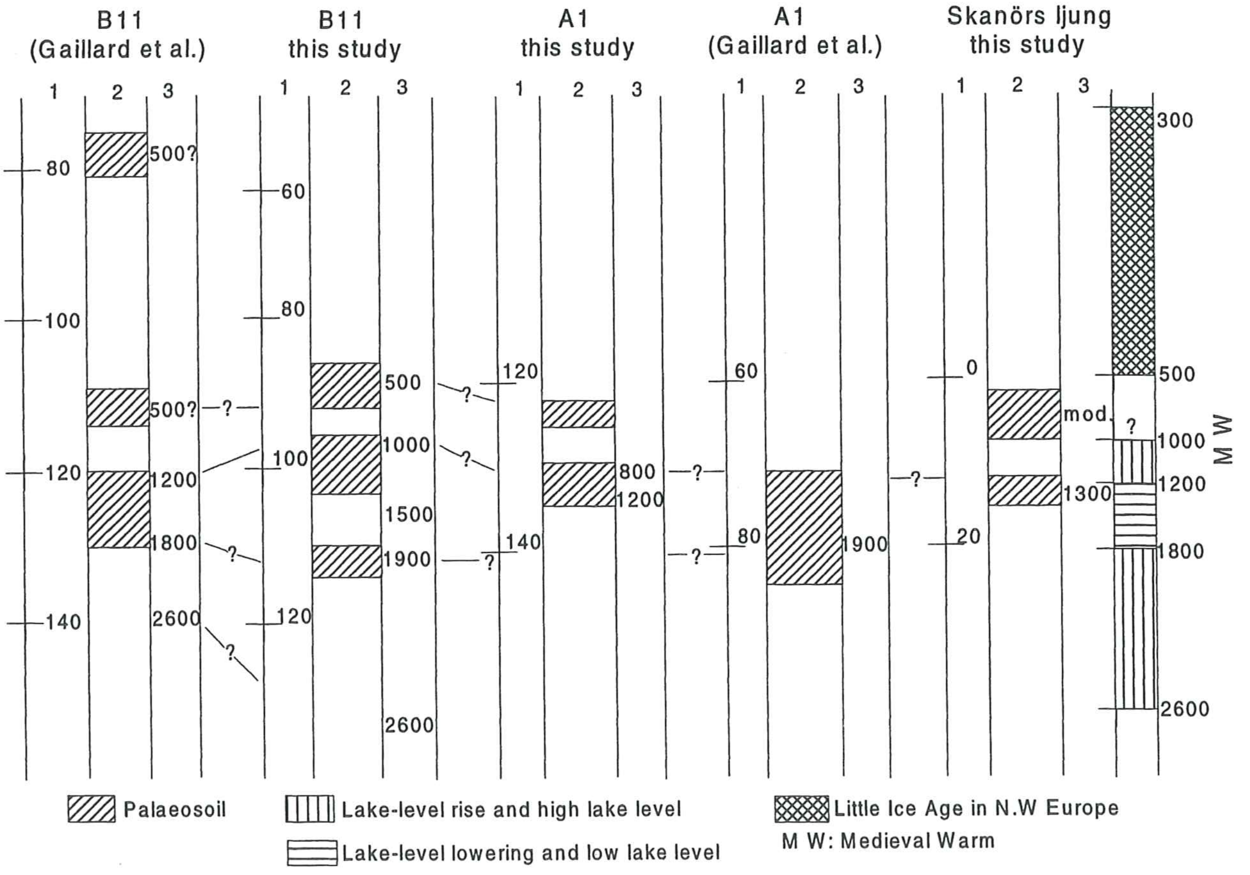

Fig. 14. Correlation between the palaeosoils from the former study (Gaillard et al. unpublished) and the present study. 1: Depth below modern soil surface. 2: Ahb horizons. 3: Approximate age in cal. years BP.

(1875±75 cal. BP (UZ-2606), former study). The two excavations were made at the same site, but not exactly at the same point. Therefore, the organic layers found in the two investigations are not necessarily contemporaneous. The organic layer dated by Gaillard *et al.* (unpublished) may well belong to an older soil formation (synchronous to the bottom Ahb horizon at B11). The organic layer in profile A1 dated in the present investigation may correspond to the second Ahb horizon at B11. A possible time correlation of the different palaeosoils studied at Sandhammaren and Skanörs ljung is presented in Fig. 14.

Palaeopedogenesis

Soil development can be regarded as the result of five major soil-forming factors: climate, topography, biosphere, parent material, and time (Bohn *et al.* 1979). By studying palaeosoil development, the role and changes of these factors can be appreciated. The relative importance of each factor varies with local and regional conditions, and the understanding of these factors in quantitative terms is very difficult. Climate is an integration of the intensity, duration, and seasonal distribution of temperature, moisture, and evaporation. The soil-forming factors are also interdependent. For example, the biosphere clearly depends on climate, and greatly affects for example the carbon dioxide concentration in the soil air and soil solution, which affects the soil-water relations, oxidation-reduction processes, and the reaction between soil particles and soil solution.

As organic matter decays in a soil, partial decomposition products form, which have acid radicals or functional groups capable of forming chelates and complexes with iron, aluminium, manganese and other elements. The formation of organo-metallic complexes makes these elements prepared for eluviation (Atkinson & Wright, 1957). After these elements have been dissolved they can be leached and translocated downthrough the soil profile, where they eventually accumulate because of changes in acidity and redox conditions. Podzol formation is characterised by the eluviation of free oxides and humus from the uppermost layer of the soil profile which develops a bleached horizon, followed by illuviation creating an accumulation zone, where the leaching products deposit (Birkeland, 1974). The extent to which a soil profile is leached depends on the five soil-forming factors mentioned above. Podzol development is usual in cool to temperate and humid regions, since the podzolisation process is dependent on percolating water.

In a leached soil profile, pH normally increases towards the C-horizon, whereas the lowest pH values are found within the organic layer, where pH is buffered by humic and other organic acids. A "normal" iron podzol has pH values between *c.*3.4 and 4.0 in the Ah horizon, *c.* 4.5 in the E horizon and *c.* 6.0 in the C horizon (Wiklander, 1976). The buried soils in this study show evidence of leaching and formation of eluvial and illuvial zones, but not the characteristic variations in pH. The pH values are over 5 in the Ahb horizons and only profile B11 has values near 6 in the Cb horizon. The pH trend could be due to the highly permeable soil parent material, which has allowed the soil profile to be continuously affected by water percolating through the superimposed organic and minerogenic material. According to Wilson & Bateman (1986), present pH status in buried soils is unlikely related to their original pedogenesis and they may show post-burial characteristics which often involve increases in pH. Furthermore, the soil profiles studied have developed through several generations of soil formation, interrupted by soil regeneration. The unstable conditions for soil formation have created the complex soil profiles that can be observed today and prevented intense podzolisation, and, thus, maintained pH at a relatively high level.

The good correlation between Al, Fe, and the carbon concentration (Fig. 15) in the Ahb and Eb horizons, is probably due to the fact that organic material has a high capacity to adsorb inorganic elements (Fitzpatrick, 1986). The most significant trend is seen within the Ahb and Eb horizons of profile A1. Here, the concentration gradient of carbon is much steeper than in the other profiles, as is reflected also in other chemical parameters. Accordingly, the second Ahb horizon has a relatively low pH (5.0), and the highest concentrations of carbon, Al and Fe. The poor correlation in profile B11, where the second Ahb horizon exhibits the highest carbon content but not the highest Fe and Al concentrations, may be explained by slightly different sample levels for the two types of chemical analysis, i.e. carbon or Fe and Al.

In both profile B11 and A1, the second Eb horizon has the greatest thickness and, therefore, can be regarded as the most leached Eb horizon. This Eb horizon is overlain by the thickest and most organic-rich Ahb horizon, suggesting soil formation of long duration and/or a dense vegetation cover, which would favour strong leaching. These Ahb horizons in profile B11 (96-103 cm) and profile A1 (128-135 cm) appear to belong to to the same time period of soil formation, according to the ^{14}C dates, and to the same local pollen assemblage zone, according to the pollen diagrams. The good correlation is further confirmed by the chemical data which show that, in both profiles (1) the horizons are thick (2) the carbon concentrations are high and (3) the Ahb horizons are both overlying the most leached Eb horizon.

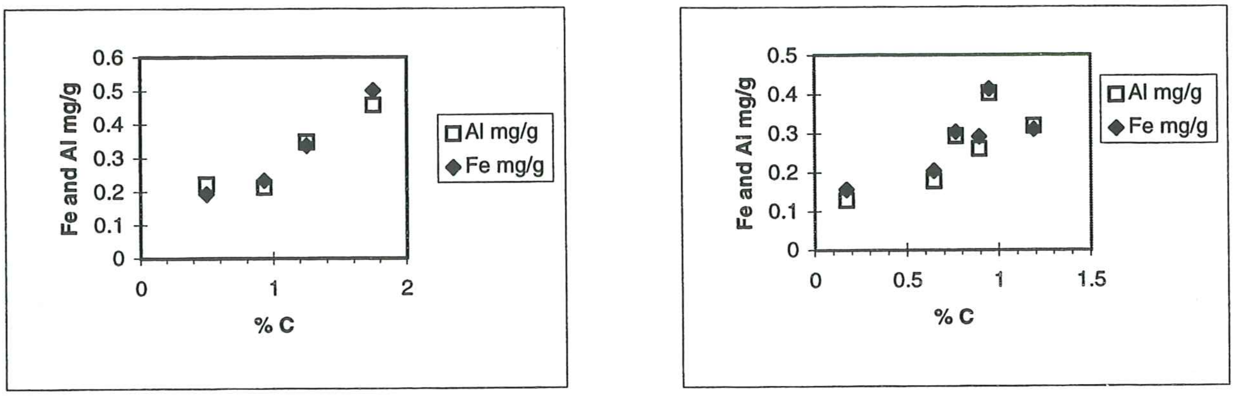

Fig. 15. Concentration of Fe and Al plotted against the carbon content within the Ahb-and Eb horizons. Left: Profile A1. Right: Profile B11. The plots indicate a fairly good correlation of Fe and Al concentrations to the carbon content, in particular for profile A1.

Within the illuvial zone, the accumulation of Fe and Al is independent of the concentration of organic material. The increase of Al and Fe from the second Eb horizons to the Bb horizons in both profile A1 and profile B11 is the result of eluviation and illuviation processes, and hence, of podzolisation. The latter is difficult to quantify without more detailed chemical and mineralogical analyses. However, the soil profiles do not show the characteristic bleached colour within the Eb horizons, and this implies, together with the trend in pH, that the soils cannot be regarded as fully developed podzols.

The illuvial zone can be divided into two subzones: the upper subzone has a major peak in both Al and Fe values and the lower one displays a minor peak in these elements. This trend is detectable in both profile B11 and A1 and could reflect two B horizons, whose formation was associated with different A and E horizons. Although variable in intensity through time, illuviation has probably been a continuous process, which would explain why the illuvial zone has a considerable thickness. In contrast, the position of the eluviation zone has changed due to repeated burial, which halted leaching and prevented full development of the E horizon. Theoretically, there is a possibility that thick, iron-rich zones can form due to fluctuations in the groundwater-table, but this seems to be a less likely explanation. A rise in the water table would certainly favour reducing conditions and thereby mobilisation and transport of Fe^{2+} from underlying levels. If the water-level decreases, oxidation of Fe^{2+} to Fe^{3+} will occur and Fe (III)-oxides precipitate (Berner, 1971). These reactions are of importance when redox-sensitive elements like Fe and Mn are involved, but would hardly affect an element like Al, whose mobilisation mainly depends on pH. Because Fe and Al exhibit similar trend in the profiles, their accumulation ought to be a consequence of downward transport and illuviation. In addition, changing levels of the water table would also affect the distribution of Mn, which reacts in a similar manner as Fe upon a change from reducing to oxidising conditions. However, Mn can remain in a reduced state also under slightly oxidising conditions (Berner, 1971). This difference in chemical behaviour often results in a separation of Fe and Mn oxides along a redox gradient. However, in profile A1, Mn covaries with Fe and has the same two peaks as Fe in the illuvial zone. Thus, the good correlation between Fe, Al and Mn in this part of the profile indicates that they are leaching products translocated downward by percolating water.

The concentration of Mn in soil solutions is usually very low (Wiklander, 1976), which explains the low values in the soil profiles. The high concentrations of Mn in the three upper samples in B11 are probably due to a Mn accretion.

There is no increase in the phosphorous concentration in the Ahb horizons, which seems to rule out the possibility that the organic horizons formed as cultural layers. The good correlation between P, Al and Fe within the illuvial zone is due to the formation of sparingly soluble phosphates with iron and aluminium (Fig. 16). The distribution of P within the soil profiles is therefore strongly controlled by the pH status, due to the precipitation of Fe-and Al oxides at lower pH values (Troedsson & Nykvist, 1973).

The soil profile at Skanörs ljung does not show the same significant variations in the chemical parameters as the profiles at Sandhammaren. Nevertheless, pH is low in the Ah-and Ahb horizons and increases towards the C horizon. However, there is no indication of a Bb horizon with accumulation of elements, so the characteristic eluviation- and illuviation zones have not developed. The limiting factors for podzolisation at this site are probably time and low density in the vegetation cover. The pollen diagram from Skanörs ljung shows very low total concentrations and suggests that the vegetation was sparse.

Vegetation history

Sandhammaren

All pollen spectra from the palaeosoils of Sandhammaren are characterised by a large dominance of *Calluna vulgaris*, except for the bottom sample of profile B11. The dominant vegetation at the investigated sites during the periods of soil formation (Ahb horizons) was a *Calluna* heath. The periods of soil formation (Ahb horizons) are characterised by a denser vegetation cover (see total pollen concentrations Fig. 10).

The transition from the basal Eb horizon to the first Ahb horizon is marked by a distinct change in the pollen percentages of trees and *Calluna*, less prominent in the pollen concentrations. Before the formation of the first organic horizon, dune activity at the site was high, and vegetation sparse. Some pine, oak, and possibly hazel were probably growing on the sandy soils (charcoal of pine was found in the two investigated B11 profiles), together with herbs such as Gramineae, Compositae, Caryophyllaceae, Chenopodiaceae, and *Artemisia*. Alder may have grown in small wet depressions close to the sampling site, and in the larger wetlands of the area (e.g. long-distance transported pollen from Hagestads peatbog).

Around 2000 cal. BP (or even earlier, 2600 cal. BP, see discussion of the chronology), soil formation started. There is no sign in the pollen data of a natural succession from pioneer species such as Cyperaceae and Gramineae, through *Calluna* heath, and eventual overgrowing by *Empetrum, Deschampsia flexuosa*, and *Quercus* (Olsson, 1974). A possible scenario would be that the sandy soils stabilised due to a climate change from dry to wetter conditions, and *Calluna* invaded rapidly most of the area. The numerous signs of fire in the Ahb horizons, i.e. the occurrence of macroscopic charcoals, charred rootlets and stems of *Calluna*, and the decrease in pollen percentages and concentrations of pine, birch, hazel, and oak may indicate a strong human interference in the area. Once the landscape was covered by *Calluna* heath vegetation, it was of enormous value as a grazing area. Fire may have been used to maintain the *Calluna* heaths, a practice that is known from historical sources, and still is used in restricted areas of southern Sweden for *Calluna* heaths' rejuvenation. Uncontrolled fires may also have affected trees growing in the area.

The same scenario can be proposed for each period of soil formation, i.e. three Ahb horizons at B11, and two at A1. The second Ahb horizon at B11, and the first at A1 appear to represent the most pronounced periods of *Calluna* heath both in terms of duration and vegetation density. The exact duration of this period is impossible to specify, but it can be estimated to *c.* a minimum of 250 years (first half of the second Ahb horizon in B11; see discussion of the chronology), around 1200 cal. BP. The pollen findings of *Rumex acetosa/acetosella*, *Galium* type, *Scabiosa*, and *Plantago lanceolata* in profile B11 and A1 are good indicators of grazing. Note that the period of increased dune activity *c.* 1800-1400 cal. BP did not imply a decrease in density of *Calluna* heath (see pollen concentration diagram Fig. 10). In contrast, the increase in dune activity after *c.* 1000 cal. BP was accompanied by a significant decrease in vegetation density that never recovered to the levels reached around 1200 cal. BP.

The latest period of *Calluna* development is dated to *c.* 500-600 cal. BP (i.e. 1400-1500 AD) in profile B11. At that time, the vegetation was sparser than around 1200 cal. BP. However, there are no significant differences in the pollen spectra, which indicates a similar vegetation and land-use. The slight increase in *Fagus* pollen in the upper Eb horizon is most probably a reflection of the known regional change in the forest composition of southernmost Sweden around 1000 cal. BP (Björkman, 1997). *Fagus* was never an important element in the dune areas. Isolated trees may have grown

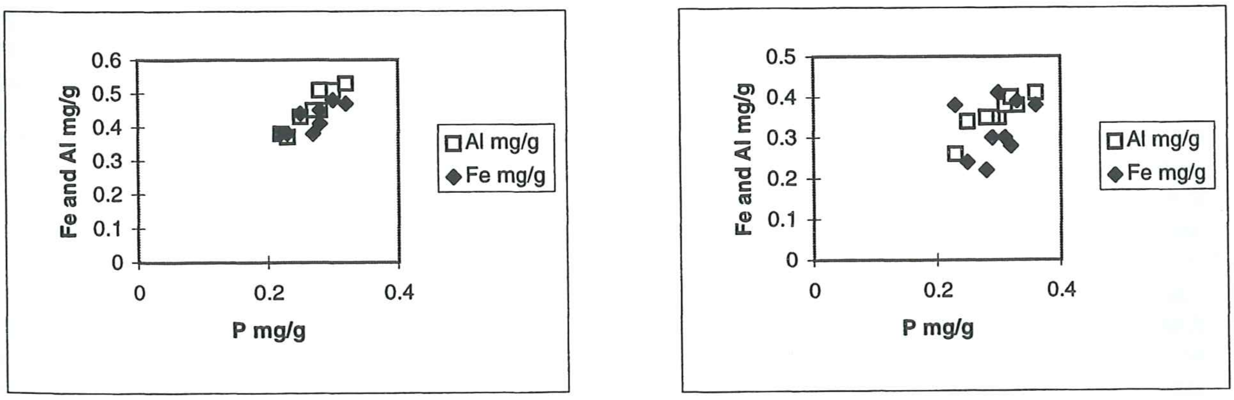

Fig. 16. Concentration of P plotted against the Fe and Al concentrations, within the illuvial zones. Left: Profile A1. Right: Profile B11. The P concentration is best correlated to Al.

in protected areas. Similarly, the low *Quercus* pollen percentages and concentrations imply that oak was never common at Sandhammaren. It is known from historical sources that the most treeless period in the area occurred during the nineteenth century (Emanuelsson, 1993). Since the beginning of the twentieth century, a profound change in land-use occurred, and trees such as oak and pine recolonised the area. Today oak is relatively common in the dune landscape, but it is highly affected by wind and sand activity. It grows mainly as low bushes, groves of larger trees being restricted to the lee side of older dune systems. Before AD 1800, i.e. around 1500 AD and earlier, oak may have been as common as today, but certainly not more common.

The Holocene history of *Calluna* heaths in north-western Europe is relatively well known. Pollen evidence indicates treeless conditions with grass and heathland communities throughout the Holocene in e.g. Britain (Walker, 1984; Birks, 1986), Denmark (Iversen, 1973; Andersen *et al.* 1983; Odgaard, 1988), and Norway (Kaland, 1986). The earlier dates are from western Norway where heaths formed around 5000 cal. BP. Heathland formation became extensive in north-western Europe during the Bronze Age. This environmental change was mostly interpreted as a result of deforestation, grazing and burning (Bell & Walker, 1992). It is clear that many heaths have been maintained by grazing and burning as part of a traditional land use which has only declined in the present century leading to woodland regeneration on some heaths (e.g. Kaland, 1986). This study shows that similar processes acted in the case of the south Swedish heathlands. However, climate change is proposed to be the decisive factor for dune stabilisation and initiation of soil formation (see discussion on dune activity below).

There are no similarities in the vegetation history between Sandhammaren and the southern coastal dune areas of the Baltic sea, e.g. the central part of the Łeba Bar in Poland. There, the palaeosoils dated to *c.* 2800-2000 ^{14}C BP were formed under a deciduous forest dominated by oak. From *c.* 1800 ^{14}C BP the tree cover changed significantly, and beech became dominant. This vegetation shift was interpreted in terms of climatic and edaphic changes from warm to colder conditions and more acidic soils at the transition between the Subboreal and Subatlantic climatozones. Moreover, fire was demonstrated and suggested as a possible factor behind the change in forest composition (Tobolski, 1980). The pollen spectra from past beech forests are comparable to those from the modern beech forests covering the morainic ridges of the Wolin Island in north-western Poland (Tobolski, 1980). Around *c.* 1500 cal. BP, a gradual change towards a pine forest began, which lead to the present-day forests characteristic of the Polish dunes.

It is noteworthy that the oldest Ahb horizons at Sandhammaren are dated to *c.* 1800-1900 cal. BP, corresponding to the time of forest change (oak to beech) in Poland. The reason why oak and beech forests never developed at Sandhammaren as they did in Poland are probably several. The main factors may be (1) the strong human impact from at least 2600 years ago (Late Bronze Age) (Berglund , 1991), and (2) the local dune environment at Sandhammaren where very large dunes as those of Łeba Bar never developed because of the restricted area of sandy material, and the hard impact of wind (deflation). Such conditions imply less lee situations where vegetation could develop and stabilise the dune system.

The modern occurrence of oak at Sandhammaren, while oak is uncommon in Poland, may be the result of the conscious maintenance of this tree in southern Sweden during the last centuries. Oak could spread rapidly into the dune area from the old trees still growing around farms and along roads. In conclusion, humans strongly influenced the vegetation development at Sandhammaren.

Skanörs ljung

The thin palaeosoil layer at Skanörs ljung is dated to the same period as the second Ahb horizon at Sandhammaren. It is also characterised by a dominance of *Calluna*. However, the total pollen concentrations are much lower than at Sandhammaren, which may indicate that vegetation always has been sparser in the area. The upper pollen spectra is more similar to the pollen spectra from the palaeosoils at Sandhammaren, with high pollen percentages and concentrations of *Calluna*. Gramineae are more common at Skanörs ljung than at Sandhammaren, which is a further indication of a more open landscape, very much affected by deflation. It is unfortunately impossible to estimate the age of the initial soil formation under the modern *Calluna* heath at Skanörs ljung. Nevertheless, it may be considered as a possible modern analogue of the palaeosoils at Sandhammaren. However, more analyses would be necessary to confirm this possibility.

Dune activity and soil formation

The formation of coastal dunes requires: (1) a substantial sand supply, (2) strong onshore wind for transport of material during at least part of the year, and (3) an area where sand can accumulate (Christiansen & Bowman, 1986). There are two principal models for development of dunes. The first one suggests that dune formation takes place in periods with rising or high sea level. The other proposes that dune building takes place during periods of falling, or low sea level. According to Christiansen & Bowman (1986), the best model for dune formation periods in Denmark is the second one. The lowering of the wave base makes more sand available for landward transport, exposes wide areas for aeolian activity and results in shoreline progradation. During rising or high sea level, the dunes are cut off from their sand supply and become stabilised. The dune development at Sandhammaren is probably connected to similar processes as the Danish dunes because of their comparable environment. At Sandhammaren, the dune sand is underlain by marine sand and gravel, which indicates that sea level fell before the aeolian sand accumulated. Dune formation related to falling sea levels has been reported from other regions in Europe (Christiansen & Bowman, 1986). The Holocene history of the Baltic sea is complex, and many factors are involved, the most important ones being climate and isostatic changes. We are lacking data on shore-line displacement along the coast at Sandhammaren for the time period of palaeosoil formation. Therefore, the model proposed by Christiansen & Bowman (1986) could not be tested in this investigation.

Soil formation in coastal dune areas may also have been influenced by changes in ground water-level due to regional climate shifts. The alternating dune and soil formation periods during the late Holocene appear to be closely related to climate change as reconstructed from several palaeoecological evidences, i.e. lake-level changes (e.g. Gaillard & Digerfeldt, 1991), glacier fluctuations, and tree limit variations (e.g. Karlén & Kuylenstierna, 1996).

Lake-level fluctuations in southern Sweden are suggested to be climatically induced palaeohydrological changes (e.g. Gaillard & Digerfeldt, 1991). One major rise in the water-table has been dated at several sites to c. 2600-2700 ^{14}C BP, and may be compared to the dates from the profiles B11, 2575±95 cal. BP and 2630±160 cal. BP. A distinct lake-level lowering took place between *c.* 1800 and 1200 ^{14}C BP, corresponding to the time of minor reinforced sand drift *c.* 1800-1400 cal. BP at Sandhammaren. A regional rise in the water-level is dated to *c.* 1200 ^{14}C BP, which also correlates to the second organic-rich horizons at Sandhammaren (1205±75 cal. BP, 1055±85 cal. BP, 825±85 cal. BP) and to the palaeosoil of Skanörs ljung (1280±50 cal. BP). The fact that the regional rise in water-level seems to have occurred at the same time as soil formation at Sandhammaren suggests that the alternating periods of soil and dune formation may be climatically induced.

There are evidences of four major periods of glacier advances in northern Sweden during Late Holocene, (1) *c.* 2600-2000 BP (2) *c.* 1800-1600 BP (3) *c.* 1200-1000 BP, and (4) *c.* 1500-1800 AD (Little Ice Age) (Karlén & Kuylenstierna, 1996).These periods of glacier advances may be compared to the reconstructed periods of rising and high lake levels in southern Sweden i.e. *c.* 2600-1800 ^{14}C BP and from *c.* 1200 ^{14}C BP (e.g. Gaillard & Digerfeldt, 1991), except for the second glacier advance. The reconstruction of lake-level changes from *c.* 1000 BP and onwards are too few too allow a regional synthesis, and, therefore, is not discussed here. The Medieval Warm period (Little Optimum AD 800-1300) and the Little Ice Age (AD 1500-1800) are climatic changes that are well documented in all north-western Europe (Grove, 1988).

The oldest soil formation (*c.* 2000 cal. BP or even earlier *c.* 2600 cal. BP) at Sandhammaren corresponds to the first period (1) of climate deterioration during Late Holocene. The first period of sand drift (1800-1400 cal. BP) may be associated with the warmer and drier period that started around *c.* 2000 BP. The second palaeosoil (*c.* 1200-1000 cal. BP, Sandhammaren profile B11 and A1, and Skanörs ljung) corresponds to the third period (3) of climate deterioration, predating the amelioration during the Medieval period. The latter corresponds to the second period of sand drift which continued through the whole duration of the Little Optimum. The last period of soil formation at Sandhammaren (*c.* 500 cal. BP), probably corresponds to the fourth period (4) and represents the time period of the Little Ice Age. The thick layer of aeolian sand overlying the latest palaeosoil may be related to the warmer and drier conditions after the Little Ice Age. However, the pronounced human impact during the eighteenth and nineteenth centuries (see discussion of vegetation history) was probably the major limiting factor for vegetation establishment and soil formation.

Human impact in the coastal areas during Late Holocene, and differences in local conditions, makes it difficult to fully understand regional trends in climatically induced changes in dune activity. Within a buried soil, percolation of younger organic compounds, may be at the origin of too young ^{14}C ages (Geyh *et al.* 1971). Deep percolation would be expected in well-drained, well-sorted sand as in coastal dunes. Formation of soil or peat can also be time-transgressive. A gradual rise in water-level causes the deepest depressions to stabilise, and soils or peats to form earlier than in higher located interridge depressions (Wilson & Bateman, 1985). This process can also explain differences in the age of soil development within an area. These factors make it difficult to determine the exact age boundaries of the periods characterised by either soil development or dune

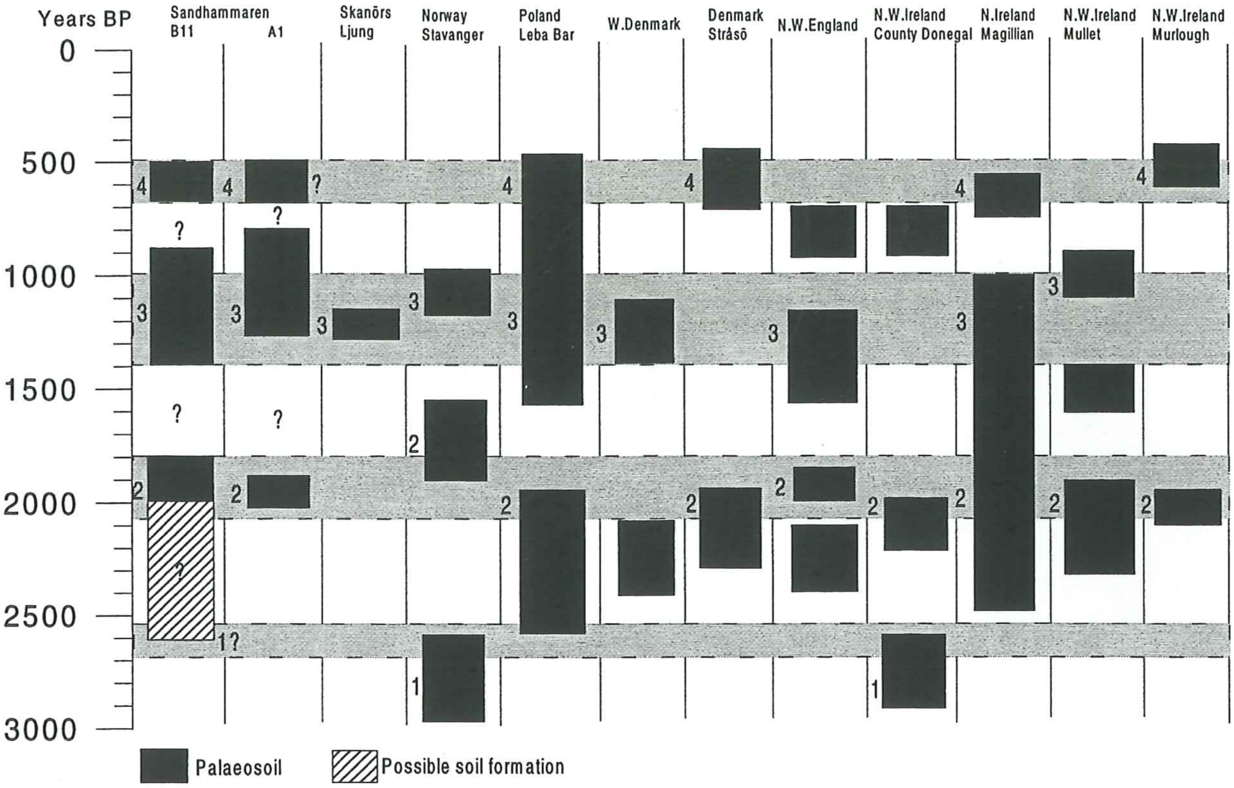

Fig. 17. The chronology of alternating periods of soil formation and dune activity from different parts of Europe, and tentative correlation. Norway (Selsing & Mejdahl, 1994), Poland (Tobolski, 1980), W. Denmark (Christiansen & Bowman, 1986), Stråsö, Denmark (Dalsgaard & Odgaard, unpublished), NW England (Tooley, 1990), NW Ireland, County Donegal (Shaw & Carter, 1994), N. Ireland, Magillian (Wilson & Bateman, 1986), NW Ireland, Mullet (Wilson, 1990), NW Ireland, Murlough (Cruickshank, 1980).

activity/sand drift, and could explain differences and discrepancies in the chronologies proposed by different authors (Fig. 17).

In spite of that, the time periods suggested for soil formation in other parts of Europe show a relatively good conformity. At some localities, e.g. Stavanger (Norway); Ståsö (Denmark); and County Donegal (NW Ireland), an old generation (1) of palaeosoils is dated to 3000-2600 BP. A second generation (2) of palaeosoils (c. 2500-1800 BP) is described at almost all sites (Sandhammaren, Stavanger, County Donegal, Leba bar, Northwest England, Denmark, Mullet, and Murlough) and may correspond to the second period of Late Holocene climate deterioration discussed above. Good correlation between palaeosoils can also be seen within the period *c.* 1400-1000 BP (3) and around *c.* 500 BP(4), that also agree with the Late Holocene climate deterioration periods (4) and (5), respectively (see discussion above).

The discrepancies that still remain in the correlation between sites and regions in Europe, makes it problematic to identify with certainty the decisive factors behind the reinforced dune activity. Selsing & Mejdahl (1994) suggest that the decisive factor for aeolian activity in Southwest Norway is human impact. This is in contrast to Christiansen *et al.* (1990) who suggest that low sea-level and availability of sediments play a more deterministic role in coastal dune formation in Denmark rather than any anthropogenic cause. In northern Ireland, the causes of dune development are not fully understood. No clear trends in the age of dune has been found, and human activity has undoubtedly played a prominent role. Local conditions such as variations in wave energy between the east, north, and west coasts have also played an important role in dune formation (Delaney & Devoy, 1995; Devoy *et al.* 1996). Evidence from Northwest Ireland suggests that the relative sea level has varied due to both local conditions, such as sediment budget, and more regional factors, such as glacial unloading and climatic change (Shaw & Carter, 1994). Regional trends and patterns of dune history during the Holocene in NW Europe in relation to sea-level fluctuations, climatic changes and human activities are not yet fully established and further investigations are required.

Conclusions

- The results of the chemical analyses imply that the soil profiles have been exposed to podzolisation processes. However, the leaching process has been weak, so the soils cannot be regarded as fully developed podzols. The soils are located in an area of relatively humid climate, and the well sorted sand provided good conditions for the downward movement of percolating waters, which is a prerequisite for podzol development. The limiting factors are probably time and the production of organic material, both due to the climate and human-induced dune activity/sand drift. Unstable conditions for soil formation have prevented mature podzols to develop.
- Soil formation took place between *c.* 2000 cal. BP (possibly earlier, e.g. 2600 cal. BP) and 500 cal. BP, with minor reinforced sand drift between *c.* 1800-1400 cal. BP and *c.* 900-700 cal. BP. These time interval, 400 and 200 years, respectively, are the maximum estimates for the sand drift. The most prominent dune activity took place prior to *c.* 2600 cal. BP and after *c.* 500 cal. BP (AD 1450), probably after the Little Ice Age, i.e. from the end of the 18th century.
- The dominant vegetation at the investigated sites during the periods of soil formation was a *Calluna* heath, with a low representation of trees. The most common tree species were *Pinus, Corylus, Quercus* (on sandy soils), and *Alnus* (in wet depressions). The *Calluna* heath vegetation was maintained by grazing and burning as part of a traditional land use which has only declined in the present century, leading to woodland regeneration. The low *Quercus* pollen percentages and concentrations imply that oak never was common in Sandhammaren. There are no similarities in the vegetation history between Sandhammaren and the southern coastal dune areas of the Baltic sea, e.g. the central part of the Łeba Bar in Poland. The modern occurrence of oak at Sandhammaren may be the result of the conscious maintenance of this tree in southern Sweden during the last centuries.
- The alternating dune and soil formation periods during the Late Holocene at Sandhammaren appear to be closely related to climate changes as reconstructed from several palaeoecological evidences, i.e. lake-level changes in southern Sweden, and glacier fluctuations in northern Sweden. Periods with minor sand drift i.e. 1800-1400 cal. BP and 900-700 cal. BP correspond to the Late Holocene climate amelioration periods (warmer and drier) between *c.* 1800-1200 BP and during the Medieval period (around 1000 BP). Periods of more active dune formation took place prior to *c.* 2600 cal. BP, and after *c.* 500 cal. BP (probably after the Little Ice Age, i.e. from the end of the eighteenth century), and represent warm and dry climatic conditions. However, the profound human impact during the nineteenth century was probably the major limiting factor for vegetation establishment and soil formation during the last period of dune formation.
- The alternating dune and soil periods described from several sites in NW Europe show a relatively good correlation, and may be associated to regional climate changes. These facts imply that the major trends of dune activity in north-western Europe may be ascribed to climate change. However, human impact and other local factors also played a prominent role in the local dune development. This explain discrepancies in the decisive factors proposed for dune activity, e.g. climate or human impact.
- The major conclusion of this study is that soil formation at Sandhammaren was initiated through climate shifts, from warm and dry to cold and wet conditions, while the maintenance of *Calluna* heaths during the periods of soil formation was due to human impact. The initiation of dune activity was also induced by climate change, except for the time after the Little Ice Age, when mainly human impact, i.e. extensive deforestation and intensive grazing, produced the most treeless Holocene landscape ever known in southern Sweden, and caused the most serious sand drift in the investigated area.

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