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We dedicate this paper to Professor Magdalena Ralska-Jasiewiczowa on the occasion of her 70th Birthday with very good wishes and thanks for so many interesting scientific meetings over the past years. With her extensive experience in working with laminated sediments we hope she will appreciate our small attempt to produce the same temporal resolution from peat.

A near annual record of recent tree-line dynamics from northern Finland*

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ABSTRACT. Some 2500 years of vegetation history are revealed through pollen analysis of a peat profile from Kevo in northernmost Finland. The aim of the investigation was to see if it is possible to obtain an annual pollen accumulation record from peats (comparable to those potentially obtainable from laminated lake sediments) to use as a proxy climate record and correlate with the local dendrochronological record. Two closely located peat profiles are analysed and the results compared with those from an adjacent pollen trap which has been monitoring pollen deposition continuously since AD 1982. An age-depth chronology is established for one of the peat profiles by wiggle-matching a series of AMS ^{14}C dates with the atmospheric ^{14}C curve around the "bomb peak", and then transferred to the second profile. By this means the depth location of individual years is obtained for the period AD 1872 to 1996. Pollen concentration is calculated for consecutive 2mm slices of peat down to a depth of 10 cm and the values converted to annual pollen accumulation rates using the age-depth chronology. *Betula* and *Pinus* are seen to have dominated the vegetation throughout the time covered by the profile. An interval of disturbance caused by fire followed by grazing is visible in the pollen record and dated to the very early years of 20th century. The gradual regeneration of pine after this fire and the fluctuating history of birch due to a series of defoliation attacks by *Epirrita autumnata* is also visible. It is concluded that, although it is possible to obtain a near-annual temporal resolution for the pollen record in this way, it is not possible to slice the peat in such a way that individual calendar years can be extracted which would give a clear year by year pollen or climate signal. Pollen accumulation rates for the individual tree taxa, however, do agree with the values predicted for presence/absence and degree of abundance of these species on the basis of pollen trap monitoring.

KEY WORDS: annual pollen accumulation, ^{14}C wiggle-matching, high temporal resolution, boreal forest limit, northern Finland

INTRODUCTION

Palaeoecological and palaeoclimatological reconstructions can be made using a range of techniques and proxies. Increasingly, it is being demonstrated that more detailed and quantitative reconstructions can be achieved by combining two or several proxies (Ralska-Jasiewiczowa et al. 1998, Birks & Wright 2000, McCarroll et al. 2003). However, the nature of each individual proxy often puts a constraint on the temporal resolution of the results. When reconstructions are based on microfossils recovered from lake sediments, such as pollen, diatoms, chironomids etc. the

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rate of accumulation of the sediment and the extent to which it is bioturbated determines the temporal resolution so that, even with a very thin sample, the record may be only on a decadal scale. Laminated sediments provide an exception (Peglar 1993, Lotter & Sturm 1994 Ralska-Jasiewiczowa et al. 1998) and high temporal resolution has been achieved from peat deposits (Simmons & Innes 1996). In general, though, it is the long-term trends which are best recorded.

The opposite is true of dendroclimatology. Reconstructions based on tree rings have an annual resolution and it is the high frequency signal which dominates, while the long-term trends, (being partly obscured by the ageing of the tree itself), have to be numerically extracted. In this respect pollen analysis and dendroclimatology are complementary and, taken together, should give a more complete picture of past climate change. There is, indeed, enormous potential in combining these two sets of records if only the difference in their temporal resolution can be reconciled. This was one aim of a recently completed EU funded project, FOREST (Forest Response to Environmental Stress and Timberlines) and is still an aim of the ongoing project, PINE (Predicting Impacts on Natural Ecotones). As one part of these two projects an attempt is being made to produce annual pollen accumulation records (grains/cm^2/year) from peat deposits from the same sites as the dendroclimatological records. Some preliminary results for a site in northern Finland are presented here.

The pollen and the tree-ring records, besides differing in the exactness of their temporal resolution, also differ in their spatial and ecological resolution. The trees used for the dendroclimatological record have experienced the effects of climate at just the site where they are growing and the record itself is based on a series of individual trees of one single species. In contrast pollen preserved in peat comes from a much wider catchment area, some of it from tens or hundreds of kilometers away and the pollen record comprises the whole plant spectrum, though not always at the lowest taxonomic resolution. However, by using annual pollen accumulation values (rather than percentages), individual species can be considered independently of the whole pollen assemblage, i.e. *Pinus* pollen values can be compared with the dendroclimatological record from pine trees, although the signal from the *Pinus* pollen will still be from a larger area than the signal encompassed in the trees.

Preliminary results of studies monitoring modern pollen deposition (Hicks 1996, 1999, 2001, van der Knaap et al. 2001, Autio & Hicks 2004) show that the annual pollen deposition (grains/cm^2/year) of certain tree species (e.g. *Pinus*, *Picea*) is correlated with the temperature during specific parts of the growing season of the year prior to pollen emission. In contrast, however, the long-term average pollen deposition (10–15 years), is related to the presence-absence of those tree species in the characteristic pollen source area. Numerically, pollen deposition values (both annual and the long-term average) also reflect the size of the opening in the forest where pollen deposition is taking place. Given the same density of trees in the region, the long-term average annual pollen deposition will be higher in a small opening (inside the forest) than in a large opening (in the centre of an extensive mire), and in both situations the actual quantity will be higher in years following a hot summer than in years following a cool one. These monitoring results add incentive to the aim of obtaining an annual resolution of pollen deposition from sediments.

The site chosen for this investigation, Kevo (Fig. 1) is situated in the far north of Finland (69°45.005′ N, 26°59.861′ E, 152 m a.s.l.) within the mountain birch *Betula pubescens* spp. *tortuosa* (Hämet-Ahti et al. 1986) woodland zone. It is 60 km north of the pine (*Pinus sylvestris*) forest limit, but, nevertheless, locally there are fairly extensive areas of mature pine forest. This extreme situation was chosen deliberately. Pines growing at their ecological limit are much more sensitive to even small changes in climate than those within the pine forest zone. The climate at the site is characterized by a mean annual July temperature of +13°C, a mean annual January temperature of –16°C and 395 mm annual precipitation. For much of the year the area is snow covered and the growing season is 110 days. The site is a small mire (0.75 ha) with a surface vegetation dominated by sedges and *Empetrum nigrum* with *Ledum palustre*, *Vaccinium vitis-idaea*, *V. uliginosum*, *Betula nana*, and *Rubus chamaemorus*.

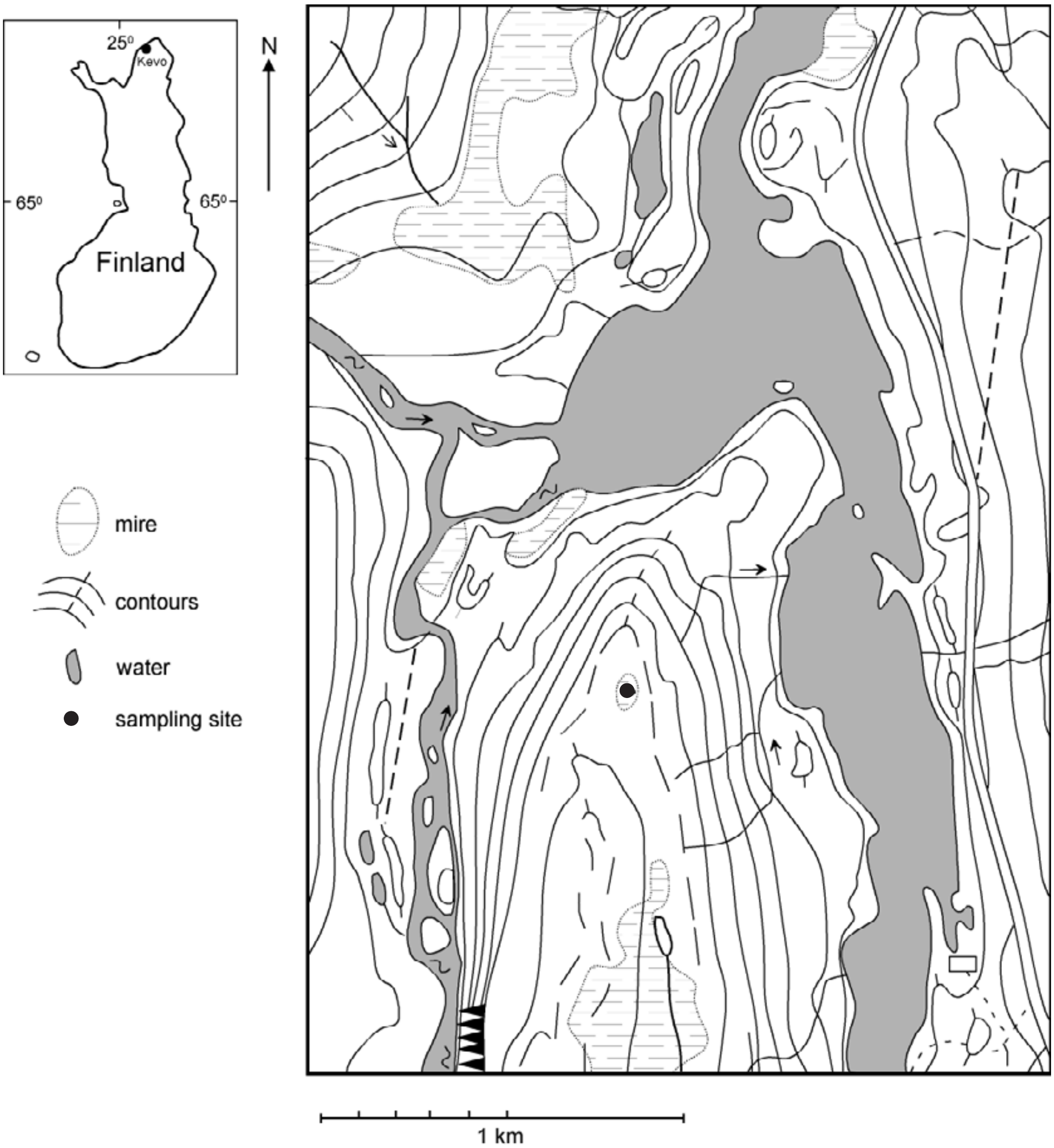


Fig. 1. Topographic map of the Kevo area in northern Finnish Lapland showing the location of the peat profiles and the pollen trap Ke8

MATERIAL AND METHODS

FIELD SAMPLING

The pollen record comes from two separate but adjacent peat profiles. The first was dug with a spade and extracted as a ca. 18 × 18 cm (surface area) peat monolith in September 1996. It extends down to 34 cm depth and is referred to hereafter as "monolith 96". The second profile was taken a year later (September 1997) with a 21 cm diameter manual Clymo peat corer. It extends down to a depth 60 cm (at which depth mineral substrate was encountered) and is hereafter referred to as the "Utrecht" profile since it was sampled by the Utrecht team and taken back to The Netherlands. Both profiles were taken in *Sphagnum fuscum* hummocks which rise ca. 10 cm above the general surface of the mire. The horizontal distance between the two profiles is ca. 50 cm.

Both have comparable stratigraphy. That of "monolith 96" is given here:

0–0.5 cm	living *Sphagnum*
0.5–8.0 cm	homogenous, light brown, slightly humified *Sphagnum* peat with some woody roots (Tb^1 Sphag 4, Tl+)
8.0–34.0 cm	darker more humified *Sphagnum* peat with both herbaceous and woody stems and roots, darker bands occur at 25 and 30 cm depth (Tb^2 Sphag 4, Th Erioph. +, Tl+)

The peat profiles are also adjacent (less than 1 m) to a modified Tauber pollen trap (with an aperture of 5 cm diameter) which has been monitoring pollen deposition on the mire surface since 1980 (code number Ke8 in Hicks 2001). The existence of this independent record of pollen deposition makes it possible to test the degree to which any high resolution record obtained from the peat approaches a real annual record, i.e. comparable to that from tree-rings. The modified Tauber trap is of the PMP standard design (Pollen Monitoring Programme http://wdc.obs-mip.fr/paleo/pmp/pmp.html) and, like the peat profiles, is located in a *Sphagnum fuscum* hummock with its opening at surface hummock level. The trap contents are collected annually in September and records are available from 1982 onwards.

LABORATORY TREATMENT

”Monolith 96” was sampled in Oulu, Finland and the “Utrecht” profile in Utrecht, The Netherlands “Monolith 96” was frozen and then cut into a series of columns of precisely measured surface area for a range of different analyses and pollen experiments. Only one such frozen column is described here. The block finally used for pollen analysis was 4 × 4 cm in surface area and was cut into contiguous 2 mm slices down to a depth of 15 cm beyond which it was sampled in cm cubes, every cm down to 29 cm depth. The 2 mm slices were obtained in the following way. Millimeter graph paper was frozen to the vertical (i.e. the depth) surface of the peat column. The column was then clamped into a wooden trough with open ends (in which one set of ends was reinforced with metal), such that the graph-paper covered-surface ran the length of the trough. The column was pushed towards the end of the trough so that exactly 2 mm of peat protruded beyond the metal reinforcements (measured by means of the graph paper) and this 2 mm slice was cut off with a well-sharpened knife (kept vertical by pressing against the metal reinforcements). The process was continued, extruding each 2 mm slice in turn. Samples were also taken from “monolith 96” for loss-on-ignition analyses. These were in contiguous 1 cm slices.

The “Utrecht” profile was used to extend the pollen analysis sequence to the base of the peat profile. Consecutive samples in the form of cm cubes were cut from the profile between the depths of 25 and 57 cm. These were dried and sent to Oulu for analysis. In order to match the two profiles additional samples for pollen analysis were taken from the upper 25 cm of the core at points where the pollen assemblage (based on the analysis and depths of the “monolith 96”) was expected to be sufficiently distinctive to provide matching criteria. These samples were 1 × 2 cm in surface area and 0.5 cm thick. In practice a whole section of the “Utrecht” profile from the surface down to 30.5 cm depth was sliced into consecutive 0.5 cm thick slices, which were dried and sent to Oulu. Like “monolith 96” the “Utrecht” peat profile was also sampled for a number of different analyses which, in the latter case, included radiocarbon measurements. From the uppermost 10 cm of the profile 6 leaves of *Betula nana* were picked out and the ^{14}C of each measured by AMS (see Tab. 1). These measurements were supplemented, 6 years later, with AMS measurements made on *Sphagnum* fragments (in one case bulk peat) extracted from the 0.5 cm thick dried slices which had been provided for pollen analysis (see Tab. 1).

Thus the two peat profiles provide two pollen profiles, a high resolution (2 mm slices) but short one from “monolith 96” and a coarser resolution but longer one from “Utrecht”. The loss-on-ignition measurements are related to the former but the radiocarbon measurements to the latter. The integration of the two is described under the results section below.

Each of the pollen samples was prepared in the same way. Before any laboratory treatment tablets containing *Lycopodium* spores (Stockmarr 1971) were added. The exact number varied being 1 per sample for the 2 mm slices, 2 for the cm^3 samples of “monolith 96” and 3 for all samples from the “Utrecht” profile. This was to insure that the ratio between added *Lycopodium* spores and pollen in the pollen counts was such that the confidence limits on the pollen concentration calculations would be as narrow as possible (Bennett 1994). Chemical treatment consisted of heating in dilute KOH followed by sieving through a coarse

Table 1. Details of the material submitted for radiocarbon dating. The first 9 measurements are expressed as percent of modern carbon (pMC). The last four measurements are expressed as ^{14}C years BP

Utrecht profile Sample depth in cm (mid point)	Sample thickness mm	Material analysed	Code	Measurement
2.0	1	*Betula nana* leaf	Utc-8183	114.2 ± 0.8 pMC
4.0	1	*Betula nana* leaf	Utc-8184	120.8 ± 0.5 pMC
5.1	1	*Betula nana* leaf	Utc-8185	115.9 ± 0.6 pMC
5.2	1	*Betula nana* leaf	Utc-8134	126.0 ± 0.5 pMC
5.25	5	*Sphagnum*	Poz-4403	119.1 ± 0.3 pMC
7.0	1	*Betula nana* leaf	Utc-8135	118.9 ± 1.8 pMC
9.0	1	*Betula nana* leaf	Utc-8136	130.6 ± 0.7 pMC
10.0	1	*Betula nana* leaf	Utc-8158	132.1 ± 0.6 pMC
14.25	5	*Sphagnum*	Poz-2375	160.9 ± 0.4 pMC
18.25	5	*Sphagnum*	Poz-2376	75 ± 25 BP
22.75	5	*Sphagnum*	Poz-2377	75 ± 25 BP
26.2	5	*Sphagnum*	Poz-3680	120 ± 30 BP
55.5	10	Peat	Poz-2378	2475 ± 30 BP

sieve, acetolysis (9 parts acetic anhydride and 1 part sulphuric acid) in a water bath, washing, and mounting in silicone oil.

Pollen and spores, charcoal and spherical carbonaceous particles (SCP) were counted for each sample to a minimum total of 500 AP (Arboreal Pollen. This includes all northern boreal tree taxa but excludes middle and southern boreal thermophilous tree taxa). Pollen taxonomy follows that of the European Pollen Database (EPD). *Betula* pollen was divided into three groups: *Betula nana, Betula pubescens* type and *Betula tortuosa* type on the basis of size and morphological characteristics (see Hicks 2001 for precise details). The pollen diagrams have been constructed using the programs TILIA, TILIA-GRAPH and TGView (Grimm 1992). The basis for the percentage calculations in Figure 3a, b is total dry land pollen and spores, that for Figure 2 is slightly different, the rational for which is explained below.

The pollen trap collections were centrifuged or filtered and then prepared in a comparable way to the peat profile samples (see Hicks 2001 for precise details). The results for the years 1982–1996 (i.e. the value of the last year corresponds to the most recent year that can be present in "monolith 96") are illustrated in Figure 6 (expressed as grains/cm^2/year) which has also been drawn using the Tilia suite of programs.

RESULTS AND DISCUSSION

The two pollen diagrams together (Fig. 3a, b) record the changes in vegetation around the mire over the last 2500 years. During the whole of that time birch and pine have been the only trees present in any quantity in the region. The percentage diagrams show how these two species have varied relative to each other over that period but may not give a true picture of the actual abundance and density of these tree species. For a better understanding of this aspect, and to allow calibration with the dendroclimatological record, pollen accumulation rates (PARs) are necessary (Hyvärinen 1975, 1976, Hicks & Hyvärinen 1999, Hicks 2001). These cannot be calculated unless the rate of peat accumulation is known. Neither is it possible to say what period of time the 2 mm slices represent without an age-depth chronology. An additional problem comes from the fact that the high resolution pollen analysis results come from a different profile from that from which the radiocarbon measurements have been made. Two steps are then needed, (1) to establish how the two peat profiles link together and (2) to construct a robust age-depth chronology for the top 30 cm of peat so that each pollen sample can be assigned a calendar age. These are addressed below. Since the aim is to look at changes in pollen accumulation at an annual scale the successful establishment of these two points is crucial.

ESTABLISHING A LINK BETWEEN THE TWO PEAT PROFILES

In matching the two profiles attention has been given primarily to changes in the percentage presence of mire surface species and secondarily to plants from the regional vegetation. For this purpose pollen taxa representing those plants which may have grown on the mire surface (*Betula nana*, all Ericales, Cyperaceae, *Rubus chamaemorus*, *Equisetum*, Liliaceae, *Menyanthes*, and *Selaginella*) were taken as a separate group and their percentage values calculated from the sum of this group. *Betula* (total of *B. pubescens* type and *B. tortuosa* type), *Pinus* and *Salix* percentages are calculated from total dry land taxa minus the dwarf shrubs, while *Sphagnum* spores were calculated as a percentage of this latter total plus *Sphagnum*. The two abbreviated diagrams are illustrated side by side in Figure 2. The features on which they are matched are highlighted with lines. A distinctive combination of features is seen at the very base of the "monolith 96": a peak in *Rubus chamaemorus* followed by the decreasing presence of this pollen taxon, contemporaneous with the appearance of *Salix*, extremely low values of *Sphagnum* and rapidly increasing values of Cyperaceae. This can be matched with the same sequence of features in the central part of the Utrecht profile. When the depths of this feature in the two profiles are compared it is seen that it occurs 1.5 cm deeper in the "Utrecht" profile than in "monolith 96". This is in keeping with the fact that the "Utrecht" profile was sampled one year later than "monolith 96". Later experiments to measure the rate of peat growth have been inconclusive but seem to suggest that the surface of the *Sphagnum fuscum* hummocks grows by at least 5 mm in one year. One would not expect an absolute match because, after all, the profiles were taken from different though adjacent hummocks. On the basis of the pollen match the radiocarbon dates are transferred to points 1.5 cm higher up the monolith 96 profile. i.e. 10 cm in the "Utrecht" is equivalent to 8.5 cm in "monolith 96".

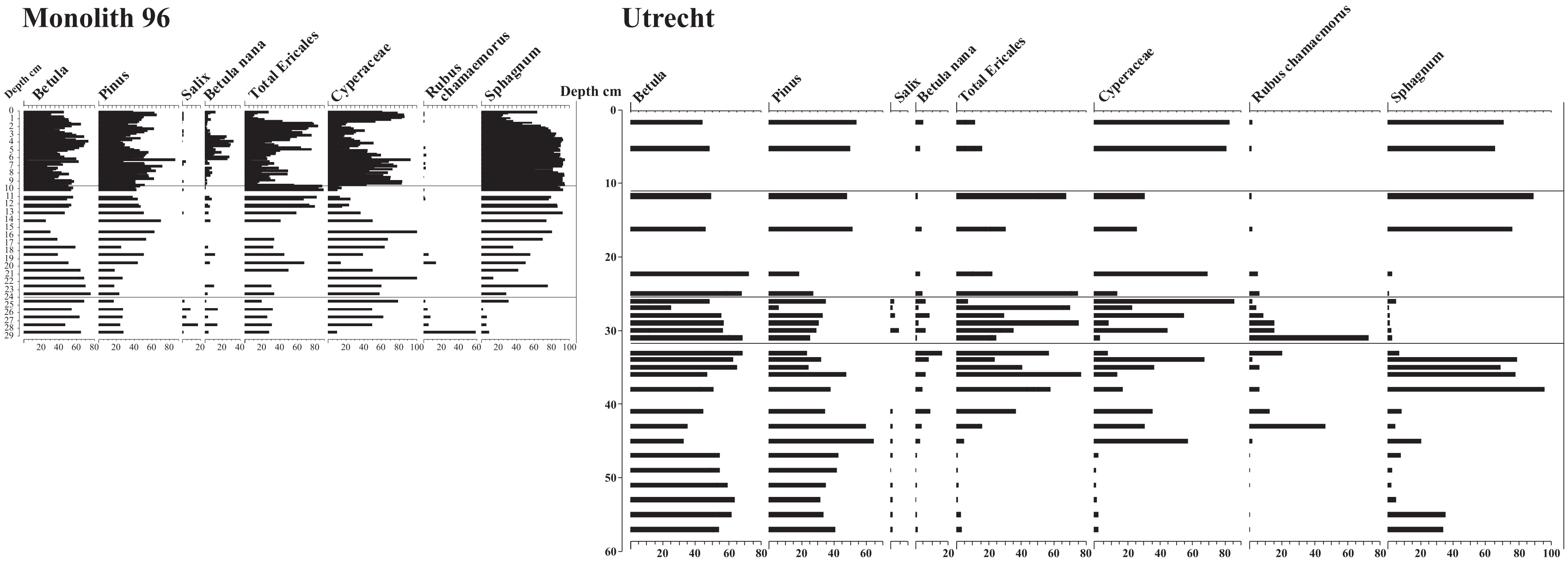


Fig. 2. Percentage pollen diagrams (selected curves only) from the "monolith 96" and "Urtrecht" peat profiles. The percentages of the tree and shrub species are calculated from the total of dry-land pollen taxa while those of dwarf shrubs and other mire species are calculated from the total of these mire pollen taxa. The horizontal lines show points at which the two profiles have been matched

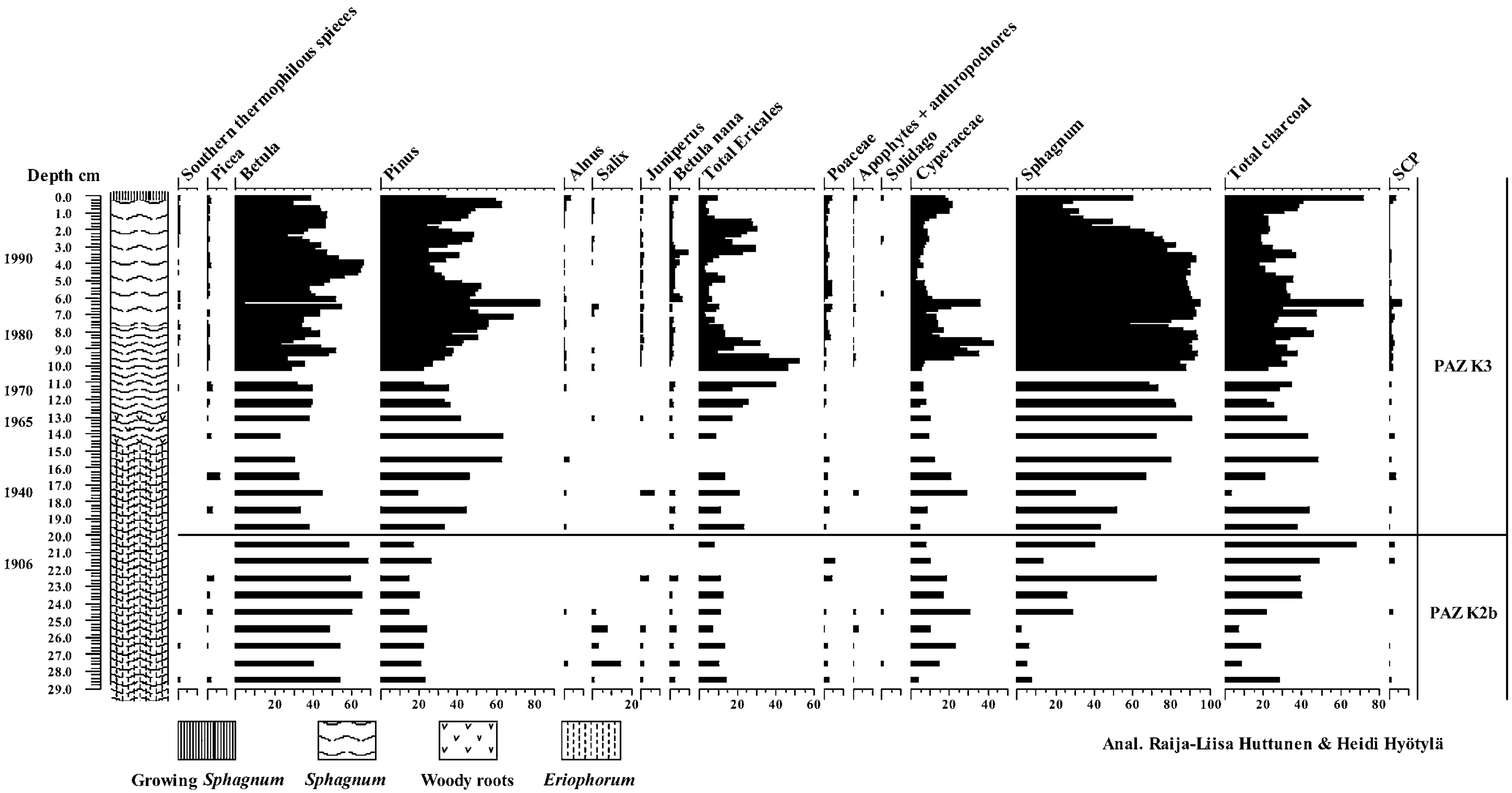
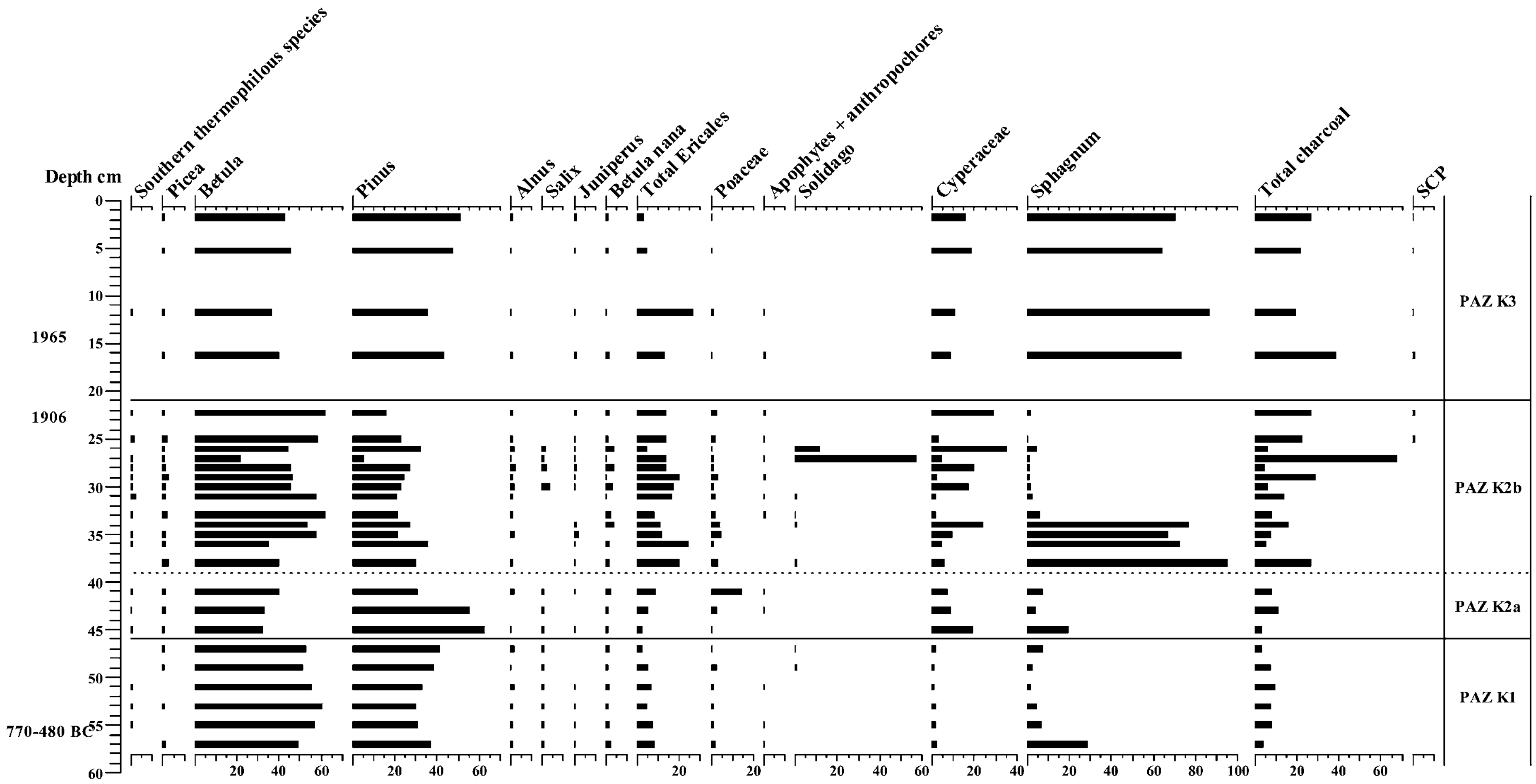


Fig. 3a. Percentage pollen diagram from the Kevo "monolith 96" peat profile (selected taxa, percentages for dry land taxa are calculated from the total dry land taxa pollen sum including dwarf shrubs = $\sum P$, *Sphagnum* and charcoal percentages are calculated from $\sum P$ + spores and $\sum P$ + charcoal respectively). This diagram covers the second half of PAZ K2b and the whole of PAZ K3



Anal. Raija-Liisa Huttunen and Heidi Hyötylä

Fig. 3b. Percentage pollen diagram from the Kevo "Utrecht" peat profile. The basis of the percentage calculation is the same as in Fig. 3a. The three PAZ described in the text are marked together with a line showing the basal sample from the "monolith 96" diagram. Both diagrams are annotated with dates taken from the age-depth chronology

THE AGE-DEPTH CHRONOLOGY

The samples from the upper part of the "Utrecht" profile contain "modern" carbon, with a ^{14}C concentration that is higher than in the ^{14}C standard and is expressed in pMC (percent of modern carbon). This reflects the large peak of atmospheric ^{14}C, produced in the late 50s and early 60s by the atomic weapon tests (Nydal & Lövseth 1983, 1996, Levin et al. 1992, 1997). Lower down in the profile, the dates are "normal" and expressed in years BP. A precise age determination of the modern samples by means of ^{14}C would seem to be relatively easy, as the ^{14}C concentration in the atmosphere after 1963 was changing rapidly, and in each year the value was distinctly different from the next (Fig. 4). However, the samples analyzed rarely contain carbon derived during a single year, so the ^{14}C concentrations measured through the profile are not directly comparable with the atmospheric concentrations. ^{14}C dating of 8 modern peat profiles studied in the framework of the PINE project led to the conclusion that the signal of atmospheric ^{14}C in peat is "integrated" over some time interval, the length of this being specific for the site (Goslar et al. in prep.). So, ^{14}C concentrations in peat follow the "atmospheric" curve but modified by integration. Detailed analysis (Goslar et al. in prep.) suggests that the integration time in the Kevo profile is 4–5 years.

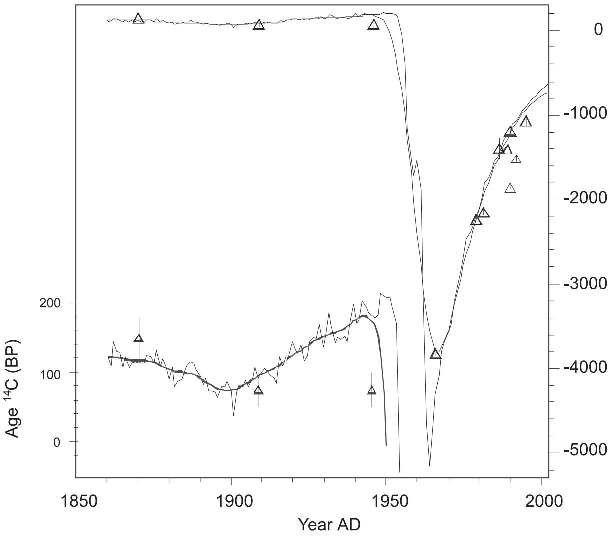


Fig. 4. ^{14}C *vs.* calendar ages of samples from the Kevo profile (triangles) in comparison with the extended ^{14}C calibration curve. The thin line shows the single tree-ring calibration curve (AD 1870–1950, Stuiver & Braziunas 1993), extended using the data on atmospheric ^{14}C concentrations in the bomb and post-bomb period (Nydal & Lövseth 1996, Levin et al. 1997). The thick line presents the atmospheric signal integrated over ±5 years. The two outlying ^{14}C dates (thin trangles) were obtained on samples of birch leaves. At the left-bottom corner: the pre-bomb part of the graph (before 1950), presented at a stretched scale of ^{14}C years

Absolute ^{14}C dating of samples older than 1950 AD (from the "pre-bomb period") is also problematical because of large wiggles in the ^{14}C calibration curve. Therefore, individual ^{14}C dates in the interval 0–200 BP may correspond to a number of different calendar ages. This difficulty may be overcome when a series of samples from the profile (encompassing both the pre-bomb and post-bomb periods) are dated and treated jointly.

In the present approach we applied a recently developed computer program (Goslar et al. in prep.). This program, using a standard algorithm for calibration of ^{14}C ages (Michczyńska et al. 1990), calculates the probability distributions of the calendar age of individual samples in the profile and displays them with vertical positions proportional to sample depths (Fig. 5). On such a graph, the age-depth curve should pass through the maxima of probability distributions.

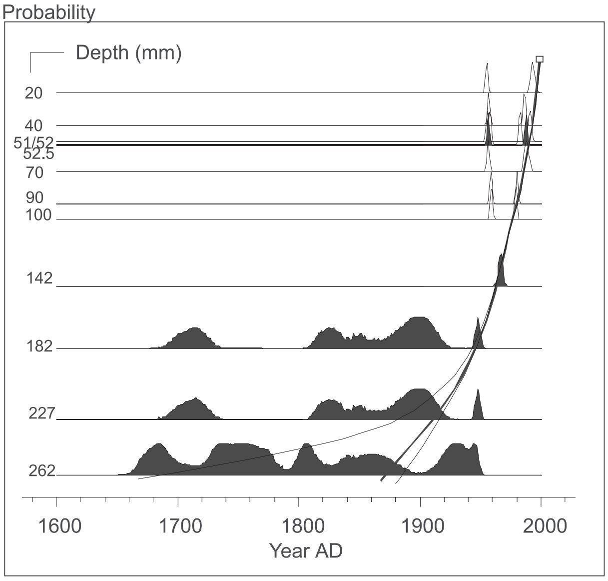


Fig. 5. Probability distributions of calendar ages of samples dated with the ^{14}C method. The sample depths (in mm) are given to the left. The distributions obtained for samples of birch leaves are shown with white silhouettes, those obtained for samples of *Sphagnum* are shown with black silhouettes. The small white square at the upper-right corner represents the year AD 1997 at the surface of the mire (0 mm). The smooth black line passing through the distribution shows the age-depth model, derived under the assumption of the "least variable" peat growth rate, the uncertainty of the model is shown with dashed lines

As shown in Figure 5, most probability maxima for the samples down to 18.2 cm lie along a smooth line. As expected, this line indicates the year AD 1997 at the top of the profile ("Utrecht"). The slope of this line decreases downwards, which is also expected as an effect of decomposition and compaction. Two clearly outlying ^{14}C results were obtained for samples of *Betula* leaves from 40 and 52 mm. This would mean that the dated leaves grew earlier, and were only redeposited at the spot from which they were ultimately recovered, after a few years. A problem with ^{14}C dating of leaves is evident in the case of the samples from 5.1 and 5.2 cm, which, although incorporated in the peat at the same depth, have distinctly different ^{14}C concentrations. Of course, such a problem does not concern material growing in situ, such as fragments of *Sphagnum* tissues.

Calibration of individual ^{14}C dates for the samples between 18.2–26.2 cm gives very wide calendar age intervals (ca. AD 1700–1950), because of the large wiggles in the ^{14}C calibration curve during that period. However, the incorporation of all data in one profile (and the assumption of a stratigraphical age order), imposes strong constraints on the age estimates. An important additional assumption is that plant decomposition and compaction processes produce an increasing slope of the age-depth curve (i.e. decreasing deposition rate) down the profile. The latter assumption is in agreement with the profile stratigraphy, which confirms increased decomposition with depth. In detail, the intervals ca. AD 1690–1730 and AD 1810–1920, proposed by the calibration of ^{14}C age at 18.2 cm (Fig. 5), appear improbable as they would imply an increase in peat accumulation below that sample. The interval AD 1690–1730 is also improbable at 22.7 cm, and similarly we can discriminate intervals AD 1940–1950 at 22.7 cm and AD 1910–1950 at 26.2 cm. Additionally, the date at 22.7 cm is most probably younger than AD 1880.

The ultimate age-depth model is very precise in the profile section above ca. 18.0 cm (with a precision of ±2 years or better) and still fine at ca. 23.0 cm, but below that level uncertainty in the model rises drastically. An improvement of the absolute dating at 26.2 mm would require ^{14}C dating of the underlying peat (at, say, 30.0 cm).

VEGETATION HISTORY OF THE KEVO PENINSULA INTERPRETED FROM THE PERCENTAGE POLLEN DIAGRAMS

The percentage diagrams (Fig. 3a, b) have been divided into three pollen assemblage zones (PAZs) of which PAZ K2 is divided into two sub-zones. The "monolith 96" pollen diagram covers the later part of PAZ K2b and PAZ K3.

PAZs K1 and K2 are described from the "Utrecht" profile and zone K3 from "monolith 96".

PAZ K1

Basal peat (56 cm depth) from the "Utrecht" profile produced a radiocarbon age of 2475 ± 30 BP (calibrated to between 770 and 480 BC). At this point the pollen diagram indicates that birch woodland dominated the vegetation but that pine must have been locally present (values 30–40% dry land pollen). Some grains of *Picea* pollen are recorded. These will have been blown in from further south. Their presence is in keeping with evidence from elsewhere in Lapland (Hyvärinen 1975, 1976, Hicks & Hyvärinen 1997, 1999) that spruce had achieved its present northernmost limit by 3000 ^{14}C BP. The presence of Ericales pollen and the very low representation of Cyperaceae pollen in the basal 10 cm suggests that the mire surface was not especially wet. The dwarf shrubs and grasses recorded could well have been part of the understory of the birch woodland.

PAZ K2

The percentage of Cyperaceae pollen begins to increase from a depth of 45 cm and, during PAZ K2a, *Pinus* percentages are at their highest, suggesting that pine was much more abundant in the surrounding forest than during PAZ K1. However, the biggest changes in the diagram are seen in the section between 38 and 21 cm depth (PAZ K2b). *Pinus* values fall, those of dwarf shrubs increase and there are slightly higher values of both charcoal fragments, *Picea* and "southern thermophilous species". At the beginning of this subzone there is a dramatic peak in *Sphagnum* spores and, in the later part, low *Sphagnum* but increasing values of Cyperacaeae, and the increased values of *Salix* and *Rubus chamaemorus* (not illustrated in Fig. 3), which were used in matching the two profiles. At a depth of 26–27 cm there is also a sharp peak (up to nearly 60%) of *Solidago* pollen, which is not, however, present in "monolith 96".

A number of things are happening. The changes in *Sphagnum* and then Cyperaceae, *Rubus chamaemorus* and *Salix* reflect changes in the vegetation on the surface of the mire at the point of the pollen profile and indicate the development of wetter conditions, while the fall in *Pinus*, rise in Ericales and more abundant presence of charcoal pieces suggest that the forest was being opened up by people, felling pines and using fire. Apophytes and anthropochores are more consistently present during the later part of PAZ K2b when charcoal values are at their highest. The fact that the pollen types which originated from very far away, *Picea* and the thermophilous forest trees, increase proportionally during this phase, supports the interpretation that the local forest was considerably opened up (i.e. there was a distinct reduction in the quantity of local pollen so that the presumably more or less constant input of long-distance pollen appears to increase).

This type of disturbance is common in connection with Saami reindeer hunters (Aronsson 1991, Hicks 1993, Carpelan & Hicks 1995) who may also have been felling pines for their inner bark (Itkonen 1911, Zackrisson et al. 2000). The presence of the apophyte and anthropochore pollen taxa at only very low percentages is also in keeping with this type of use of the forests.

An explanation must be sought for the peak in *Solidago* pollen. The fact that there is so much in the "Utrecht" profile and only low values in "monolith 96" for the same time period suggests that a whole flower head must have dropped onto the peat surface at just that point, but this also suggests that the plant was reasonably common in the surroundings. Charcoal fragments have their highest values in connection with this sample (again more clearly in the "Utrecht" profile than in "monolith 96") which is taken to indicate local fire (but see Tinner & Hu 2003). Local history verbally recounts (Saini Heino pers. com.) that there has been a fire on the peninsula. The presence of a charcoal horizon within the soils (Lasse Iivari pers. com.) confirms this. Photographs from a time before the Kevo Subarctic research station was built on the peninsula (construction started 1956) show that the peninsula supported only young pine trees, while coring of pines at present growing on the peninsula (Niemi pers. com.) reveals that, although a few large pines are more than 150 years in age, the majority are between 50 and 65 years old or younger. These facts are in agreement with a map by Hustich (1948) which shows the presence of 1–3 year old seedlings of pine in 1939/1940. Observations in the Kevo – Utsjoki area confirm that when land from which the trees have been removed is abandoned, the commonest "weed" to colonize the area is *Solidago virgaurea*. It should also be mentioned that the one occurrence of *Epilobium* pollen (*Epilobium angustifolium* characteristically spreads after fire) occurs in "monolith 96" at just this point. At this point also, the loss-on-ignition values are lowest, suggesting a higher proportion of mineral material, reflecting areas of exposed soil and wind erosion. In the pollen sample that has the very high values of *Solidago* there are numerous spores of the fungus *Sporormiella* which is common on dung (van Geel et al. 2003). Unfortunately this fungal spore was not routinely counted, so it is not possible to include a curve of its presence throughout the pollen diagram. One other feature of note in the pollen diagrams is that in the "monolith 96" peat section for the very end of subzone K2b there was so little pollen in the preparations that it was difficult to obtain a reliable count.

On the basis of all these features the following interpretation is suggested. The woodland/forest on the peninsula around the mire from which the profiles come, was burnt down leaving just a few mature pine trees standing (at present these do not have any obvious fire scars but the position, size and nature of a scar on one tree suggests that it might have had its bark and inner cambium collected). The exact timing of this is unclear but it appears to be at the end of the 19th century (the depth of 22.7 cm is calculated to be AD 1909). Following the fire there was a short period when *Solidago* was abundant on the treeless peninsula. Animals grazing on the peninsula (reindeer but possibly also cattle, since it is known that both cows and sheep were kept locally) ate the *Solidago* and a concentrated input of pollen of this plant occurred in the dung. The openness of the vegetation resulted in very low pollen deposition. During this period the mire surface was also wetter.

PAZ K3

This PAZ is illustrated in greatest detail in the "monolith 96" diagram, and the age-depth chronology shows that it covers the last century. This zone has consistently high values for *Sphagnum* spores in keeping with the fact that the peat is composed almost entirely of *Sphagnum fuscum.* There is no such clear relationship between the presence of *Eriophorum* remain in the peat and Cyperaceae pollen. Many of the dwarf shrubs contributing pollen in the "Total Ericales" catalogue will also be among the peat-forming taxa but the only visible evidence of this in the stratigraphy are the woody roots at 13–15 cm depth just below the rise in the Total Ericales pollen curve. The mire surface has probably looked much as it does today throughout the whole of the period covered by PAZ K3.

During PAZ K3 the proportions of *Pinus* and *Betula* pollen have fluctuated considerably. In order to correctly interpret these fluctuations at this high temporal resolution (65 samples cover 100 years) a number of aspects have to be borne in mind. Since these two taxa are the major contributors to the pollen assemblage their percentage representation in the pollen diagram need not necessarily directly reflect the abundance of trees of the two species in the surrounding vegetation (e.g. complete non-flowering of *Betula,* for whatever reason, would result in *Pinus* percentages rising to very high values, even if there was no actual change in the number or flowering of the pine trees present). Factors which could affect the relative pollen production and deposition of these two taxa are first considered.

As has already been mentioned, the pines on the peninsula itself are of different age classes. The few old pines which survived the fire would be pollen producers throughout this zone. Hustich (1948) examined records of pine flowering and writes that male flowering was extremely rich in 1938. In contrast, the next generation of pines (those 50–65 years old today) would not have started producing pollen until around the 1960s. At the regional scale the number of pines has been increasing in the last 20 years.

Alongside this, the birches on the peninsula have been subject to attack by caterpillars of the moth *Epirrita autumnata.* The last major attack, which defoliated many of the birches at the highest elevations in the surroundings (ca. 135 000 hectares in the Utsjoki administrative district) and a proportion of the Kevo birches, occurred in 1964–65 (Tenow 1972). However, it is known that there have been attacks before that, in 1926–1927, 1939, 1949 and 1954–1955 although those in 1939 and 1949 were restricted in extent and not local to Kevo (Tenow 1972). Kallio & Lehtonen (1973) also mention that old residents of the villages along the Teno river speak of extensive birch damage in the first decade of the 20th century.

Following defoliation it can take 25–75 years for the birches to recover, if they recover at all, recovery being slowest in areas where there is reindeer grazing. Reindeer herds were at their maximum in the Utsjoki area in 1980s. Kukkonen (2002) studied the recovery of mountain birch forests in Utsjoki after the *Epirrita* damage of the mid 1960s and calculated that the mean recovery percentage was only 5%. For the Utsjoki area, as a whole, there has been an enormous decrease in birch forest between 1960s and now, with very poor recovery under the present climate and grazing conditions (Tømmervik et al. in press). However the birches on the Kevo peninsula had completely recovered by 1980s. Kallio & Lehtonen (1973) comment that following defoliation there is an obvious increase in grasses and herbs and more prolific flowering of *Trientalis europaea, Linnaea borealis*, *Solidago virgaurea*, and *Epilobium angustifolium.*

On the basis of this known historical documentation, the last century can be divided into four phases. From 1900 to ca. 1940, pines were few but, nevertheless, in certain years were flowering prolifically and birches were defoliated by *Epirrita* on at least one occasion. For the period 1940 to 1970 a similar situation persisted but *Epirrita* attacks were somewhat more frequent with the last devastating attack in the region taking place in 1964/1965. From 1970 to 1980 pine pollen production greatly increased as the young pines, which were seedlings after the peninsula fire, reach maturity and birch pollen production was also increasing as those birches on the peninsula which had been affected by the *Epirrita* attack were recovering. From 1980 to 1996 both pine and birch are producing pollen in accordance with annual changes in temperature but "non pollen producing" areas persist at high altitudes in the surroundings where birches have not been able to recover.

In percentage terms this should mean that between 1900–1940 *Pinus* and *Betula* pollen are likely to be equally abundant, but both low in quantity. During the period AD 1940 to 1970 *Pinus* values would be gradually increasing relative to *Betula,* and after 1964 *Pinus* values should sharply rise to be much more abundant than those of *Betula*. From 1970 to 1996 the two pollen types should be equally abundant again but with higher quantities but if the pollen source area encompasses the whole region then *Pinus* values could be increasing relative to *Betula*. In Figure 3 the curves cannot be ”read” directly in this way because Ericales are included in the pollen sum, but they can be read from Figure 2 where the Ericales values are included in the mire plants sum and excluded from the dry-land plants sum. These predicted variations between *Pinus* and *Betula* are visible in the diagram, and there is a distinct *Betula* low at the horizon dated to AD 1964. *Betula* values are high and fluctuating during the period 1980 to present suggesting that it is the local rather than the regional situation which is being recorded and that the effect of climate variation on flowering may also be visible.

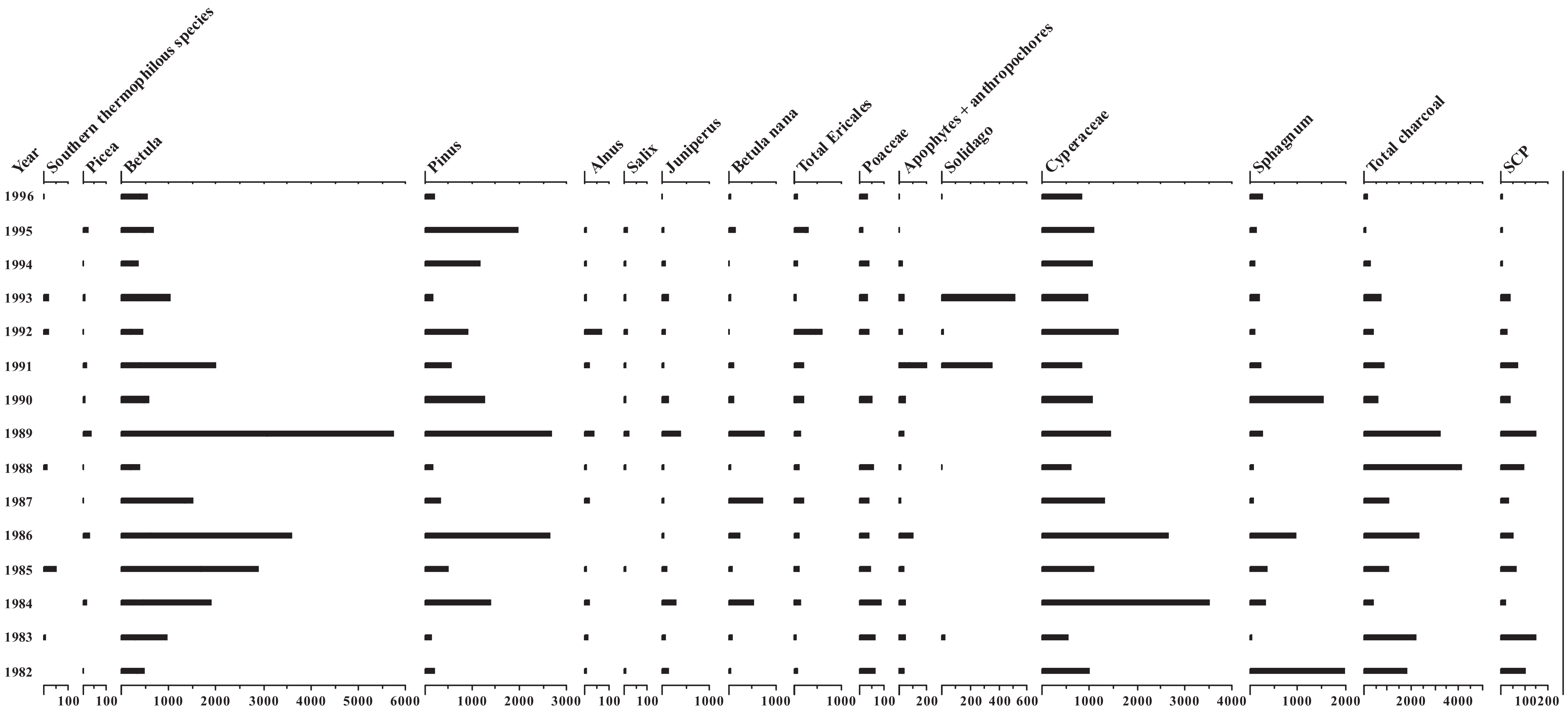
To look at the actual quantities of pollen involved it is necessary to turn to pollen accumulations rates (PARs). These are illustrated in Fig. 6a, b for just the last 20 years, the period during which both *Pinus* and *Betula* pollen should have been relatively abundant.

COMPARISON OF POLLEN ACCUMULATION RATES (PARS) CALCULATED FROM THE PEAT PROFILE WITH ANNUAL POLLEN DEPOSITION MONITORED BY THE POLLEN TRAP

The strong age-depth chronology produced with a ±2 year accuracy for the upper layers of the “Utrecht” profile has been transferred to the “monolith 96” profile, taking into account the 1.5 cm difference in the measured depths. This chronology has been used to convert the pollen concentration of the 2 mm slice samples to pollen accumulation rates (grains/cm^2/year). The result for the upper 8 cm of sediment is illustrated in Figure 6b. An evaluation of the possibility of extracting an annual pollen signal from peat deposits plus a control on the validity of the age-depth chronology can be made by comparing these PARs with the annual pollen deposition values monitored by the adjacent pollen trap (Fig. 6a). This was attempted in an earlier publication (Hicks & Hyvärinen 1999) for *Betula* and *Pinus,* but the age-depth chronology used in that publication for the conversion of the peat-slice pollen concentration into PARs, was based on ^{210}Pb dating. The ^{210}Pb dating produced three alternative chronologies depending upon the length of the profile considered (Kunzendorf pers. com.). In the Hicks & Hyvärinen (1999) publication the ^{210}Pb chronology “model 1”, that involving the shortest depth of profile, was used. In the light of the ^{14}C chronology illustrated here, however, this is seen to give far too slow a rate of peat accumulation. “Model 3”, which uses the greatest depth of profile more closely resembles the present ^{14}C chronology. The PARs for *Betula* and *Pinus* presented in Fig. 6b are in the range 100–3000 and 100–2500, respectively, which is the same order as the annual values recorded in the pollen trap (Fig. 6a, in just one year *Betula* reaches 6000 grains/cm^2/year). Due to the slower rate of peat accumulation predicted by ^{210}Pb “Model 1” the PARs calculated in the 1999 publication, are around 1/3 of those recorded in the traps. The better agreement achieved when using the ^{14}C chronology gives support to the claim that the ^{14}C chronology is the more realistic and the model used to produce it is robust.

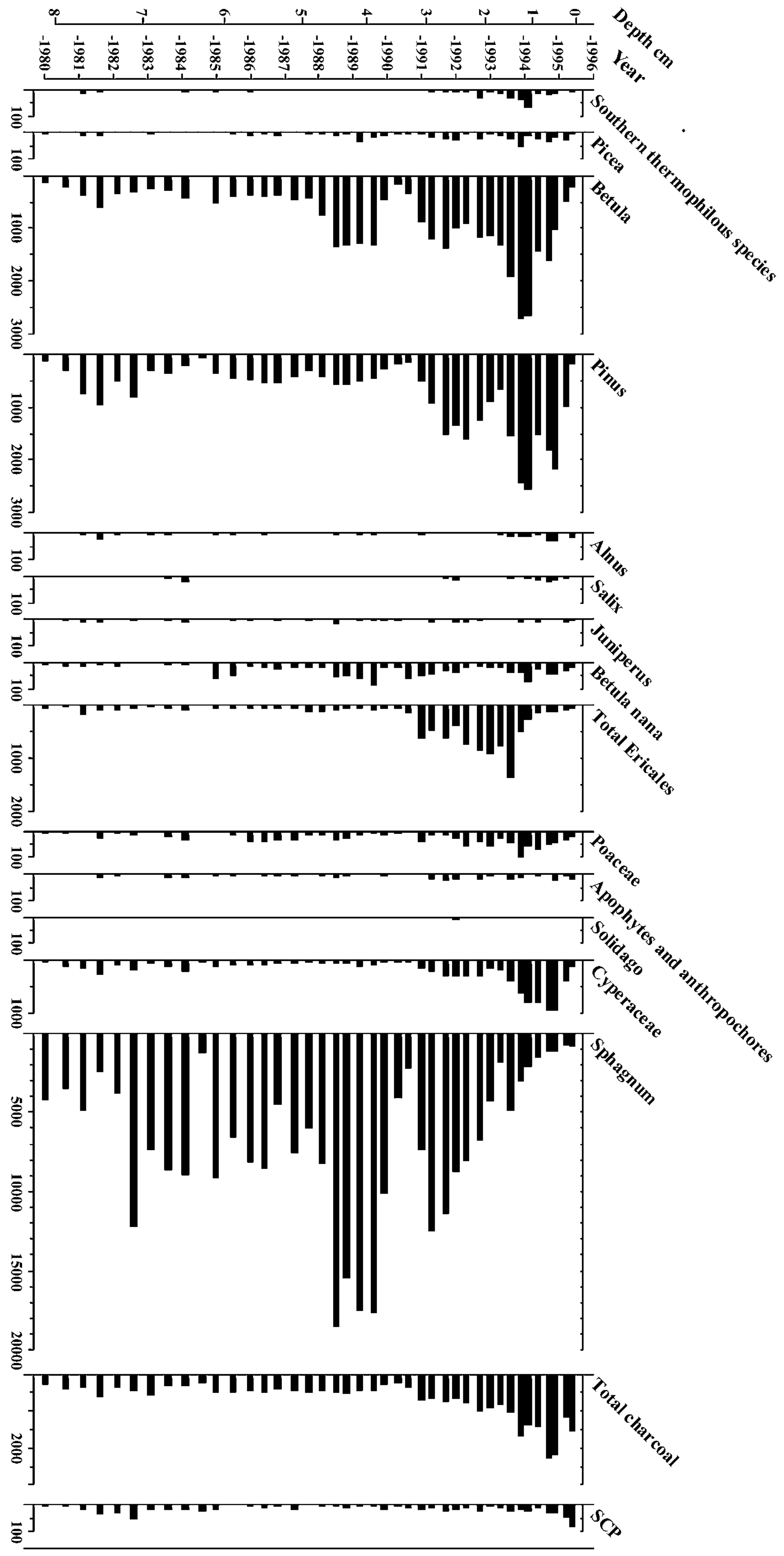
In general the trap records tend to show higher values of the main species in the period 1982–1989 than in the period 1989–1996, while the PARs are the opposite, being mostly lower in the period 1980–1990 and higher between 1990 and 1996. This could indicate that the calculated rate of peat accumulation for the upper 4 cm, as based on the ^{14}C chronology, is faster than in reality, while in the section 4–8 cm depth the calculated rate of accumulation is slower than in reality. Despite this, however, some (but by no means all) patterns are the same in the trap and the peat, for example the 1988 low, 1989 high, 1990 low, 1991 high, 1992 low cyclicity for *Betula* is seen in both, but the years before and after this series do not “match”. The 1991 low, 1992 high, 1993 low, 1994 and 1995 high, 1996 low sequence for *Pinus* is seen in both, but the high years of 1986 and 1989 that are obvious in the trap are not seen in the peat.

Hicks (2001) provides a table of long-term average pollen deposition values which are related to the abundance of birch and pine in



Anal. Sheila Hicks, Raija-Liisa Huttunen and Jacqueline van Leeuwen

Fig. 6a. Annual pollen deposition (grains/cm^2/year) of selected taxa monitored by means of the pollen trap Ke8 (1982–1996)



Anal. Raija-Liisa Huttunen

Fig. 6b. Pollen accumulation rate (PAR) diagram for the top 8 cm of the "monolith 96" profile constructed using the ^{14}C based age-depth chronology illustrated in Fig. 5

the vegetation when sampling is in a mire or similar size to that sampled at Kevo. When compared with these values, the average PARs for *Betula* and *Pinus* during the period 1990–1996 (Fig. 6b) of 1000–1500 for *Betula* and 1500 for *Pinus* should be interpreted as "open forest" of both these species, which is indeed the case for the surroundings of the mire at present. Whereas the average PARs for the period 1980–1990, taking the same comparison, would indicate that both trees were present but only sparsely, which is not the case. This also supports the suggestion that the calculated rate of peat accumulation in the section 4–8 cm depth is slightly slower than in reality.

The plant taxa growing on the mire surface, especially *Sphagnum* and, to a lesser extent, Ericales have considerably higher PARs in the peat profile than their deposition values in the pollen trap. *Sphagnum* values are nearly × 10, and Ericales × 2 although some of the patterns of the changes are similar: 1990 is one of the highest years for *Sphagnum* in both trap and peat profile. This could be due to the fact that the trap has a 15 cm wide "collar" surrounding the collecting aperture which is clear of vegetation, so no plants are actually overhanging the trap aperture, whereas the peat-forming plants are able to deliver their spores and pollen directly to the peat at the point where they are growing.

The 2 mm sample slices in "monolith 96" represent less than 1 year. Had sample slices been thicker and closer to the one year that was being aimed at, the peaks and lows may have been more focused. However, it is unlikely that any sampling could extract an exact calendar year from the peat, since the surface of the peat fluctuates – at least within 2 mm. At this very high resolution the climate signal that would come through if the pollen values were related to actual calendar years is lost, but neither is the signal of tree abundance in the vegetation obtainable because that requires a long-term average value. However, the PARs give a better record of changing pollen abundance than do percentage values (see also Hicks & Bennett in prep.).

The confidence limits on the calculated pollen values, both for the trap results and for the peat slices, are not shown here. Those on the monitored pollen deposition values are given in Hicks (2001) and are quite large in those sampling years when the number of *Lycopodium* spores from the added tablets is far less than the pollen counted. For the values from the peat slices the limits on the pollen concentration values are narrow because, in general, the number of added exotic marker *Lycopodium* spores exceeded the pollen counted. However, uncertainty inevitably increases when the concentration values are converted to PARs.

CONCLUSIONS

Analyses from *Sphagnum fuscum* hummocks afford the possibility of obtaining a very high temporal resolution record of pollen deposition. When two peat monoliths are taken within close proximity of each other, the duplication of the pollen record is sufficiently clear that it can be matched with a high degree of confidence. Using ^{14}C measurements on *in situ Sphagnum* it is possible to wiggle-match with the atmospheric carbon curve to produce an age-depth chronology for the last 40 years with an accuracy of ±2 years. The rate of peat accumulation was much faster than expected and the time resolution for last 100 years calculated in this way is, consequently, much better than expected. When this is used to convert the pollen content of the peat to pollen accumulation rates (grains/cm^2 /year), although the results are of the order of magnitude known from pollen deposition monitored at the same site, known high and low pollen years cannot be reproduced. This is primarily because the peat cannot be cut in exact calendar year slices. Here the sampling interval of 2 mm mostly represented less than a year's accumulation. The PARs are generally in agreement with the published annual pollen deposition "threshold" values for the presence and density of birch and pine in the vegetation calculated for northern Finland (Hicks 2001).

When the whole record is considered in more conventional pollen percentage terms, it is possible to trace the history of vegetation development on the peninsula. There are features in the pollen diagrams which can be interpreted as corresponding to known historical events (*Epirrita* attack defoliating birches, pine trees reaching an age when they can produce pollen) and the dates calculated by the ^{14}C model are also in agreement with this interpretation.

The exercise reveals both the potential and the problem of this approach. By dating the profile first and then sampling at intervals of one year it should be possible to obtain a stronger annual pollen record. The degree of unreliability can be tested if pollen monitoring results are available for the same site. This degree of temporal resolution is probably only feasible for the last 100 years. Any calibration with the dendrochronological record or instrumental meteorological record may have to involve running means over 3–4 years to match the resolution obtainable from the peat as applied by van der Knaap and van Leeuwen (2003).

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