Strong correlation between summer temperature and pollen accumulation rates for *Pinus sylvestris*, *Picea abies* and *Betula* spp. in a high-resolution record from northern Sweden

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ABSTRACT: Highly resolved pollen spectra analysed from a 47 cm peat monolith recovered from a mire in northern Sweden exhibit climatic sensitivity in the pollen accumulation rates (PAR) of boreal treeline species. Robust temporal control, afforded through multiple AMS radiocarbon dating of the post-atomic-bomb-test period (AD 1961–2002), provides a unique opportunity to compare pollen accumulation rates with the instrumental meteorological record. Strong correlations are observed between summer temperature and PAR for *Pinus sylvestris*, *Picea abies* and *Betula* spp. (excluding *B. nana*). Despite well constrained, contiguous (‘annual’) sampling, the temporal resolution of the pollen signal preserved within each sample appears to be degraded to ca. 3–5 year resolution. This is likely to reflect processes occurring during peat accumulation and pollen deposition, as well as dating uncertainties and the effects of subsampling. These findings identify limitations to the maximum resolution that may realistically be recovered from the peat archive using high-resolution sampling protocols and AMS 14C dating. We also identify the need for additional work to quantify the role of climate on peat accumulation and the resultant impact on assemblage-based palaeoenvironmental reconstructions within mire sequences. The strongest climate association observed for *Picea abies* ($r^2_{\text{adjusted}} = 0.53; n = 36$) was extended through the monolith beyond the 42 year period of ‘annual’ sampling and the response successfully correlated with the Bottenviken historical instrumental record to AD 1860. Although only presenting data from a single site, and requiring wider replication, we conclude that for sites close to the ecological limits of tree species, where levels of anthropogenic/non-climatic forcing on pollen production are low, well-dated records of PAR may potentially provide a proxy for reconstructing past summer temperature variability.

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KEYWORDS: PAR; high-resolution pollen record; temperature reconstruction.

Introduction

The analysis of pollen preserved within sedimentary archives represents one of the most powerful techniques in Quaternary research for the study of past vegetation dynamics and environmental change (Guiot et al., 1989; Birks and Line, 1993; Tzedakis and Bennett, 1995; Lowe and Walker, 1997; Huntley, 2001; Loader and Hemming, 2001, 2004). Analysis of annual pollen deposition as a proxy for pollen production has revealed a strong dependence upon summer climatic conditions for the years prior to efflorescence in some species (Hicks, 2001; McCarroll et al., 2003; Autio and Hicks, 2004), and so it has been proposed that pollen accumulation rates (PAR) may provide a record of climatic forcing over the short-medium term (sub-decadal to centennial) where preservation conditions are favourable and the signal from community dynamics or disturbance is low. Where pollen is preserved within varved sediments, palaeocological information can be obtained with annual temporal precision.
(Peglar, 1993). Such records are unfortunately not always available and/or difficult to recover (especially for the last 100 years) and, particularly in areas where lake sediment accumulation rates are very slow, pollen analysis is often conducted using less structured archives such as peat and non-laminated lake sediments.

Analysis of plant community response to environmental forcing at near-annual resolution would represent a significant advance and powerful tool in the detection of environmental change and its impact on pollen production. However, the validity of such an approach and the direct transfer of the climatic signals observed in vivo have yet to be widely assessed or identified in the palaeorecord. Bennett and Hicks (2005) explored the relationship between pollen trap data and a highly resolved pollen record recovered from a mire in northern Finland. Using principal components analysis, a network of pollen traps and a co-located peat monolith they identified that the trap data (pollen deposition) preserved a regional vegetation signal and that within this a secondary direction of variation could be identified related to ‘the annual variation of the pollen productivity’. Bennett and Hicks (2005) concluded that while it is impossible to delimit such palaeoecological samples with precise annual resolution, when peat profiles are sampled at high (near-annual) temporal resolution, analyses of pollen accumulation rates ‘do not reflect vegetation abundance, but temperature related pollen abundance’.

Advances in radiocarbon dating techniques and sampling protocols have enabled smaller samples to be prepared from the peat archive such that sufficient time control and sampling density may be attained for the recent past with which to infer annual or near-annual temporal resolution (Goslar et al., 2005). This study will apply such a well-constrained dating and high-resolution sampling approach to a near-treeline peat monolith to explore the nature of the signal preserved within the resulting pollen abundance records and address the following research questions: Can an annually resolved record be obtained through high-resolution subsampling of the peat archive? Is there evidence for preservation of a climatic signal within the pollen accumulation record at high–medium temporal resolution?

Materials and methods

A peat monolith was cut from a mire surface near Kiruna, Sweden (67°59’ N, 20°19’ E). This site is located near the boreal treeline for *Picea abies* L. (spruce) and *Pinus sylvestris* L. (Scots pine) and is likely to be more sensitive to climate forcing than at less marginal sites. To radiocarbon-date the profile, ten samples consisting of *Sphagnum* stems were extracted manually and dated using AMS radiocarbon dating methods. In this study, six of the samples analysed were deposited immediately prior to, or following, the atomic weapons testing of the 1960s. It was therefore possible to calculate radiocarbon dates with high levels of precision (Table 1). These control points were subsequently used to construct an age–depth chronology (after Goslar et al., 2005). Based upon this age–depth model, subsampling of the frozen monolith was carried out at an ‘annual’ resolution, assuming uniform peat accumulation between dating control points. Where annual resolution would fail to yield sufficient sample material the monolith was cut in contiguous slices corresponding to either 3 or 5 years (between AD 1954 and 1721). The dated age range for each sample was inferred from the associated radiocarbon dating.

Tablets containing marker *Lycopodium* spores were added to the samples at the beginning of sample preparation to allow pollen concentration and pollen accumulation rates (PAR) to be calculated (Stockmarr, 1971). Pollen was extracted from each ‘annual’ peat slice using method A described by Berglund and Ralska-Jasiewiczowa (1986). A 250 μm mesh was used to exclude plant remains. The samples were mounted in glycerol and sealed. Pollen counts were made at a light microscope at 400× and 1000× magnification. Four principal arboreal taxa were recorded at this site—*Alnus* spp., *Betula* spp. (excluding *B. nana*), *Picea abies* and *Pinus sylvestris*—and their pollen accumulation rates (grains cm⁻² yr⁻¹) calculated.

To detect the presence of high-frequency climate signals the resulting pollen profile was correlated against monthly temperature data from the nearby meteorological station at Kiruna for the period AD 1961–2002. Based upon field observations and analysis of modern PAR (Hicks, 2001; Bennett and Hicks, 2005), experiments were also conducted to assess the presence of delays in response and signal integration through the introduction of lags and the application of smoothing filters to the data. Such an approach was only possible for this period as each sample represents approximately 1 year. Beyond this initial ‘calibration period’ such direct comparison was not possible without averaging as a reduction in the precision of the radiocarbon dates and compaction of the peat profile prevented recovery of ‘annual’ samples.

**Results and discussion**

Pollen accumulation rates for each of the trees studied were correlated against the monthly temperature record for the

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>¹⁴C laboratory reference no.</th>
<th>¹⁴C ages BP</th>
<th>Year</th>
<th>Year +</th>
<th>Year −</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface (0)</td>
<td>N/A</td>
<td>N/A</td>
<td>2002</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>30</td>
<td>Poz-3902</td>
<td>109.9 ± 0.3 pMC</td>
<td>2000.9</td>
<td>2001.9</td>
<td>2000</td>
</tr>
<tr>
<td>60</td>
<td>Poz-3903</td>
<td>112.1 ± 0.3 pMC</td>
<td>1997.7</td>
<td>1998.9</td>
<td>1996.9</td>
</tr>
<tr>
<td>85</td>
<td>Poz-3904</td>
<td>114.5 ± 0.4 pMC</td>
<td>1994.05</td>
<td>1995.05</td>
<td>1993.05</td>
</tr>
<tr>
<td>120</td>
<td>Poz-3905</td>
<td>118.4 ± 0.1 pMC</td>
<td>1988.2</td>
<td>1989</td>
<td>1987</td>
</tr>
<tr>
<td>170</td>
<td>Poz-3906</td>
<td>129.3 ± 0.3 pMC</td>
<td>1979.2</td>
<td>1980</td>
<td>1978.1</td>
</tr>
<tr>
<td>240</td>
<td>Poz-3907</td>
<td>131.5 ± 0.5 pMC</td>
<td>1960.1</td>
<td>1961.9</td>
<td>1957.9</td>
</tr>
<tr>
<td>285</td>
<td>Poz-3908</td>
<td>65 ± 30 BP</td>
<td>1937.85</td>
<td>1941.95</td>
<td>1926.05</td>
</tr>
<tr>
<td>360</td>
<td>Poz-3909</td>
<td>130 ± 25 BP</td>
<td>1878.6</td>
<td>1897.5</td>
<td>1865.2</td>
</tr>
<tr>
<td>420</td>
<td>Poz-3911</td>
<td>95 ± 30 BP</td>
<td>1814.8</td>
<td>1849.2</td>
<td>1803.8</td>
</tr>
<tr>
<td>468</td>
<td>Poz-4635</td>
<td>95 ± 25 BP</td>
<td>1718.1</td>
<td>1769.4</td>
<td>1681.6</td>
</tr>
</tbody>
</table>

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period AD 1961–2002. In addition to simple paired correlations, the signal preserved within the ‘annual’ records was investigated further through introduction of a lag of 1–10 years and smoothing functions based upon 2–10 year running means (Table 2). The justification for such an approach lies in the mechanisms of pollen formation (Hicks, 2001; Carroll et al., 2003; Autio and Hicks, 2004; Bennett and Hicks, 2005) and its subsequent deposition and signal integration during preservation within the mire.

Summer temperature for the years immediately prior to efflorescence has been identified as a significant factor controlling the amount of pollen produced (Autio and Hicks, 2004). Introduction of a lag to the climate data strengthens the correlations observed with PAR and may partly reflect the mechanisms of pollen formation. However, the limits and uncertainties of the archive and methods applied (especially dating precision; approximately ±0.6–1.8 years AD 1961–2002) are also likely to contribute to the statistical relationships observed, such that the details of this plant physiological response cannot be isolated.

Betula (excluding B. nana), Pinus sylvestris and Picea abies all appear to support these findings and respond best to summer (July and/or August) temperature. Alnus spp. do not respond so strongly suggesting that, at this site, temperature is likely not to be the primary factor controlling pollen production (Fig. 1).

A further significant improvement in the correlations between summer temperatures and PAR was observed when the meteorological and pollen data are smoothed. The correlation coefficient typically increased as the effect of smoothing becomes more significant. Beyond a ca. 5 increment (‘year’) filter the correlation coefficient against summer temperature for each species starts to diminish. Such an approach would suggest that, despite sampling at an intended annual resolution, the most appropriate environmental information that can be achieved at this site is a signal integrating information from ca. 3–5 years prior to the dated level.

An analogy can be drawn between the process of pollen deposition and the process of air-bubble entrainment in ice cores. For a number of years the mire surface is open and able to accept pollen. However, as time proceeds the Sphagnum (which can live for several years in the uppermost part) grows taller while the dead parts below become more compacted, closing off the once-exposed deposition surfaces in a manner similar to pore close-off during the transition from firn to ice. Based upon the distribution of the correlation data for all species studied we would suggest that the Kiruna mire surface is capable of accepting pollen for at least five years prior to the dated level.

In the light of the immense effort and resources required to produce such a well-dated high-resolution pollen profile, where records are known to be sensitive to climate forcing and where large-scale community effects are negligible, it is logical...
to suggest that contiguous subsampling of the recent period at a coarser (ca. 5 mm) resolution could potentially yield comparable low–medium frequency results. However, detailed quantification and verification of any climate relationships observed would probably be severely constrained through associated reductions in temporal precision, sensitivity and sample population ($n$).

The strongest climate signal at Kiruna was observed in the *Picea abies* record ($r_{\text{adjusted}} = 0.73$; $n = 36$ significant at 99%) (Table 2) and is perhaps to be expected since Kiruna is located close to the northern tree line for this species. Prior to AD 1961 compaction of the peat record and increasing dating uncertainties meant that ‘annual’ resolution sampling was not possible. However, it was possible to verify the relationship identified in the most recent 42 years by comparing the lower resolution samples with July–August temperature from the regional historical record at Bottenviken ($65^\circ$ 00' N, $23^\circ$ 00' E) which covers the period AD 1860–2002.

For these non-annual samples, the pollen accumulation rate was compared with the mean temperature calculated for the years corresponding to the individual increment age and treated in an identical manner as the ‘annual’ (post-AD 1961) samples. The 70 increment record was then split into two sections and the regression equations calculated on each half to test the stability of the signal through time (Table 3). The coefficients remain remarkably stable throughout this ca. 150 year period although a slight deviation was observed, most likely reflecting increased dating uncertainties at lower levels. The regression equation was then applied to the pollen data to develop a reconstructed temperature dataset and plotted against the Bottenviken temperature series (Fig. 2). The two data series compare favourably throughout the extended period ($r^2_{\text{adjusted}} = 0.72$; $n = 70$ significant at 99%), demonstrate the preservation of a climate signal in the PAR record and serve to provide an effective calibration and independent verification of our findings.

When sampling at high resolution, additional factors may become important controls on signal preservation that may not be as significant in lower-resolution studies. A potential concern examined in this study is that at high latitudes it is possible that the close association observed between PAR and temperature may reflect climatically controlled changes in the rate of peat accumulation rather than pollen production.

If indeed the observed correlation ‘PAR-temperature’ is an artefact of peat growth and temperature, then it is possible theoretically to test this hypothesis. Assuming that the pollen

Table 3 Summary statistics relating to regression (calibration/verification) of the extended *Picea abies* record against the Bottenviken meteorological data AD 1866–2002. (Note that the regional Bottenviken and local Kiruna meteorological records are highly correlated ($r^2 = 0.95$; $n = 41$) and exhibit a mean ($\pm 1\sigma_{\text{inter}}$) difference of $1.7 \pm 0.3^\circ$C)

<table>
<thead>
<tr>
<th>Calibration period</th>
<th>$r^2_{\text{adjusted}}$</th>
<th>Regression coefficient</th>
<th>Intercept</th>
<th>Significance level</th>
<th>No. of observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1967–2002</td>
<td>0.52</td>
<td>0.009</td>
<td>11.90</td>
<td>95%</td>
<td>35</td>
</tr>
<tr>
<td>1866–1966</td>
<td>0.62</td>
<td>0.012</td>
<td>11.91</td>
<td>99%</td>
<td>35</td>
</tr>
<tr>
<td>1866–2002</td>
<td>0.52</td>
<td>0.010</td>
<td>11.98</td>
<td>99%</td>
<td>70</td>
</tr>
</tbody>
</table>
accumulation rate was constant, and the changes of peat growth rate were positively correlated with temperature, the resulting PAR calculated in sections of faster peat growth would be underestimated, provided that the increase of peat growth rate is not reflected in the age–depth model. In such a case we should observe negative correlation between PAR and temperature. This is clearly not the case here.

While the controls, impacts and timing of such growth processes are currently only partially understood and require further study, we attempted to test this hypothesis practically through analysis of the spheroidal carbonaceous particle (SCP) counts. The accumulation rates of these particles are the result of industrial input to the atmosphere and should not exhibit strong climate trends. Consequently, if correlations are observed in these non-biological indicators then it is likely that peat growth, rather than pollen accumulation, exerts a significant influence upon the variability observed in the pollen record.

Correlation of the SCP data (with lag and smoothing as for the pollen) did not identify the same high levels of correlation as the pollen data, although some interannual correlations were identified (Table 2). These findings in association with the low Alnus correlation and climatic sensitivity reported elsewhere (McCarroll et al., 2003; Autio and Hicks, 2004; Bennett and Hicks, 2005) would suggest that changing rates of accumulation in the peat at Kiruna do not appear to dominate the climatic signal preserved within the pollen record.

Conclusion

Where physical sampling of the modern peat archive may theoretically provide a record with annual resolution, such high-frequency environmental information can rarely be attained owing to dating uncertainties and the incorporation and integration of pollen from several years (flowering seasons) into each ‘annual’ slice. Consequently, assuming uniform deposition and preservation conditions, the ultimate resolution that may be attainable from such records will be a function of the nature of peat formation (i.e. the time that the mire surface is continuing to receive pollen), the precision and accuracy of the dating method (essential to development of a reliable age–depth chronology), the amount of sample required for analysis (controlling the time preserved in each slice) and the degree of integration between levels (reflecting variability in the topography of the mire surface and the effects of subsampling).

Through high-resolution contiguous sampling of a well-dated peat monolith from the boreal treeline a significant climate signal (July–August temperature) suitable for palaeoclimate analysis has been identified, calibrated and independently verified within the recent pollen archive (for Betula (excluding B. nana), Picea abies and Pinus sylvestris). These findings support the results from modern pollen monitoring and demonstrate that this signal is preserved within the peat archive.

The potential impact of variations in peat accumulation on the nature of the climate associations observed was identified and addressed through comparison of the SCP record. The generally weak resulting correlations and theory would suggest that peat accumulation is not the primary controlling factor in this high-resolution study; however, we stress the difficulty of testing this hypothesis independently of the pollen record and conclude that our approach, whilst perhaps the most appropriate available to us, could not provide a definitive answer. To understand this archive more completely there is a need for additional research into the growth of Sphagnum and the impact of climate-controlled changes in peat accumulation on highly resolved pollen and associated assemblage-based studies.

In providing a direct link to meteorological variables the Kiruna monolith represents an important ‘proof of concept’ study. These results require replication across a range of environments and their further extension and evaluation back through time to determine the impact of larger-scale community dynamics upon the stability of the climatic signal. Assuming that these findings are successfully replicated for other locations at the boreal treeline then this approach could potentially provide a means for reconstructing sub-decadal
climatic variability in remote (undisturbed) regions of the Arctic during the last 150 years. Such an extension of this work to sensitive treeline sites would provide a valuable tool in improving understanding of recent climate trends for regions where reliable instrumental data are sparse and where the onset and impacts of (anthropogenic) climate change are likely to be the most acute.

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