

Evidence of temperature and precipitation change over the past 100 years in a high-resolution pollen record from the boreal forest of Central European Russia

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Abstract

Near-annual pollen records for the last 100 years were obtained from a 65-cm peat monolith from a raised peat bog in the Central Forest State Natural Biosphere Reserve (southern part of the Valdai Hills, European Russia) and compared with the available long-term meteorological observations. An age–depth model for the peat monolith was constructed by ²¹⁰Pb and ¹³⁷Cs dating. Cross-correlation and the Granger causality analysis indicated a broad range of statistically significant correlations between the pollen accumulation rate (PAR) of the main forest-forming trees and shrubs (*Picea*, *Pinus*, *Betula*, *Tilia*, *Quercus*, *Ulmus*, *Alnus*, and *Corylus*) and the air temperature and precipitation during the previous 3 years. Results showed that high air temperatures during the growing season (May–September) in the year prior to the flowering led to an increase in pollen productivity of the main tree species. The statistically significant correlation between the PAR of trees and shrubs and winter precipitation of the current and previous years could reflect the influence of winter precipitation on soil water availability and as a result on tree growth and functioning in the spring.

Keywords

²¹⁰Pb and ¹³⁷Cs dating, boreal forests, European Russia, Granger causality test, high-resolution peat profile, peat bog, pollen accumulation rates

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Introduction

The vegetation and climate interactions and feedbacks are one of the key issues in palaeoecological studies because of their importance for better understanding and reconstruction of environmental processes and climate changes. Plants are highly adapted to climate conditions and their pollen can be a very good indicator of plant functioning and climate conditions at the time when they were living. To reconstruct vegetation, land-cover and climate change in the past several approaches have been used. They are based on modern pollen surface samples and moss polsters, that is, transfer functions for describing climate influences on the composition of pollen assemblages (Seppä et al., 2004), the best modern analogue technique (Nakagawa et al., 2002; Novenko and Olchev, 2015), and some models of pollen-dispersal patterns (Prentice, 1986; Sugita, 2007). A less commonly used alternative to these methods is to take time series of pollen abundance with robust chronological control and calibrate them against instrumental meteorological data. This approach has great potential using networks of pollen traps with over 20 years of observations (Hicks, 2001; Huusko and Hicks, 2009; Mazier et al., 2012; Van der Knaap et al., 2010), data from annually laminated lake sediments (Seppä et al., 2009), and precisely dated peat monoliths (Kuoppamaa et al., 2009; Mazier et al., 2012).

A pollen accumulation rate (PAR; number of pollen grains $\text{cm}^{-2} \text{yr}^{-1}$) is a very useful characteristic in palaeoecological studies because it allows to reflect independent variations in each plant

species in the pollen assemblage alternatively to percentages that are affected by the variations in other taxa in the pollen sum (Davis, 1967; Davis et al., 1973, 1984). The PAR is now widely applied for assessment of temperature impacts on pollen productivity (Barnekow et al., 2007; Kamenik et al., 2009; Nielsen et al., 2010), reconstruction of plant abundance and biomass (Broström et al., 2004; Mazier et al., 2010; Seppä et al., 2009), land-use changes (Kuoppamaa et al., 2009), and pollen diversity and its interpretation in terms of taxonomic richness on the landscape

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(Van der Knaap, 2010). However, the challenge of climate reconstruction using the PAR still remains one of the most important tasks in palaeoecology.

According to pollen trap studies from various European regions (Autio and Hicks, 2004; Barnekow et al., 2007; Huusko and Hicks, 2009; Nielsen et al., 2010; Van der Knaap et al., 2010), pollen loading of tree species is significantly influenced by interannual variations in climate parameters, such as the air temperature and precipitation, not only within the growing season but also during the previous year, when generative buds were formed. In northern Fennoscandia in particular, the strongest relationships were obtained between the PAR of *Picea*, *Pinus*, and *Betula* and the summer (July) air temperature of the previous year (Autio and Hicks, 2004; Barnekow et al., 2007; Huusko and Hicks, 2009). Positive effects of summer drought in 2010, resulting in an increase in pollen productivity of the main tree taxa, were demonstrated in the pollen trap records described by Nosova et al. (2013) for boreal forests in European Russia. As it was indicated in studies of Tauber traps, the climate impact on PAR appeared most significantly at the boundaries between biomes. Most studies, therefore, are focused on the northern timberline (Barnekow et al., 2007; Hicks, 2001; Seppä et al., 2009; Sjögren et al., 2015) and on the upper tree-line in mountainous regions (Jensen et al., 2007). Despite significant worldwide interest in the relationships between meteorological conditions and PAR, such studies for the forested area of European Russia are still very scarce. The period of available observations on pollen traps does not usually exceed 10 years (Nosova et al., 2015). Considering that the forests, including taiga and mixed coniferous broad-leaved forests, cover about 50% of the land area of the central part of European Russia, this region can be very interesting for multidisciplinary palaeoecological and palaeoclimatological studies.

The Central Forest State Natural Biosphere Reserve (CFS-NBR) has been selected as a key region for this study. The CFS-NBR is situated in the southern part of the Valdai Hills at the ecological transition zone from the boreal to broad-leaved forests, far away from any sources of anthropogenic pollution. Such location of the CFSNBR makes obviously its flora and vegetation very sensitive to even small changes in climatic and environmental conditions (Novenko et al., 2009a). Since 1985, the CFSNBR is recognized as part of international network of biosphere reserves (program of UNESCO on 'Man and the Biosphere' (MAB)).

This study presents near-annual pollen records from a peat monolith from a raised peat bog in a protected area of the CFS-NBR. We use the results to assess the temporal variability of pollen assemblages during the last 100 years and compare them with the available meteorological data. An age–depth model was produced by ^{210}Pb and ^{137}Cs dating. Studies of the PAR from pollen traps and high-resolution continuous sampling of well-dated peat monoliths from the boreal tree-line in Northern Finland have shown that the temperature signal is clearly pronounced in the peat archive, and peat monoliths are suitable for palaeoclimate analysis with annual or near-annual time resolution (Barnekow et al., 2007).

The aim of this paper is to illustrate and quantify climate–pollen relationships, taking into account both the air temperature and precipitation, in order to provide a tool to interpret the fossil record. In our study, we use both PAR and percentage ratio of taxa in pollen assemblages as the latter is the most common subject in palaeoclimatic reconstructions.

The primary focus is on analysis of the plant species that are most significant in pollen spectra of the boreal forest: *Picea*, *Pinus*, *Betula*, *Alnus*, *Tilia*, *Ulmus*, *Quercus*, *Corylus* – among trees and shrubs; *Artemisia*, Ericales, and Poaceae – among herbs; and *Sphagnum* moss.

Materials and methods

Study area

The CFSNBR is situated about 360 km north-west of Moscow (the Tver region) in the southern Valdai Hills (56°35'N, 32°55'E, Figure 1). The topography of the area is a slightly hilly plain, with elevations ranging between 220 and 250 m. The highest moraine ridge in the southern part of the CFSNBR (up to 280 m a.s.l.) is a main watershed in the East European Plain between the Baltic Sea (the Daugava River catchment) and the Caspian Sea (the Upper Volga catchment) basins. The landscape of the CFSNBR is very typical for the boreal zone, and over at least the last 85 years it has been undisturbed by any human activities.

The climate of the study area is temperate moderately continental with relatively cold winters and warm summers. According to meteorological observations carried out in the CFSNBR (since 1963), the mean July temperature is 17.1°C, the mean January temperature is –10°C, and the mean annual temperature is 4.1°C. The annual precipitation does not usually exceed 700 mm (Desherevskaya et al., 2010; Oltshev et al., 2002). More than half of precipitation falls as rain in the summer–autumn period with the rest falling as snow during winter and spring.

The area of CFSNBR is mainly covered by primary southern taiga forests. The forest is very heterogeneous and comprises mixed uneven-age spruce (*Picea abies*), birch (*Betula pendula*), and aspen (*Populus tremula*) trees with admixture of alder (*Alnus glutinosa*), rare old pine (*Pinus sylvestris*), and maple (*Acer platanoides*) trees.

The peat monolith for pollen analysis was taken in the central part of the Staroselsky Moch peat bog that is situated in the south-east part of the CFSNBR and has an area of about 617 ha. Peat accumulation in Staroselsky Moch began in the early-Holocene (Novenko et al., 2009b; Payne et al., 2015). The plant cover around the peat bog (see Figure 1) is represented mainly by mature spruce stands, secondary deciduous birch – aspen, and mixed with spruce forests, brushwood, swampy pine woodland, and areas of meadow. Broad-leaved species (*Tilia cordata*, *Ulmus laevis*, *Acer platanoides*, *Fraxinus excelsior*) grow sporadically under the canopy layer of spruce in well-drained habitats. Old trees of lime and oak (*Quercus robur*) occur around former settlements where they were planted.

The sampling point is located in the central part of the Staroselsky Moch peat bog in a hummock–ridge complex with rare pine, abundant ericaceous dwarf shrubs, herbaceous plants (*Carex lasiocarpa*, *Rhynchospora alba*, and *Scheuchzeria palustris*), and dense cover of *Sphagnum* mosses (*Sphagnum magellanicum*, *Sphagnum angustifolium*, and *Sphagnum balticum*).

Peat core sampling and pollen analysis

A peat monolith for high-temporal-resolution pollen analysis was taken using a Wardenar' peat profile sampler in August, 2013. The peat monolith was 65 cm deep and consisted completely of low decomposed (7–10%) cottongrass–*Sphagnum* high-moor peat. The peat block was continuously sliced into samples with 1 cm thickness.

Samples for pollen analysis with volume of 2 cm³ were prepared using the pollen extraction procedure developed by Moore et al. (1991). The treatment included heating for 10 min in 10% KOH to remove humic material, followed by acetolysis in a water bath for 5 min to dissolve the cellulose. Calculation of relative pollen frequency is based on the total terrestrial pollen sum, arboreal pollen (AP) plus non-arboreal pollen (NAP); spores were excluded. A minimum of 500 pollen grains per sample were counted (AP+NAP). Morphological determinations of pollen were carried out following Reille (1992), Beug (2004), and the reference pollen collection of the Institute of Geography of the

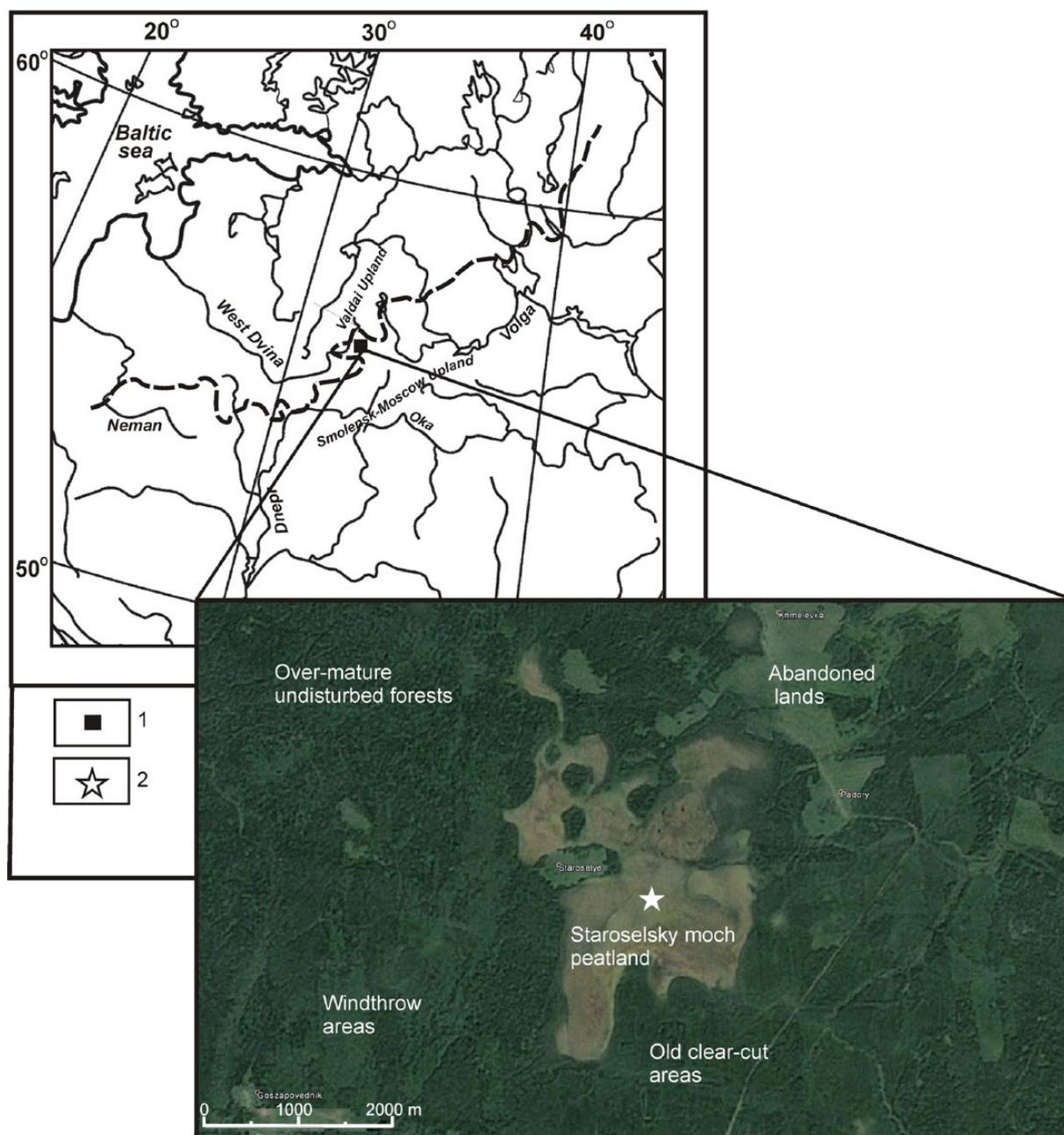


Figure 1. Geographical location of the experimental site in European Russia (the East European Plain). 1: Location of the CFSNBR; 2: location of the sampling point in the Staroselsky peat bog.

Russian Academy of Science. For calculating pollen concentrations, *Lycopodium* tablets were added to each sample during the pollen preparation process (Stockmarr, 1971). Pollen diagrams were constructed using Tilia and Tilia Graph program (Grimm, 1990). The results are presented as percentages and PARs (grains $\text{cm}^{-2} \text{yr}^{-1}$).

Peat dating

The peat samples were dated radiometrically using ^{210}Pb and ^{137}Cs (Appleby, 2001). The natural radionuclide ^{210}Pb (half-life of 22.3 years) has an atmospheric component which is widely used for dating of sediments and ombrotrophic peat deposits younger than 150 years. Dating using ^{210}Pb is often validated by independent measurements of ^{137}Cs activity allowing identification of the layers corresponding to nuclear bombs testing culminating in 1963 and ^{137}Cs fallout after the Chernobyl accident in 1986.

Eleven 1–2 cm sections of the monolith (0–64 cm) were analyzed for total ^{210}Pb activity. The ^{210}Pb activity was determined by measuring the α -emitting grand-daughter isotope of ^{210}Po . Geogenically supported ^{210}Pb was corrected for by determining ^{226}Ra in three sections and subtracting the nearest neighboring ^{226}Ra measurements (which all were much lower than any measured activity of ^{210}Pb) from the total ^{210}Pb . The ^{210}Pb and ^{226}Ra activities were measured by Flett Research Ltd (<http://www.flettresearch.ca>). Activity concentrations of ^{210}Pb decreased exponentially with mass depth, showing little irregularity ($R^2=0.957$ for total ^{210}Pb versus linear depth and $R^2=0.954$ for unsupported ^{210}Pb versus mass depth).

Seventeen 1–2 cm sections of the monolith were analyzed for ^{137}Cs activity at Stockholm University using an automated gamma spectrometer (Intertechnique Model CG 4000 Gamma Counting System) equipped with 3×3 in NaI(Tl) well scintillation detector. Parallel readings from different energy windows were converted to ^{137}Cs activities, based on frequently measured blanks and standard

samples (containing either pure ^{137}Cs or Chernobyl fallout), thereby correcting for background radiation (both external and internal), sample geometry, and radioactive decay.

The profile of ^{137}Cs showed a distinct peak with a maximum activity concentration of $>1 \text{ Bq g}^{-1}$ in the interval 18–19 cm. This peak was attributed to the Chernobyl fallout in 1986, since both peak concentration and total core inventory of ^{137}Cs were an order of magnitude higher than in peat profiles exposed solely to the global fallout from nuclear weapon testing culminating in 1963. The latter could not be discerned and may well have been covered by a redistribution tail from the much larger Chernobyl fallout, as also indicated by the ^{137}Cs inventory below the peak found to be far larger than the expected bomb fallout alone.

The ages of peat sections were calculated using two models: the concentration-based linear regression model (LRM) and the constant rate of ^{210}Pb supply (CRS) model (<http://www.flettresearch.ca/UnderstandingPb210.html>; Appleby, 2001). Both models assume no post-depositional migration of Pb in the peat profile.

The LRM assumes that ^{210}Pb input and peat accumulation rate ($\text{g}^{-1}\text{cm}^{-2} \text{ yr}^{-1}$) are constant. In this case, the initial activity of unsupported ^{210}Pb is constant in each section and age is determined by the decline in the activity relative to the initial one with increasing accumulated mass of peat.

The CRS allows calculating of ages when peat accumulation rate is not constant along the profile. In this case, the initial activity of unsupported ^{210}Pb will vary in different sections depending on their accumulation rates, and the age determination for a given depth is based on comparison of the inventory of unsupported

^{210}Pb below that depth with the total inventory in the profile (Appleby, 2001). In our case, the monolith was not deep enough to reach the background activity of ^{210}Pb , and the total unsupported ^{210}Pb inventory in the profile cannot be calculated directly. It was determined that assuming the average accumulation rate in the profile is equal to the accumulation rate determined by LRM.

Dates derived by LRM and CRS agree quite well considering the uncertainties in age calculation. Furthermore, the ^{137}Cs dating agrees quite well with ^{210}Pb dating: the age of peat in the section with the observed Chernobyl fallout maximum (1986 ± 2) was determined as 1992 (CRS) and 1988 (LRM) (Figure 2). Normally, the CRS model is preferable for peat as it allows dating even if the peat accumulation rate is not constant. However, there is an uncertainty in estimating the missing fraction of the total inventory of unsupported ^{210}Pb below a sampled profile. In addition, LRM showed slightly better agreement with ^{137}Cs dating. Therefore, LRM dates were used for further comparisons (Figures 3 and 4).

According to the radiometric dating based on ^{210}Pb and ^{137}Cs , each cm of the peat profile corresponds to about one year of accumulation within the upper decimeter and to about two years in the lower part of the peat monolith (Figure 2). Absolute dates based on ^{210}Pb have an uncertainty that increases exponentially with depth and can be substantial in strata older than a century but may be around 1–2 years for the most recent decades (Binford, 1990).

Meteorological data

Monthly time series of air temperature and precipitation in the study region were obtained from regular meteorological observations carried out by the local meteorological station in the CFSNBR as well as from observations conducted at neighboring meteorological stations of the Russian Weather Service (RWS) situated at about 150 km around the CFSNBR (Toropez, Staritsa, Velikiye Luki, Vyshniy Volochek). Meteorological data for the RWS stations were taken from the hydrometeorological data service system of the All Russian Research Institute of Hydrometeorological Information – World Data Center (<http://meteo.ru/data>). They were used both to close the gaps in meteorological time series of the CFSNBR station and to reconstruct the temperature and precipitation patterns in the study region for the period before the beginning of instrumental observations in the CFSNBR. Since the period of meteorological observations in the CFSNBR does not exceed 50 years, the RWS data allow us to obtain continuous records of meteorological parameters in the

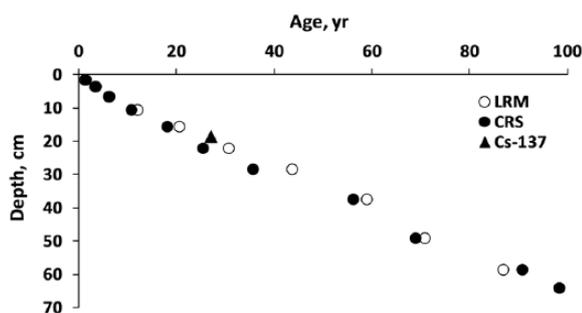


Figure 2. Age of peat vs depth, calculated with the LRM and CRS models. Triangle indicates a maximum of ^{137}Cs activity, corresponding to the Chernobyl fallout.

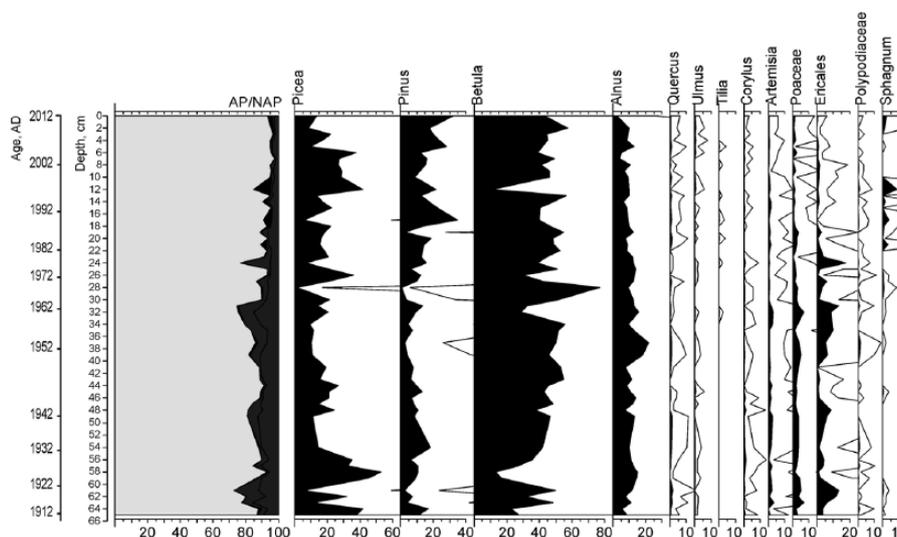


Figure 3. Percentage diagram of the selected pollen types of the peat monolith from the Staroselsky peat bog. Pollen types used for pollen–climate relationships are shown. Pollen sum: AP + NAP; additional curves represent 10× exaggeration of base curves.

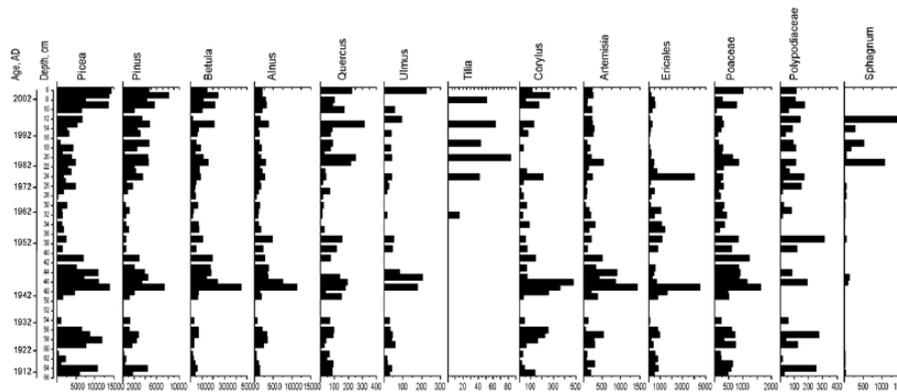


Figure 4. Pollen accumulation rate (PAR; number of pollen grains cm⁻²yr⁻¹) of the peat monolith from the Staroselsky peat bog.

study region for the period since 1890. The algorithm that was used for spatial interpolation for RWS meteorological data takes into account the distance between the corresponding station of RWS and the station in the CFSNBR, as well as the differences among station elevations (Olchev et al., 2008). Considering that the relief of the study area is relatively flat and uniform, we can minimize uncertainties caused by local orographic effects (e.g. the precipitation difference between windward and leeward slopes in hilly regions, the influence of the terrain complexity on air temperature patterns).

Statistical analysis of time series

To analyze the relationship between the PARs and the key meteorological parameters (air temperature, precipitation), the Spearman cross-correlation analysis and the Granger causality test were applied. The Spearman rank-order cross-correlation analysis is used to discover the strength of a link between two sets of data (PARs and meteorological parameters) as a function of the time lag of one relative to the other. With respect to the Pearson correlation analysis, it assumes that the variables are not normally distributed and the relationship between the variables is not linear.

In general form, the Spearman correlation coefficient (r_{xy}) between two time series (X_i, Y_i) of size n is defined as the Pearson correlation coefficient between two ranked variables and can be calculated as (Myers and Well, 2003; Spearman, 1904) follows:

$$r_{xy} = 1 - \frac{6 \sum_i (rank(X_i) - rank(Y_i))^2}{n(n^2 - 1)}$$

The test statistics and associated statistical significance (p -values) are used for testing the hypothesis that a correlation coefficient is equal to 0.

In our study for ordinary Spearman correlations, the t -statistic was computed as

$$t = \frac{r\sqrt{n-k-1}}{\sqrt{1-r^2}}$$

where r is the estimated correlation coefficient, and k is the number of conditioning variables, including the implicit mean adjustment term. The p -value is obtained from a t -distribution with $n-k-1$ degrees of freedom.

To cover the different direct and indirect influences of meteorological conditions on pollen generation, we analyzed the possible relationships between the PARs and meteorological parameters up to 36 months prior to the moment in spring when the pollen grains are released.

The Granger causality test is a statistical hypothesis test for determining whether one time series is useful in forecasting another, first proposed in 1969 (Granger, 1969). According to the test, a time

series X is said to Granger-cause Y if it can be shown, usually through a series of t -tests and F -tests on the lagged values of X (and with the lagged values of Y also included), that those X values provide statistically significant information about future values of Y . We can say that a variable X that evolves over time Granger-causes another evolving variable Y if the predictions of the value of Y based on its own past values and on the past values of X are better than the predictions of Y based only on its own past values.

Granger defined the causality relationship based on two main principles (Eichler, 2012, 2013; Granger, 1980):

1. The cause happens prior to its effect.
2. The cause has unique information about the future values of its effect.

If the time series can be considered as a stationary process, the test is performed using the level values of two (or more) variables. If the time series are non-stationary, then the test is done using first (or higher) differences. The number of lags to be included is usually chosen using an information criterion, such as the Akaike or the Schwarz information criteria.

We used EViews software for data analysis that runs bivariate regressions of the following form:

$$Y_t = \alpha_0 + \alpha_1 Y_{t-1} + \dots + \alpha_L Y_{t-L} + \beta_1 X_{t-1} + \dots + \beta_L X_{t-L} + \varepsilon_t$$

$$X_t = \alpha_0 + \alpha_1 X_{t-1} + \dots + \alpha_L X_{t-L} + \beta_1 Y_{t-1} + \dots + \beta_L Y_{t-L} + \mu_t$$

for all possible pairs of (X, Y) series in the group. The reported F -statistics are the Wald statistics for the joint hypothesis:

$$\beta_1 = \beta_2 = \dots = \beta_L = 0$$

for each equation. The null hypothesis is that X does not Granger-cause Y in the first regression and that Y does not Granger-cause X in the second regression.

The Granger causality test was applied to analyse the relationship between the PARs and values of meteorological parameters of the corresponding months for different lags ranging from 0 (influence on the PAR of conditions of the corresponding month of the current year) to 3 (influence on the PAR of meteorological conditions of the corresponding month of the current and three previous years).

Results

Pollen analysis

Pollen assemblages of the peat monolith are characterized by high amount of tree pollen (75–90%), among them *Betula*, *Picea*, *Alnus*, and *Pinus* are abundant (Figure 3). Pollen of broad-leaved

trees (*Tilia*, *Ulmus*, *Quercus*) occurred in small quantities (1–2%); pollen of shrubs, such as *Salix* and *Corylus*, was rarely detected.

The content of *Picea* pollen within the peat monolith varies in a wide range: from 2–10% at 27 and 62 cm depth to 50–60% in the depth intervals 5–12 and 46–60 cm. Vertical distribution of pine pollen is also very heterogeneous. Its content is relatively low in 60–30 cm depth interval (7–20%) and increases in the upper part of the peat monolith. At 27 cm depth, the amount of pine pollen is also very low (up to 1%), similar to *Picea* pollen distribution. The amount of birch pollen in the monolith is very high – up to 30–40%, and it forms a noticeable peak at a depth of 27 cm. The share of *Alnus* pollen is smaller – about 10–15%. *Quercus* forms a continuous pollen curve. The distribution of *Ulmus* pollen is also quite homogeneous. Pollen of *Tilia* is absent in the lowest part of the monolith below the depth of 30 cm, and in the upper part it occurs sporadically only. *Artemisia*, Poaceae, and Ericales pollen are the most frequent in NAP group. Besides them, pollen assemblages include a relatively high variety of herbaceous pollen (Chenopodiaceae, Rosaceae, Ranunculaceae, Asteraceae, Apiaceae, Fabaceae, etc.).

The total sum of spores does not exceed 10% relative to the AP+NAP in the entire peat monolith. Spores are represented mainly by *Sphagnum* (1–3% in average with some variability of maximum values) and Polypodiaceae (5–7%). A series of peaks of *Sphagnum* spores (up to 10%) are recorded in the depth interval between 10 and 17 cm and in the upper 3 cm.

The calculation of pollen concentration in samples has shown an extremely high pollen concentration of all taxa in the uppermost 5 cm of the peat monolith (living mosses and their undercomposed remains), that is, an order of magnitude higher than in other samples of the peat profile. Apparently, the 1-cm-thick samples from the living mosses may contain pollen from only the last few months (Bennett and Hicks, 2005), that is, the sampling resolution is less than 1 year. To avoid such uncertainties associated with estimation of PARs within the upper segment of the peat monolith, we excluded the upper 5 cm of the monolith from further analysis.

The PARs of the abundant tree taxa (*Pinus*, *Betula*, *Picea*, *Alnus*) are larger than 2000 grains $\text{cm}^{-2} \text{yr}^{-1}$ (Figure 4), and in particular the PARs for *Betula*, the most abundant tree, exceed 10,000 grains $\text{cm}^{-2} \text{yr}^{-1}$ and reach up to more than 30,000 grains $\text{cm}^{-2} \text{yr}^{-1}$. PARs for *Picea* and *Alnus* vary from 160 to 13,000 grains $\text{cm}^{-2} \text{yr}^{-1}$. These values of PARs for spruce and alder are close to values, estimated for these tree species in, for example, Eastern Germany (Matthias and Giesecke, 2014), but higher than values in Northern Finland (Barnekow et al., 2007; Hicks, 2001). PARs for broad-leaved trees are much lower and vary from 14 to 330 grains $\text{cm}^{-2} \text{yr}^{-1}$ for *Quercus* and from 15 to 220 grains $\text{cm}^{-2} \text{yr}^{-1}$ for *Ulmus*. The PAR of *Tilia* in the samples is only 14–80 grains $\text{cm}^{-2} \text{yr}^{-1}$.

Within the peat monolith, the depth intervals with relatively high and low PARs of the main forest-forming trees were identified. Increasing PARs of all trees are found at the depths 54–60, 40–47, and 20–24 cm. The PARs of *Pinus* and *Quercus* also increase in the interval 12–18 cm. Decreased PARs of *Picea*, *Pinus*, *Betula*, and *Alnus* are detected in the intervals 27–37, 50–55, and 63–67 cm.

Comparison of the PAR values for dominant tree species in the peat samples and pollen traps located in the same region (Nosova et al., 2013) revealed well comparable values for *Betula*. The PARs of *Pinus* and *Picea* in pollen traps for the period 2008–2013 amounted to 1153–3743 and 29–2266 grains $\text{cm}^{-2} \text{yr}^{-1}$, respectively. These values are comparable to the values in periods with low PARs, but much lower than in periods when the PARs of pine and spruce are increased. However, inconsistencies between the PAR detected in moss and peat samples and pollen traps have also been demonstrated by researchers in other regions (Broström et al., 2004; Soepboer et al., 2007).

The PARs of the main herbaceous taxa – *Artemisia*, Poaceae, and Ericales – vary from 70 to 500 grains $\text{cm}^{-2} \text{yr}^{-1}$ and increase up to 1500 grains $\text{cm}^{-2} \text{yr}^{-1}$ in the depth intervals 30–45 and 19–22 cm. The PAR of Ericales increases in the depth interval 25–40 cm. It makes the sharp peaks above 4000 grains $\text{cm}^{-2} \text{yr}^{-1}$ at the depths of 24 and 47 cm. The PAR of *Sphagnum* is relatively low; it ranges from 15 to 200 grains $\text{cm}^{-2} \text{yr}^{-1}$ and is close to the values obtained in pollen traps. Peaks up to 1000 grains $\text{cm}^{-2} \text{yr}^{-1}$ are recorded for the depths of 12 and 21 cm.

Response of the PAR to variability in climatic parameters

Cross-correlation and the Granger causality analysis indicate a broad range of statistically significant correlational relationships between the PAR and the air temperature and precipitation variability in the previous years (Tables 1–3).

In particular, the PAR of *Picea* has a positive correlation with the air temperature of July of the previous year ($r = 0.42$ at the significance level $p < 0.05$) as well as with precipitation of November and December of the previous year ($r = 0.30$ and $r = 0.29$, respectively, at $p < 0.05$; Tables 1 and 2). The Granger causality test showed that the air temperature of July and winter precipitation of the previous year (Lag = 1) can be appropriately used for PAR forecasting (Table 3). Additionally, the Granger causality test also indicates the possible influence of the air temperature in November on the PAR at Lag 3 (mean air temperature of November over the last 3 years).

The cross-correlation analysis for *Pinus* shows similar results. In particular, it also indicates a positive correlation of the PAR with the air temperature of July of the previous year ($r = 0.28$, $p < 0.05$) and with precipitation of November of the previous year ($r = 0.41$, $p < 0.05$). Moreover, the analysis shows significant correlation of the PAR with the air temperature of November of the previous year ($r = 0.33$, $p < 0.05$) and with the air temperature in spring (March) of the year before last ($r = 0.39$, $p < 0.05$), relatively high positive correlation between the PAR and winter precipitation (January) of the current year ($r = 0.51$, $p < 0.05$), and negative correlation of the PAR with precipitation of April of the previous year ($r = -0.32$, $p < 0.05$; Tables 1 and 2). The Granger test shows causal relationships between both the pine PAR and the air temperature (of July for Lag = 1, March for Lag = 2, 3, November for Lag = 1, 3, and December for Lag = 3) and the PAR and precipitation amount (of February and April with Lag = 1, January with Lag = 2, October and November with Lag = 2, 3, and Lag = 1, 3, respectively; Table 3).

For *Betula*, the cross-correlation analysis shows a positive correlation of the PAR with the air temperature of March of the previous year ($r = 0.31$, $p < 0.05$) as well as with precipitation of January of the current year ($r = 0.36$, $p < 0.05$). Similar results are obtained for the Granger causality test indicating that the air temperature of March (Lag = 2), September (Lag = 3), November (Lag = 1), and December (Lag = 2) as well as precipitation amount of January (Lag = 2), February (Lag = 1), and November (Lag = 3) can be used for the birch PAR forecasting.

The PAR of genus *Alnus* is correlated with the air temperature of July of the previous year ($r = 0.34$, $p < 0.05$) as well as with precipitation of November of the previous year ($r = 0.37$, $p < 0.05$). The possible influence of November precipitation on the alder PAR is confirmed also by the Granger causality test for Lags 1 and 3. The Granger test shows a causal relationship between the PAR and the air temperature of July (Lag = 1), September (Lag = 3), and November–December (Lag = 3).

Tilia is characterized by positive correlation of the PAR with the air temperature of March of the current year ($r = 0.29$, $p < 0.05$) and with precipitation amount of November of the previous year ($r = 0.30$, $p < 0.05$; Tables 1 and 2). Similar results were obtained for the Granger causality test (Table 3).

Table 1. The Spearman cross-correlation coefficients between the PARs of the different plant species and mean monthly air temperature. Cross-correlation coefficients calculated for different lags ranged from 0 (current year) to 3 (3 years before pollen releasing). Non-filled white boxes correspond to correlations with attained statistical significance ($p < 0.05$) and filled gray boxes correspond to correlations with $p > 0.05$.

Species	Months											
	January	February	March	April	May	June	July	August	September	October	November	December
Lag 0 year												
<i>Alnus</i>	-0.149	-0.101	0.189	-0.260	0.128	0.018	0.146	–	–	–	–	–
<i>Artemisia</i>	-0.132	-0.280	-0.063	0.045	0.010	0.110	-0.169	–	–	–	–	–
<i>Betula</i>	-0.045	-0.115	0.252	0.104	0.136	0.056	0.167	–	–	–	–	–
<i>Corylus</i>	-0.138	-0.186	0.004	-0.072	0.027	-0.167	0.259	–	–	–	–	–
Ericales	-0.028	0.024	-0.355	-0.394	-0.049	-0.047	0.208	–	–	–	–	–
<i>Picea</i>	-0.030	-0.064	0.033	-0.058	0.142	-0.059	0.216	–	–	–	–	–
<i>Pinus</i>	0.174	-0.069	0.292	0.059	0.108	-0.059	0.103	–	–	–	–	–
Poaceae	-0.468	-0.281	-0.051	-0.134	-0.025	0.137	-0.017	–	–	–	–	–
<i>Quercus</i>	-0.187	-0.264	0.222	0.017	-0.023	0.146	0.254	–	–	–	–	–
<i>Sphagnum</i>	-0.112	-0.199	0.200	0.033	-0.089	0.272	-0.089	–	–	–	–	–
<i>Tilia</i>	0.196	-0.031	0.293	-0.081	-0.014	-0.140	-0.203	–	–	–	–	–
<i>Ulmus</i>	-0.037	-0.301	0.060	0.001	0.007	0.114	0.077	–	–	–	–	–
Lag 1 year												
<i>Alnus</i>	0.028	-0.176	-0.002	0.073	0.043	0.016	0.335	0.233	0.225	-0.068	0.247	-0.054
<i>Artemisia</i>	0.043	-0.082	-0.109	-0.222	0.019	-0.144	0.163	0.153	0.115	0.055	0.232	-0.045
<i>Betula</i>	0.132	-0.220	-0.046	0.138	0.146	0.014	0.156	0.153	0.276	0.232	0.309	0.099
<i>Corylus</i>	0.097	-0.059	0.025	-0.038	0.086	0.041	0.274	0.235	0.318	-0.101	0.182	-0.085
Ericales	-0.186	-0.120	-0.184	-0.127	-0.157	-0.092	0.108	-0.051	-0.118	0.128	0.056	-0.030
<i>Picea</i>	0.234	0.093	0.191	0.051	0.054	-0.045	0.424	0.170	0.240	-0.099	0.260	0.041
<i>Pinus</i>	0.110	0.048	0.199	0.111	0.178	-0.088	0.278	0.094	0.196	0.116	0.329	0.027
Poaceae	0.208	-0.097	-0.098	-0.021	0.145	-0.074	0.298	0.181	0.156	0.070	0.222	-0.054
<i>Quercus</i>	0.093	-0.118	0.019	0.270	0.090	-0.065	0.220	0.170	0.088	0.273	0.182	-0.019
<i>Sphagnum</i>	-0.108	-0.002	0.084	0.024	0.031	0.244	-0.091	0.035	-0.082	-0.050	-0.110	-0.116
<i>Tilia</i>	-0.049	-0.014	0.115	0.064	0.062	-0.048	-0.068	0.057	-0.184	0.149	0.218	-0.107
<i>Ulmus</i>	0.137	0.024	0.129	0.122	0.071	0.131	0.458	0.184	0.083	-0.126	0.271	0.116
Lag 2 years												
<i>Alnus</i>	0.032	0.203	0.193	-0.104	-0.042	0.008	0.028	0.053	-0.032	-0.027	0.140	0.058
<i>Artemisia</i>	0.153	0.104	0.076	-0.189	0.049	-0.135	0.054	0.046	0.038	-0.343	-0.156	-0.133
<i>Betula</i>	0.261	0.206	0.322	0.126	0.022	-0.059	0.117	0.077	0.067	0.131	-0.049	0.147
<i>Corylus</i>	-0.264	0.061	0.055	-0.137	0.099	-0.144	0.077	0.163	-0.013	-0.066	0.294	0.137
Ericales	-0.236	-0.101	-0.296	-0.094	-0.217	-0.267	-0.040	0.176	-0.151	-0.039	0.064	-0.174
<i>Picea</i>	-0.175	-0.049	0.249	-0.024	0.065	0.082	0.144	0.275	-0.033	0.088	0.259	0.159
<i>Pinus</i>	0.184	0.138	0.388	0.246	0.163	-0.064	0.066	0.061	0.083	0.009	0.136	0.134
Poaceae	-0.075	0.019	0.032	-0.029	-0.007	-0.081	0.038	0.254	-0.009	-0.122	0.068	0.098
<i>Quercus</i>	0.351	0.147	0.338	0.315	-0.014	-0.169	0.073	0.125	0.296	0.004	-0.009	-0.091
<i>Sphagnum</i>	0.100	-0.081	-0.050	0.207	0.212	0.025	-0.027	-0.174	0.023	-0.117	0.155	-0.267
<i>Tilia</i>	0.219	0.030	0.008	0.273	0.082	0.024	-0.084	-0.275	0.021	-0.020	-0.166	-0.090
<i>Ulmus</i>	-0.186	-0.042	0.142	0.042	-0.060	0.094	0.079	0.283	0.132	-0.114	0.200	0.179
Lag 3 years												
<i>Alnus</i>	0.042	-0.003	0.140	0.178	-0.123	-0.142	-0.206	0.140	0.398	0.190	0.418	0.282
<i>Artemisia</i>	-0.043	0.141	-0.005	0.008	-0.033	0.032	-0.131	-0.066	0.162	0.040	0.166	0.103
<i>Betula</i>	-0.062	-0.178	0.176	0.254	-0.219	-0.125	-0.130	0.128	0.279	0.267	0.206	0.390
<i>Corylus</i>	0.160	0.084	0.226	0.088	0.021	-0.208	0.108	0.048	0.151	-0.020	0.269	0.032
Ericales	-0.207	-0.109	-0.041	-0.147	-0.262	0.169	-0.070	-0.044	0.013	-0.133	0.047	-0.009
<i>Picea</i>	0.187	0.163	0.159	0.148	-0.120	-0.103	-0.089	-0.043	0.150	0.099	0.432	0.216
<i>Pinus</i>	0.252	0.132	0.443	0.241	-0.132	-0.103	-0.111	-0.009	0.192	0.245	0.277	0.291
Poaceae	-0.111	-0.106	-0.240	-0.127	-0.038	-0.069	-0.138	-0.044	0.224	0.053	0.297	0.425
<i>Quercus</i>	0.012	-0.116	0.142	0.211	0.113	-0.182	-0.045	0.048	0.391	0.265	0.297	0.559
<i>Sphagnum</i>	-0.069	0.255	0.191	0.102	0.086	-0.066	-0.206	-0.084	-0.083	0.163	-0.056	0.059
<i>Tilia</i>	0.222	0.077	0.168	0.274	0.075	-0.134	0.082	-0.029	0.146	0.070	-0.134	0.033
<i>Ulmus</i>	0.219	0.110	0.040	0.040	0.163	-0.076	-0.157	0.039	0.271	0.162	0.237	0.269

Table 2. The Spearman cross-correlation coefficients between the PARs of the different plant species and monthly precipitation amount. Cross-correlation coefficients calculated for different lags ranged from 0 (current year) to 3 (3 years before pollen releasing). Non-filled white boxes correspond to correlations with attained statistical significance ($p < 0.05$) and filled gray boxes correspond to correlations with p -value > 0.05 .

Species	Months											
	January	February	March	April	May	June	July	August	September	October	November	December
Lag 0 year												
<i>Alnus</i>	0.214	0.101	0.078	-0.042	-0.036	0.096	-0.045	-	-	-	-	-
<i>Artemisia</i>	0.114	-0.041	0.013	0.075	-0.059	0.039	0.140	-	-	-	-	-
<i>Betula</i>	0.365	0.079	0.078	0.145	-0.075	0.166	-0.160	-	-	-	-	-
<i>Corylus</i>	0.029	0.032	0.313	-0.047	0.007	-0.037	-0.324	-	-	-	-	-
Ericales	-0.078	-0.211	0.116	0.085	-0.256	0.067	-0.208	-	-	-	-	-
<i>Picea</i>	0.220	0.115	0.261	-0.144	-0.174	0.049	-0.083	-	-	-	-	-
<i>Pinus</i>	0.510	0.096	0.087	-0.020	0.141	0.040	-0.036	-	-	-	-	-
Poaceae	-0.087	0.006	0.053	0.160	-0.279	-0.021	0.016	-	-	-	-	-
<i>Quercus</i>	0.192	0.182	0.053	0.193	-0.137	-0.054	-0.137	-	-	-	-	-
<i>Sphagnum</i>	0.003	0.179	-0.079	0.009	-0.053	-0.199	0.402	-	-	-	-	-
<i>Tilia</i>	0.226	-0.144	-0.143	0.160	0.418	-0.027	0.016	-	-	-	-	-
<i>Ulmus</i>	0.153	0.065	0.260	0.141	-0.024	-0.245	0.092	-	-	-	-	-
Lag 1 year												
<i>Alnus</i>	-0.207	0.130	0.033	-0.080	-0.134	0.048	0.141	0.193	0.058	0.153	0.368	0.006
<i>Artemisia</i>	-0.032	0.162	-0.026	-0.116	0.092	0.078	0.009	0.240	0.179	-0.048	-0.066	0.051
<i>Betula</i>	0.163	0.288	0.085	-0.216	-0.130	0.058	0.176	0.157	-0.062	0.073	0.226	0.170
<i>Corylus</i>	0.060	0.155	0.006	-0.133	-0.036	-0.082	0.050	0.189	-0.015	0.028	0.058	0.206
Ericales	-0.147	-0.213	-0.372	0.005	-0.138	0.004	0.038	0.076	-0.182	-0.230	-0.197	-0.345
<i>Picea</i>	0.203	0.187	0.239	-0.219	-0.066	0.059	-0.053	0.012	-0.021	0.043	0.296	0.289
<i>Pinus</i>	0.185	0.355	0.127	-0.317	-0.102	-0.092	-0.006	0.114	0.252	0.211	0.407	0.273
Poaceae	-0.043	-0.137	0.113	-0.160	-0.041	0.112	0.007	0.036	-0.036	-0.380	-0.032	-0.094
<i>Quercus</i>	0.009	0.012	0.012	-0.111	-0.139	0.095	0.189	0.089	0.214	0.050	0.138	-0.069
<i>Sphagnum</i>	-0.063	0.006	0.164	0.075	0.146	-0.145	-0.041	0.095	0.422	0.092	-0.107	-0.061
<i>Tilia</i>	-0.027	0.012	0.025	-0.080	-0.041	-0.037	-0.037	0.007	0.148	0.082	0.304	0.007
<i>Ulmus</i>	-0.135	0.114	0.185	0.119	-0.008	-0.113	-0.073	0.262	0.012	-0.106	0.323	0.179
Lag 2 years												
<i>Alnus</i>	0.097	0.081	-0.025	0.011	0.129	0.139	-0.053	-0.224	-0.120	-0.006	0.272	-0.043
<i>Artemisia</i>	0.256	-0.123	0.050	0.059	0.213	0.150	-0.383	-0.049	0.292	0.071	-0.088	-0.149
<i>Betula</i>	0.376	0.146	0.099	0.032	0.075	-0.018	-0.051	0.174	-0.110	0.016	0.032	0.007
<i>Corylus</i>	0.020	0.078	0.012	-0.104	0.268	0.325	-0.236	-0.049	-0.233	-0.047	0.079	0.028
Ericales	-0.042	-0.048	-0.005	0.124	0.127	0.243	-0.050	-0.136	-0.019	-0.340	-0.145	-0.111
<i>Picea</i>	0.010	0.112	-0.140	-0.264	0.043	-0.031	0.033	-0.099	-0.078	0.060	0.248	-0.048
<i>Pinus</i>	0.298	0.006	0.193	-0.099	0.085	0.086	0.051	-0.004	-0.092	0.238	0.177	0.113
Poaceae	-0.057	0.026	-0.099	0.055	-0.094	0.121	-0.104	-0.156	0.152	-0.238	0.032	-0.188
<i>Quercus</i>	0.409	0.075	0.152	-0.035	-0.029	0.056	-0.056	-0.204	0.080	0.091	0.115	0.128
<i>Sphagnum</i>	-0.118	-0.259	-0.094	-0.027	-0.010	0.162	0.109	0.040	0.072	-0.085	0.171	-0.057
<i>Tilia</i>	0.189	-0.011	0.130	-0.031	-0.026	0.259	-0.043	0.028	-0.131	0.082	-0.104	0.142
<i>Ulmus</i>	0.066	0.215	0.053	-0.239	0.081	0.162	-0.029	-0.165	0.152	0.202	0.290	0.105
Lag 3 years												
<i>Alnus</i>	-0.117	0.047	-0.070	-0.206	0.183	0.287	0.159	-0.189	-0.071	0.173	0.409	-0.159
<i>Artemisia</i>	0.182	-0.004	-0.024	0.067	0.093	0.165	0.057	-0.315	0.118	0.014	0.074	-0.134
<i>Betula</i>	0.106	0.072	-0.093	-0.116	0.160	0.237	0.215	-0.028	-0.146	0.242	0.291	0.014
<i>Corylus</i>	0.188	0.225	-0.056	-0.203	0.081	0.240	-0.060	-0.201	-0.289	0.151	0.195	0.031
Ericales	-0.205	-0.385	-0.190	0.098	0.065	0.027	0.092	-0.219	-0.127	-0.026	-0.248	-0.113
<i>Picea</i>	0.099	0.156	-0.142	-0.125	0.248	0.183	0.088	-0.085	-0.081	0.276	0.277	0.034
<i>Pinus</i>	0.219	0.247	0.125	-0.220	0.250	0.136	0.119	-0.026	-0.091	0.345	0.354	0.183
Poaceae	-0.059	-0.281	-0.219	0.000	-0.106	0.166	-0.084	-0.117	-0.225	-0.120	0.081	0.026
<i>Quercus</i>	0.260	-0.211	0.028	-0.171	0.190	0.055	0.169	-0.014	-0.066	0.015	0.349	0.194
<i>Sphagnum</i>	0.092	0.042	0.051	-0.027	-0.117	0.051	0.052	-0.082	0.129	-0.193	-0.024	0.059
<i>Tilia</i>	0.206	0.057	0.167	0.101	-0.110	0.031	0.112	-0.001	-0.105	0.023	0.212	0.133
<i>Ulmus</i>	0.077	0.094	-0.016	-0.070	0.318	0.056	0.050	-0.090	-0.008	0.198	0.134	0.013

Table 3. The results of the Granger causality test calculated between the PARs of the different plant species and mean monthly values of meteorological parameters (air temperature and precipitation). Symbol '+' indicates that the change of PAR is a Granger-cause of a change of some meteorological parameters for corresponding month. Lag for with statistically significant values shown in brackets. Symbol '-' indicates an absence of Granger causality.

Species	Months											
	January	February	March	April	May	June	July	August	September	October	November	December
Air temperature												
<i>Alnus</i>	-	-	-	-	-	-	+(1)	-	+(3)	-	+(3)	+(3)
<i>Artemisia</i>	-	-	-	-	-	-	-	-	-	-	-	-
<i>Betula</i>	-	-	+(2)	-	-	-	-	-	+(3)	-	+(1)	+(3)
<i>Corylus</i>	-	-	-	-	-	-	-	-	+(1)	-	+(2)	-
Ericales	-	-	+(1)	+(0)	-	-	-	-	-	-	-	-
<i>Picea</i>	-	-	-	-	-	-	+(1)	-	-	-	+(3)	-
<i>Pinus</i>	-	-	+(2, 3)	-	-	-	+(1)	-	-	-	+(1, 3)	+(3)
Poaceae	+(0)	+(0)	-	-	-	-	+(1)	-	-	-	+(3)	+(3)
<i>Quercus</i>	+(2)	-	+(2)	+(2)	-	-	-	-	+(2, 3)	-	+(3)	+(3)
<i>Sphagnum</i>	-	-	-	-	-	-	-	-	-	-	-	-
<i>Tilia</i>	-	-	+(0)	-	-	-	-	-	-	-	-	-
<i>Ulmus</i>	-	+(0)	-	-	-	-	+(1)	-	-	-	-	-
Precipitation												
<i>Alnus</i>	-	-	-	-	-	-	-	-	-	-	+(1, 3)	-
<i>Artemisia</i>	-	-	-	-	-	-	+(2)	+(3)	+(2)	-	-	-
<i>Betula</i>	+(2)	+(1)	-	-	-	-	-	-	-	-	+(3)	-
<i>Corylus</i>	-	-	+(0)	-	-	+(2)	-	-	+(3)	-	-	-
Ericales	-	+(3)	-	+(1)	-	-	-	-	-	-	-	+(1)
<i>Picea</i>	-	-	-	-	-	-	-	-	-	-	+(1)	+(1)
<i>Pinus</i>	+(2)	+(1)	-	+(1)	-	-	-	-	-	+(2, 3)	+(1, 3)	-
Poaceae	-	-	-	-	-	-	-	-	-	+(1)	-	-
<i>Quercus</i>	+(2)	-	-	-	-	-	-	-	-	-	+(3)	-
<i>Sphagnum</i>	-	-	-	-	-	-	+(0)	-	+(1)	-	-	-
<i>Tilia</i>	-	-	-	-	-	-	-	-	-	-	+(1)	-
<i>Ulmus</i>	-	-	-	-	+(3)	-	-	-	-	-	+(1, 2)	-

Analysis of correlations for *Quercus* shows significant positive correlation between the PAR and the values of the air temperature and precipitation observed 2 and 3 years prior to the year of pollen release only (Tables 1 and 2). The Granger test also shows a causal relationship between the oak PAR and the air temperature (of January, March, and April with Lag = 2, September with Lag = 2, 3, and November and December with Lag = 3) and between the oak PAR and precipitation amount (of January with Lag = 2 and in November with Lag = 3).

The PAR of *Ulmus* is characterized by negative correlation with the winter air temperature (February) of the current year ($r = -0.30$, $p < 0.05$) and relatively high positive correlation with the air temperature of July of the previous year ($r = 0.46$, $p < 0.05$). It can be assumed therefore that colder winters result in elm PAR reduction. These relationships are also manifested in the Granger causality test: there are causal relationships between the PAR of elm trees and the air temperature of February (Lag = 0) and July (Lag = 1), as well as between the elm PAR and precipitation of May (Lag = 3) and November (Lag = 1, 2).

The cross-correlation analysis for the PAR of *Corylus* indicates a positive correlation with the air temperature of February of the previous year ($r = 0.32$, $p < 0.05$) and with precipitation of the first spring month (March) of the current year ($r = 0.31$, $p < 0.05$). The influence of the February air temperature is not apparent in the Granger causality test. However, the test indicates a causal relationship between the *Corylus* PAR and the air temperature of September (Lag = 1) and November (Lag = 2). Moreover, the test shows a causal relationship between the hazelnut PAR and precipitation of March (Lag = 0), June (Lag = 2), and September (Lag = 3).

The correlation analysis for herbaceous and spore-producing plants also showed a clear relationship between their PAR and

climatic characteristics. In particular, our results indicate a negative correlation between the PAR of herbs (Poaceae) and the air temperature of January and February of the current year ($r = -0.47$ and $r = -0.28$, respectively, at $p < 0.05$), a surprisingly positive correlation of the PAR with the air temperature of January of the previous year ($r = 0.30$, $p < 0.05$) and negative correlations with precipitation of October of the previous year. The PAR of Ericales ($r = 0.35$ for March and $r = 0.39$ for April at $p < 0.05$) is characterized by a similar negative correlation with the winter and spring air temperatures of the current year. The causal relationships between the Poaceae and Ericales PAR and the meteorological parameters are confirmed by the Granger test: the air temperature of March (Lag = 2) and April (Lag = 0) as well as the precipitation of February (Lag = 3), April (Lag = 1), and December (Lag = 1) can be used for forecasting of the Ericales PAR, and the air temperature of January and February (Lag = 0), July (Lag = 1), and November and December (Lag = 3), as well as the precipitation of October (Lag = 1) can be used for forecasting of the Poaceae PAR, respectively. The Granger test indicates a causal relationship between the PAR of *Artemisia* and precipitation amount for period from July to September (Table 3). The spore accumulation rate of *Sphagnum* moss is well correlated with precipitation amount of September of the previous year ($r = 0.42$, $p < 0.05$). The same results are confirmed by the Granger causality test.

Discussion

The statistical analysis of possible effects of climate on the amount of pollen released by different tree species shows that a warm summer of the previous year encourages pollen productivity of the main tree species. Significant positive coefficients of correlation

and positive results of the Granger causality test are detected between the July temperature of the previous year and the PAR of *Picea*, *Pinus*, and *Ulmus*. A consistent correlation between the PAR of *Pinus*, *Betula*, *Alnus*, and *Corylus* and the air temperature in summer and autumn of the previous year is also revealed. Similar results were obtained from a large number of records from pollen traps in various European regions (Autio and Hicks, 2004; Barnekow et al., 2007; Huusko and Hicks, 2009; Mazier et al., 2012; Nielsen et al., 2010). All these studies showed a significant influence of the air temperature of the previous years on the PAR. Huusko and Hicks (2009) and Barnekow et al. (2007) using data from long-term observations of pollen traps in Northern Finland demonstrated a strong correlation of the *Picea*, *Pinus*, and *Betula* PAR with the air temperature of July of the previous year. Some studies have indicated that the relationships between PAR and meteorological parameters are nonlinear, and PAR changes can be affected by non-climatic factors (Kamenik et al., 2009). A comprehensive overview provided by Van der Knaap et al. (2010) for several regions of Eastern and Central Europe showed not only a close relationship between summer temperature and *Picea* and *Pinus* PARs in pollen traps and peat monoliths but also a strong correlation between PAR and summer temperatures observed during a longer time interval before pollen release. The reason for the high correlation between the PAR and summer air temperatures of the previous year is that generative buds of tree species are mostly formed late in the year preceding its release. A warm summer in the previous year influences not only the pollen productivity of the trees but also the growth of tree rings, which can be traced by dendrochronological data (Bunn et al., 2013; McCarroll et al., 2003).

The response of pollen productivity of the different tree species on cold winter conditions is somewhat different. The forest-forming tree species (*Picea*, *Pinus*, *Quercus*, *Alnus*, *Betula*) are characterized by positive correlations between the PAR and the air temperatures of November and December in 3 years before flowering (Table 1). It assumes the reduction in pollen production for the tree species because of very cold weather conditions in the corresponding winter months. It was also found that the PARs of *Quercus* and *Tilia* are reduced with a decrease in the air temperature of March of several previous years. The negative correlation is observed between the *Ulmus* PAR and the air temperature of February of the current year. These relationships are also confirmed by the Granger causality test. The obtained results are well agreed with the results of, for example, continuous observations on pollen traps in the Czech Republic and South Sweden. They showed particularly that a mild autumn and winter are favorable for *Quercus* PAR (Van der Knaap et al., 2010). According to the data obtained from pollen traps in Swiss Jura Mountains, the high values of *Alnus* and *Corylus* PARs are correlated with warm autumn of the previous year (Sjögren et al., 2006). The reasons for the strong influence of cold period temperatures on PAR can be high sensitivity of some species (mainly broad-leaved) to strong negative temperature anomalies in winter. Frost in late autumn and spring can lead to damage of generative buds of trees (Körner, 1999).

The possible influence of precipitation patterns on the PAR is still relatively poorly investigated. The studies provided in various European regions showed the different, even opposite, correlations between PAR and monthly precipitation of the previous years even for the same tree species (Autio and Hicks, 2004; Nielsen et al., 2010; Van der Knaap et al., 2010). In our studies, we found positive correlations and positive results of the Granger causality test between the PAR of several tree species and shrubs and precipitation of November, December, and January of the previous and current years. This correlation reflects the influence of winter precipitation on soil water availability in spring and as a result on tree growth and functioning in the following flowering season.

The PARs of the main herbaceous taxa show negative correlations with summer precipitation of the previous years, in contrast to the relationships observed for some dominant tree species in the region (*Picea*, *Pinus*, *Ulmus*). As exact species identification of most NAP taxa (especially Poaceae, Cyperaceae, Asteraceae, etc.) is impossible, the correlation between climatic characteristics and the PAR of herbs may be determined by both climatic and anthropogenic reasons. Obviously, these correlations do not reflect the response of specific taxa to the changes in weather conditions but the response of the plant community as a whole.

The PAR of *Sphagnum* spores is not sensitive to the air temperature variation. However, it is relatively strongly correlated with precipitation of July of the current year and September of the previous one that is confirmed by the Granger causality test. Probably, the vitality of *Sphagnum* mosses is affected by surface wetness of the upper peat layer and ground water level in summer and autumn periods (Olchev et al., 2013).

The reliability and accuracy of the provided statistical analysis are mainly influenced by possible errors in dating, uncertainties of used age–depth model, and very high intraannual variability of the peat accumulation rate. It is obvious that the peat samples (with a thickness of about 1 cm in our case) at different depths were formed during various time intervals depending on the rate of peat accumulation determined by weather and moistening conditions.

In order to avoid any possible uncertainties in dating and used age–depth model, the smoothed PAR time series (2 and 3 years of running means) are used (Barnekow et al., 2007). A key disadvantage of such smoothing approach is that it results usually in reducing any irregularities in PAR time series data that can be actually caused by some abnormal weather conditions with, for example, very high or low air temperatures and precipitation. So, in our study, we used non-smoothed PAR values for cross-correlation analysis mainly to retain in the data analysis the response of PARs to, for example, any irregular (positive or negative) deviations of the meteorological parameters from the monthly mean values. It is obvious that such events can have a significant impact on pollen generation and the effect of its influence can be lost after time series smoothing. To take into account the possible effects of non-uniform peat accumulation rate on the age–depth model, the cross-correlation analysis was provided with different lags ranging from 0 to 3 years. Moreover, the Granger causality test was applied for different lags ranging from 0 (current year only) to 3 (cumulative effect of meteorological conditions for the corresponding month on PAR for period from the year of pollen release to 3 years prior to this event).

Conclusion

Near-annual pollen records from a peat monolith from a raised peat bog in the CFSNBR have shown that the PAR could be an effective indicator for interpreting the pollen–climate relationships. Cross-correlation and the Granger causality analysis indicated a broad range of statistically significant correlations between the PAR and air temperature and precipitation variability in the previous and current years. Some of the results are confirmed by results of pollen trap analysis carried out in the other European regions. According to the results, high air temperature during the growing season (from spring to autumn) in the year previous to the flowering led to an increase in pollen productivity of the main tree species. Besides that, positive correlations were obtained between PARs of the forest-forming trees and the air temperature of some winter months in the current and previous years with some time lag.

Our studies also demonstrate positive correlations and positive results of the Granger causality test between PAR of trees and shrubs and winter precipitation in various years that could reflect

the influence of winter precipitation on soil water availability and as a result on tree growth and functioning in spring.

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