

Forecasting the start of *Quercus* pollen season using several methods – the evaluation of their efficiency

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Abstract Forecasting the time when the atmospheric pollen season of allergenic plants begins is particularly important for doctors and their patients. The aim of this paper is to determine whether it is possible to forecast the start of the oak (*Quercus*) pollen season in Rzeszów, Poland. In the elaboration of the most effective model, various forecasting techniques were tested: growth degree days (GDD°C); meteorological factors; bioclimatic factors; and indicator taxon. The aerobiological monitoring was carried out in 1997–2005 and 2007 in Rzeszów (SE Poland). In the presented investigation, three methods defining the start of the *Quercus* pollen season were selected on the basis of accumulated sums of pollen or the constant occurrence of pollen grains in air. Despite the application of different combinations of GDD°C methods and threshold temperatures, the correlation coefficients between the expected and obtained values were low. In some cases, however, they proved highly effective for the test years (2005, 2007) with the accuracy of a few days. For GDD°C methods, the best threshold temperatures range between 5 and 6°C. Models based on bioclimatic indices and meteorological variables were not satisfactory. On the basis of the 10 years of results, the method of indicator species were good for forecast the start of oak pollen season. Birch was the best indicator taxa.

Keywords Forecasting · Growth degree days · Indicator species · Pollen · *Quercus*

Introduction

In aerobiology, the mathematical, statistical, and numerical analysis of data is most frequently used in forecasting the numerous phenomena associated with the occurrence of pollen and spores in the air (García-Mozo et al. 2002; Rodríguez-Rajo et al. 2003, 2004; Chuine and Belmonte 2004; Pasken and Pietrowicz 2005; Alba et al. 2006; García-Mozo et al. 2006). These forecast models have practical applications in fields such as agriculture, forestry, and allergology, and are highly important in such fields of science as botany, plant taxonomy, and plant ecology. Forecasting the time when the atmospheric pollen season of allergenic plants begins is particularly important for allergologists and their patients, because such information allows them to undertake suitable treatment. The most effective models often include combinations of different methods and are presented in numerous phenological and aerobiological papers (Frenguelli and Bricchi 1998; Gómez-Casero et al. 2004; Masin et al. 2005; Alba et al. 2006; Rodríguez-Rajo et al. 2006; Jato et al. 2007a, b; Fuertez-Rodríguez et al. 2007).

This work concentrates on the pollen of *Quercus* (oak). Species of this genus commonly occur in forest communities of southeastern Poland and are planted in towns. Oak pollen is generally considered to have weak allergenic properties, but it was observed the cross-reaction between allergens of some species of Fagales and Betulaceae. However, recent data have shown increased sensitization to tree pollen in Europe (Mothes and Valenta 2004). The enormous production of pollen grains by the flowers/inflorescences of oak trees (Gómez-Casero et al. 2004) means that *Quercus* pollen can present a problem in regions where oak trees frequently occur in stands (Fairley and George 1986; García-Mozo et al. 2007). Several papers

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have presented effective methods for forecasting the start of the *Quercus* pollen season (Norris-Hill 1998; García-Mozo et al. 2002; Rodríguez-Rajo et al. 2003). The aim of this paper is to determine whether it is possible to forecast the start of the oak pollen season in Rzeszów, Poland. Various forecasting techniques were tested with the aim of selecting the most effective method: growth degree days; meteorological factors; bioclimatic factors; “indicator taxon”.

Materials and methods

Site information

Aerobiological monitoring took place in the town of Rzeszów (the region of Rzeszów Foothills) in south-eastern Poland. There are no natural barriers in this region and altitude differences vary between 80 and 200 m above sea level. The town lies at the altitude of 200 m. In the climatic regionalization based on weather conditions (Woś 1999), Rzeszów lies in the Tarnów-Rzeszów region with boundaries delimited by distinct climatic differences. Very warm days with simultaneous atmospheric precipitation are fairly frequent (about 34 days a year), as are days that are sunny but have an early ground frost, and temperatures that are moderately cool or very cool. Conversely, cool days with precipitation and heavy clouds are fairly rare. In the last decade, the mean annual temperature was 8.1°C and mean annual precipitation was 633 mm. Mean temperatures for July (the warmest month) and January (the coldest month) were 18.3 and −2.1°C, respectively.

Quercus pollen data

In Poland, the genus *Quercus* is most frequently represented by *Q. robur*, *Q. rubra*, and *Q. petraea*. The most common species is *Q. robur*, which does not reach the boundary of its natural range but is not evenly distributed (Boratyński et al. 2006). Other species (*Q. pubescens*, *Q. cerris*, *Q. coccinea*, and *Q. palustris*) occur sporadically on natural sites or are rarely planted. In the neighbourhood of the monitoring station, *Q. robur* belongs to the basic forest-forming species. In forest stands, *Q. robur* appears in the composition of frequently encountered *Querco-Pinetum* and *Tilio-Carpinetum* associations, and is also a component in other forest types, e.g., in the *Dentario glandulosae-Fagetum* association. Another frequently occurring species is *Q. rubra*. This is a non-native species planted in forests, but is known to self-sow. In urban areas, oaks can generally be encountered in parks and squares, but the trees are not frequently planted. In the Carpathian Foothills, the distribution of *Q. petraea* is uneven.

The aerobiological investigation was carried out from 1997 to 2005 and in 2007. The monitoring was continuously conducted using a Hirst-type volumetric spore trap (Burkard, Lanzoni VPPS 2000) situated about 12 m above the ground level. The sampler sucks air by a pump with a constant suction flow of 10 l/min corresponding to 14.4 m³ 24 h^{−1}. Pollen grains are impacted on a drum covered by a tape coated with a sticky substance. Sampler drum was changed weekly, and then the tape was cut into 48-mm parts corresponding to the previous 7 days. Samples were examined at ×400 magnification using light microscopes. Pollen grains were counted along 12 latitudinal transects on each microscope slide. The results were expressed as daily average pollen grains/m³.

Methods used to determine the start of the pollen season (referred to as SPS in the text)

In the aerobiological literature, numerous methods for defining the SPS are quoted (Nilsson and Persson 1981; Norris-Hill 1998; García-Mozo et al. 2002; Sánchez-Mesa et al. 2005). The choice of the method for determining SPS has a pronounced effect on the results of analyses (Jato et al. 2006), hence the aim of the studies must be taken into consideration as well as the geographical and climatic conditions of the measurement station, range of the taxonomic level of the pollen type, and its occurrence in the flora and vegetation of the region. Three methods for defining the SPS were selected for this study which were used to determine the start of the pollen season (SPS) just after the first appearance of oak pollen grains in the air. These methods are based on accumulated sums of pollen or on the constant occurrence of pollen grains in the air, and as a result they could be applied before the end of the whole pollen season. This means that they are capable of being applied in real time rather than retrospectively:

- The first day of the continuous occurrence of pollen grains when no breaks appear on at least 5 successive days ($\infty 1$) (García-Mozo et al. 2002)
- The day when the cumulative sum pollen grains reached 5 ($\Sigma 5$) (Norris-Hill 1998)
- The day when the cumulative sum of pollen grains reached 25 ($\Sigma 25$) (Norris-Hill 1998).

The dates of SPS were expressed as the days from 1 January.

The next stage was to find the most effective way of forecasting the SPS defined by using the previously mentioned methods. The forecasting methods included: growth degree days (GDD°C) using several different threshold temperatures, methods based on bioclimatic indices, on weather elements, and on indicator species.

The forecast models were constructed using data from 1997–2004 and tested on data from 2005 and 2007.

Method based on growth degree methods (GDD°C)

Heat units are often used to predict the SPS of different pollen taxa (Rodríguez-Rajo et al. 2003; Fuertez-Rodríguez et al. 2007), and the heat requirement is expressed as GDD°C (Snyder et al. 1999). The 1°-day is noted when the mean daily air temperature is above a threshold temperature. The summing of daily temperatures was carried out according to the following methods:

- I. $\sum T_{\max} - T_b$; if $T_{\max} < T_b$, the difference is 0 (Rodríguez-Rajo et al. 2004)
- II. $\sum \frac{T_{\max} + T_{\min}}{2} - T_b$; if $\frac{T_{\max} + T_{\min}}{2} < T_b$ the value of the expression is 0 (Rodríguez-Rajo et al. 2003)
- III. $\sum T_{\text{mean}}$; $T_{\text{mean}} > T_b$ (Rodríguez-Rajo et al. 2003)

where $T_{\max}$ is maximum temperature, $T_{\min}$ minimum temperature, and T_b threshold temperature

Temperatures were always summed from 1 January to the day preceding the SPS (Cenci et al. 1997).

According to the literature, the threshold values for crop plants and trees flowering in spring in moderate climates are in the lower temperature ranges (0–6°C), while for plants from warmer regions or flowering in summer the basic temperatures are higher (Cenci et al. 1997). Oaks flower in the period of full spring and therefore the following threshold temperatures in 1°-steps from 2 to 6°C were tested to select the temperature most effective in forecasting (García-Mozo et al. 2002; Rodríguez-Rajo et al. 2004; Fuertes-Rodríguez et al. 2007). For each methods, threshold temperature combinations, the means, and the variability coefficients (V%) were calculated.

Method based on bioclimatic indices

The previous methods described for predicting the SPS of *Quercus* are only based on temperatures. This work compares the effectiveness of these methods with forecasts based on bioclimatic indices modified from Valencia-Barrera et al. (2002). The indices which were selected for the comparison have been calculated on the basis of available basic meteorological data. They are based on water movement in the plant/atmosphere system (evapotranspiration) and on the relationship between temperature and water availability (precipitation). The following indices were tested, i.e., the pluviothermic ratio (PR), aridity index (AI), and evapotranspiration estimate (ETE).

$$PR = 2P[(T_{\max} + T_{\min})(T_{\max} - T_{\min})]^{-1}$$

$AI = P(T + 10)^{-1}$; in order to get rid of eventual negative temperature values, a value of 10 is added to temperature.

$$ETE_{TP} = P[0.9 + (P^2 L^{-2})]^{-1/2}$$

where

P	total precipitation in the investigated period
$T_{\max}$	mean maximum temperature in the investigated period
$T_{\min}$	mean minimum temperature in the investigated period
T	average temperature in the investigated period
L	$300 + 2.5T + 0.5T_3$

These indices were calculate for the periods from 1 January to the day preceding the SPS of *Quercus*.

Method based on indicator taxa

Time linkages between the SPS of different taxa have been investigated previously (Bricchi et al. 1995). The criteria for selecting indicator taxa in this study was high or relatively high concentrations of pollen in air and a SPS before the SPS of *Quercus*. The following taxa were selected: *Alnus*, *Corylus*, *Populus*, *Fraxinus*, and *Betula*. The indicator taxa did not always end their pollen season before the SPS of *Quercus*; hence the SPS was determined using the same three methods used for defining the SPS of *Quercus*. Relationships between the SPS of *Quercus* and SPS of indicator species were described by linear regression and a two-degree polynomial function. These are statistical models which do not include other environmental factors like weather.

Method based on weather data

The connection between the SPS of *Quercus* and selected meteorological elements as an independent factors (mean $T_{\max}$, $T_{\min}$, T_{mean} ; total precipitation) was tested. On the basis of meteorological parameters, long-term and short-term models could be prepared, so the weather data from January, February, March, and the second half of March, were taken into consideration. The dataset was not long enough for multiple regression analysis. The relationships were described by Pearson coefficients.

For each year, the expected values were calculated for the tested methods. In comparing the efficiency of these methods, the root mean square error (RMSE) was calculated for each year, and the correlation coefficient was calculated for the expected and obtained values:

$$RMSE = \sqrt{\frac{(d_i - d)^2}{n}}$$

where d_i is the expected value, d the obtained value, and n the number.

The best method was deemed to be the one with the highest Pearson correlation coefficient between the obtained and the expected values and the lowest RMSE value (Snyder et al. 1999; García-Mozo et al. 2002). For each SPS method the (in the author's opinion) most effective forecasting methods were selected and tested for the years 2005 and 2007, which were not included in the models.

Statistic significance of Pearson coefficients was tested using Student's t test:

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

where r is the Pearson coefficient.

In all methods, the standard $\alpha < 0.05$ level of significance was used.

The Rzeszow-Jasionka weather station, situated 7 km northeast of the pollen-monitoring site, supplied the meteorological data used in the analyses. The calculations were carried out using computer programs Statistica 7.0 and Excel.

Results

Based on the 1997–2004 mean, the oak pollen season usually began in the third decade of April. Irrespective of SPS methods, the dates were characterized by a moderate variability as shown by standard deviation (SD) and variability coefficients (V%). The lowest V% ($< 7\%$) and SD (8 days) was noted in the case of the $\Sigma 25$ method. The latest SPS was noted on 13 May 1997 (day 133; $\Sigma 25$), and the earliest on 15 April 1999 (day 105; $\Sigma 5$, $\infty 1$). The difference between the extreme dates was 25 ($\Sigma 5$) to 27 days ($\Sigma 25$, $\infty 1$). Dates of SPS defining by the $\Sigma 25$ and $\infty 1$ methods were very similar; the mean difference was below 2 days. Pollen seasons defined by the $\Sigma 5$ method started first followed by the $\infty 1$ and $\Sigma 25$ methods. No statistically significant trend in SPS was recorded for the period 1997–2004. The yearly total sums of pollen grains (SPI) oscillated between 2,842 in 2003 and 369 in 1997. Generally, the peak concentrations occurred in the first pentad of May (Table 1).

GDD°C calculated according to the proposed methods showed a great deal of variability with variability coefficients exceeding 20%. It was found that the variability was slightly lower for lower threshold temperatures (2°C) compared with higher temperatures (6°C) (Table 2). Correlation coefficients between the expected and obtained values were usually statistically

Table 1 Start of the *Quercus* atmospheric pollen seasons (SPS expressed as day of year from 1 January) defined according to three methods and descriptive statistics for 1997–2004

Years	SPS			SPI ^a	Peak	Date of peak
	$\infty 1$	$\Sigma 5$	$\Sigma 25$			
1997	132	130	133	369	86	16 May
1998	117	109	118	607	93	09 May
1999	105	105	106	591	59	01 May
2000	107	105	110	876	196	28 April
2001	116	109	116	502	67	05 May
2002	112	112	117	1,266	259	04 May
2003	117	117	119	2,842	471	05 May
2004	119	113	121	875	133	04 May
Mean	115.6	112.5	117.5	991	170.5	05 May
SD	8.3	8.1	8.0	798.4	139.6	5.3 days
V%	7.2	7.2	6.8	88.2	78.0	4.3 days

^a SPI Yearly total pollen sum

significant (with $\alpha \leq 0.05$), most frequently in the case of the II and III GDD°C methods and higher threshold values (5–6°C; $r = 0.718$ – 0.877). The lowest RMSE values were also found at these temperatures (Fig. 1). In the case of the I GDD°C method and the lowest threshold values (2–4°C), correlation coefficients were not statistically significant (with $\alpha \leq 0.05$). Comparing the obtained and expected values, the highest RSME values and the lowest correlation coefficients were obtained when the start of the atmospheric pollen season was defined using method $\Sigma 25$; in the case of these indices, the best results were obtained when the start of pollen season was determined using method $\Sigma 5$ (Fig. 1). After comparison between obtained and expected data for 2005, it was found that the GDD°C models were most reliable when the SPS was determined using the $\infty 1$ method but not method $\Sigma 5$, which was characterized by the highest errors, 7–9 days (Table 3). In the case of the I and II GDD°C models at the threshold values (5–6°C), the errors were the lowest (0; –3). For 2007, the lowest differences between obtained and expected data were found for the III GDD°C model at the threshold values 5–6°C. The errors range from 0 to 6 days for all methods determining SPS (Table 4).

Further tests were concerned with methods based on bioclimatic indices. The pluviometric index (PR) was characterized by a very high variability coefficient and therefore, was discarded in further stages of the analysis (Table 5). For evapotranspiration and aridity indices the expected values were calculated. Correlation coefficients between obtained and expected values were not significant, RMSE values were also very high (above 45) and so these models were not tested for 2005 and 2007 years.

Table 2 Values of average growing degree days (GDD °C) calculated using three different methods and five threshold temperatures for the start of the atmospheric pollen season defined using methods $\infty 1$, $\Sigma 5$, and $\Sigma 25$

Methods		$\Sigma T_{\max} - T_b$					$\Sigma \frac{T_{\max} + T_{\min}}{2} - T_b$					$\Sigma T_{\text{mean}}; T_{\text{mean}} > T_b$				
		2°C	3°C	4°C	5°C	6°C	2°C	3°C	4°C	5°C	6°C	2°C	3°C	4°C	5°C	6°C
$\infty 1$	Mean	592.38	517.66	449.94	387.20	331.06	289.53	233.66	185.93	148.69	111.69	370.73	352.19	327.56	298.10	272.03
	SD	118.79	107.19	95.94	85.11	74.25	68.82	57.38	47.10	40.04	33.24	86.30	82.78	79.48	68.73	68.52
	V%	20.1	20.7	21.3	22.0	22.4	23.8	24.6	25.3	26.9	29.8	23.3	23.5	24.3	23.1	25.2
$\Sigma 5$	Mean	552.89	479.48	414.88	355.26	302.25	264.91	212.15	167.53	132.30	97.86	339.66	321.13	296.50	267.10	241.70
	SD	110.38	107.10	96.41	86.17	75.67	64.92	54.25	43.90	36.06	29.16	77.80	76.69	73.18	57.93	52.34
	V%	20.0	22.3	23.2	24.3	25.0	24.5	25.6	26.2	27.3	29.8	22.9	23.9	24.7	21.7	21.7
$\Sigma 25$	Mean	624.04	547.45	477.85	413.24	355.23	304.77	242.18	200.74	161.37	122.77	394.26	374.60	347.73	320.58	294.44
	SD	120.62	108.67	97.14	85.93	74.66	65.83	57.17	47.01	38.28	30.99	83.54	82.54	75.77	67.01	64.39
	V%	19.3	19.9	20.3	20.8	21.0	21.6	23.6	23.4	23.7	25.2	21.2	22.0	21.8	20.9	21.9

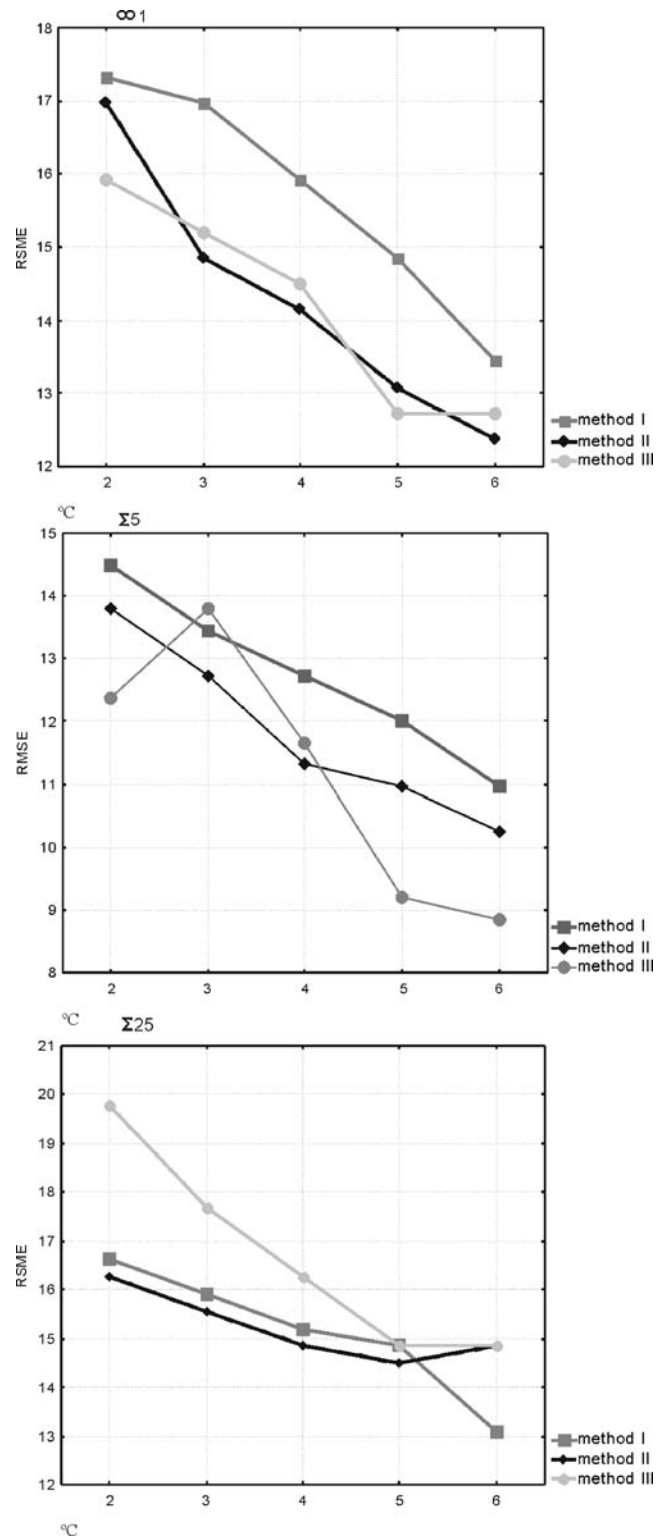
**Fig. 1** RMSE values calculated for several threshold temperatures with different GDD methods for three methods defining the start of the *Quercus* pollen seasons ($\infty 1$, $\Sigma 5$, $\Sigma 25$). method I - $\Sigma T_{\max} - T_b$; method II - $\Sigma \frac{T_{\max} + T_{\min}}{2} - T_b$; method III - $\Sigma T_{\text{mean}}; T_{\text{mean}} > T_b$

Table 3 Actual and predicted dates of the start of the atmospheric seasons for 2005 for methods with the lowest values of RMSE and the highest correlation coefficients between obtained and expected values

SPS methods	Models	Actual SPS day 1 Jan = 1)	Predicted SPS day	Range of days: predicted–actual
$\infty 1$	ΣT_{mean} ; when $T_{mean} > 5$	121	121	0
	ΣT_{mean} ; when $T_{mean} > 6$		118	-3
	$\sum \frac{T_{max} + T_{min}}{2} - 5$		118	-3
	$\sum \frac{T_{max} + T_{min}}{2} - 6$		118	-3
	$y = -4.123 \times T_{min \text{ March}} + 112.98$		130	9
$\Sigma 5$	ΣT_{mean} ; when $T_{mean} > 5$	107	116	9
	ΣT_{mean} ; when $T_{mean} > 6$		115	8
	$\sum \frac{T_{max} + T_{min}}{2} - 6$		114	7
	$y = 0.6183 \times \text{Bet } \Sigma 25 + 50.821$		115	8
	$y = 0.0561(\text{Bet } \Sigma 25)^2 - 10.989 \times \text{Bet } \Sigma 25 + 645.49$		109	2
$\Sigma 25$	ΣT_{max-6}	118	124	6
	ΣT_{mean} ; when $T_{mean} > 5$		121	3
	ΣT_{mean} ; when $T_{mean} > 6$		120	2

Predicted year (2007) was not included in the models

Correlation analysis between meteorological data and the SPS of oak did not give the expected results. Most of the Pearson coefficients were not statistically significant. Only the $\infty 1$ SPS significantly correlated with minimum temperature of March (Table 6).

There was a high degree of variability in the SPS of the early spring flowering trees, *Alnus*, *Corylus*, *Populus*, and *Fraxinus*. Correlations between the SPS of these taxa and the SPS oak were not significant and, as a result, *Alnus*, *Corylus*, *Populus*, and *Fraxinus* were removed from the group of potential indicators. The $\Sigma 25$ SPS of *Betula* correlated significantly with the $\Sigma 5$ SPS of *Quercus*. The linear regression explained 60% of the variability. The nonlinear function explained this variabil-

ity better, e.g., 84.7%. All coefficients of functions were statistically significant.

Based on 8 years of results, for the two test years the most efficient method of predicting the $\Sigma 5$ SPS of oak has proved to be use of *Betula* as the indicator species using a nonlinear function. The RMSE value were the lowest, and the highest correlation coefficient was found, between the expected and obtained values for nonlinear formula ($r = 0.92$; $\alpha \leq 0.05$). For linear regression, $r = 0.76$ ($\alpha \leq 0.05$). The effectiveness of forecasting the $\Sigma 5$ SPS of *Quercus* in 2005 and 2007 was very high, within only 2 days of error (Tables 3 and 4). For both test years, good efficiency of forecasting the $\infty 1$ and $\Sigma 5$ SPS of *Quercus* was obtained using the III GDD°C method at the threshold temperatures 5–6°C (Tables 3 and 4).

Table 4 Actual and predicted dates of the start of the atmospheric seasons for 2007 for methods with the lowest values of RMSE and the highest correlation coefficients between obtained and expected values

SPS methods	Models	Actual SPS day	Predicted SPS day	Range days: predicted–actual
$\infty 1$	ΣT_{mean} ; when $T_{mean} > 5$	104	100	-4
	ΣT_{mean} ; when $T_{mean} > 6$		104	0
	$\sum \frac{T_{max} + T_{min}}{2} - 5$		115	11
	$\sum \frac{T_{max} + T_{min}}{2} - 6$		118	14
	$y = -4.123 \times T_{min \text{ March}} + 112.98$		109	5
$\Sigma 5$	ΣT_{mean} ; when $T_{mean} > 5$	105	96	-9
	ΣT_{mean} ; when $T_{mean} > 6$		101	-4
	$\sum \frac{T_{max} + T_{min}}{2} - 6$		105	0
	$y = 0.6183 \times \text{Bet } \Sigma 25 + 50.821$		113	8
	$y = 0.0561(\text{Bet } \Sigma 25)^2 - 10.989 \times \text{Bet } \Sigma 25 + 645.49$		108	3
$\Sigma 25$	ΣT_{max-6}	108	102	-6
	ΣT_{mean} ; when $T_{mean} > 5$		103	-5
	ΣT_{mean} ; when $T_{mean} > 6$		106	-2

Predicted year (2007) was not included in the models

Table 5 Means, standard deviations (SD), and variation coefficients (V%) of three bioclimatic indices for three methods defining the start of the *Quercus* atmospheric pollen season for the years 1997–2004

Indices	Methods	$\infty 1$	$\Sigma 5$	$\Sigma 25$
PR				
Mean		8.5	9.4	7.7
SD		6.11	8.1	5.4
V%		72.0	86.3	69.3
AI				
Mean		13.2	12.4	13.3
SD		3.9	3.6	3.9
V%		29.8	29.4	29.5
ETE_{TP}				
Mean		140.2	131.1	142.9
SD		35.1	27.4	34.5
V%		25.0	20.9	24.2

PR Puviothermic ratio, AI aridity index, ETE_{TP} evapotranspiration based on mean temperature and precipitation

Discussion

Analysis of annual variations in temperature and phenological phases of *Q. robur* suggests a connection between the quantities of accumulated heat and the time of initiation of physiological processes (Modrzyński et al. 2006). In recent years, numerous authors have witnessed a negative trend in the time of flowering and the SPS of oaks, suggesting that earlier flowering times are related to climatic warming (Corden and Millington 1999; Menzel and Estrella 2001; García-Mozo et al. 2002, 2006; Jato et al. 2006; Emberlin et al. 2007). In Rzeszów, the observation period was too short to identify any trend.

In the temperate climate zone, trees form resting buds in the late summer of the previous year and enter a dormant period. Buds require chilling (vernalization) and then, in spring, higher temperatures are needed to start flowering. The method of heat-sums assumes that the plant enters a

given phenological phase after accumulating a definite amount of heat. German oaks enter the generative development when the daily temperature sum above 5°C is very similar to the data presented here, about 250 GDD°C when SPS was defined by the $\Sigma 5$ method (Chalupka 2006). The drawbacks of the GDD°C method are the frequently disputable dates from which the temperatures should be summed, what temperatures should be summed, and what are the proper threshold temperatures (Rodríguez-Rajo et al. 2003; Sánchez-Mesa et al. 2005; González-Parrado et al. 2006; Schieber 2006; Fuertes-Rodríguez et al. 2007). In order to develop the most effective method, all possible combinations of variables should be tested. In many phenological and aerobiological works, this method was found highly effective in the forecasting of this type of phenomena (Sparks et al. 2000; Rodríguez-Rajo et al. 2003; Sánchez-Mesa et al. 2005; Schieber 2006). The results obtained from the analysis of heat accumulation were not as encouraging as the results from Spain (García-Mozo et al. 2002; Rodríguez-Rajo et al. 2003), which was probably caused by the different climate and the different *Quercus* species present in Poland. Despite the application of different combinations of methods and threshold temperatures, the RSME values were usually too high and the correlation coefficients between the expected and obtained values were too low. In some cases, however, they proved highly effective for the test years (2005, 2007) with an accuracy of a few days. These models belong to short-term forecasting methods, because temperature can be accurately forecasted a few days in advance.

Pollination and the occurrence of pollen in air are very complicated phenomena; therefore, it is thought that bioclimatic indices would be more effective in forecasting SPS compared with indices based on only one independent variable. On the basis of a 6-year study period, Valencia-Barrera et al. (2002) showed that in the period preceding pollination of different taxa it is not the temperature but the water that is a more important factor of forecasting. The presented results of the investigation

Table 6 The Pearson correlation coefficients between selected meteorological parameters and three *Quercus* SPS methods for 1997–2004

SPS methods	T _{mean}			T _{max}			T _{min}			Rainfall		
	Months											
	J	F	M	J	F	M	J	F	M	J	F	M
∞1	−0.529	−0.062	−0.587	−0.501	0.009	−0.421	−0.558	−0.126	−0.722	−0.348	−0.116	−0.265
Σ5	−0.566	−0.178	−0.441	−0.633	−0.117	−0.204	−0.676	−0.175	−0.631	−0.555	−0.187	−0.508
Σ25	−0.509	−0.003	−0.537	−0.568	0.079	−0.344	−0.610	−0.049	−0.694	−0.406	−0.113	−0.314

Statistically significant correlation coefficients at $\alpha \leq 0.05$ shown in bold

J January, F February, M March

are not so promising as in the conditions of the Mediterranean climate. As a result, it was decided to evaluate the effectiveness of methods based on meteorological factors.

In aerobiological investigations, forecast models for tree pollen were chiefly based on temperature and precipitation, air humidity, irradiance, and sunshine during the months preceding flowering and in the autumn and winter of the previous year (Fairley and George 1986; Rodríguez-Rajo et al. 2003; González-Parrado et al. 2006; Fuertes-Rodríguez et al. 2007; García-Mozo et al. 2007). In Rzeszów, the start of oak pollen seasons were significantly correlated with the minimum temperature of March and a forecast would be possible 2 weeks in advance. The effectiveness of forecasting was low with an error of 5–9 days. Now, it is impossible to represent the preliminary predictive models based on the other meteorological variables, which give us the satisfactory forecast. It can be conjectured that, in this case, the factor reducing the effectiveness of the method is the number of years, since the results stand in contradiction to papers by other authors (Corden and Millington 1999; García-Mozo et al. 2006).

In aerobiology, the beginning of the pollen season depends among others on the pattern of flowering, weather conditions, movements in the atmosphere, soil, and age of the plant. However, in this type of investigation, the method of indicator taxa can also be applied. It assumes that the investigated taxon responds to the environmental conditions like the indicator one, but this is not always the case (Bricchi et al. 1995; Norris-Hill 1998) and, hence, it is sometimes difficult to obtain precise forecasting models. Four of the taxa selected as potential indicators of the SPS of *Quercus* (*Alnus*, *Corylus*, *Populus*, and *Fraxinus*) are characterized by a pronounced variability due to the fact that they flower in early spring in the period of unstable weather conditions. Bricchi et al. (1995) proved that, in Central Italy, *Populus* and *Salix* were the best indicators for the beginning of oak pollination. It was found that *Betula* was the only taxa that could be used in forecasting. Generally SPS of *Betula* usually started 2 weeks earlier than SPS of *Quercus* and theoretically the forecast is possible about 14 days in advance. The same phenomena was noted in Lublin in 2004 and 2005 (eastern Poland; Weryszko-Chmielewska et al. 2006). But in 2000, SPS of *Betula* started only few days before SPS of *Quercus*. Apart from the good efficiency of these methods for 2005 and 2007, the possibility of using these models in allergology is now difficult to estimate. The results suggest that this method would be useful for predicting the SPS of other taxa; particularly, as Frenguelli and Bricchi (1998) showed, its effectiveness for taxa flowering in summer.

Conclusion

This study has shown that it is possible to predict the start of *Quercus* pollen seasons to within a period of several days. It should be noted, however, that the results of this study were greatly affected by the different methods used for determining SPS. For instance, the most effective forecast model used to predict the SPS defined using the $\Sigma 1$ and $\Sigma 25$ methods was based on heat accumulation with threshold temperatures of 56°C. For the $\Sigma 5$ method, the best results were obtained using indicator taxa. It is therefore important to consider different methods when undertaking studies of this kind. It is also worth stressing that, in Poland, oak flowers when daily mean temperatures become higher than 5°C, which usually occurs at the beginning of April. In a similar range, the threshold temperatures (5°C and 6°C) were found most effective in forecasting in spite of the greatest variability of temperature sums in the investigated years.

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