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INVITED ORIGINAL RESEARCH PAPER

The phenological phases of flowering and pollen seasons of spring flowering tree taxa against a background of meteorological conditions in Kraków, Poland

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Abstract

The aim of the study was to compare phenological observations of pollen seasons of selected early spring trees. Special attention was paid to meteorological conditions which favored or did not favor tree flowering and pollen release. For this reason, we used phenological observation, pollen counts, and meteorological data in five sites in the center of Kraków in the period 2009–2011. Phenological phases (5) of four tree species: *Alnus glutinosa*, *Alnus incana*, *Corylus avellana*, and *Betula pendula*, were analyzed. It was found that in case of *A. glutinosa* the pollen season often preceded the flowering period, while for *A. incana* those two phenomena were more correlated. As regards *Corylus avellana*, the beginning of the pollen season and phenological phases was simultaneous. However, pollen grains occurred in the air longer, even by a dozen or so days. The phenological phases and pollen seasons of *Alnus* and *Corylus* were dependent on meteorological conditions. To give the definition of the relationship between pollen concentration and weather conditions, Spearman rank correlation analysis was applied. High *Alnus* and *Corylus* pollen concentrations were found on sunny days with a maximum temperature over 10°C and no precipitation, and when the snow cover was gone. In case of *Betula*, the phenological phases of the full pollination period usually coincided with the periods of high pollen concentrations. However, *Betula* pollen sometimes appears earlier and stays in the air longer than the flowering period of local trees in the nearest vicinity. This situation indicates long-distance transport or secondary deposition.

Keywords

Alnus; *Corylus*; *Betula*; phenophases; pollen seasons; weather conditions

Introduction

The integration of phenological observations and aerobiological studies can deliver a proper interpretation of data obtained from pollen monitoring in different regions [1,2]. Knowledge of phenological phases of some plants is important to determine etiology of many allergic diseases provoked by plant allergens. Allergies, particularly pollen allergies, are increasing in the western world. Therefore, interdisciplinary research involving botanists, allergologists, and climatologists is of great value [3]. The relationship between plant flowering and pollen seasons is evident but not closely connected [4]. The pollen season of a given plant generally is longer than the flowering period because pollen catches can originate not only from flowering of local plants. They can also result from long-distance transport and redeposition [5]. Variation in meteorological parameters during a year immensely influences the beginning, end and duration of the particular phenological phases of plants. Their life cycle, including leaf development, flowering, fruit ripening, senescence and leaf fall, is useful for climatology, among others as "a natural indicator of periodic changes and regional differences in weather" [6]. The occurrence of pollen in the atmosphere results from interaction between factors affecting inflorescence formation, pollination, and pollen transport in the air. Knowledge of the dates and duration of phenological phases as well as of the distribution of potential sources of pollen is required to estimate properly the results of aeropalynological studies [7].

For phenological and aeropalynological studies conducted in Kraków, we selected four tree species: *Alnus glutinosa*, *A. incana*, *Corylus avellana*, and *Betula pendula*. *Alnus* (Mill.) and *Corylus* (L.) are common trees in Poland. They are members of the Fagales order and the Betulaceae family, which also includes *Betula*. In Europe, four species of *Alnus* occur: *A. glutinosa* (L.) Gaertn., *A. incana* (L.) Moench., *A. viridis* (Chaix) DC. in Lam. & DC., and *A. cordata* (Loisel.) Loisel. In Poland, both *A. glutinosa* and *A. incana* have a tree life form and the shrub form of *A. viridis* occurs in the Bieszczady Mountains. *Alnus glutinosa* occurs commonly throughout the country, while *A. incana* is less common and limited to southern Poland, along the Vistula River [8]. Both species occur on mineral and organic soils showing tolerance for considerable fluctuations of the water level. If they occur in the same habitat, *A. incana* flowers several days to 3 weeks earlier than *A. glutinosa* [9].

In Europe, three species of the *Corylus* genus occur: *Corylus avellana* L., *C. colurna* L., and *C. maxima* Mill. The *Corylus avellana* is the most widespread species and is present almost in the whole Europe. In Poland, *Corylus avellana* occurs in natural habitats; it is common in forests and also in the lower montane forest regions. It favors sunny sites and a wide variety of soils. *Corylus colurna* (Turkish hazel) is cultivated as an ornamental tree in Europe and it is also often seen in Poland [10].

The onset of *Alnus* and *Corylus* pollen seasons greatly depends on meteorological conditions before and during pollen release. *Alnus* and *Corylus* produce male inflorescences in late summer of the year before pollination and time of dormancy (chilling period) is required to start a new life process. The chilling period is over when the cumulative temperature reaches a species-specific threshold temperature (thermal energy) and hence temperature in January and February is of great importance for the start of flowering [11–13].

The *Betula* genus is spread worldwide in the Northern Hemisphere, often going beyond the moderate zone [14]. About 40 *Betula* species occur in the Northern Hemisphere, mainly in natural sites in mixed and pine forests [15], while in the Mediterranean area, especially in the northern parts of Italy and Spain, *Betula* trees are cultivated as ornamental trees [15,16]. In Poland, seven species of *Betula* occur. The most common are *Betula pendula* Roth (= *B. verrucosa* Ehrh) and *B. pubescens* Ehrh. *Betula pendula* is the most frequent species occurring in the whole country. In Kraków and its close surroundings, *B. pendula* dominates, whereas *B. pubescens* occurs occasionally in the Niepołomice Forest and towards the northwestern part of Kraków [17]. *Betula pendula* starts flowering 10–12 days before the onset of *B. pubescens* flowering [18].

Alnus, *Corylus*, and *Betula* pollen is thought to be the main source of allergens provoking allergy symptoms in humans during the spring season. The high degree of cross-reactivity between the major allergens of those species indicates the need for observation of their pollen concentrations, although *Corylus* pollen occurs in low concentrations [19,20].

The aim of our study was to define the course of phenological phases in *Alnus*, *Corylus*, and *Betula* and compare them to their pollen seasons against a background of meteorological conditions.

Material and methods

Study site

The study (2009–2011) was performed in Kraków (50°04′ N, 19°58′ E; 220 m a.s.l.) which is located in the Małopolska Province (Lesser Poland). The green areas within the city include numerous parks, lawns, gardens, and forests. The forests occupy 4.23% of the Kraków area (1383 ha), including the largest forest community of Las Wolski (422 ha) in the western part of Kraków. Among trees in the city, the following species dominate: *Fagus* (20.5%), *Quercus* (19.0%), *Betula* (14%), and *Alnus* (10.1%) [21]. Kraków is immediately surrounded by farmlands and forests. To the north of Kraków there are farmlands and small forest patches; in the south and east of Kraków there are roughly equal areas of farmlands and forests, while to the west of the city forest communities prevail [22].

Phenological observations

During phenological observations performed at five sites in the southern and the northwestern parts of Kraków (Fig. 1), seven successive stages of the annual life cycle, known as phenophases (F) of the generative development of plants, were singled out according to the Łukasiewicz method [23]. Because *Alnus*, *Corylus*, and *Betula* form inflorescence buds in late summer of the previous year, the first phenological observations started from phase F2:

- F2 – first flowers blooming
- F3 – the start of full flowering (25% of flowers open)
- F4 – the first flowers fall
- F5 – the end of the full flowering period (75% of flowers open)
- F6 – the last flower buds
- F7 – the end of the flowering period.

The full pollination period consists of phases from F3 to F5. The observations, performed at intervals of a few days, depended on the promotion of flowering. In the full pollination period (F3–F5), observations of three individual plants growing at the same sites were carried out every 2 or 3 days over 3 years of the study. The preliminary analysis of phenological data showed that at each studied site the differences between the beginnings of particular phases of individual plants were insignificant. In a few cases the dates of phase beginning differed by 2 days at most. Thus, in further analysis only one plant that was most representative for each site was examined.

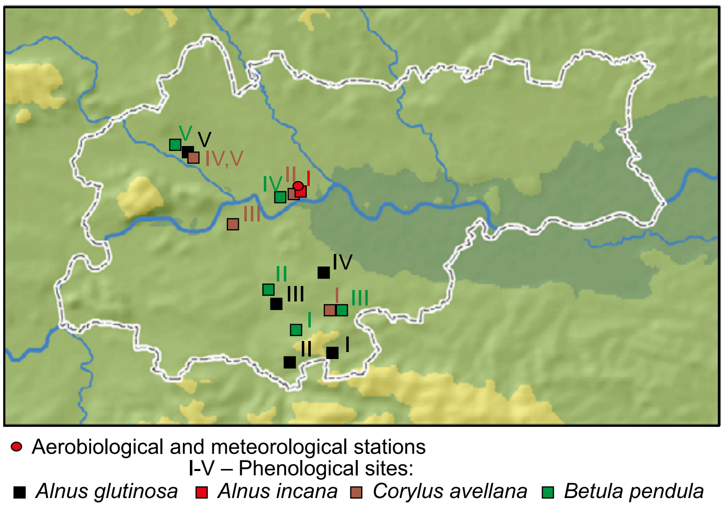

Fig. 1 The sites of aerobiological, meteorological, and phenological observations in Kraków, Poland. Aerobiological, meteorological stations, and *Alnus incana* site are located close to each other.

Aerobiological data and statistics

Pollen concentrations of *Alnus*, *Corylus*, and *Betula* were monitored using a volumetric trap of the Hirst design [24]. The trap was located on the roof (20 m above ground level) of the University building situated in the center of Kraków. The trap was installed at a height recommended by the EAS (European Aerobiology Society, Quality Control Working Group; 15–25 m above ground level) [25]. Airborne pollen grains were sampled every year from the 1st January until the end of flowering of the last of the investigated species during 2009–2011. Melinex tape used for catching pollen grains was replaced every Tuesday at 8 a.m. and cut into segments corresponding to 24-h periods. Daily average pollen counts were expressed as pollen grains per cubic meter of air (PG/m^3). The pollen season was calculated using the 95% method. The start of the season was defined as the date when 2.5% of the seasonal cumulative pollen count was trapped and the end of the season as the date when 97.5% of the seasonal cumulative pollen count was reached [26]. The total pollen count over this period is defined as seasonal pollen index (SPI). To characterize the weather during the flowering periods and pollen seasons of early spring trees, the Department of Climatology at Jagiellonian University provided us with basic meteorological elements influencing flowering and pollen seasons such as daily maximum air temperature, precipitation, height of snow cover, and sunshine hours as independent variables recorded at the weather station located in the immediate vicinity of the monitoring site. The Spearman rank correlation analysis was applied to find the relationship between pollen concentrations and meteorological data using the Statistica software (StatSoft Polska Sp. z o.o., Kraków, Poland), version 12. The significance level was set at $\alpha < 0.05$.

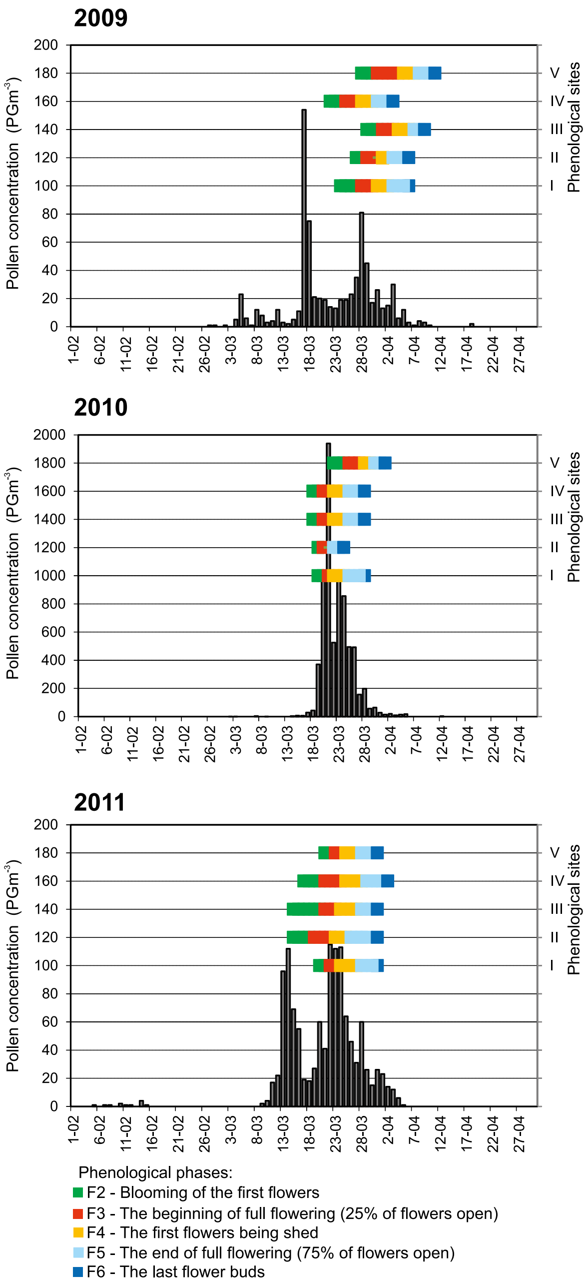

Fig. 2 Daily *Alnus* pollen concentrations against a background of *Alnus glutinosa* phenological phases (see different scales).

Meteorological data

Kraków is located at the point of junction of three types of climate: central uplands, lowlands at the foothills, and valleys. The city area is one of the warmest climatic regions of Poland [27]. The prevailing atmospheric circulation from the northern direction most often causes air masses advection of polar-maritime origin which mainly determines the weather in Kraków, bringing a warming, fog, and precipitation in winter, whereas in summer coolness, passing precipitation, and storms [28]. The specific location of Kraków along the valley of the Vistula River and the hills surrounding the city are the reason for variation in local air circulation and a considerable reduction of wind velocity. Thus, the calms are the often phenomena in the city. The mean annual air temperature is about 8.5°C, the warmest month is usually July (20.5–21.0°C), and the coolest one is January (−1.5°C). The mean annual precipitation is 650–700 mm. The highest precipitation occurs in July (about 100 mm) and the lowest one in November and December (<45 mm).

Results

Alnus

In Kraków, pollen grains of *Alnus* originate from two species: *A. incana* and *A. glutinosa*. *Alnus incana* grew only at one site and in 2011 it was not possible to determine its phenophases because the tree was damaged. Each phenophase of *Alnus* was limited, on the average, to 2–3 days, although usually the shortest phase was phase F6 (1 day) and the longest one was phase F3 (6 days; Fig. 2). However, in 2011 almost all phases were somewhat longer and their duration was 3–4 days or even 6 days. There were some differences between phenophases in two species of *Alnus*. Phenophases in *Alnus incana* were longer on average by 3–4 days or even by 6–7 days (F5, F6). Phase F2 of flowering also started earlier than in the case of *A. glutinosa* – in 2009 by 20 days and in 2010 by 2 days earlier than the earliest date of phase F2 in *A. glutinosa* among five sites. These differences in the start of flowering influenced pollen concentrations. The

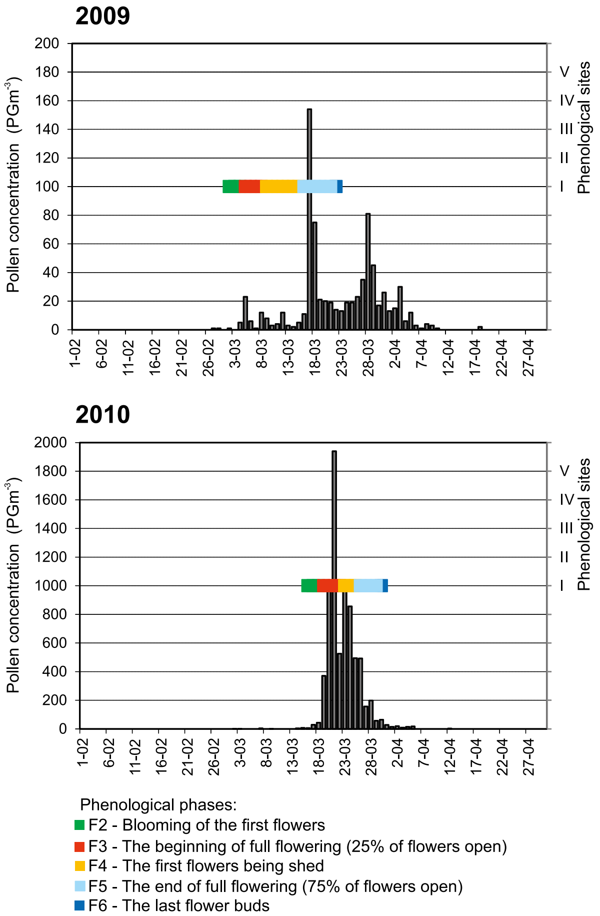

Fig. 3 Daily *Alnus* pollen concentrations against a background of *Alnus incana* phenological phases (see different scales).

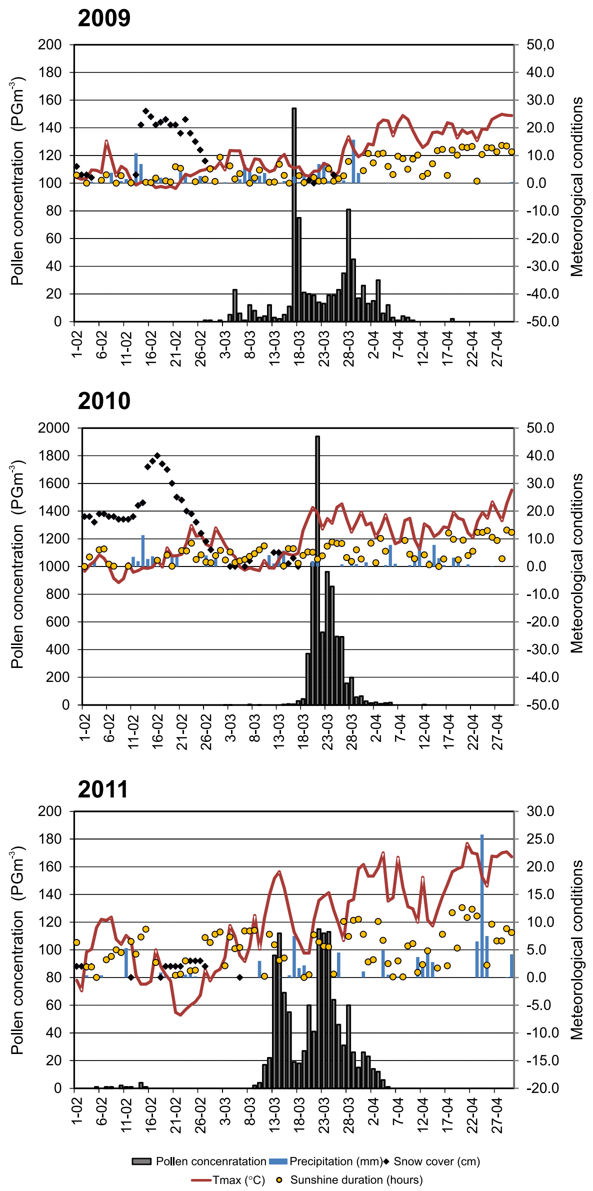

Fig. 4 *Alnus* pollen concentrations vs. meteorological conditions in Kraków (see different scales).

daily *Alnus* pollen concentrations against a background of phenological phases are presented in Fig. 2 and Fig. 3. The *Alnus* pollen season in 2009 was evidently divided into two parts. It started on the 5 of March when the meteorological conditions had improved, the snow cover had disappeared, and the maximum air temperature had reached over 10°C for 3 successive days (Fig. 4). This pollen season started 2 days after the beginning of flowering of *Alnus incana*. The maximum pollen concentration of *Alnus incana* was recorded when this species was in bloom (F4, F5), while *Alnus glutinosa* was just before flowering. Between 19 and 26 of March, the pollen concentration was low (about 20 PG/m^3), which resulted from deteriorated meteorological conditions. A clear decrease in air temperature (T_{max} < 5°C), cloudiness and precipitation (rain and snow) took place (Fig. 4). In the middle of this period, the first phase of *Alnus glutinosa* flowering started. The second concentration increase was recorded during the full flowering period of *Alnus glutinosa*. In 2010, the onset of the *Alnus* pollen season was latest, on the 19 of March, and the season was short, only 19 days, although it was characterized by high pollen concentrations (SPI 4909 PG/m^3) which were 4 times as high as those in 2009 and 2011. The end of February in 2010 was warm, the temperature was about 8–15°C, but the snow cover was still 12 cm high. The first two weeks of March were again chilly and overcast with precipitation (rain,

Tab. 1 Values of the Spearman rank correlation coefficient for the consecutive tree pollen seasons and the selected meteorological elements.

Trees	T_{max} (°C)	T_{mean} (°C)	Humidity at 12 UTC (%)	Mean humidity (%)	Precipitation (mm)	Sunshine duration (hours)
2009						
Alnus	0.090	0.224	−0.112	−0.240	−0.032	0.003
Corylus	−0.066	0.081	−0.070	−0.095	−0.022	−0.065
Betula	−0.151	−0.192	−0.020	−0.104	−0.156	−0.044
2010						
Alnus	0.870*	0.778*	−0.588*	−0.340	0.152	0.265
Corylus	0.860*	0.797*	−0.524*	−0.467*	0.073	−0.016
Betula	0.032	−0.102	−0.325*	−0.455*	−0.502	0.270
2011						
Alnus	0.650*	0.783*	−0.017	−0.158	0.331	−0.308
Corylus	0.734*	0.844*	−0.856*	−0.189	0.138	−0.315
Betula	0.014	−0.106	−0.096	−0.169	−0.073	−0.230

* $p < 0.05$.

snow); thus, both *Alnus* species started flowering and the pollen concentration almost simultaneously and rapidly increased after the 18 of March. This year, the weather favored flowering and high pollen concentration and therefore the pollen season was condensed. In 2011 the meteorological conditions, flowering phases, and the *Alnus* pollen season were similar to those in 2009. Probably, the onset of the pollen season was also associated with the full flowering period of *Alnus incana* and the second pollen concentration increase followed the full flowering period of *Alnus glutinosa*. It must be stressed that in 2011 first *Alnus* pollen grains in the air in Kraków appeared at the beginning of February when the *Alnus* species did not flower in the nearest vicinity. The Spearman rank correlation analysis revealed that daily *Alnus* pollen concentrations in 2010 were statistically significantly correlated with maximum air temperature ($r = 0.870$, $\alpha < 0.05$) and relative humidity ($r = -0.588$, $\alpha < 0.05$), while in 2011 only with maximum temperature ($r = 0.650$, $\alpha < 0.05$). In 2009 the correlations were not statistically significant (Tab. 1).

Corylus

The *Corylus* pollen season in Kraków is the most unstable from year to year in comparison with pollen seasons of other taxa. The first pollen grains can appear already at the beginning of January. In the years of interest, however, the pollen seasons did not vary very much regarding the start dates. In 2009 the pollen season started most early on the 5 of March, whereas in 2010 it started latest, on the 18 of March (Fig. 5). It was influenced by meteorological conditions. Similarly as in case of *Alnus*, the onset of the early spring tree vegetation cycle in 2009–2011 was not possible before March. However, it would be a good thing to note that over a few days at the beginning of February in 2009 and 2011 the thermal conditions (T_{max} > 10°C) were sufficient for *Alnus* and *Corylus* to start flowering; nevertheless, it was a short period after which the winter and snow cover came back (Fig. 6). The relationship between daily pollen concentrations and meteorological conditions proved to be statistically insignificant (Tab. 1). However, there is a close relationship between pollen concentrations and phenological phases. In all study years, the beginning of the pollen season was found

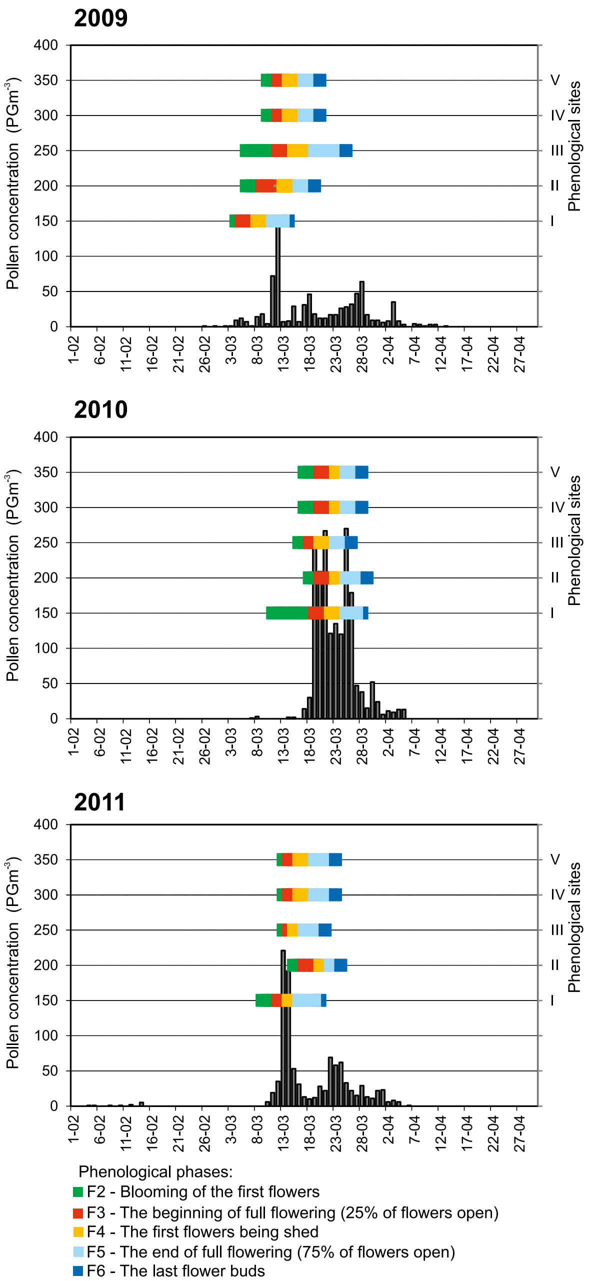

Fig. 5 Daily *Corylus* pollen concentrations against a background of *Corylus avellana* phenological phases.

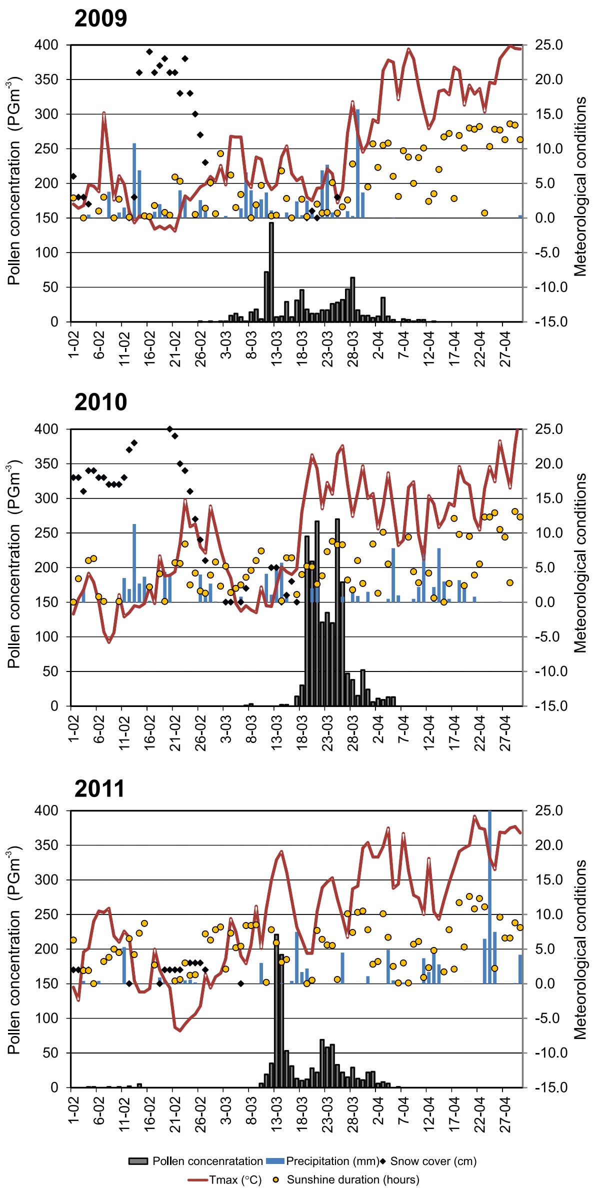

Fig. 6 *Corylus* pollen concentrations vs. meteorological conditions in Kraków.

when flowering started (F2) at least at one site, while the maximum pollen concentration occurred during the time of full flowering (F3–F5). It must be stressed that *Corylus* pollen grains are found in the air in Kraków longer than the flowering period lasts. The end of the *Corylus* pollen season comes 7–11 days later than the last day of phase F6 at the site where this phase occurred latest.

Betula

The onset of the *Betula* pollen seasons in 2009–2011 was very constant and occurred between 7 and 9 of April. However, other season characteristics varied more. The seasons in 2009 and 2011 were long enough, 30 and 35 days respectively, and SPI was 1718 and 2052 pollen grains, respectively. In 2010 the pollen season was short, 23 days and SPI was about 11 000 grains (Fig. 7).

Comparing the course of the particular *Betula* pollen seasons to the flowering phases in 2009–2011, it can be stated that: (***i***) *Betula* pollen grains appear, on the average, 5 days earlier than phenophase F2 at the site where this phase occurs earliest;

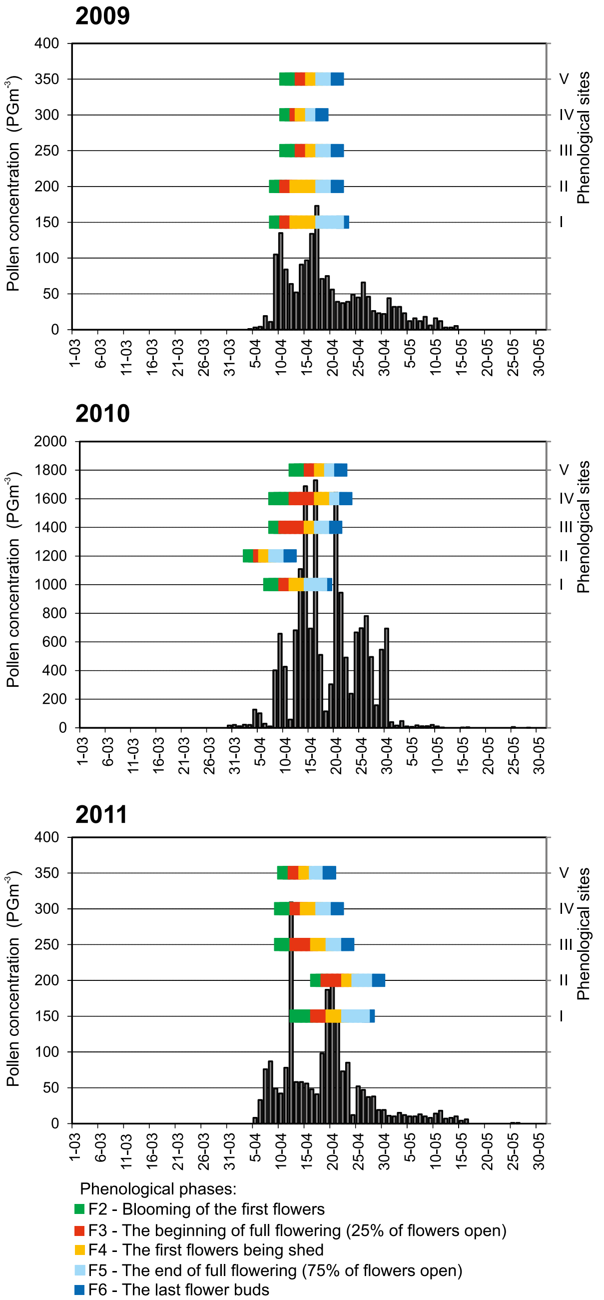

Fig. 7 Daily *Betula* pollen concentrations against a background of *Betula pendula* phenological phases (see different scales).

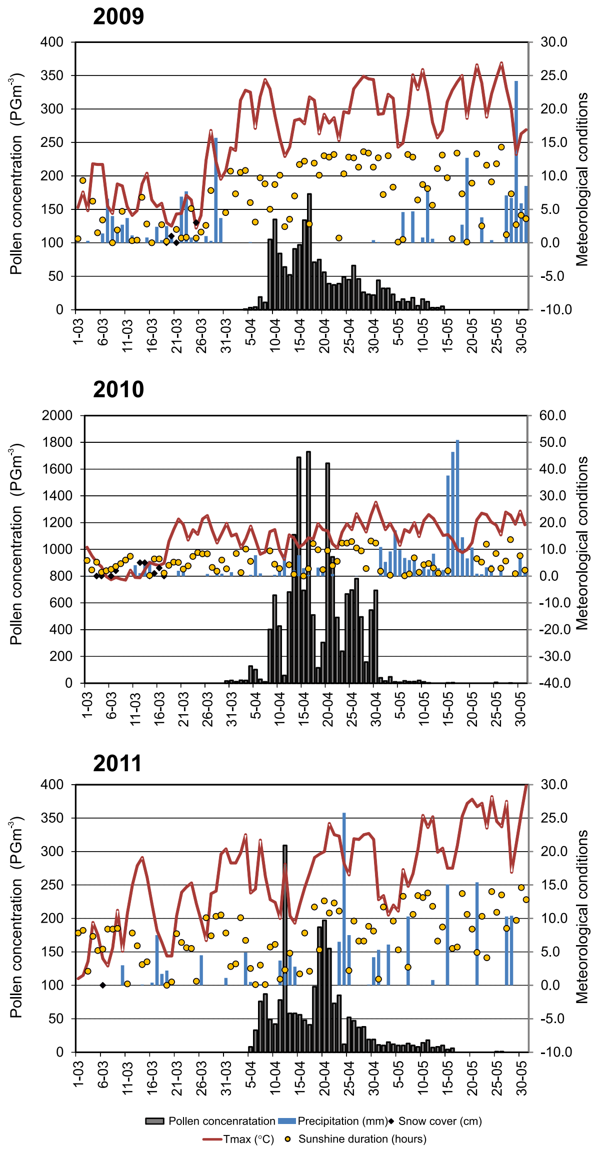

Fig. 8 *Betula* pollen concentrations vs. meteorological conditions in Kraków (see different scales).

(***ii***) high daily pollen concentrations (over 150 PG/m^3) occurred even in phases F2 and F6, although most often they were associated with the full flowering period (F3–F5) at the majority of the sites; (***iii***) the end of the flowering period of *Betula pendula* did not mean the end of the pollen season, as high pollen concentrations were still observed over 16 days after the end of flowering; (***iv***) however, it is impossible to explain such high daily and annual pollen concentrations in 2010 only through phenological observation. Such a long *Betula* pollen season before and after flowering of trees in the nearest vicinity of the sites evidences the presence of pollen originating from long-distance transport or redeposition.

The weather conditions before and during the *Betula* pollen seasons varied significantly in 2009–2011 and therefore the correlation did not show a statistically significant relationship (Tab. 1) However, first *Betula* pollen grains appear when the maximum air temperature reaches over 20°C. Pollen concentrations increase when the daily sunshine duration is over 5 hours and decline when precipitation arrives (Fig. 8).

Discussion

The pollen season generally follows flowering, although often it is also influenced by other factors including weather conditions, atmospheric situation, soil status, and plant age [29]. Pollen concentrations are considered to be a biological indicator for studying phenology in anemophilous plants [30]. Many authors in different regions observe that the start of *Alnus* and *Corylus* pollen seasons in consecutive years can vary from 2 to 6 weeks [31–34]. Szczepanek [35] observed that pollen seasons of *Alnus*, *Corylus*, and *Betula* can start even with a 2-month delay. This situation can be interpreted as the influence of meteorological factors, especially air temperature, during the period before the pollen season (January–February) which strongly affects phenology of spring flowering species [36–39]. When weather conditions, in particular temperature, are favorable, the dormancy period is over and plant growth and flowering begin [37]. In early spring, when *Alnus* and *Corylus* bloom, the weather is usually very unstable and temperature varies during the season and among years. This is associated with flowering dates of *Alnus* and *Corylus* being more inconstant than those of *Betula*. Białobok [40] reported that *Alnus incana* flowers about two weeks earlier than *A. glutinosa*. In our research, such a situation is clearly found in 2009 when the pollen season shows two peak concentrations. We suppose that a similar situation occurred in 2011 when the pollen season also showed two peaks, but we could not determine phenophases of the *Alnus incana* tree because of its damage. In this year, at the beginning of February first *Alnus* pollen grains appeared in spite of the fact that *Alnus* species did not flower in the immediate neighborhood. It is possible that pollen grains were transported from distant sources [41–43]. In 2010, in the last 2 weeks of March, the favorable weather caused both *Alnus* species to start flowering and the pollen season simultaneously. Similarly to phenophases, the dates of pollen seasons also vary, the most for *Alnus* and *Corylus*. Variation in *Corylus* flowering dates is also confirmed by Rizzi Longo and Pizzulin Sauli [44].

In Poland, Sokołowska [11] reported that in the 1950s the flowering isophens (lines connecting points of the same flowering dates) of *Corylus* followed the pattern of the March isotherms. Presently, *Corylus* flowers earlier and therefore the temperature in January–February matters greatly for the beginning of flowering [13]. Our 3-year study resulted in a conclusion that the *Corylus* flowering period is shorter than the period when pollen grains remain in the air. It could have resulted from pollen of other species of this genus or long-distance transport from areas where *Corylus* flowering took place later than in Kraków. Similar results for other taxa were observed by Lattore [45,46] and Lorenzoni et al. [47].

The beginnings of *Betula* pollen seasons in the years under investigation were much more constant than those of *Alnus* and *Corylus*, but the weather was also more stable in April than at the beginning of the year. The temperature reaching about 20°C caused the first pollen grains to appear. The occurrence of *Betula* pollen grains outside the flowering period (before and after this period) evidences the effect of secondary fall or long transport. Our results are in contrast with the findings by Kasprzyk [4] who found the *Betula* pollen season to be shorter than its flowering period, which may result from the method of pollen season estimation. A research study conducted in Germany revealed that the start of the *Betula* pollen season occurred on average 5.7 days earlier than local *Betula* flowering, which agrees with our analysis (5 days earlier) [48].

Conclusions

The *Alnus glutinosa* pollen season often preceded the flowering period, whereas in the case of *A. incana* those two phenomena were more correlated. Daily pollen concentrations were significantly correlated with maximum air temperature and relative humidity in 2010, with maximum temperature in 2011, whereas the correlation in 2009 was not statistically significant.

As regards *Corylus avellana*, the onset of the pollen season and phenological phases were simultaneous, although pollen grains remain for clearly longer time in the air.

High *Alnus* and *Corylus* pollen concentrations occurred on sunny days with the maximum temperature over 10°C, no precipitation, and no snow cover.

In *Betula*, the phenophases of the full pollination period usually coincided with the periods of high pollen concentration, but pollen grains sometimes appeared before and after the pollen season.

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Fenologiczne fazy kwitnienia i sezony pyłkowe wybranych taksonów drzew w Krakowie w latach 2009–2011 na tle warunków meteorologicznych

Streszczenie

Celem badań było porównanie faz fenologicznych ze stężeniem pyłku wybranych drzew wczesnowiosennych. Szczególną uwagę zwrócono na panujące wówczas warunki meteorologiczne sprzyjające lub nie kwitnieniu i uwalnianiu pyłku. W tym celu wykorzystano obserwacje fenologiczne, stężenie pyłku i dane meteorologiczne w 5 stanowiskach w centrum Krakowa w latach 2009–2011. Analizie poddano 5 faz fenologicznych 4 gatunków drzew: *Alnus glutinosa*, *Alnus incana*, *Corylus avellana* i *Betula pendula*. Stwierdzono, że w przypadku *Alnus glutinosa* sezon pyłkowy często poprzedzał fazę kwitnienia podczas gdy u *Alnus incana* te dwa okresy były bardziej skorelowane. W przypadku *Corylus avellana* początek sezonu pyłkowego i fazy kwitnienia były równoczesne. Niemniej jednak ziarna pyłku występowały dłużej nawet o kilkanaście dni. Zarówno fenologiczne fazy kwitnienia jak i sezony pyłkowe były uzależnione od warunków meteorologicznych. Zastosowano analizę Spearmana do stwierdzenia czy istnieje związek między stężeniem pyłku i warunkami meteorologicznymi. Wysokie stężenie pyłku *Alnus* i *Corylus* występowało w dniach słonecznych z maksymalną temperaturą powyżej 10°C bez opadów i po zaniku pokrywy śnieżnej. W przypadku *Betula* fenologiczne fazy kwitnienia pokrywały się zazwyczaj z wysokim stężeniem pyłku. Jednak pyłek *Betula* pojawia się czasami wcześniej i pozostaje dłużej w powietrzu niż okres kwitnienia lokalnych drzew w najbliższej okolicy, co wskazuje na daleki transport lub redepozycję.