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Possible implications of the variability of the most allergenic plant pollen seasons in Poland

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It is stated, that air temperature is the leading element of the climate, including its changes, of which a well-known indicator of these changes is the seasonal dynamics of plant pollen occurrence, on the local and regional scales. The aim of this study was to assess the variability of pollen seasons in Poland in terms of temporal and spatial aspects and potential trends in seasonal dynamics related to air temperature. The pollen seasons of five allergenic plants (alder, hazel, birch, grass, and mugwort) at eight sites in Poland from to 2001–2020 were analysed. The seasonal parameters were assessed against the thermal conditions, that is, the mean monthly values of air temperature (in °C). To determine the trends in air temperature changes, measurements over a longer period (1961–2020) and a linear regression equation were used. The beginning of the pollen seasons in Poland is highly variable for early pollinating trees is closely related to the ongoing rise in air temperature during winter months, mainly in December. Birch pollen appeared earlier in Poland because of the increasing trend in the average monthly air temperature in April. Warm and humid summers contribute to a higher SPIn value for grass pollen, whereas warm and dry summers do not affect the season intensity. The mugwort pollen seasons are getting shorter due to lower temperatures in June and July. The present study showed a clear increase in the mean annual air temperature in all studied cities, which affected the pollen season of allergenic plants.

Keywords Allergenic pollen, Seasons, Temperature, Trends in pollen seasons

It has been stated that global climate change will have a direct or indirect impact on the life of all organisms on Earth, and the groups that will suffer the most from this process will be plants, especially trees, which have a very limited migration mechanism[1].

The vast majority of scientists have shown that air temperature is the leading element of the climate, including its changes, pointing to a rapid increase in temperature, unprecedented on such a scale, and in such a short time until now[2–9]. Air temperature has been growing rapidly in the last three decades (1991–2020), when the temperature of the Earth's surface was higher than that in the previous decade and at the same time higher than that in any of the decades since the end of the 19th century[8]. According to the Copernicus Programme[10], 2016 and 2020 were the warmest periods in the history of meteorological measurements in Europe. The year 2018 was

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also exceptional in Poland, because it was the warmest year in the multi-annual period (1966–2018) over a major area (65% of stations)[11]. Subsequent national climate assessments confirm that the last several years (2020–2024) have been also anomalously warm at the national scale, reinforcing the long-term warming signal[12]. Moreover, numerous studies have demonstrated a clear relationship between air temperature and pollen season parameters (start, duration, and intensity)[13]. Long-term analyses show differences in pollen phenology consistent with climate warming, while the process-based models for hazel (*Corylus*) and birch (*Betula*) reproduce temperature-driven variations in pollen seasons timing and intensity.

A well-known indicator of climate change is the seasonal dynamics of plant pollen occurrence[14–16], which is also a factor that determines the objective assessment of pollen exposure on the local[17–20] and regional scales[14,21–27]. The flowering process is genetically regulated, through influence on photoperiod, vernalization, and autonomic pathways[28] however, the start of flowering is also influenced by environmental conditions[23].

In Poland, a statistically significant increasing trend in air temperature was observed in all seasons, with the highest intensity in spring (approx. 0.3 °C/10 years[7]. The frequency of heat waves and their intensity are clearly increasing[29–31], while the frequency of frost waves is decreasing. Such changes affect plant behavior and, consequently, the frequency or severity of allergies[32].

Taking into account, that since the late 90ties a rapid increase in the frequency of allergic diseases, especially allergic rhinitis and asthma, was observed in Poland[33–35], the analyses of pollen seasons dynamics is more and more expected.

According to the Epidemiology of Allergic Diseases in Poland (ECAP) study (2006–2008), allergies affect as many as 40% of Poles, allergic rhinitis is diagnosed in 23% of adults in big cities, while more than 24% in children[36]. In 2018, a statement on climate change, natural disasters, allergies, and asthma was published[32], under auspices of the Polish Society of Allergology. The guidelines refers to that how to reduce the risk of adverse health events provoked by climate and weather factors, and they contain the description of the factors related to climate changes affecting the course of allergic diseases. Among others, a Polish study on the prevalence of mugwort (*Artemisia*) pollinosis in Western Poland in relation to the impact of climate changes in 1995–2004 was cited[37].

There is a great need to present wide-scale analyses of pollen season changes against a background of thermal conditions in Poland, as the most important factor determining the pollen occurrence. The aim of this study was to estimate the variability of the pollen seasons in Poland features determined by the clinical method in the temporal and spatial aspects and the potential trends in seasonal dynamics related to thermal conditions, that is, the mean monthly values of air temperature (in °C). The obtained results could explain the seasonal variation in allergic symptoms in sensitive individuals, both when assessing symptoms after a given season and when planning treatment in subsequent years.

Materials and methods

The pollen seasons of five allergenic plants: alder (*Alnus* spp.), hazel (*Corylus* spp.), birch (*Betula* spp.), grasses (Poaceae), and mugwort (*Artemisia* spp.) at eight sites in Poland (Fig. 1; Table 1) from to 2001–2020 were analysed. Pollen data were obtained using volumetric spore traps in the Hirst design[38]. The samples were then placed on glass slides and covered with cover clips, and their contents were identified and counted under an optical microscope according to the procedures proposed by the European Aerobiology Society[39,40] and the European Standard EN 16,868[41].

The following season parameters were considered in the analyses: the dates of the season start (start), season end (end), the length of the season (duration), the pollen concentration in the season, the maximum daily pollen concentration (max value), the day of the maximum concentration (max day), and the number of days with a concentration above the cut-off value.

The clinical method, proposed by[42], was used to calculate the season parameters. It is recommended by the European Academy of Allergy and Clinical Immunology which is highly useful when the Main Pollen Season is in focus and a high, continuous exposure to a specific aeroallergen has to be assured[43–45]. Grass and birch pollen seasons were calculated according to the instruction given by Pfaar et al.[42], while for hazel and alder seasons the birch pollen season calculation was applied because all of them are shrubs or trees. In addition, for mugwort, 50 pollen m^{-3} was assessed as the threshold for high concentration, according to de Weger et al.[46].

The seasonal parameters were assessed against the thermal conditions – mean monthly values of air temperature (in °C), which represent the weather conditions in individual months and seasons of the year. Air temperature measurements were obtained from the meteorological stations of the Institute of Meteorology and Water Management – National Research Institute (IMWM-NRI) and Research Station of the Department of Climatology Jagiellonian University in Kraków from to 2001–2020. To determine the trends in air temperature changes, measurements over a longer period (1961–2020) and a linear regression equation were used. This period was selected to ensure a sufficiently long and homogeneous data series for reliable estimation of climatic trends (°C per decade). The 60-year interval corresponds to two climate norms defined by the World Meteorological Organization (WMO; 1961–1990 and 1991–2020) and provides a robust climatic background for illustrating multi-decadal temperature changes in the study region.

The statistical analyses were designed to test three main hypotheses: (1) pollen season characteristics differ significantly among the study sites; (2) the variability of pollen season parameters is significantly related to selected thermal conditions; and (3) long-term temporal trends (2001–2020) can be used to estimate the expected values of pollen season parameters in subsequent years (2021–2023).

Prior to the analyses, the Shapiro–Wilk test was applied to verify the normality of the distributions for each seasonal parameter. Since most datasets did not meet the assumption of normality, non-parametric methods were used in subsequent analyses.

Fig. 1. Study sites location.

Study site	Longitude (E)	Latitude (*N*)	Altitude a.s.l. (m)	Hirst sampler setting high (m)
Szczecin	14º 33'	53º 26'	52	21
Poznań	16º 53'	52º 24'	65–92	53
Wrocław	17º 01'	51º 06'	105–155	20
Łódź	19º 28'	51º 47'	150	15
Sosnowiec	19º 08'	50º 17'	263	20
Kraków	19º 59'	50º 04'	220	20
Rzeszów	22º 02'	50º 01'	200–215	12
Lublin	22º 32'	51º 14'	197	18

Table 1. Some information on study sites, including geographical location (coordinates, height above sea level and height above ground level) and the study period.

To test the first hypothesis, differences in pollen season parameters among the study sites were assessed using the Kruskal–Wallis test, performed separately for each taxon. When statistically significant differences were detected ($p < 0.05$), post-hoc pairwise comparisons were conducted to identify which sites differed significantly. The post-hoc analysis was performed using Dunn's multiple comparison test with p-values adjusted with Bonferroni correction.

To test the second hypothesis, the influence of selected thermal conditions on pollen season variability was examined using the Spearman rank correlation, which measures the strength and direction of monotonic relationships between variables. Additionally, the same analysis was applied to assess correlations between SPIn values at different sites, in order to evaluate the spatial consistency and possible alternation patterns in pollen productivity between years.

Temporal changes in pollen season parameters during 2001–2020 were analyzed using simple linear regression, corresponding to the third hypothesis. The statistical significance of each trend was evaluated using a t-test. Based on the significant regression models, predicted values and their 95% confidence intervals (CIs) were calculated for 2021–2023 to assess whether the recent observations were consistent with long-term trends. The accuracy of the models was evaluated according to the proportion of observed values falling within the 95% CI of the predicted values.

All statistical analyses were performed using STATISTICA 13.3[47]. The level of statistical significance was set at $\alpha = 0.05$ for all tests.

Results

Pollen seasons dynamics

In Poland, the pollen season begins with the appearance of hazel and/or alder pollen grains in air (Fig. 2). Airborne hazel pollen usually precedes alder pollen seasons slightly. Both taxa were characterized by very high variability in the start dates and duration of the pollen season (Fig. 3A; Table S1). Despite the high variability at the beginning of the season, the day of maximum value was much more stable in the examined years and occurred on average on March 12 for alder and March 17 for hazel (Fig. 3B).

Birches pollen seasons are definitely more stable during occurrence and the V% value for the start does not exceed 10% (Table S1). Birch pollen seasons started the earliest in Wrocław (April 3) and in most of the other locations around April 8. Seasons of herbaceous plants (grasses, mugwort) are relatively stable in time; the grass pollen season starts similarly in different regions (May 7, on average), and mugwort pollen seasons are almost constant over time (V% ± 3%) and start around July 16.

The results of the comparison of the seasonal characteristics among the study sites for the five taxa indicated that all season parameters for grasses and mugwort differed significantly from the other taxa. In the case of alder and hazel pollen seasons, only season duration, SPIn value and the maximum concentrations differed among the study sites, while in the case of birches, the difference related to the SPIn value only (Table 2).

The post-hoc tests related to the Kruskal-Wallis test showed the strongest differences between Kraków and Lublin in relation to the different taxa, especially for mugwort, and for the different parameters, first of all, for the maximum concentration (Table S2).

Trends in season characteristics

The birch pollen seasons were most similar in terms of the occurrence and intensity of pollen, and they also tended to start earlier (by an average of 12 days/10 years) (Table S3). The trend analysis of changes in pollen season parameters showed that the beginning of the alder, hazel, and birch seasons was earlier, although some of them were not statistically significant. The pollen seasons of early pollinated trees started earlier and earlier, but they also lasted slightly longer and became increasingly intensive. SPIn values of grasses decreased at the studied stations, mainly in Lublin, Szczecin, and Sosnowiec. Mugwort pollen seasons shorten by 5.5 days /10 years on

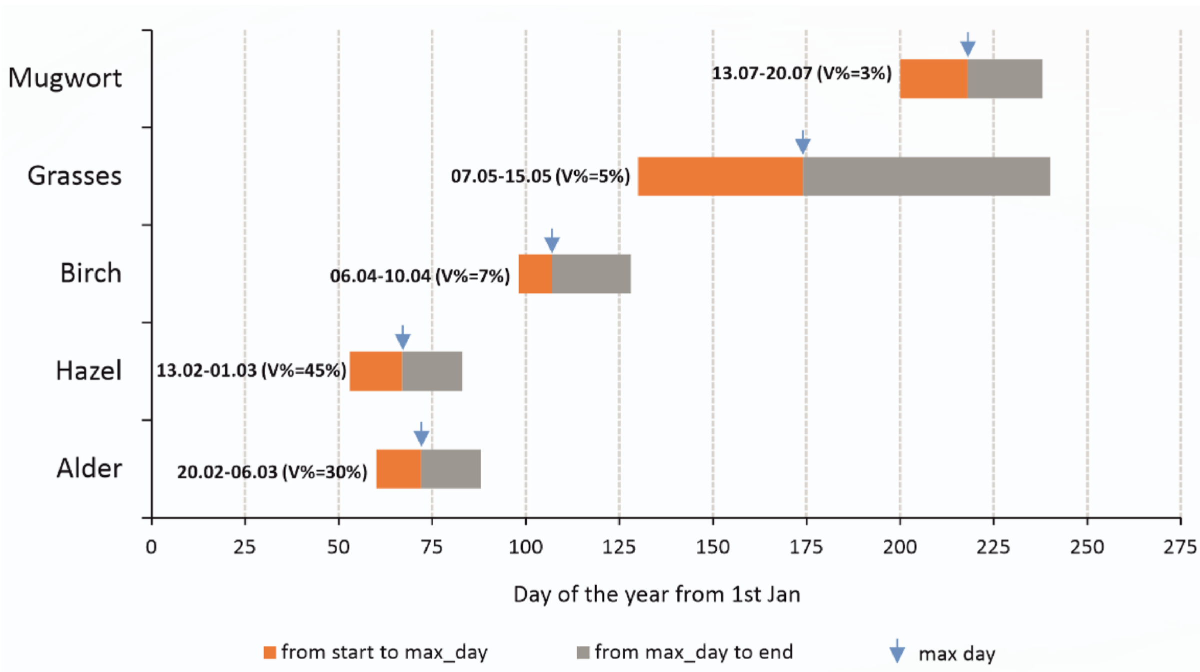

Fig. 2. Occurrence of the pollen seasons of the studied taxa in Poland. The range of average start dates of the calculated pollen seasons and the mean coefficient of variation (V%) for this feature are indicated.

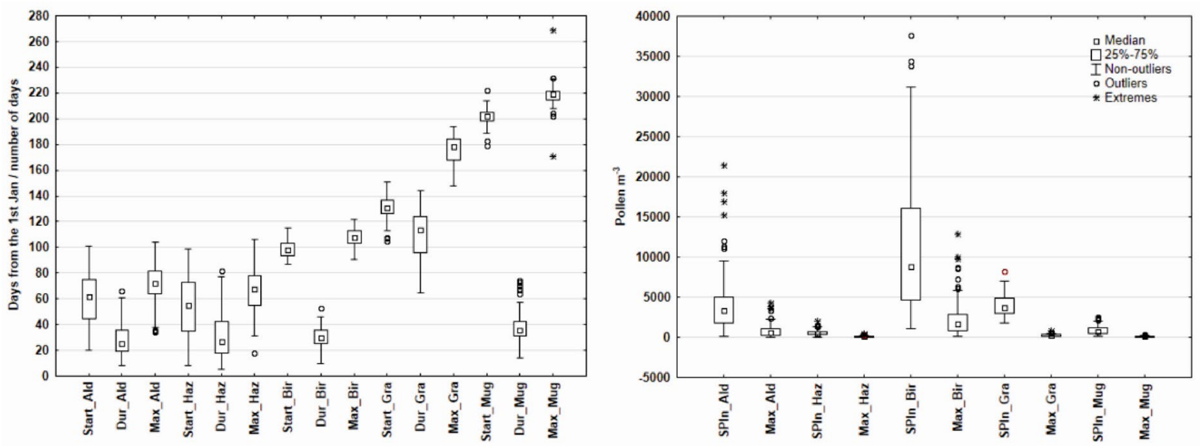

Fig. 3. Pollen season parameters of the selected taxa in Poland, including: (**A**) parameters connected to the season duration, and (**B**) connected to the pollen amount. Legend: median, interquartile range, a range of non-outliers; Start - season start, Dur - season duration, Max - maximum value, Max_d – day of maximum concentration, SPIn – Seasonal Pollen Integral.

Season parameter/ taxon	Alder	Hazel	Birch	Grasses	Mugwort
Start	0.139	0.2710	0.234	0.001*	< 0.001*
Duration	0.019*	0.0285*	0.466	< 0.001*	< 0.001*
Max_day	0.784	0.2489	0.553	0.005*	0.005*
Max_value	0.002*	< 0.001*	0.101	< 0.001*	< 0.001*
SPIn	0.003*	< 0.001*	0.045*	< 0.001*	< 0.001*

Table 2. Significance (p-value) of the differences among the study sites in relation to the season parameters (Kruskal-Wallis test). *Statistically significant with $p < 0.05$.

Data sources	Taxon	Hazel	Birch		Grasses		Mugwort		
	Year of the study/ Season parameter	SPIn (Pollen m^{-3})	Start (day)	Max day (day)	SPIn (Pollen m^{-3})	Max value (Pollen m^{-3})	Duration (days)	SPIn (Pollen m^{-3})	Max value (Pollen m^{-3})
Observed data	2021	690.10	**107.88**	**117.50**	3565.21	240.97	26.33	402.19	45.73
	2022	**1319.26**	99.13	**113.00**	2562.49	137.46	32.00	509.09	53.62
	2023	779.49	96.38	101.50	3882.03	189.82	34.88	431.45	43.95
Predicted data with 95% CI	2021	712.91 [494.04;931.78]	93.03 [81.54;104.51]	100.82 [86.83;112.46]	3466.59 [2424.31;4508.87]	194.86 [91.31;298.41]	31.66 [20.97;42.34]	528.99 [-12.60;1070.58]	55.29 [-13;123.59]
	2022	726.01 [504.19;947.84]	92.49 [80.84;104.13]	100.17 [85.99;111.97]	3415.82 [2359.45;4472.18]	189.99 [85.03;294.94]	31.08 [20.24;41.91]	496.00 [-52.92;1044.91]	52.09 [-17.13;121.30]
	2023	739.11 [514.10;964.12]	91.95 [80.14;103.76]	99.52 [85.14;111.49]	3365.04 [2293.52;4436.56]	185.11 [78.66;291.57]	10.99 [19.51;41.49]	463.00 [-93.78;1019.79]	48.88 [-21.33;119.09]

Table 3. Observed and predicted pollen season parameters for the selected taxa in 2021–2023 for all studied stations, for which the trend in 2001–2020 was statistically significant. In bold were presented the values being outside the 95% confidence interval.

average, in Sosnowiec and Kraków these changes were the most spectacular (-13.06 days and – 10.409 days/10 years), respectively.

The analyses of the threshold values adopted from the Standards of Polish Allergology[48], indicated an increasing trend in the number of days with alder pollen concentrations above 80 Pollen m^{-3} in Krakow and Lublin, and with grass pollen concentrations above 50 Pollen m^{-3} in Wrocław (Table S3).

The consistency of the observed seasonal parameter values with the linear trend indicated that, in most cases with statistically significant trends, the observations fell within the 95% confidence interval of the expected values (Table 3). However, the SPIn value for hazel was clearly higher in 2022 than expected, while in the case of birch, the season start was delayed in 2021, and the maximum value increased in 2021 and 2022.

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Szczecin	0.54	0.50	0.38	0.48	0.30	0.18	0.36	0.42	0.20	0.16	0.25	0.54	0.36
Poznań	0.52	0.46	0.40	0.49	0.35	0.26	0.45	0.53	0.25	0.18	0.26	0.55	0.39
Wrocław	0.58	0.50	0.42	0.46	0.41	0.40	0.58	0.64	0.30	0.26	0.32	0.56	0.45
Katowice	0.47	0.39	0.36	0.40	0.28	0.38	0.47	0.51	0.16	0.10	0.26	0.46	0.35
Kraków	0.52	0.44	0.37	0.35	0.28	0.41	0.50	0.54	0.19	0.14	0.18	0.43	0.37
Rzeszów	0.62	0.52	0.44	0.37	0.31	0.42	0.51	0.55	0.21	0.20	0.22	0.46	0.40
Łódź	0.50	0.47	0.39	0.39	0.29	0.28	0.45	0.47	0.17	0.12	0.28	0.54	0.37
Lublin	0.48	0.42	0.37	0.27	0.14	0.20	0.36	0.46	0.20	0.10	0.16	0.42	0.30

White records – non statistically significant (NS) with p> 0.05

NS 0.31 0.41 0.51 0.55 0.61

Table 4. Trends in mean monthly temperature (°C per 10 years) at selected study stations in 1961-2020 (the own study based on meteorological data from IMWM-PIB and Department of Climatology Jagiellonian University).

	Alder		Hazel	
Station / taxon	January	February	January	February
Szczecin	-0.900*	-0.366	-0.670*	-0.286
Poznań	-0.694*	-0.704*	-0.802*	-0.235
Wrocław	-0.669*	-0.658*	-0.771*	-0.475*
Sosnowiec	-0.623*	-0.683*	-0.517*	-0.640*
Kraków	-0.591*	-0.726*	-0.602*	-0.753*
Rzeszów	-0.441	-0.611*	-0.612*	-0.623*
Łódź	-0.477*	-0.733*	-0.566*	-0.617*
Lublin	-0.398	-0.808*	-0.568*	-0.559*

Table 5. Spearman rank correlation coefficients between alder and hazel season starts and the average temperature in January and February (in 2001-2020) at the selected stations. *Statistically significant with $p < 0.05$.

Influence of air temperature on the pollen season variability in a long data series

Trends in air temperature at selected stations in Poland were determined based on the average monthly values for 1961–2020. There was a clear increase in the mean annual air temperature in all cities, the highest in Wrocław (south-western Poland) and the lowest in Lublin (south-eastern Poland) (Table 4). This phenomenon was mostly influenced by the temperature in January, April, July, August, and December, when at all analyzed stations, the tendency of changes ranged from 0.27 to 0.64 °C per 10 years.

Analysis of the impact of air temperature at the beginning of the alder and hazel seasons showed a very strong relationship between the beginning of the season and the average temperature in January and/or February (Table 5).

During a 60-year period from 1961 to 2020, the highest increase in temperature in January and February was detected in Wrocław and Rzeszów (0.50–0.62 °C/10 years) (Table 5). Interestingly, in Rzeszów one of the most evident trends (along with Łódź) into the earlier starts of alder and hazel pollen seasons was observed (Table S3). The start of the birch pollen season was strongly related to air temperature in March and less frequently in April. The lower the temperature in a given month, the later the pollen season begins (Table 6), whereas the higher the average March temperature, the earlier the maximum daily concentration is achieved.

A two-year cycle of higher and lower SPIn values was found in the case of birch pollen seasons, at all stations, and in almost all studied years (Fig. 4). The intensity of the pollen seasons presented as SPIn values was clearly related to each other (Table 7). Interestingly, in four years, the cycle was disturbed at all studied sites, independent of the location (2002, 2004, 2017, and 2018).

The pollen seasons of grasses and mugwort occurred during the summer months (June-August) (Figs. 2 and 3). In the long-term course (1961–2020) a distinct increasing trend in the mean air temperature in these months was observed (Table 4). In the period 2001–2020, a statistically significant tendency was found to decrease the concentration of grains in the season (SPIn) and the maximum daily values (max value) of both taxa (Table 3).

For grasses, the months of April and May were selected for analysis, as they directly precede and determine the onset of the grass pollen season in Central Europe, when rising temperatures stimulate flowering and pollen

Season parameter	Szczecin	Poznań	Wrocław	Sosnowiec	Kraków	Rzeszów	Łódź	Lublin
Start	-0.699*	-0.678*	-0.789*	-0.522*	-0.615*	-0.696*	-0.657*	-0.667*
Duration	0.591*	0.430	0.472*	0.255	0.068	0.518*	0.473*	0.247
SPIn	0.186	0.239	0.193	-0.108	0.293	-0.080	0.169	0.268
Max day	-0.444*	-0.406	-0.585*	-0.420	-0.476*	-0.402	-0.443	-0.477*

Table 6. Spearman rank correlation coefficients between the selected Birch pollen season parameters and the average March temperature at the studied stations in 2001–2020. *Statistically significant with $p < 0.05$.

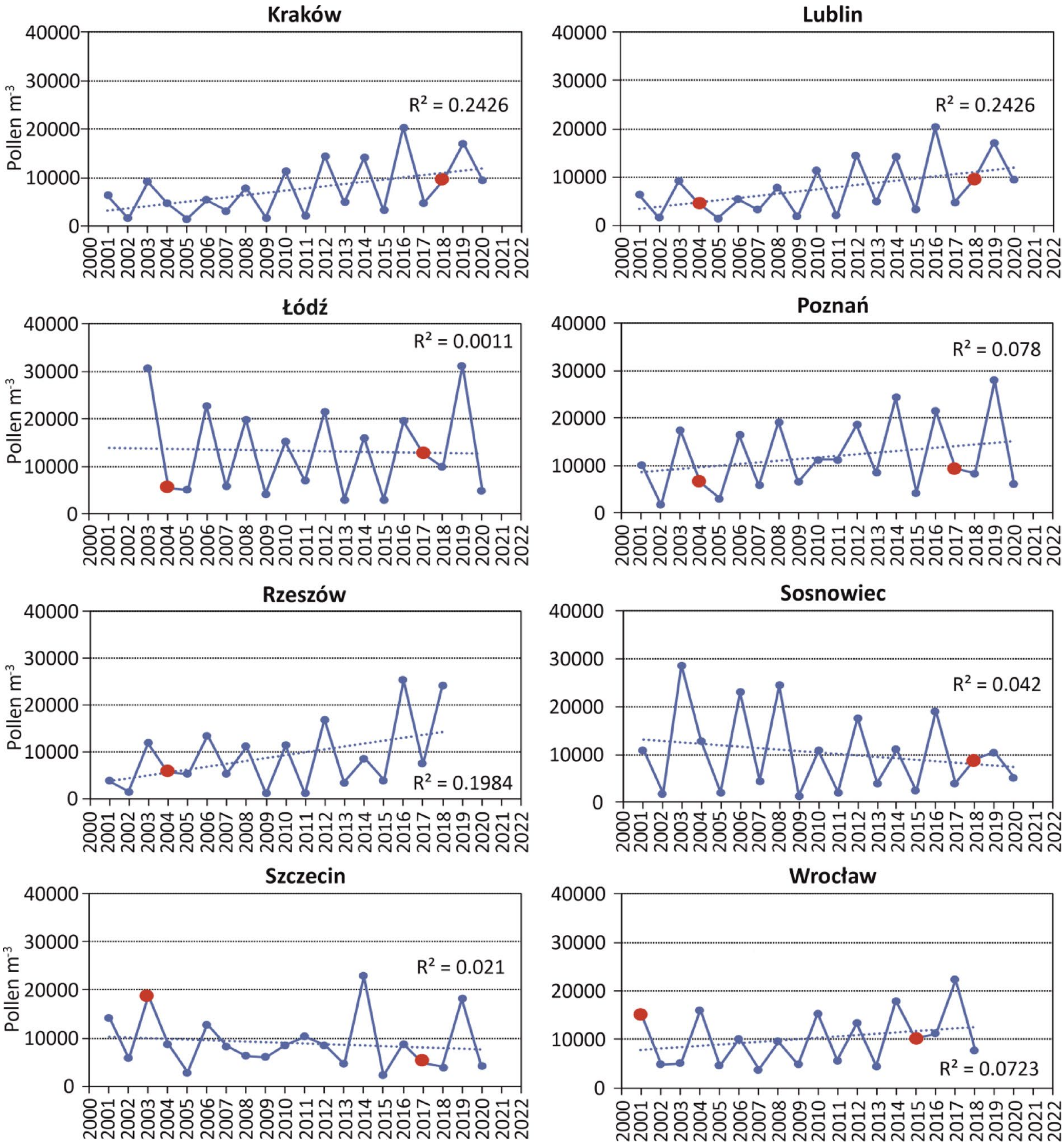

Fig. 4. Multi-year dynamics of birch pollen intensity (SPIn values) in eight selected cities in 2001 – 2020, highlighting the years that disturbed this rhythm.

	Lublin	Kraków	Łódź	Poznań	Rzeszów	Szczecin	Sosnowiec
Lublin		0.835*	0.842*	0.864*	0.643*	0.694*	0.800*
Kraków	0.835*		0.621*	0.785*	0.796*	0.400	0.557*
Łódź	0.842*	0.621*		0.802*	0.587*	0.602*	0.905*
Poznań	0.864*	0.795*	0.802*		0.520*	0.703*	0.728*
Rzeszów	0.643*	0.796*	0.587*	0.520*		0.091	0.580*
Szczecin	0.694*	0.400	0.602*	0.703*	0.091		0.507*
Sosnowiec	0.800*	0.557*	0.905*	0.728*	0.580*	0.507*	

Table 7. Spearman correlation coefficients of the Birch spin values among the studied sites, in 2001–2020. *Statistically significant with $p < 0.05$.

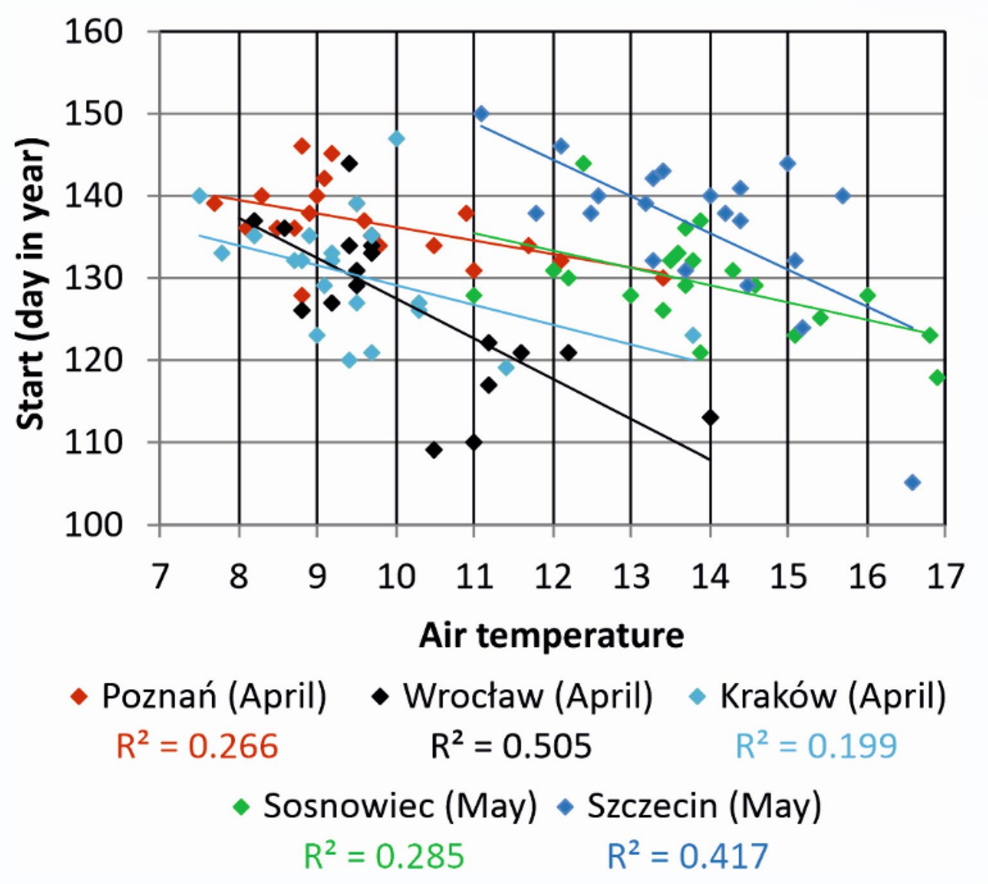

Fig. 5. Start of the grasses season and mean air temperature in April and May.

release. It was found the grass pollen seasons start at five studied stations were affected by temperature in May, that is, the higher the temperature in one of these months, the later it begins the season (Fig. 5).

A clear decrease in SPIn of mugwort pollen seasons at some stations in the southern and south-western parts of the country, with an increase in temperature in June (Fig. 6A), whereas the SPIn increases in northern, western, and central Poland (Fig. 6B) could be related to the increase in air temperature in July. It was found that an increase in temperature in July by 1 °C in Poznań and Wrocław causes a decrease in the SPIn value by -138.1 Pollen m^{-3}/1°C and – 230.2 Pollen m^{-3}/1°C, respectively ($p < 0.05$).

Discussion

Studies on the relationship between the pollen season and meteorological conditions should account for both similarities and differences in the potential impact of air temperature on the developmental phases of different plant taxa, including allergenic taxa[6,49,50]. The results of the present study indicate that variable thermal conditions in Poland affect the dynamics of pollen seasons of allergenic plants, which may result in fluctuating allergen exposure to sensitive individuals.

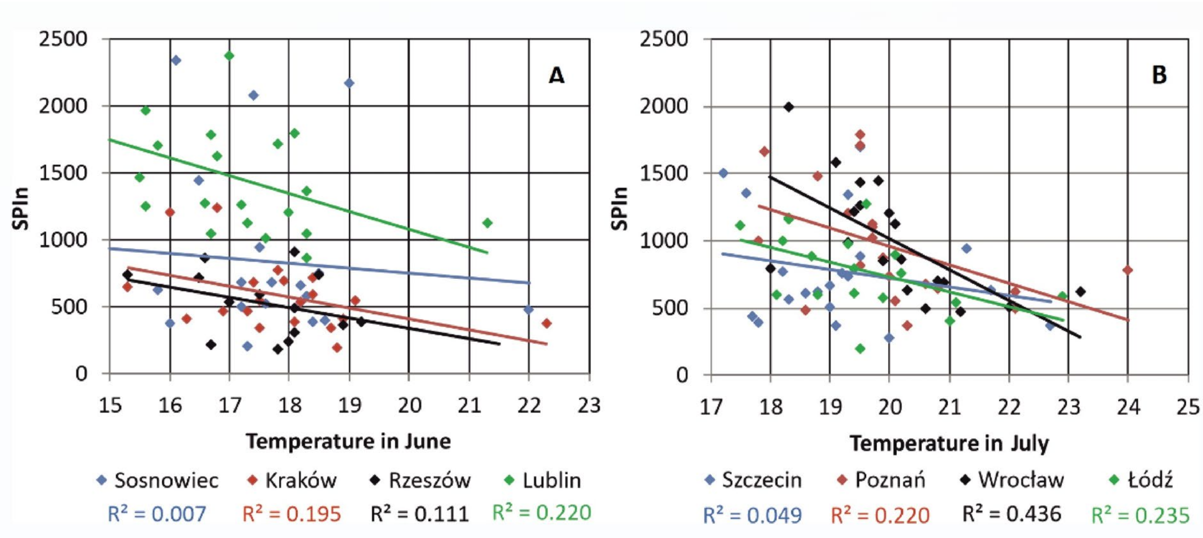

Fig. 6. SPIn of mugwort pollen detected in 2001–2020 and mean monthly temperature in June (**A**) and in July (**B**).

With the ongoing rise in air temperature during winter months, calculated by Kejna and Rudzki[51] for the entire area of Poland at 0.46 °C per decade, the range of temperature fluctuations in winter can still be quite large. In the studied period (2001–2020), the range of average temperature fluctuations in January was about 11 °C. Therefore, periods of low winter temperatures may still occur and are likely to be associated with a delayed onset of pollen seasons. However, it should be noted that other meteorological factors, such as precipitation or solar radiation, can also influence pollen phenology. In the 21st century, at the very beginning of the calendar year, the temperature across a large area of Poland was above 0 °C, with weather patterns more characteristic of late winter or early spring. Such conditions may promote early flowering of spring trees and the subsequent presence of pollen in the air[45,50]. Many reports underline that the impact of thermal conditions on pollen seasons depends on the regional microclimate features and a given plant[1,6,24,49,52].

A 30 year studies in Bavaria indicated that climate change in this part of Germany was characterized by an increase in mean temperature, but not during winter[53]. Wind-pollinated species (e.g., *Alnus*, *Betula* and Cupressaceae/Taxaceae) showed advances in the start and end dates of pollen seasons and an increase in pollen load, which correlated negatively with late winter (in February) and spring (in April) temperatures[53]. To date, winters in Switzerland are still cold enough, but a lack of chilling does not appear to play a role in the season onset date and spring plant phenology[54].

In our study, a significant increase in temperature was found at all stations in December, which may be one of the reasons why not only the start of the hazel and alder pollen seasons is advancing (although this trend is not statistically significant) but also the seasonal amount of this taxa pollen (SPIn) increasingly reaches higher values during the season. Previous studies performed in Kraków[18,55] also indicated that weather conditions prevailing from December to February and March significantly affected the onset of hazel flowering. Only a few very warm and sunny days in mid-January and February were sufficient for the first pollen grains to be released and appear in the air. Prolonged warm periods during winter, even without ground frost, are becoming increasingly common in the Polish climate, especially in recent years, starting in the western regions[4,55,56]. A 10 year (2003–2013) study in Wrocław confirmed a great impact of heat resources on alder, hazel, and birch pollination seasons, although no significant trend of annual total pollen count or shift in timing of the pollen season were found[57]. In our study, the observed data for 2021–2023 confirmed an increasing trend towards more intensive seasons, with twice as high an SPIn value in 2022. In an excellent review published by Mousavi et al.[58]. , the authors confirmed the rising trend in APIn for alder in European countries from 1974 to 2020. Hence, the intensification of exposure to alder pollen, also planted in the Mediterranean region, is becoming more and more important from medical point of view.

In the case of birches, a study performed at five stations in Poland showed that the season started less varied within years than at the end of the season, the annual total pollen count, and the peak value[52]. One of the first cross-sectional studies performed in European aerobiological stations showed a clear trend towards higher birch pollen concentrations, probably related to air altitude[59–61]. The similar trend was confirmed in UK by[49]. In Poland, a statistically significant trend towards a higher SPIn value was confirmed only in Kraków, but it did not influence the resulting trend in Poland.

The biannual birch cycle of the lower and higher birch pollen seasons is an interesting phenomenon, as reported in several other papers[25,52,59,62–64]. Latałowa et al.[63] reported for the first time the bi-annual trend in Gdańsk. This was also reported by[64] on the basis of data from the Roztocze National Park and using Tauber traps. Studies performed in Lublin (Eastern Poland) from 2001 to 2019 to[65] showed similar results to those presented in the current study. Taking into account a 2–3 year rhythm of high and low concentrations of birch pollen in the atmospheric air, linear trends were fitted for the subsets of high- and low-abundance seasons, indicating the same years as deviations in the biannual rhythm (2001, 2005, 2018).

Grass pollen seasons were relatively stable over time, following previous results referring to the period 1992–2014[66]. High temperatures in summer, combined with longer periods without rainfall, may cause herbaceous plants, especially grasses, to dry out, consequently reducing the production of pollen grains. Previous studies[55,66] indicated that grass pollen concentrations largely depend not only on air temperature but also on precipitation in April–August.

According to the report by[67], the surface area of permanent grasslands in Poland has markedly decreased during the last decade. Considering these facts and the increasing frequency of heat waves, that is, sequences of days with maximum air temperatures exceeding 30 °C and occurring in Poland more often (7,29,51], the trends towards less intense grass pollen seasons should not raise any doubts. The previous research indicates[66] indicated that the course of the grass pollen season may be influenced more by the sum of summer rainfall than by air temperature, but the relationship between grass pollen intensity and weather conditions is more complex than expected. It is worth noting that not only do the SPIn values decrease over time, but also the number of days with a concentration over the threshold value is lower in most of the studied cities. The results of the study on the effect of climate change in Northwest Europe suggest that annual severity of grass pollen in the Northern Europe is largely governed by pre-seasonal meteorological conditions[27]. If the climate change continues and intensifies, the season severity can increase by up to 60%.

Mugwort is the main pollen source in late summer and autumn in Europe[68] being relatively stable over time. Cross-sectional, on European scale analyses showed that *Artemisia* pollen season start is greatly dependent on temperature in June and July, with hot summer temperatures having a tendency to delay summer flowering. However, this relationship is not linear and the rate at which seasons become later increases when mean minimum June–July temperatures reach a threshold of about 13 ∘C[69]. Our current analyses indicate that the mugwort pollen seasons become shorter, less intense, and, most importantly, the number of days with pollen concentrations exceeding the threshold value is decreasing. We suppose that the lower pollen load could be related to the lower monthly temperatures in June and July, in the contrary to the season start.

However, some patients allergic to *Artemisia* pollen might also present clinical symptoms after exposure *Ambrosia* pollen during elevated episodes of long-distance transport or originating from local sources[70]. This problem could be closely related to the phenomena of cross-reactivity or co-sensitization[71]. The co-occurrence of both taxa pollen seasons depends on the inflow of air masses and appears more often in the southeastern part of Poland[72]. The problem of ragweed sensitization should be studied in the near future in Poland because it will become a common health problem across Europe, expanding into areas where it is currently uncommon[73]. Several authors reported also the occurrence of the second peaks in *Artemisia* pollen seasons related to the late flowering *Artemisia* species, in the geographical area south of the Carpathian Mountains[69]. Bastl et al.[74] showed a positive correlation between higher temperatures in autumn and the occurrence of mugwort pollen in Vienna, probably originating from *A. annua* and *A. verlotiorum*. This suggests that a significant change in the *Artemisia* pollen season can be expected during years with a mild, summer-like autumn. The spread of these species can affect human health, increasing the length and severity of allergenic pollen exposure to mugwort pollen in autumn, as reported by Cristofori et al.[75], on the basis of a 25 year aerobiological studies in the Northern Italy. In summary, two different scenarios of pollen occurrence in Poland are possible in the following years: short intensive seasons and longer seasons, but usually with a slightly lower concentration of pollen grains in the season. Nevertheless, high- and low-temperature extremes may have an impact on the vulnerability of plants to heat stress and are heterogeneously distributed over Europe. It is thought that the highest densities of significant event coincidence rates for extreme temperature events are displayed[5]. The presented results are consistent with the considerations of[76], who pointed out that global warming is expected to affect the start, duration, and intensity of the pollen season, but the effects of climate change on respiratory allergies are still not well defined.

Conclusions

The present study showed a clear increase in the mean annual air temperature in all studied cities from to 1960–2020, that affected the pollen seasons of the allergenic plants, as follows:

(1) The beginning of the pollen seasons in Poland is highly variable for early pollinating trees, including alders and hazels. This phenomenon is closely related to the ongoing increase in air temperature during the winter months, mainly in December. Prolonged warm periods during winter, even without frosts, are becoming increasingly common in the Polish climate, especially in recent years, starting in the western regions.
(2) Birch pollen appeared earlier in Poland because of the increasing trend in the average monthly air temperature in April. A two-year cycle of intense and less intense birch pollen seasons across the country was confirmed, with the “disturbed” years, independent of the location (2004, 2017, and 2018).
(3) Grasses begin to release pollen the earliest in Southern Poland, but the seasonal length does not change. Warm and humid summers contribute to a higher SPIn value for grass pollen, whereas warm and dry summers do not affect the season intensity.
(4) Mugwort pollen seasons are getting shorter due to lower temperature in June and July.
(5) The number of days exceeding the threshold value was higher in the case of alder only; for grasses and mugwort, the daily high pollen concentrations above the threshold were less frequently detected.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request. Meteorological data are available on https://imgw.pl/en/.

Received: 28 May 2025; Accepted: 9 January 2026
Published online: 13 February 2026

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Acknowledgements
The study was supported by the Minister of Science under the "Regional Excellence Initiative" Program for 2024-2027 (RID/SP/0045/2024/01).

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Funding
The study was supported by the Minister of Science under the "Regional Excellence Initiative" Program for 2024–2027 (RID/SP/0045/2024/01).

Declarations

Competing interests
The authors declare no competing interests.

Additional information
Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-026-36159-0.

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