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Changes in pollen season duration and their relationship with meteorological conditions in Lithuania

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ABSTRACT

Climate change is a key factor determining changes in plant phenology. The start and end dates of the pollen season, as well as its duration, are closely linked to shifting meteorological conditions. Rising air temperatures have a particularly strong impact, but changes in other meteorological factors, such as precipitation, are also important. This study analyses two genera within the Betulaceae family, alder (*Alnus*) and birch (*Betula)* pollen seasons from 2005 to 2023 in Lithuania, focusing on season dates, duration, pollen concentration, and their relationships with meteorological parameters. The dates and duration of the pollen season were evaluated using two definitions. The analysis is based on daily aerobiological observation data from Vilnius, Siauliai, and Klaipeda.

The alder pollen season typically begins in March and lasts, on average, from 24 to 36 days in different study sites. Over the past two decades, a significant trend toward an earlier start of the season has been observed, with the beginning date moving up by 13–34 days, depending on the location and calculation method. The duration of the season varied slightly, and the end dates did not show statistically significant differences. The increase in air temperature during February and March was the primary factor driving the season's earlier start.

The birch pollen season in Lithuania usually begins in mid-April and lasts about 30 days. Changes are statistically insignificant, despite minor shifts in the start and end dates. A weak but significant correlation exists between February–March temperatures and the beginning of the birch pollen season, while a weak negative correlation was observed between April–May temperatures and the season-end dates.

1. Introduction

As global climate change progresses, plant phenological periods are gradually shifting. Consequently, in some regions of the world, various trees and plants have begun flowering earlier, and the duration of the pollen season has increased (Adams-Groom et al., 2022; Glick et al., 2021; de Weger et al., 2021). This phenomenon is primarily linked to rising air temperatures (Ziska et al., 2019; Schramm et al., 2021), although precipitation patterns can also influence pollen season indicators (Schramm et al., 2021). In addition to meteorological factors, land use changes can impact pollen season characteristics (Adams-Groom et al., 2022). Investigations show that temperature increases associated with climate change may lead to the spread of new pollen species (Ziska et al., 2011).

The flowering period and its duration affect human health, especially for people with allergies, whose numbers are increasing globally. The World Allergy Organization reports that allergies, including allergic rhinitis, affect 10 %–30 % of adults worldwide and up to 40 % of children (Pawankar et al., 2013). Allergic reactions to pollen have become more frequent and severe in particular regions over the past few decades (Damialis et al., 2019; Aerts et al., 2021) and are likely to keep increasing due to urbanization, air pollution, and climate change, especially in urban environments (Lake et al., 2017).

Numerous studies, often focusing on the pollen dynamics of individual plant species, have reported local or regional increases in allergenic pollen concentrations from plants like ragweed (*Ambrosia*), oak (*Quercus*), alder (*Alnus*), and birch (*Betula*) (Ščevková et al., 2024; Myszkowska et al., 2011). These studies also highlight increased pollen load for multiple species (Ariano et al., 2010; Mousavi et al., 2024).

Pollen seasonality and concentration have been widely analysed from ecological and human health perspectives. The evaluation of meteorological conditions is essential in predicting the airborne pollen

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distribution. Various studies have examined the relationship between pollen seasonality and meteorological conditions, particularly the links between flowering seasons, start and end dates, and duration, and their correlation with meteorological indicators. Temperature and precipitation are key factors in plant phenology and can substantially impact the concentration and distribution of airborne pollen (García-Mozo et al., 2015; Schramm et al., 2021; Tang et al., 2023).

The main meteorological factors influencing pollen distribution dynamics are air temperature, precipitation, wind speed, relative humidity, and solar radiation. Temperature and precipitation play the most significant role in determining pollen concentrations, though their effects are complex and influenced by additional factors. High air temperatures are often associated with an earlier start to the pollen season, longer duration, and higher pollen concentrations (Schramm et al., 2021). Therefore, changing temperatures can affect the season's onset, which, in turn, can influence the intensity and duration of allergic reactions (Ziska et al., 2011). Precipitation can affect pollen concentration in several ways. For instance, it can reduce airborne pollen concentrations by washing pollen out of the atmosphere (Muzaylova et al., 2021), delay pollen release if rain follows initial flowering, and influence the overall spread and duration of the season. For example, if trees begin flowering and are followed by several days of heavy rainfall, pollen concentration in the air may significantly decrease due to precipitation effectively removing pollen and limiting their dispersion (Rathnayake et al., 2017). Wind speed and direction influence the transport and distribution of airborne pollen. Studies show that wind direction and the distribution of plant species strongly influence pollen concentration (Silva Palacios et al., 2000). According to some studies, pollen concentrations positively correlate with wind speed (Ščevková et al., 2015; Chico-Fernández and Ayuga-Téllez, 2025), while other studies find that the concentration of certain pollen types has a negative correlation (Tormo Molina et al., 2001). Relative humidity generally correlates negatively with pollen concentration (Ščevková, 2003; Puc, 2012), as high humidity leads to more moisture being absorbed by the pollen, which reduces its ability to stay airborne. Furthermore, some plant species release more pollen when weather conditions are dry. The solar radiation and sunshine duration positively correlate with pollen concentration (Iglesias-Otero et al., 2015). Some species release more pollen under sunny conditions, and when dry, warm, sunny weather prevails, pollen stays airborne longer (Juprasong et al., 2022).

Aerobiological observations and research in Lithuania started in 2003 (Šukienė and Šaulienė, 2013). The first measurements were conducted in Siauliai. The previous studies focused on the analysis of pollen seasonal characteristics, pollen dispersion, and long-range transport (Veriankaite et al., 2010; Šaulienė et al., 2019) as well as the impact of allergenic pollen on residents (Šukienė et al., 2021). The research includes the assessment of pollen indicators from various plant species (alder, birch, hazel, mugwort, and grass). Additionally, the influence of meteorological factors on pollen dispersion has been investigated (Šaulienė et al., 2019). *The novelty of this study lies in two main aspects. First, no comparable research has been conducted in the Baltic region using such an extensive pollen dataset. Lithuania has been under continuous monitoring since 2003, offering a unique source of information. Although a 19-year record has statistical limitations, it is considered sufficiently long and robust for aerobiological studies. Second, our study makes a methodological contribution by comparing the EAN* (European Aerobiology Network) *and EAACI* (European Academy of Allergy and Clinical Immunology) *definitions of pollen season characteristics within the same dataset. This approach is rarely undertaken, as these definitions are usually applied in different research communities.*

In addition to academic inquiry, these data have proven essential in the development of public-oriented tools such as PASYFO – the Personal Allergy Symptom Forecast system (see more at pasyfo. eu). Meteorological data, particularly air temperature and precipitation trends, play a key role in improving the accuracy of such forecasts and enabling individuals sensitive to airborne pollen to better plan their outdoor activities. As climate conditions shift, the ability to anticipate how changes in meteorological factors affect allergenic pollen risk becomes increasingly important. Recognizing the intensity and pace of these climatic changes is crucial not only for generating accurate predictions but also for expanding services like PASYFO to broader European contexts. The analysis of pollen concentrations in Lithuania directly supports these goals by strengthening the model's accuracy and relevance at the regional level.

This study analyses the differences in *Alnus* and *Betula* pollen seasons and pollen concentrations at three locations in Lithuania (Siauliai, Vilnius, Klaipeda). It evaluates the changes in these parameters from 2005 to 2023. It also examines the relationship between pollen seasonality, concentration, and meteorological parameters such as air temperature and precipitation amount. In Europe, only a few studies have been done using both the EAN definition and the EAACI definition (Glick et al. (2021); Bastl et al. (2018)). However, this type of research is even more rarely combined with meteorological information.

1.1. Study area

Lithuania is located on the eastern Baltic Sea coast, and its territory (65,300 km^2) is characterised by lowlands and undulating plains, with the highest point reaching 294 m above sea level. Forests cover 33.7 % of the country. Coniferous trees dominate (56 %), including Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies (L.) H. Karst.*) (Petrokas et al., 2025). Deciduous forests (44 %) are dominated by silver birch (*Betula pendula Roth.*; 22 %) and alders (*Alnus glutinosa (L.) Gaertn* and *Alnus incana (L.) Moenx*; 14 %) (Manton et al., 2022). In addition to silver birch, downy birch (*Betula pubescens* Ehrh.) also occurs in Lithuania, while shrub birch (*Betula humilis* Schrank.) and dwarf birch (*Betula nana* L.) are rare and of limited silvicultural relevance. The latter two species are not identified in practical forestry inventories due to their restricted distribution and minor economic significance.

The average annual temperature in Lithuania is 7.4 °C over the period from 1991 to 2020. According to the Köppen climate classification, the majority of the country falls under the Dfb type (warm-summer humid continental climate): the average temperature of the coldest month drops below −3 °C, and the temperature of the four warmest months (May–August) exceeds 10 °C, with the temperature of the warmest month remaining below 22 °C. However, the western and southwestern parts of the country fall into the Cfb (humid temperate climate sub-type) type, as the average temperature of the coldest month does not drop below −3 °C. It is likely that over the next few decades, the entire territory of Lithuania will fall under the Cfb type, as even now, the average temperature of the coldest month drops below −4 °C only in the easternmost part of the territory. The warmest month's temperature across Lithuania's territory is nearly 18 °C. Since the 1960s, the air temperature in Lithuania has increased by 2.5 °C (https://klimatokaita.lt/), with the most significant changes recorded in February and March. On average, the country receives 550–800 mm of precipitation (with the highest amounts in the western part of the country). Seasonal precipitation differences are modest. In inland regions, most precipitation occurs in the second half of summer, whereas coastal areas experience maximum rainfall in autumn. In winter, a thin snow cover forms, becoming increasingly unstable in recent years due to the warming climate. On average, snow cover persists for 68 days yearly, dropping to fewer than 50 days along the coastline.

1.2. Data and methods

The airborne pollen concentration data used in this study were collected in Siauliai, Klaipeda, and Vilnius (Fig. 1) from 2005 to 2023. The collection and analysis of samples were conducted according to EN 16868:2019 standard (European Committee for Standardization, 2019), which specifies the technical requirements for equipment, sampling height, and calibration. The observation stations in Vilnius, Siauliai, and

Fig. 1. The location of Lithuania in Europe (bottom corner map) and the location of aerobiological observation stations used in this study (Basemap: Esri, 2017).

Klaipeda are equipped with Hirst-type volumetric traps (Burkard Manufacturing Co. Ltd., UK) installed on building rooftops (±15 m above ground level) in urban environments. Measuring uncertainty remains within the limits defined by the EN 16868:2019 standard. The data are expressed as pollen concentration per cubic meter of air per day. The study analysed *Alnus* (Miller, 1754) and *Betula* (Linnaeus, 1753) pollen concentrations over this period, except for data gaps in Vilnius (2010 (*Alnus and Betula)* and 2016 (*Alnus*)) and Klaipeda (2016 (*Alnus*)). Daily meteorological data, including temperature and precipitation, were obtained from the Lithuanian Hydrometeorological Service (https://www.meteo.lt/en).

The study analysed the start and end dates of the pollen season, its duration, the annual daily maximum pollen concentration (particles/m^3), and the corresponding date. The Annual Pollen Integral (APIn) and the Seasonal Pollen Integral (SPIn) were also evaluated during the analysis (Galán et al., 2017). The study also determined the part of the total annual pollen concentration recorded over 5, 10, 15, 20, 25, and 30 consecutive days during the highest pollen concentration. Pollen seasons, their start and end dates, and season duration were evaluated using EAN and EAACI definitions (Table 1). The autocorrelation analysis showed no statistically significant autocorrelation in the time series of season start, end, duration, or annual pollen concentrations.

The EAN definition method is straightforward, easy to calculate, and generally suitable for the climatological assessment of pollen indices.

Table 1
EAN and EAACI standard pollen season definitions (Bastl et al., 2015, 2018; Pfaar et al., 2017).

	Season start	Season end
EAN (European Aerobiology Network) definition	1 % of the total annual pollen concentration	95 % of the total annual pollen concentration
EAACI (European Academy of Allergy and Clinical Immunology) definition	On the first of five consecutive days, each with a pollen concentration of at least 10 pollen/m^3 and a cumulative sum of ≥100 pollen/m^3 over those five days	The season ends on the last day that meets the same criteria as start date

However, this method is unsuitable for real-time assessment of the pollen season onset, as it can only be accurately determined after the end of the season when the Annual Pollen Index (API) is known. According to the EAACI definition, the start of the season is associated with a concentration of 10 pollen/m^3. However, this may also be inaccurate, as it strongly depends on the number and proximity of such plant species near the trap. Therefore, the aerodynamic characteristics of pollen types and the height of a plant relative to the trap can contribute to differences in pollen concentration (Jochner et al., 2012).

The study examines the correlation between pollen season parameters and meteorological conditions. We primarily focus on air temperature and precipitation, as these variables are most relevant for assessing the influence of general climatic conditions on pollen indicators, while factors such as wind, humidity, and solar radiation are more relevant to short-term fluctuations. In all cases this relationship was evaluated using Spearman's (Spearman, 1904) correlation coefficient. The non-parametric Mann-Kendall (Mann, 1945; Kendall, 1975) test was used to assess the statistical significance of changes. Both correlation and trends were considered statistically significant when $p < 0.05$.

2. Results

2.1. Alder pollen season

On average, the alder pollen season begins in the first half of March and ends at the beginning of April (Table 2). According to the EAN definition, the start is recorded slightly earlier than according to the EAACI definition, while the end time almost coincides. Using different calculation methods, the season lasts, on average, from 24 to 36 days in different study sites. The season duration can extend to two months in some years, although it usually does not exceed one month. In Siauliai and Klaipeda, the season duration, according to EAN definition, is longer, whereas in Vilnius, it is slightly shorter. The peak pollen concentration on average is recorded between March 22 and 24 in Lithuania.

However, during the 2005–2023 period, the start of the alder pollen season, which is associated with the beginning of spring, has significantly advanced at all study sites (Fig. 2a and b). The changes ranged from 13 days in Siauliai to 34 days in Vilnius, according to the EAN definition, and from 22 days in Siauliai to 27 days in Vilnius and Klaipeda, according to the EAACI definition. However, according to the Mann–Kendall test, statistically significant changes in the pollen season were found only in Vilnius for both definitions, while in Klaipėda significant changes were detected only under the EAACI definition. The standard deviation of pollen season start dates ranged from 17 to 21 days, which explains why relatively large shifts were not statistically significant at other locations. Although air temperature increases were similar across Lithuania, the warming was slightly weaker near the Baltic coast.

Such an advancement in the season start dates is driven by air temperature rise in February and March (Fig. 3a and b). Since the 1980s, intense warming in Lithuania has been particularly pronounced during these months, with temperatures rising well above 2 °C across the entire territory. Strong negative correlations were observed between the average February–March temperature and the start dates of the alder pollen season, with Spearman's rank coefficients ranging from −0.85 to −0.61 (p = 0.0001–0.007). The negative correlation with precipitation amount is weaker and statistically significant only in some cases. However, this relationship is more likely associated with higher humidity in warmer air rather than directly impacting the start of the pollen season. In early spring, soil moisture in Lithuania is generally sufficient to initiate vegetation growth after the snow cover melts.

The dates for the end of the season have also shifted by 19–22 days, according to the EAN definition, and by 12–21 days according to the EAACI definition. However, these changes are not statistically significant. The timing of the season's end is closely linked to March air

Table 2
The average start, end, and peak concentration dates of the *Alnus* and *Betula* pollen seasons and the season duration at three measurement sites according to EAN definition and EAACI definition in 2005–2023.

Pollen season indices	*Alnus*			*Betula*		
	Siauliai	Vilnius	Klaipeda	Siauliai	Vilnius	Klaipeda
Peak concentration data	22-Mar	24-Mar	22-Mar	28-Apr	27-Apr	27-Apr
EAN definition						
Start date	1-Mar	9-Mar	6-Mar	14-Apr	15-Apr	15-Apr
End date	5-Apr	5-Apr	5-Apr	12-May	7-May	13-May
Duration (days)	36	28	32	29	24	29
EAACI definition						
Start date	12-Mar	10-Mar	13-Mar	19-Apr	16-Apr	20-Apr
End date	4-Apr	8-Apr	7-Apr	18-May	20-May	16-May
Duration (days)	24	31	26	30	35	28

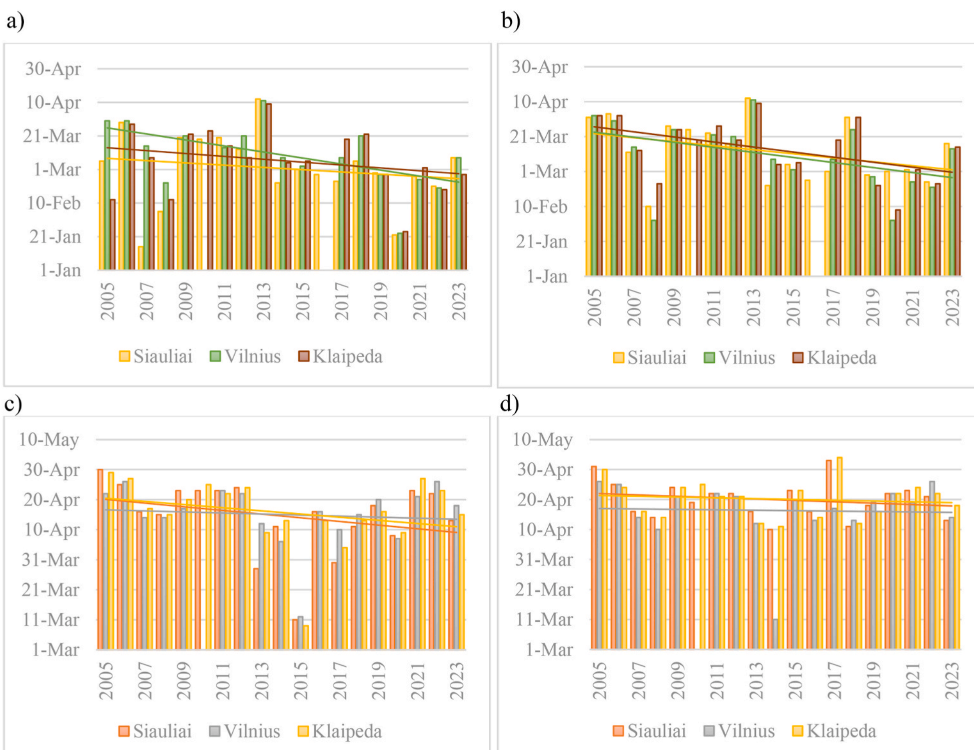

Fig. 2. Changes and linear trends in the start dates of the pollen season from 2005 to 2023: a) alder (EAN definition); b) alder (EAACI definition); c) birch (EAN definition); d) birch (EAACI definition).

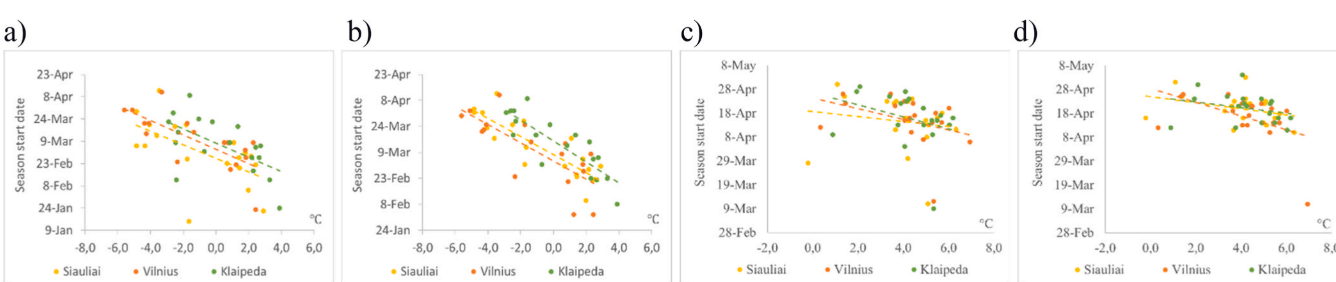

Fig. 3. Relationship between the average air temperature and the pollen season start date for alder and birch: a) alder (EAN definition); b) alder (EAACI definition); c) birch (EAN definition); and d) birch (EAACI definition). Average temperature was calculated for February–March for alder and March–April for birch.

temperatures, with Spearman's correlation coefficients ranging from −0.81 to −0.85 ($p < 0{,}0001$) for the EAN definition and from −0.71 to −0.79 (p = 0,0007–0,0001) for the EAACI definition. The overall duration of the season has changed little. Only in Vilnius does the pollen season lengthen by more than 10 days, while in Siauliai and Klaipeda, it slightly shortens according to the EAN definition but increases according to the EAACI definition.

The average APIn ranges from more than 2500 in Siauliai to over 3700 in Vilnius (Fig. 4). The highest pollen levels were recorded in 2019 when the concentration exceeded the average from 1.9 times in Siauliai

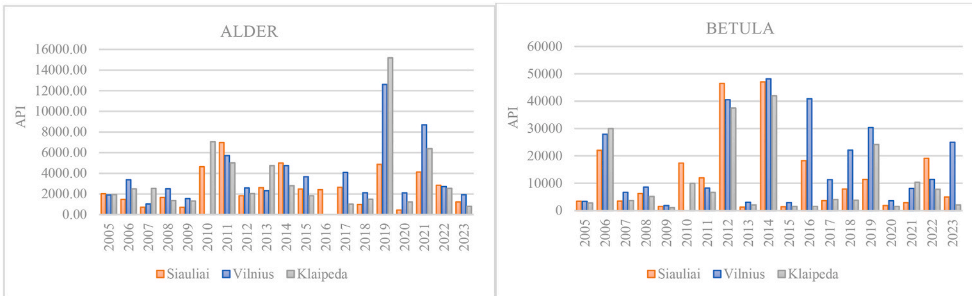

Fig. 4. Dynamics of the Annual Pollen Index (API) values from 2005 to 2023.

to 4.4 times in Klaipeda. That year, due to the very warm February (In February 2019, the average air temperature was 3.6–5.0 °C higher than usual in all three different locations compared to the 1991–2020 average), the pollen season started at the end of the month. The weather became extremely dry toward the end of March. Only 1–3 mm of precipitation (LHMS data) was recorded in these areas from late March to early May. As a result, even if pollen production had decreased, the pollen remained in the air for an extended period and was not washed away by rain.

The relationship between APIn values of alder in different locations is relatively high, reaching 0.84 ($p < 0.0001$) between Vilnius and Siauliai. Due to the peculiarities of the maritime climate, the correlation with Klaipeda is slightly weaker but still statistically significant. Meanwhile, changes in APIn values during the investigation period are insignificant in all locations, according to the Mann-Kendall test.

While the SPIn ratio to APIn, according to the EAN definition, is very close to 0.94 (as defined by the calculation routine), according to the EAACI definition, this number is slightly higher, ranging from 0.94 in Siauliai to 0.96 in Vilnius. On days when pollen concentrations are highest, the average pollen count is 21–26 % of the APIn. (Table 3). In some years, nearly half of the total annual pollen concentration has been recorded in a single day (2005 in Siauliai, 2011 in Klaipeda).

On the peak days of alder pollen concentration, an average anomaly of 3.2 °C in mean and 4.4 °C in maximum air temperature is recorded, indicating sunny weather conditions. Precipitation was typically absent on these days, with only 17 % of cases registering light rainfall exceeding 1 mm.

There are approximately 25 days per year when pollen concentration exceeds 10 pollen/m^3, while more than 100 pollen/m^3 are recorded on average for 7 days per year (Table 3). On days with the highest pollen concentrations, an average of more than 600 pollen/m^3 is recorded across all cities, with the highest concentration in Klaipeda, nearly 1000 pollen/m^3. On average, more than half of the alder pollen is recorded over five consecutive days with the highest pollen concentration, and more than 80 % of the annual pollen count is reached over 15 days. The standard error of the mean is very small (≤2 %), indicating that the mean values are quite precise and variability around them is minimal. (Fig. 5). Analysing the 15-day period with the highest pollen concentration, it was found that during those days, a positive temperature anomaly of 2.1 °C was recorded on average. The precipitation sum was nearly the same as the mean value.

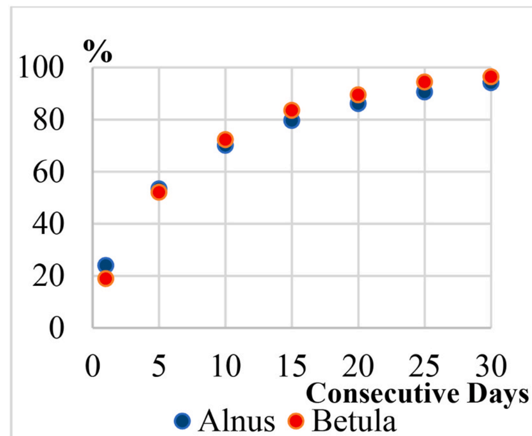

Fig. 5. The average pollen concentration (% from APIn) recorded over 1–30 consecutive days during the period with the highest pollen concentration.

The differences in alder pollen concentration over the 30 days of peak pollen concentration are not very pronounced (Fig. 6a). The daily pollen concentration remains close to or above 2 % of APIn throughout most of the period. Slightly higher pollen levels are observed in the first half of the period, with values exceeding 4 % on days 6–15. On average the highest concentration is recorded on day 14 (4.7 % of APIn).

The relationship between pollen season duration and APIn depends on the method used to define the start and end of the pollen season. When the alder season duration is based on the EAN definition method, the correlation between these two parameters is very weak and not statistically significant. Using this method, the season often appears prolonged if there is no clearly defined pollen peak, and in such cases, APIn also tends to be relatively low.

In contrast, when calculated using the EAACI definition method, Spearman's rank correlation is positive (r = 0.51–0.71; p = 0.026-0.0007) and statistically significant. The longer the period with days

Table 3
Alnus and Betula pollen concentration, average values, and standard errors at three measurement sites, according to EAN and EAACI definitions, from 2005 to 2023.

Pollen concentration parameters	*Alnus*			*Betula*		
	Siauliai	Vilnius	Klaipeda	Siauliai	Vilnius	Klaipeda
Mean API value	2610 ± 416	3744 ± 693	3429 ± 817	12208 ± 3275	16869 ± 3556	10393 ± 3043
Mean SPI value (EAN definition)	2434 ± 389	3520 ± 655	3200 ± 763	11339 ± 3023	14091 ± 3322	9596 ± 2815
Mean SPI value (EAACI definition)	2448 ± 420	3597 ± 702	3273 ± 824	12031 ± 3257	16697 ± 3553	10178 ± 2998
Mean pollen concentration per season day (EAN definition)	88 ± 19	130 ± 22	114 ± 29	660 ± 242	1115 ± 329	573 ± 198
Mean pollen concentration per season day (EAACI definition)	97 ± 13	122 ± 15	118 ± 20	374 ± 89	430 ± 75	326 ± 80
Days with pollen concentration ≥10 pollen/m^3	23 ± 2	27 ± 2	23 ± 2	30 ± 2	34 ± 3	27 ± 2
Days with pollen concentration ≥100 pollen/m^3	6 ± 1	8 ± 2	7 ± 1	13 ± 2	16 ± 2	11 ± 1
Mean maximum daily pollen concentration	635 ± 113	728 ± 182	996 ± 273	2256 ± 672	2981 ± 652	1950 ± 610

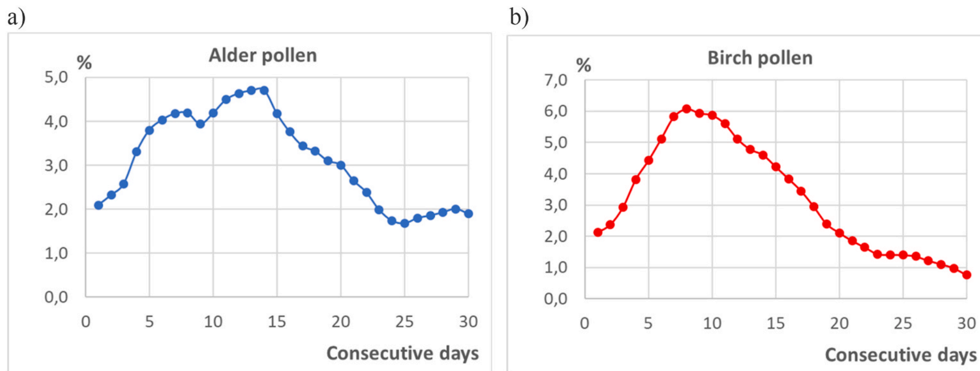

Fig. 6. Distribution of alder (a) and birch (b) pollen concentration (% from APIn; 5-day moving average) over a 30-day consecutive period during the peak pollen concentration.

where pollen concentration exceeds 10 pollen/m^3, the higher the APIn.

2.2. Birch pollen season

According to the EAN definition, the birch pollen season in Lithuania typically begins in mid-April or up to five days later, according to the EAACI definition (Table 2). In rare cases, the season may start as early as March. The pollen season usually ends in the second decade of May; however, in some cases, it may end in April. A more considerable difference was observed in Vilnius; according to the EAACI definition, the season, on average, ends 13 days later than the EAN definition.

The average duration of the birch pollen season is approximately 30 days. However, significant differences are observed in Vilnius, where the season lasts, on average, 25 days according to the EAN definition but extends to 35 days according to the EAACI definition (Table 2). The season has been remarkably short in some years, lasting fewer than 10 days. The shortest recorded season was just 8 days in 2016 in Vilnius (according to EAN definition). Conversely, in some cases, the season can persist for over two months (up to 68 days in Vilnius in 2014, according to EAACI definition).

Although both methods show similar mean pollen season start and end dates and season duration, a weak correlation exists between the analysed values calculated using different techniques. The only statistically significant correlation is in the season start dates in Vilnius ($r = 0.61$; $p = 0.006$), based on Spearman's rank correlation.

On average, the peak pollen concentration is recorded on April 27–28 (Table 2). On peak days, the recorded pollen concentration is, on average, around one-fifth of the total APIn, which is a few percentage points lower than in the case of alder. The highest concentration, above 11000 pollen/m^3, was recorded in Siauliai on April 28, 2012. Birch pollen is more evenly distributed than alder pollen, and the 40 % from API was exceeded only once on a peak day (in Klaipeda in 2009).

The birch pollen season date changes are less pronounced than alder. According to the EAN definition, during the study period, the start of the birch pollen season advanced by 3–12 days, while the EAACI definition indicates a shift of only 1–4 days (Fig. 2c and d). The end-of-season dates varied even less, with the only significant change observed in Vilnius, where the season end shifted 8 days later based on the EAACI definition. The season duration slightly increased, with the most notable changes recorded in Siauliai and Klaipeda—up to 14 and 13 days, respectively, according to the EAN definition. However, all these changes are statistically insignificant based on the Mann-Kendall test. This could be attributed to the high variability in season start and end dates and the relatively short observation period from a statistical point of view.

A weak but statistically significant negative correlation was found between March–April air temperatures and the start of the birch pollen season (according to EAN definition) (Fig. 3c). A weak negative correlation was observed between April–May temperatures and the season's end dates as well. However, no statistically significant relationship was found with season start and end data according to the EAACI definition (Fig. 3d). Similarly, no significant correlations were detected for season duration. The correlation with precipitation amount was even weaker.

The average APIn values range from above 10000 in Klaipeda to almost 17000 in Vilnius (Fig. 4). However, in some years, the index value exceeded 40000 at all locations (2.9–4.0 times above the average). In all places, the maximum APIn was reached in 2014. That year, anomalously warm and extremely dry weather settled in during the second half of April, just after the start of the pollen season. The average air temperature was 12.5–13.5 °C (3–4 °C above normal), and no precipitation was recorded in Klaipeda and Siauliai, while in Vilnius, it rained only once. The warm weather increased pollen production, and the absence of precipitation allowed the pollen to remain airborne for an extended period. No statistically significant changes in birch APIn values were recorded.

The correlation of APIn values is stronger between Vilnius and Siauliai ($r = 0.89$; $p < 0.0001$), while the correlation with Klaipeda is weaker ($r = 0.64$–0.73; $p = 0.0031$–0.0004). The SPIn to APIn ratio, according to the EAACI definition, was even higher than in the alder case, reaching 0.98–0.99. This indicates that nearly all pollen are captured during the pollen season. The average number of days with a pollen concentration >10 pollen/m^3 ranges from 27 in Klaipeda to 34 in Vilnius, while the number of days with a concentration exceeding 100 pollen/m^3 varies from 11 to 16 on average (Table 3).

As with alder pollen, the pollen peak is observed on warm, sunny, and dry days. On average, the mean air temperature anomaly was 2.6 °C, while the daily maximum temperature anomaly reached 4 °C. Moreover, more than 1 mm of precipitation was recorded on only 8 % of these days. Nearly three-quarters of the total pollen concentration is recorded within 10 consecutive days, with the highest concentrations, and almost 90 % within 20 days (Fig. 4). During the 15 days of highest concentration, the average temperature was, on average, 1.1 °C higher than the long-term average. Since a greater-than-average air temperature amplitude was also recorded during these days, it can be stated that this day can be characterised by lower cloudiness and longer sunshine duration. Precipitation was, on average, 29 % lower. In the case of alder pollen, the key factor was a relatively strong positive temperature anomaly, however, peak concentrations were recorded on sunny days with less precipitation.

Analysis of the 30 days with the highest birch pollen concentrations revealed a sharp increase in pollen levels at the beginning of the period, peaking on days 7–10, most commonly on day 8. 6 % of the total APIn (on average accounts for 6 % of the total APIn). Thereafter, the concentration gradually declines, and from around day 20 onward, it typically remains below 2 % of the APIn (Fig. 6b).

A negative and statistically significant correlation between APIn values and the pollen season duration defined by the EAN definition (r =

−0.65 to −0.80; $p = 0.0026$-0.0001) was recorded. In contrast, a weaker positive correlation is observed with the season duration calculated according to the EAACI definition (r = 0.51–0.62; $p = 0.0257$–0.0046).

3. Discussion

Due to changing cold-season patterns in Lithuania—such as rising winter and spring air temperatures, increasingly frequent winters without long-lasting snow cover, and earlier occurrences of the last spring frosts (Rimkus et al., 2018; Klimavičius and Rimkus, 2024)—corresponding plant responses have been observed, including an earlier onset of the pollen season. It was determined that the pollen season is advancing, and this shift is likely caused by earlier springs and milder winters (Figs. 2 and 3). Other studies have also shown that the start of the pollen season tends to occur earlier when average temperatures are higher, particularly during the spring months (Kubik-Komar et al., 2021). Warmer springs may also lead to a more extended period of pollen activity. Because trees are early pollen producers, the effects of a shorter winter due to warmer temperatures have a pronounced impact on the earlier start of the pollen season (Fig. 2). Research by Schramm et al. (2021) demonstrated that air temperature significantly influences the start date of the pollen season. As climate change causes warmer temperatures earlier in the year, an earlier onset of the pollen season is increasingly being observed. Similarly, Malkiewicz et al. (2016) found that the earlier start of alder (*Alnus*) and birch (*Betula*) pollen seasons in southwest Poland over the past 60 years is closely linked to rising air temperatures. Zhang and Steiner (2022) also reported that warmer temperatures in the United States have advanced the onset of spring pollen emissions by 10–40 days, with the overall season lasting longer. Additionally, Emberlin et al. (2007) observed that the alder pollen season had become longer in the Worcester area of the UK. However, Haobeke et al. (2018) noted that the alder pollen season is stable, and season start and end dates are stable over the years of research.

Our findings align with previous studies highlighting the complex relationship between environmental conditions and pollen season timing. The start and development of pollen seasons are influenced by many factors, including meteorological conditions and the specific location of the plants (e.g., urban vs. rural environments), making it challenging to isolate and interpret individual correlations (Tischer et al., 2017). As in our case, among the various indicators of pollen season timing, the start date most frequently shows a statistically significant correlation with air temperature (Schramm et al., 2021). Higher spring temperatures and shifts in precipitation timing can lead to earlier pollen season onset, longer durations, and increased airborne pollen concentrations (Cristofolini et al., 2024). Consistent with our results, Hajkova et al. (2015) also did not find a significant correlation between pollen and precipitation sums. Likewise, Schramm et al. (2021) reported that the majority of analyses revealed no significant associations between precipitation and various pollen season timing indicators. Our study found statistically significant correlations between air temperature and the start dates of the pollen season (Fig. 2). However, almost no significant relationships were identified between these airborne pollen season parameters and precipitation amount. These results are consistent with Schramm et al. (2021), who reported that higher temperatures were associated with an earlier onset of the primary pollen season and increased average daily pollen concentrations, while correlations with precipitation were less evident. In some cases, early spring precipitation delays the start of the pollen period (Guada et al., 2024). It should be noted that the relatively short time series (19 years) may limit the robustness of the statistical tests and the interpretation of effect sizes. For this reason, the significance test results should be interpreted cautiously, as indicative rather than definitive. The limited study period may also limit the ability to detect long-term trends correctly and potential nonlinear changes.

During the 2005–2023 period, statistically significant trends were identified mainly for the alder pollen season, while changes in the birch pollen season were weaker and insignificant. The start of the alder pollen season advanced the most, especially in Vilnius, reflecting the substantial impact of rising late-winter and early-spring temperatures. Meanwhile, the indicators of the birch pollen season showed only minor shifts. The fact that the Betula pollen season has not occurred earlier in the last few decades is also noted in other research (Adams-Groom et al., 2022; Glick et al., 2021). The differences between *alder* and b*irch* suggest that early-flowering species such as alder are more sensitive to short-term temperature fluctuations. Overall, these results highlight the contrasting phenological responses of tree species to ongoing climate change in Lithuania.

We used two different methods to calculate pollen season dates: the EAN definition and the EAACI definition. In years with a low APIn, 1 % of the APIn might be reached very early in the year, which is sometimes unlikely to mark the actual start of the pollen season. Low pollen concentrations in winter can result from short-term warming or long-range transport events.

Even a few pollen with a low APIn can lead to a formal pollen season's early start. For example, according to the EAN definition, in Siauliai in 2007, the pollen season began on January 15. That particular year, the APIn was registered at a value of a little above 700 pollen/m^3, so a concentration with few pollens detected over several days in midwinter led to an unusually early start of the season. The unusually warm winter start in Siauliai resulted in predominantly positive temperatures in January. However, cold weather that began at the end of January persisted until late February, with minimum temperatures often dropping to −20 °C. The daily pollen concentration only reached 5 pollen/m^3 on March 8 for the first time. Thus, it is highly inaccurate to consider January 15 as the actual start of the pollen season that year.

On the other hand, such an early start is not always a misstart. For instance, in 2020, the alder pollen season began on January 22, according to the EAN definition method, with an APIn just above 400 pollen/m^3. That winter was the warmest on record, with average temperatures falling below 0 °C on only a few days. As a result, 50 % of the API was reached by February 8.

Conversely, in years with a very high APIn, the start of the pollen season can be recorded quite late, even if pollen concentrations were already relatively high earlier in the season. For example, in 2011, the season's start was recorded on March 20, even though pollen concentration had already exceeded 20 pollen/m^3 on March 13–14. On March 19, the pollen concentration had dropped to just four pollen/m^3. These examples illustrate the EAN definition method's limitations in defining the precise date of the pollen season start.

In Lithuania, the average APIn values difference is relatively minor (31 %) across the investigated locations during the study period. Therefore, the EAACI definition method is slightly more suitable for assessing pollen seasonality in Lithuania. In addition, the EAACI definition is more useful for public information purposes, as it allows the start of the pollen season to be identified earlier than with the EAN definition. This feature makes it more useful for allergy risk forecasting and for improving citizen-oriented services such as the PASYFO system currently applied in Lithuania. The EAN definition is particularly valuable for assessing pollen dispersion in the atmosphere and for improving air quality model forecasts, as it allows for a better assessment of climate impact. Even though the correlation between the pollen season dates determined by these two methods is weak, the average long-term dates and season duration are similar. Pfaar et al. (2024) compared different pollen season definitions and found that the EAN definition method generally results in a slightly later pollen season start compared to the EAACI definition. Despite this difference, calculations showed high consistency between the two definitions. The choice between these definitions depends on the context: the EAACI definition may be more suitable for real-time evaluation, while, in contrast, the EAN definition method requires the entire season before calculations can be performed. Bastl et al. (2018) support this preference for the EAACI definition in clinical contexts. Ultimately, the definition of the pollen season should align with the study's specific aims. Deviations from established or recommended definitions can be justified if the methods and terminology are clearly and precisely defined (Bastl et al., 2018).

Several studies have revealed that the start of the airborne pollen season does not necessarily match the beginning of local flowering. For example, as discussed in Jochner et al. (2012), the start of the birch pollen season in Germany occurred on average 6 days earlier than local flowering. However, the peak of the pollen season coincided with the mean flowering date. The mismatch of local phenological onset dates with the start of the pollen season can be partly explained by long- or medium-range transport of airborne pollen by moving air masses (Jochner et al., 2012). In some cases, there may be no correlation between pollen concentration and local meteorological conditions, as pollen can be transported over long distances, originating from other regions or even countries (Izquierdo et al., 2015). In the study by Sofiev et al. (2006), long-range birch pollen transport phenomena were also investigated. The almost spherical grains are small and belong to one of the furthest transported types of pollen.

The observed trends—such as the earlier onset and shifting intensity of alder and birch pollen seasons in Lithuania—offer concrete, regionally grounded evidence that can be directly used to calibrate and validate airborne pollen or pollinosis risk indices. For example, pollen resistance index forecasting services developed through the EO4EU platform (https://www.eo4eu.eu/), which aims to make Earth observation data more accessible, make it easier to link pollen and air quality loads to human health. This study provides actionable data by quantifying the effect of meteorological variables on pollen release and peak concentrations, and enables the improvement of pollinosis forecasts similar to PASYFO.

4. Conclusions

This study analyses the seasonal indicators of alder and birch pollen in Lithuania and their changes over time. It also investigates the relationships of pollen seasonal indicators with air temperature and precipitation. No prior research of this kind has been conducted in the Baltic region. Lithuania has been monitoring pollen continuously since 2003, making it a unique data source. Although we acknowledge the statistical limitations of a 19-year record, it is still considered a sufficiently long and robust dataset in aerobiological studies, where shorter time series are often analysed.

The findings show that the start of the alder pollen season has advanced the most (13–34 days in different locations), which can be linked to the remarkably rapid increase in air temperature during the February–March. This indicates a clear climate-driven shift in alder pollen distribution in Lithuania. Changes in birch pollen season indicators are less prominent. Although most pollen seasons' start and end dates have shifted earlier, majority of the changes were statistically insignificant due to the high variability in pollen season parameters and the relatively short study period. Season duration has changed only slightly and inconsistently across locations and calculation methods, with the highest increase observed in Vilnius by approximately 10 days. The seasonal indicators of the studied pollen also reveal a weak and inconsistent relationship with the monthly precipitation sums during the spring months. However, the absence of precipitation combined with a positive temperature anomaly, often several degrees above normal, is the most critical factor determining alder and birch pollen peak concentrations. On average, about 21–26 % of the annual alder pollen and 18–20 % of birch pollen are recorded on peak pollen days. Over half of the APIn is, on average, recorded during the five consecutive days with the highest concentrations, while over 80 % is typically captured within the 15 days. Seasonal variations in birch and alder pollen concentrations directly affect the clinical treatment of patients with seasonal allergic rhinitis, particularly regarding the timing of allergen immunotherapy and medication use. In this context, EAACI criteria provide a clinically oriented framework, while EAN criteria are more suitable for long-term aerobiological data evaluation. On the other hand, our findings may also be important for urban greening and planning policies, ensuring that allergenic burden is considered in strategies for healthier cities.

CRediT authorship contribution statement

Silvija Pipiraitė-Januškienė: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Egidijus Rimkus:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Formal analysis, Conceptualization. **Ingrida Šaulienė:** Writing – review & editing, Funding acquisition, Data curation, Conceptualization. **Laura Šukienė:** Writing – review & editing, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

Adams-Groom, B., Selby, K., Derrett, S., Frisk, C.A., Pashley, C.H., Satchwell, J., King, D., McKenzie, G., Neilson, R., 2022. Pollen season trends as markers of climate change impact: betula, quercus, and poaceae. Sci. Total Environ. 831, 154882. https://doi.org/10.1016/j.scitotenv.2022.154882.

Aerts, R., Bruffaerts, N., Somers, B., Demoury, C., Plusquin, M., Nawrot, T.S., Hendrickx, M., 2021. Tree pollen allergy risks and changes across scenarios in urban green spaces in Brussels, Belgium. Landsc. Urban Plann. 207, 104001. https://doi.org/10.1016/j.landurbplan.2020.104001.

Ariano, R., Canonica, G.W., Passalacqua, G., 2010. Possible role of climate changes in variations in pollen seasons and allergic sensitizations during 27 years. Ann. Allergy Asthma Immunol. 104 (3), 215–222. https://doi.org/10.1016/j.anai.2009.12.005.

Bastl, K., Kmenta, M., Geller-Bernstein, C., Berger, U., Jäger, S., 2015. Can we improve pollen season definitions by using the symptom load index in addition to pollen counts? Environ. Pollut. 204, 109–116. https://doi.org/10.1016/j.envpol.2015.04.016.

Bastl, K., Kmenta, M., Berger, U.E., 2018. Defining pollen seasons: background and recommendations. Curr. Allergy Asthma Rep. 18, 73. https://doi.org/10.1007/s11882-018-0829-z.

Chico-Fernández, J., Ayuga-Téllez, E., 2025. Relationship of meteorological variables with the concentration of various tree pollen types in Madrid (Spain). Appl. Sci. 15 (2), 692. https://doi.org/10.3390/app15020692.

Climate change in Lithuania. In: Lithuanian, 2025. https://klimatokaita.lt. (Accessed 15 October 2025).

Cristofolini, F., Cristofori, A., Corradini, S., Gottardini, E., 2024. The impact of temperature on increased airborne pollen and earlier onset of the pollen season in Trentino, Northern Italy. Reg. Environ. Change 24, 60. https://doi.org/10.1007/s10113-024-02223-6.

Damialis, A., Traidl-Hoffmann, C., Treudler, R., 2019. Climate change and pollen allergies. In: Marselle, M., Stadler, J., Korn, H., Irvine, K., Bonn, A. (Eds.), Biodiversity and Health in the Face of Climate Change. Springer, pp. 47–66. https://doi.org/10.1007/978-3-030-02318-8_3.

de Weger, L.A., Bruffaerts, N., Koenders, M.M.J.F., Verstraeten, W.W., Delcloo, A.W., Hentges, P., Hentges, F., 2021. Long-term pollen monitoring in the Benelux: evaluation of allergenic pollen levels and temporal variations of pollen seasons. Front. Allerg. 2 (6), 76176. https://doi.org/10.3389/falgy.2021.676176.

Emberlin, J., Smith, M., Close, R., Adams-Groom, B., 2007. Changes in the pollen seasons of the early flowering trees Alnus spp. and Corylus spp. in Worcester, United Kingdom, 1996–2005. Int. J. Biometeorol. 51, 181–191. https://doi.org/10.1007/s00484-006-0059-2.

Esri, 2017. Topographic" [basemap]. World Topograp. Map. https://www.arcgis.com/home/item.html?id=7dc6cea0b1764a1f9af2e679f642f0f5. (Accessed 14 October 2025).

European Committee for Standardization, 2019. EN 16868:2019 — Ambient Air – Sampling and Analysis of Airborne Pollen Grains and Fungal Spores for Networks Related to Allergy. CEN, Brussels.

Galán, C., Ariatti, A., Bonini, M., Clot, B., Crouzy, B., Dahl, A., Fernandez-González, D., et al., 2017. Recommended terminology for aerobiological studies. Aerobiologia 33, 293–295. https://doi.org/10.1007/s10453-017-9496-0.

García-Mozo, H., Oteros, J., Galán, C., 2015. Phenological changes in olive (Ola europaea L.) reproductive cycle in southern Spain due to climate change. Ann. Agric. Environ. Med. 22 (3), 421–428. https://doi.org/10.5604/12321966.1167706.

Glick, S., Gehrig, R., Eeftens, M., 2021. Multi-decade changes in pollen season onset, duration, and intensity: a concern for public health? Sci. Total Environ. 781, 146382. https://doi.org/10.1016/j.scitotenv.2021.146382.

Guada, G., Fernández-González, M., Amigo, R., Dias-Lorenzo, D.A., Sánchez Espinosa, K. C., Rodríguez-Rajo, F.J., 2024. Precipitation masks the effect of temperature on birch airborne pollen start, and previous summer temperature affects pollen intensity: a 31-year study at its Southwestern distribution boundary. Agric. For. Meteorol. 353, 110072. https://doi.org/10.1016/j.agrformet.2024.110072.

Hajkova, L., Koznarova, V., Mozny, M., Bartosova, L., 2015. Changes in flowering of birch in the Czech Republic in recent 25 years (1991–2015) in connection with meteorological variables. Acta Agrobot. 68 (4), 285–302z. https://doi.org/10.5586/aa.2015.043.

Hoebeke, L., Bruffaerts, N., Verstraeten, C., Delcloo, A., De Smedt, T., Packeu, A., Detandt, M., Hendrickx, M., 2018. Thirty-four years of pollen monitoring: an evaluation of the temporal variation of pollen seasons in Belgium. Aerobiologia 34, 139–155. https://doi.org/10.1007/s10453-017-9503-5.

Iglesias-Otero, M.A., Fernández-González, M., Rodríguez-Caride, D., Astray, G., Mejuto, J.C., Rodríguez-Rajo, F.J., 2015. A model to forecast the risk periods of *Plantago* pollen allergy by using the ANN methodology. Aerobiologia 31, 201–211. https://doi.org/10.1007/s10453-014-9357-z.

Izquierdo, R., Alarcón, M., Periago, C., Belmonte, J., 2015. Is long range transport of pollen in the NW Mediterranean basin influenced by Northern Hemisphere teleconnection patterns? Sci. Total Environ. 532, 771–779. https://doi.org/10.1016/j.scitotenv.2015.06.047.

Jochner, S.C., Sparks, T.H., Estrella, N., Menzel, A., 2012. The influence of altitude and urbanisation on trends and mean dates in phenology (1980-2009). Int. J. Biometeorol. 56 (2), 387–394. https://doi.org/10.1007/s00484-011-0444-3.

Juprasong, Y., Sirirakphaisarn, S., Siriwattanakul, U., Songnuan, W., 2022. Exploring the effects of seasons, diurnal cycle, and heights on airborne pollen load in a Southeast Asian atmospheric condition. Front. Public Health 10, 106703. https://doi.org/10.3389/fpubh.2022.1067034.

Kendall, 1975. Rank Correlation Methods, fourth ed. Charles Griffin, London, UK.

Klimavičius, L., Rimkus, E., 2024. False spring events in the eastern part of the Baltic Sea region. 2024. Theor. Appl. Climatol. 155 (10), 9351–9365. https://doi.org/10.1007/s00704-024-05194-0.

Kubik-Komar, A., Piotrowska-Weryszko, K., Kuna-Broniowska, I., Weryszko-Chmielewska, E., Kaszewski, B.M., 2021. Analysis of changes in Betula pollen season start including the cycle of pollen concentration in atmospheric air. PLoS One 16 (8), e0256466. https://doi.org/10.1371/journal.pone.0256466.

Lake, I.R., Jones, N.R., Agnew, M., Goodess, C.M., Giorgi, F., Hamaoui-Laguel, L., Semenov, M.A., Solomon, F., Storkey, J., Vautard, R., Epstein, M.M., 2017. Climate change and future pollen allergy in Europe. Environ. Health Perspect. 125 (3), 385–391. https://doi.org/10.1289/EHP173.

Linnaeus, C., 1753. Species Plantarum, 1. Published by the author.

Malkiewicz, M., Drzeniecka-Osiadacz, A., Krynicka, J., 2016. The dynamics of the Corylus, Alnus, and Betula pollen seasons in the context of climate change (SW Poland). Sci. Total Environ. 573, 740–750. https://doi.org/10.1016/j.scitotenv.2016.08.103.

Mann, H.B., 1945. Nonparametric tests against trend. Econometrica 13 (3), 245–259. https://doi.org/10.2307/1907187.

Manton, M., Ruffner, C., Kibirkštis, G., Brazaitis, G., Marozas, V., Pukienė, R., Makrickiene, E., Angelstam, P., 2022. Fire occurrence in hemi-boreal forests: exploring natural and cultural Scots pine fire regimes using dendrochronology in Lithuania. Land 11 (2), 260. https://doi.org/10.3390/land11020260.

Miller, P., 1754. The Gardeners Dictionary. London.

Mousavi, F., Oteros, J., Shahali, Y., Carinanos, P., 2024. Impacts of climate change on allergenic pollen production: a systematic review and meta-analysis. Agric. For. Meteorol. 349, 109948. https://doi.org/10.1016/j.agrformet.2024.109948.

Muzalyova, A., Brunner, J.O., Traidl-Hoffmann, C., Buters, J.T.M., 2021. Forecasting *Betula* and *Poaceae* airborne pollen concentrations on a 3-hourly resolution in Augsburg, Germany: toward automatically generated, real-time predictions. Aerobiologia 37 (3), 425–446. https://doi.org/10.1007/s10453-021-09699-3.

Myszkowska, D., Jenner, B., Stępalska, D., Czarnobilska, E., 2011. The pollen season dynamics and the relationship among some season parameters (start, end, annual total, season phases) in Kraków, Poland, 1991–2008. Aerobiologia 27, 229–238. https://doi.org/10.1007/s10453-010-9192-9.

Pawankar, R., Canonica, G.W., Holgate, S.T., Lockey, R.F., Blaiss, M.S., 2013. WAO white book on allergy: update 2013, executive summary. World Allerg. Organiz.

Petrokas, R., Manton, M., Kulbokas, G., Muraškienė, M., 2025. Development of forest tree species composition: selected results of the national forest inventory of Lithuania. Plants 14 (5), 667. https://doi.org/10.3390/plants14050667.

Pfaar, O., Bastl, K., Berger, U., Buters, J., Calderon, M.A., Clot, B., et al., 2017. Defining pollen exposure times for clinical trials of allergen immunotherapy for pollen-induced rhinoconjunctivitis – an EAACI position paper. Allergy 72, 713–722. https://doi.org/10.1111/all.13092.

Pfaar, O., Bastl, M., Berger, M., Berger, U.E., Karatzas, K., Tasioulis, T., Werchan, B., Werchan, M., Bergmann, K.C., 2024. Comparison of two different pollen season definitions based on 10 years of birch and grass pollen data from two distant central European cities: an EAACI task force report. Allergy 79, 3161–3165. https://doi.org/10.1111/all.16252.

Puc, M., 2012. Influence of meteorological parameters and air pollution on hourly fluctuation of birch (*Betula* L.) and ash (*Fraxinus* L.) airborne pollen. Ann. Agric. Environ. Med. 19 (4), 660–665.

Rathnayake, C.M., Metwali, N., Jayarathne, T., Kettler, J., Huang, Y., Thorne, P.S., O'Shaughnessy, P.T., Stone, E.A., 2017. Influence of rain on the abundance of bioaerosols in fine and coarse particles. Atmos. Chem. Phys. 17, 2459–2475. https://doi.org/10.5194/acp-17-2459-2017.

Rimkus, E., Briede, A., Jaagus, J., Stonevicius, E., Kilpys, J., Viru, B., 2018. Snow-cover regime in Lithuania, Latvia and Estonia and its relationship to climatic and geographical factors in 1961–2015. Boreal Environ. Res. 23, 193–208.

Šaulienė, I., Šukiene, L., Kazlauskiene, V., 2019. The assessment of atmospheric conditions and constituents on allergenic pollen loads in Lithuania. J. Environ. Manag. 250, 109469. https://doi.org/10.1016/j.jenvman.2019.109469.

Ščevková, J., 2003. The influence of temperature, relative humidity, and rainfall on the occurrence of pollen allergens (*Betula, Poaceae, Ambrosia artemisiifolia*) in the atmosphere of Bratislava (Slovakia). Int. J. Biometeorol. 48, 1–5. https://doi.org/10.1007/s00484-003-0166-2.

Ščevková, J., Dusicka, J., Micieta, K., Somorcík, J., 2015. Diurnal variation in airborne pollen concentration of six allergenic tree taxa and its relationship with meteorological parameters. Aerobiologia 31 (4), 457–468. https://doi.org/10.1007/s10453-015-9379-1.

Ščevková, J., Štefániková, N., Dušička, J., Lafférsová, J., Zahradníková, E., 2024. Long-term pollen season trends of *Fraxinus* (ash), *Quercus* (oak), and *Ambrosia artemisiifolia* (ragweed) as indicators of anthropogenic climate change impact. Environ. Sci. Pollut. Control Ser. 31, 43238–43248. https://doi.org/10.1007/s11356-024-34027-w.

Schramm, P.J., Brown, C.L., Saha, S., Conlon, K.C., Manangan, A.P., Bell, J.E., Hess, J.J., 2021. A systematic review of the effects of temperature and precipitation on pollen concentrations and season timing, and implications for human health. Int. J. Biometeorol. 65 (10), 1615–1628. https://doi.org/10.1007/s00484-021-02128-7.

Silva Palacios, I., Tormo-Molina, R., Nuñoz Rodríguez, A.F., 2000. Influence of wind direction on pollen concentration in the atmosphere. Int. J. Biometeorol. 44, 128–133. https://doi.org/10.1007/s004840000059.

Sofiev, M., Siljamo, P., Ranta, H., Rantio-Lehtimaki, A., 2006. Towards numerical forecasting of long-range air transport of birch pollen: theoretical considerations and a feasibility study. Int. J. Biometeorol. 50, 392–402. https://doi.org/10.1007/s00484-006-0027-x.

Spearman, C., 1904. The proof and measurement of association between two things. Am. J. Psychol. 15 (1), 72–101. https://doi.org/10.2307/1412159.

Šukienė, L., Šaulienė, I., 2013. Aerobiology in Lithuania: from research to information service. Allergo J. 22, 483. https://doi.org/10.1007/s15007-013-0385-8.

Šukienė, L., Šaulienė, I., Dubakienė, R., Rudzevičienė, O., Daunys, G., 2021. Analysis of allergenic pollen data, focusing on a pollen load threshold statement. Aerobiologia 37, 843–860. https://doi.org/10.1007/s10453-021-09727-2.

Tang, Y., Zhou, W., Du, Y., 2023. Effects of temperature, precipitation, and CO_2 on plant phenology in China: a circular regression approach. Forests 14 (9), 1844. https://doi.org/10.3390/f14091844.

Tischer, C., Gascon, M., Fernández-Somoano, A., Tardón, A., Lertxundi, M.A., Ibarluzea, J., Ferrero, A., Estarlich, M., Cirach, M., Vrijheid, M., Fuertes, E., Dalmau-Bueno, A., Nieuwenhuijsen, M.J., Antó, J.M., Sunyer, J., Dadvand, P., 2017. Urban green and grey space in relation to respiratory health in children. Eur. Respir. J. 49 (6), 1502112. https://doi.org/10.1183/13993003.02112-2015.

Tormo Molina, R., Silva Palacios, I., Muñoz Rodríguez, A.F., Tavira Muñoz, J., Moreno Corchero, A., 2001. Environmental factors affecting airborne pollen concentration in anemophilous species of *Plantago*. Ann. Bot. 87 (1), 1–8. https://www.jstor.org/stable/42770874.

Veriankaitė, L., Šaulienė, I., Bukantis, A., 2010. Analysis of changes in flowering phases and airborne pollen dispersion of the genus Betula (birch). J. Environ. Eng. Landsc. Manag. 18 (2), 137–144. https://doi.org/10.3846/jeelm.2010.16.

Zhang, Y., Steiner, A.L., 2022. Projected climate-driven changes in pollen emission season length and magnitude over the continental United States. Nat. Commun. 13, 1234. https://doi.org/10.1038/s41467-022-28764-0.

Ziska, L., Knowlton, K., Rogers, C., Dalan, D., Tierney, N., Elder, M.A., Filley, W., Shropshire, J., Ford, L.B., Hedberg, C., Fleetwood, P., Hovanky, K.T., Kavanaugh, T., Fulford, G., Vrtis, R.F., Patz, J.A., Portnoy, J., Coates, F., Bielory, L., Frenz, D., 2011. Recent warming by latitude associated with increased length of ragweed pollen season in central North America. Proc. Natl. Acad. Sci. 108 (10), 4248–4251. https://doi.org/10.1073/pnas.1014107108.

Ziska, L.H., Makra, L., Harry, S.K., Bruffaerts, N., Hendrickx, M., Coates, F., Saarto, A., Thibaudon, M., Oliver, G., Damialis, A., Charalampopoulos, A., Vokou, D., Heiđmarsson, S., Guđjohnsen, E., Bonini, M., Oh, J.W., Sullivan, K., Ford, L., Brooks, G.D., Myszkowska, D., Severova, E., Gehrig, R., Ramón, G.D., Beggs, P.J., Knowlton, K., Crimmins, A.R., 2019. Temperature-related changes in airborne allergenic pollen abundance and seasonality across the northern hemisphere: a retrospective data analysis. Lancet Planet. Health 3 (3), e124–e131. https://doi.org/10.1016/S2542-5196(19)30015-4.