



Trends in pollen season characteristics of *Alnus*, Poaceae and *Artemisia* allergenic taxa in Bratislava, central Europe

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Abstract Over the period 2002–2019, air temperature and precipitation significantly increased regionally for Bratislava, which could lead to phenological changes in some plant species. This study aimed to analyse the changes in the intensity, timing, and duration of pollen seasons of three allergological important plant taxa (*Alnus*, Poaceae, *Artemisia*) in the study area over 18 years. The pollen sampling was performed using a Hirst-type sampler. Mann–Kendall tau test was used to determine trends in pollen season characteristics, while Spearman’s correlation analysis was used to identify the relationships between the characteristics of pollen seasons and both air temperature and precipitation trends. The notable changes in the pollen-season-related features were observed for all analysed taxa. The *Alnus* pollen season now reaches the peak earlier and its intensity is rising in line with the summer-autumn temperature increasing trend, while unexpectedly intensity and duration of the *Artemisia* pollen season are declining in line with the increased precipitation and/or temperature trends. On the other hand, the intensity of the Poaceae pollen season is also declining, however, without statistically significant correlations with recorded increases in

meteorological parameters considered. This phenomenon is probably related to both the reduction of the area of grasslands due to urbanization and the implementation of effective maintenance of urban green areas (e.g., timely mowing preventing the repeatedly flowering of grasses).

Keywords Pollen grains · Temperature trends · Precipitation trends · Aeroallergens · Slovakia

1 Introduction

Increased surface air temperature in the last few decades is a well-known global phenomenon, which affects the timing of plant life-cycle events, and the related production of pollen and its dispersion in the air (Bogawski et al., 2014; Menzel et al., 2006; Tedeschini et al., 2006; van Vliet et al., 2002; Walther et al., 2002). The earlier start of flowering will have consequences for the start of the pollen season and thus for the start of the pollinosis season. Many European studies report changes in the pollen-season-related features of different plant taxa, e.g., *Alnus* (Myszkowska et al., 2010; Rodríguez-Rajo et al., 2011; Lindt et al., 2016), *Corylus* (Myszkowska et al., 2010), *Betula* (Emberlin et al., 2002; Estrella et al., 2006; Frei & Gassner, 2008; Lind et al., 2016; Rasmussen, 2002; Yli-Panula et al., 2009), *Quercus*

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(Jato et al., 2015), Poaceae (Rodríguez et al., 2014), and weed taxa (Bogawski et al., 2014) over time. In this context, recent climate changes may influence the timing, duration, and intensity of the pollen seasons of phytoallergens and thus contribute to a heightened risk of allergic respiratory diseases (Beggs, 2004; Bousquet et al., 2004; D'Amato et al., 2000). However, the airborne pollen concentration is highly variable over the pollen season and except for climate and weather variable depends on several other factors, such as e.g., topography, source vegetation abundance and its proximity to pollen sampler, or the aerodynamic features of pollen grains (Ciani et al., 2020). Several reports suggest that an increase in pollen season intensity or duration is accompanied by an increase in pollen allergy severity or prevalence (Ault, 2004; Clot, 2003; Ziska et al., 2003). Hence, the understanding of how recent climate change impacts the pollen-season-related features of allergenic plant taxa is of interest to both scientists and health care providers to assess future health impacts and current preventive measures.

The presence of the inhalation allergic reactions and asthma events during the vegetation period are associated with three distinct seasonal sources of plant pollen; trees (winter-spring), grasses (spring-summer), and weeds (summer-autumn). According to the data from the Public Health Office (<http://alergia.sk>), in south-west Slovakia, *Alnus* trees (*A. glutinosa* L. and *A. incana* L.) are one of the earliest producers of highly allergenic pollen (Hrubiško, 1998; Ščevková et al., 2010) and may begin to release pollen as early as mid-January to mid-March in Bratislava area. *Alnus* is a member of the *Alnus-Fraxinus* submontane floodplain forests which occur throughout the whole country. Grasses of the Poaceae family, the major cause of pollinosis in Europe (D'Amato et al., 2007) bloom from late April till the end of July. In Bratislava, the most significant grass pollen sources are *Arrhenatherum elatius* (L.) P. Beauv. ex J. Presl et C. Presl, *Lolium perenne* L., *Bromus hordeaceus* L., *B. sterilis* L., *Cynodon dactylon* Pers., *Dactylis glomerata* L., *Elytrigia repens* (L.) Nevski., *Festuca rubra* L., *Hordeum murinum* L., *Poa pratensis* L., and *Poa annua* L., which are the dominant species in urban lawns and at the edges of untreated habitats (Feráková & Jarolímek, 2011). Other grass pollen sources are cereals especially *Secale cereale* L. and *Zea mays* L. that are grown in the outskirts of the city. Grass pollen is responsible for most respiratory allergic reactions in

the pollen-sensitive population of Bratislava (Hrubiško, 1998; Ščevková et al., 2015). *Artemisia* is a typical and widespread weed. *Artemisia vulgaris* L. (mugwort), the most common species of this genus in Slovakia, bloom from late July till the end of September (Ščevková et al., 2010). From the allergological point of view, *Artemisia* is considered the most allergenic weed pollen allergen in the Bratislava area (Hrubiško, 1998). Most species of *Artemisia* commonly grow on ruderal and disturbed soils, in urban and suburban areas, at industrial and building sites, in rural areas, and the countryside along roads.

Meteorological parameters such as air temperature and precipitation can directly influence growth and reproduction in plants, and airborne pollen concentrations can fluctuate seasonally. However, we do not understand how long-term changes in weather parameters affect pollen-season-related attributes. Besides, climate change may influence the pollen-season-related characteristics of different taxa in different ways. Therefore this study aimed to analyze the incidence of changes in air temperatures and precipitation values recorded over time in Bratislava on intensity, timing, and duration of the *Alnus*, Poaceae, and *Artemisia* pollen seasons.

2 Materials and methods

2.1 Study area

Bratislava, the capital of Slovakia, with around 430,000 inhabitants is located in the south-western part of Slovakia (48°08' N, 17°06' E) on the boundary between the Malé Karpaty Mountains and the Pannonian Lowlands. Its climate is temperate continental with warm summers and cold winters (Holec et al., 2020). The lowest and highest mean monthly temperature is in January (0.1 °C) and July (21.2 °C), respectively, and the annual rainfall is 667.2 mm (1983–2019 average, data from the Meteorological Observatory of the Department of Astronomy, Physics of the Earth and Meteorology of the Comenius University in Bratislava). The city is surrounded by farmland areas (mainly cereal fields and vineyards), deciduous Carpathian forests, and remnants of alluvial forests (Feráková & Jarolímek, 2011).

2.2 Aerobiological data

Airborne pollen concentrations of three plant taxa in Bratislava were recorded over 18 consecutive years (2002–2019), using a Burkard 7-day volumetric pollen trap (Hirst, 1952). For the evaluation of allergenic plants, we have chosen those producing characteristic and easily determinable pollen with both high allergenic potential and abundant occurring in the vegetation in Bratislava. To monitor the whole vegetation period we have selected representatives of each phytoallergen group (trees, grasses, weeds) from various phenological periods. We have chosen the genus *Alnus* (*A. glutinosa* and *A. incana*) of trees, the whole Poaceae family of grasses, and the genus *Artemisia* to represent weeds. The mentioned taxa represent one of the most aggressive phytoallergens in Bratislava (Hrubíško, 1998). The Burkard sampler was situated on the roof of the Department of Botany, Faculty of Natural Sciences at 10 m a.g.l. The methodology used was performed according to the standard method adopted by the British Aerobiology Federation (1995). Pollen grains were counted in 12 transversal traverses per slide under a light microscope at $400\times$ magnification following the methods outlined by Ščevková et al. (2010). Pollen concentration was expressed as a number of pollen grains per cubic meter of air (pollen/m³).

To analyse the trends in pollen-season characteristics the main pollen season (MPS) of each taxon was considered. The MPS was established according to the method by Peel et al. (2014), which define the start (end) of the MPS as the first (last) day with a daily average equal to or greater than 10 pollen/m³.

Annual trends of the following characteristics of the MPS were analysed: (1) the Seasonal Pollen Integral (SPIn)—sum of the average daily pollen concentrations recorded over the MPS (Galán et al., 2017), (2) peak daily pollen value—the highest daily pollen concentration, (3) onset, (4) the peak date (the day on which the maximum daily pollen concentration was recorded), (5) ending date, and (6) duration (number of days) of the MPS. SPIn and peak value reflect the intensity of pollen season, whereas the timing of pollen season is expressed by onset, peak, and end dates of the MPS (these data were converted to the day of the year from 1 January—DOY).

2.3 Meteorological data

The meteorological variables considered in the present study were the surface air temperature (°C) and precipitation (mm). Temperature trends were investigated at the nine-month interval (from February to October), six-month interval (from June to October), and five-month interval (from October to February) while precipitation trends were investigated at the two-month interval (from April to May), and three-month interval (from September to November). Meteorological data were recorded at the meteorological observatory of the Department of Astronomy, Physics of the Earth and Meteorology of the Faculty of Mathematics, Physics and Informatics (48°09' N, 17°04' E, 182 m a. s. l.) situated over 800 m from the sampling site.

2.4 Data analysis

A nonparametric Mann–Kendall trend test was performed to evaluate the statistical significance of trends of all the aerobiological and meteorological variables considered during the study period. We applied this test because it does not require any strong distributional assumptions (e.g. normality) while being able to detect the presence of a variety of trends; without the need to specify in advance the form of the trend. The test “measures” the presence of a trend by the sample Kendall’s tau correlation coefficients between time and each variable considered. A positive or negative tau-value indicates the presence of an increasing or decreasing trend within a data series, respectively. When a significant trend was (p -value < 0.1) detected, we modelled it by a straight line regression model. This simple model was adopted because it used to perform well in similar situations and our data series was too short to prove the significance of a more involved model. To obtain the true slope of any existing linear trend, Theil–Sen’s nonparametric method was used (Theil, 1950), because it poses no distributional requirements on the error term of the straight-line regression model.

Spearman’s correlation coefficients (p -value < 0.5) were used to establish the relationship between the selected characteristics of pollen seasons of *Alnus*, Poaceae, and *Artemisia* taxa and meteorological variables. All data analyses were performed in the statistical software R (version 3.4.1).

3 Results

3.1 Meteorological data

During the study period (based on the results of mesoclimatic assessment of the temperature and precipitation conditions in the analysed area) a significant rise in mean, maximum, and minimum surface air temperature and precipitation values has been observed regionally for Bratislava, compared to long-term means (Table 1). During the analysed period, the highest average daily air temperature was recorded in 2018 and 2019 ($T_{\text{mean}} = 12.2$ °C), while 2010 was considered the coldest year ($T_{\text{mean}} 9.9$ °C). In terms of precipitation, the highest annual total ($P = 1088$ mm) was recorded in 2018 and the lowest ($P = 427$ mm) in 2003.

Mann–Kendall test and Sen’s method revealed the existence of five statistically significant temperature and precipitation trends (Table 2).

3.2 Aerobiological data

3.2.1 Timing of pollen seasons

Table 3 presents the features of the main pollen seasons of three analysed taxa during the study period. The *Alnus* pollen season usually started in the last fortnight of February (Table 3) and became earlier during the studied period, however, statistically insignificant (Table 4). Moreover, *Alnus* pollen season start dates show significant and negative correlations with both winter temperature and autumn precipitation trends considered ($r = -0.76, p < 0.001$ and $r = -0.51, p < 0.05$, respectively) (Table 5). On the other hand, Poaceae pollen season that usually started at the

Table 2 Significant temperature and precipitation trends in Bratislava (2002–2019) calculated from homogeneous series: Mann–Kendall trend test (test τ column), Sen’s slope estimation (Q column)

Meteorological series	τ	Q
T_{mean} February–October	0.46**	0.07
T_{mean} June–October	0.52**	0.07
T_{mean} October–February	0.29 ⁺	0.08
P April–May	0.34*	2.0
P September–November	0.37*	2.2

⁺ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$

beginning of May (Table 3) became delay over time, however, not statistically significant (Table 4) and show a significant and positive association with spring precipitation values ($r = 0.5, p < 0.05$) (Table 5). Hence, although the start of the grass pollen season did not show a statistically significant trend, we observed that with increasing rainfall in April–May period, the grass pollen season tends to start later.

Artemisia pollen season usually ended at the beginning of September (Table 3) and became earlier (-1.0 days/year, $p < 0.05$) during the studied period (Table 4). Moreover, significant and negative relationships were registered between the pollen season end dates and mean February–October daily average temperatures (Table 5).

The days with peak daily pollen levels of analysed taxa were usually recorded around the middle of the pollen seasons (Table 3). Significant and negative trends in peak dates were found for *Alnus* (-1.5 days/year, $p < 0.05$) and *Artemisia* (-0.4 days/year, $p < 0.05$). Besides, the significant and negative correlations were registered between peak dates of

Table 1 A summary of temperature and precipitation data at Bratislava for the study period 2002–2019 and long term means

Variable	2002–2019				1983–2014			
	Mean	Max.	Min.	SD	Mean	Max.	Min.	SD
T_{mean} (°C)	11.2	12.2	9.9	0.7	10.6	11.9	9.0	0.8
T_{max} (°C)	15.9	16.7	14.4	0.7	15.1	16.6	12.8	1.0
T_{min} (°C)	6.9	8.1	5.9	0.7	6.4	8.0	5.2	0.6
P (mm)	730.8	1088.0	462.8	174.6	643.6	964.4	426.8	112.4

T_{mean} mean air temperature, T_{max} maximum air temperature, T_{min} minimum air temperature, P annual total precipitation, SD standard deviation

Table 3 Descriptive statistics of pollen-season-related characteristics of *Alnus*, Poaceae and *Artemisia* pollen types in Bratislava, 2002–2019

Characteristics of pollen season	<i>Alnus</i>				Poaceae				<i>Artemisia</i>			
	Mean	Max.	Min.	SD	Mean	Max.	Min.	SD	Mean	Max.	Min.	SD
Start date (DOY)	56	76	11	15.9	127	139	104	8.6	214	225	178	9.5
End date (DOY)	86	108	65	12.13	206	258	188	21.0	244	268	233	9.7
Duration (days)	32	64	7	11.8	81	136	54	22.2	31	70	13	14.3
Peak date (DOY)	66	90	43	12.7	154	181	135	14.2	226	233	219	4.2
Peak value (pollen/m ³)	305	707	21	225.5	83	248	25	52.0	61	129	22	34.3
SPI _n (pollen*day/m ³)	1,562	3759	100	1,037.6	1591	2511	728	642.2	586	1152	113	323.8

Table 4 Mann–Kendall trend test (test *tau* column) and Sen's slope estimate (*Q* column) of pollen season parameters of *Alnus*, Poaceae and *Artemisia* pollen types in Bratislava, 2002–2019

Pollen season parameter	<i>Alnus</i>		Poaceae		<i>Artemisia</i>	
	<i>tau</i>	<i>Q</i>	<i>tau</i>	<i>Q</i>	<i>tau</i>	<i>Q</i>
Start date (DOY)	− 0.23	− 0.8	0.16	0.2	0.27	0.2
End date (DOY)	− 0.07	− 0.3	− 0.27	− 1.1	− 0.4*	− 1.0
Duration (days)	− 0.02	0.1	− 0.44*	− 1.7	− 0.4*	− 1.3
Peak date (DOY)	− 0.4*	− 1.5	0.13	0.4	− 0.34*	− 0.4
Peak value (pollen/m ³)	0.31⁺	16.3	− 0.33⁺	− 3.1	− 0.68***	− 3.8
SPI _n (pollen*day/m ³)	0.18	44.6	− 0.36*	− 59.2	− 0.49**	− 40.2

⁺*p* < 0.1, **p* < 0.05, ***p* < 0.01, ****p* < 0.001

mentioned pollen types and the majority of temperature trends and autumn precipitation trend (Table 5).

3.2.2 Duration of pollen seasons

The mean pollen season duration of *Alnus* and *Artemisia* pollen types was similar; 32 and 31 days, respectively, whereas the Poaceae pollen season was longer; the average duration was 81 days (Table 3). Significant shortening of pollen seasons was noted for Poaceae (− 1.7 days/year, *p* < 0.05) and *Artemisia* (− 1.3 days/year, *p* < 0.05) (Table 4). The results of correlation analysis revealed significant negative relationships between duration of pollen seasons of mentioned taxa and the majority of temperature trends considered (*r* value ranging from − 0.49, *p* < 0.05 to − 0.68, *p* < 0.01) and/or autumn precipitation trends (*r* = 0.51, *p* < 0.05) (Table 5).

3.2.3 The intensity of pollen seasons

The highest SPI_n values recorded in the season were for Poaceae and *Alnus* (mean = 1591 and 1562 pollen*day/m³, respectively), whereas the highest peak daily value, was recorded for *Alnus* (mean = 305 pollen/m³) (Table 3). The *Alnus* pollen season has a tendency towards increasing intensity, but the only significant trend was for peak value (+ 16.3 pollen/m³, *p* < 0.1) (Table 4). A significant positive correlation was registered between the summer-autumn temperature trend and both the *Alnus* peak daily value and SPI_n (*r* = 0.73, *p* < 0.001 and *r* = 0.54, *p* < 0.05, respectively) (Table 5). On the other hand, the decreasing intensity of Poaceae and *Artemisia* pollen seasons was observed (Table 4). However, a significant correlation was found only between the summer-autumn temperature trend and both *Artemisia* SPI_n and peak daily value (*r* = − 0.55, *p* < 0.05) (Table 5).

Table 5 Spearman correlation coefficients between the pollen season parameters of *Alnus*, Poaceae and *Artemisia* taxa and meteorological series recorded in Bratislava (2002–2019)

Taxa	Time series	Pollen season parameter					
		Start date	End date	Duration	Peak date	Peak value	SPIn
<i>Alnus</i>	T _{mean} February–October	– 0.433	– 0.048	0.269	– 0.611**	0.307	0.067
	T _{mean} June–October	0.156	0.317	0.284	– 0.367	0.734***	0.54*
	T _{mean} October–February	– 0.762***	– 0.425	0.271	– 0.71***	0.275	0.005
	P April–May	– 0.042	0.162	– 0.146	– 0.016	0.346	0.2
	P September–November	– 0.508*	– 0.146	0.251	– 0.565*	0.072	– 0.096
Poaceae	T _{mean} February–October	0.007	– 0.529*	– 0.613**	– 0.331	– 0.041	– 0.319
	T _{mean} June–October	0.361	– 0.438	– 0.677**	0.069	– 0.219	– 0.356
	T _{mean} October–February	0.076	– 0.229	– 0.221	– 0.081	0.178	– 0.04
	P April–May	0.501*	0.051	– 0.189	0.613**	– 0.289	– 0.435
	P September–November	– 0.088	– 0.239	– 0.313	– 0.214	– 0.043	– 0.199
<i>Artemisia</i>	T _{mean} February–October	0.001	– 0.572*	– 0.588*	– 0.676**	– 0.356	– 0.375
	T _{mean} June–October	0.116	– 0.351	– 0.491*	– 0.596**	– 0.553*	– 0.552*
	T _{mean} October–February	0.029	– 0.446	– 0.535*	– 0.486*	– 0.283	– 0.434
	P April–May	– 0.08	– 0.103	– 0.009	– 0.107	– 0.427	– 0.4
	P September–November	0.151	– 0.43	– 0.51*	– 0.474*	– 0.296	– 0.342

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

4 Discussion

Recent climate change can modify the features of pollen seasons of different plant taxa in different ways. The present study focused on the most allergenic pollen types of trees, grasses, and weeds, *Alnus*, Poaceae, and *Artemisia*, respectively in the airborne spectrum of Bratislava, which, according to their climate sensitivity rank among high sensitive plant taxa (Makra et al., 2011). The results of the study revealed significant changes in pollen season characteristics of analysed taxa, however, less apparent for the timing of pollen seasons.

4.1 Timing of pollen seasons

Phenological characteristics, like an earlier onset of pollen dehiscence, are suitable bioindicator to help us track climate change (Ahas et al., 2002). The effect of global warming on the shift of plant phenology, including blooming and pollen release is well documented (Walther et al., 2002; Menzel et al., 2006; Cleland et al., 2007). Shifts in the pollen season timing of phytoallergens are likely to influence the timing of allergy outbreaks in pollen-sensitized individuals

(Bielory et al., 2012). In the present study, the start date of the analysed pollen seasons showed different trends depending on whether the pollen came from arboreal or herbaceous taxa. For *Alnus* (arboreal taxa) a trend towards an earlier start date was observed, whereas delayed start dates were noted for Poaceae and *Artemisia* (herbaceous taxa). However, these trends were statistically insignificant, probably due to that the time series data in this study are relatively few. Our results, however, are in line with some other researchers (Clot, 2003; Damialis et al., 2007), who concluded, based on the earlier start date of woody plants' pollen seasons, arboreal taxa to be more sensitive to climate change than herbaceous species. Besides, a trend towards an earlier peak date (– 1.5 days/year, $p < 0.05$) of *Alnus* pollen season over time was observed in the Bratislava area.

The flowering of plants that flower in winter or early spring is directly dependent on the corresponding surface air temperature. Frei (1998) observed that air temperature rise over a long-term period led to shift phenology, especially for temperature-dependent plants like trees blooming early in the springtime. Similar to previous studies (Jäger et al., 1996; Rasmussen, 2002), a clear correlation between the

pre-season air temperatures and the start dates of *Alnus* pollen season has been shown in the present study ($r = -0.762$, $p < 0.001$). Besides, rise summer precipitation values were accompanied with the advanced start of *Alnus* pollen season.

Contrary to *Alnus*, trends towards the delayed beginning of Poaceae and *Artemisia* pollen seasons were observed in the present study. Grass normally starts to flower in May when the temperature amplitude is much smaller than in winter-spring time. Besides, there is a lot of precipitation in May and therefore the start of the Poaceae pollen season may be delayed due to this factor. Indeed it was found in this study that the precipitation rise during the April–May period was accompanied by a delayed start of Poaceae pollen season.

On the other hand, we observed a trend towards an earlier end of the pollen season for all taxa considered, significant, however, only for *Artemisia*. The results of this study indicate that the observed earlier end of *Artemisia* pollen season might be caused by the increase in air temperature as temperature rise during the vegetation period accelerates anther opening and pollen release. It is worth noticing that a significant correlation was observed between *Artemisia* pollen season end date and daily mean temperatures in February–October ($r = -0.572$, $p < 0.5$), which significantly increased in Bratislava over the same period ($+0.07$ °C/year, $p < 0.5$). In contrast, a systematic pattern towards a delayed end of *Artemisia* pollen seasons was observed in Thessaloniki, Greece (Damialis et al., 2007), Poznań, Poland (Bogawski et al., 2014), and Stockholm, Sweden (Lind et al., 2016) over time, as a result of its earlier pollen season start date.

4.2 Duration of pollen seasons

Significant shortening of Poaceae and *Artemisia* pollen seasons was observed in Bratislava during the study period. The shorter pollen period of these taxa can be attributed to both the later start dates and earlier pollen season end dates. Moreover, significant negative correlations were noted between the duration of Poaceae or *Artemisia* pollen seasons and the majority of temperature trends considered. Rising temperatures observed in Bratislava accompanied by the lack of available water during the hottest summer period may result in faster depletion of pollen resources especially

for weeds flowering in the second fortnight of the summer and thus decrease the period of its pollen release. This is consistent with prior research study (Bartková-Ščevková, 2003) that consider hot and dry weather to be responsible for accelerating of plant development and pollen release as both pollen development and dehiscence are strongly affected by the air temperature and humidity. On the other hand, an increase in autumn precipitation levels ($+2.2$ mm/year, $p < 0.5$) has been accompanied by a significant shortening of the *Artemisia* pollen season as intense precipitation is associated with suppression of anthesis (Gross et al., 2019). The results of the other research studies, concerning the trend in the duration of the Poaceae and/or *Artemisia* pollen seasons over time, are rather inconsistent. For example, Bogawski et al. (2014), and Lind et al. (2016) observed lengthening of Poaceae and *Artemisia* pollen seasons, whereas other researchers (Clot, 2003; Damialis et al., 2007; Ruiz-Valenzuela & Aguilera, 2018) discerned no clear trend in the pollen season duration of the mentioned taxa. Bogawski et al. (2014) and Lind et al. (2016) associated the lengthening of mugwort and grass pollen seasons in Poznań and Stockholm, respectively over a long-time period to climate change.

4.3 The intensity of pollen seasons

SPIn is an important marker that directly correlates with respiratory allergy disease prevalence and, consequently, healthcare and financial costs. As regards quantity-related pollen season characteristics (SPIn and daily peak pollen values), *Alnus* tends to increase the intensity, however statistically insignificant, whereas for Poaceae and *Artemisia* trends towards less intense pollen seasons were observed during the study period. Similarly to our results, the *Alnus* total annual pollen counts show an increasing trend in other European countries, as has been reported by other researchers (Clot, 2003; Damialis et al., 2007; Lind et al., 2016). An increase in *Alnus* pollen season intensity seems to be associated with temperature rise as a significant positive relationship between *Alnus* SPIn and mean June–October air temperatures preceding the *Alnus* pollen season was observed in the study area. In general, the increasing trends for the pollen season intensity of arboreal taxa are more widespread than for herbaceous taxa (Damialis et al., 2007; Marchesi, 2020; Ziello et al., 2012). Likewise,

increasing trends in SPIn were observed for several arboreal taxa in central Europe, (Jäger et al., 1996—*Corylus*, *Ulmus*, and *Pinus*; Clot, 2003—*Alnus* and Cupressaceae; Makra et al., 2011—Taxaceae/Cupressaceae and *Populus*). Also in other European areas, positive trends in SPIn have been observed for different tree taxa (Damialis et al., 2007; Ribeiro et al., 2008; Tormo-Molina et al., 2010; Alcázar et al., 2011; Lindt et al., 2016; Galán et al., 2016; Ruiz-Valenzuela & Aguilera, 2018; Marchesi, 2020).

The total annual Poaceae pollen concentration in the atmosphere of Bratislava has, similarly to in areas with Mediterranean climate—Spain (Jato et al., 2009), Turkey (Acer et al., 2017), and Italy (Marchesi, 2020) descending trend, presumably partly due to changes in the maintenance of urban greenery, e.g., regular mowing preventing the repeatedly blooming of grasses. However, taking into consideration the fact that crops are important sources of Poaceae pollen (García-Mozo, 2017) we suppose, that the loss of agricultural land use areas, due to the increased urbanization rate in the last decades might be also responsible for the decrease in Poaceae SPIn in the study area. Similarly to our results, (García-Mozo et al., 2016) pointed out that the decrease in cereal production could account for the decreasing trend in Poaceae pollen season intensity in Córdoba (Spain) over the period 1996–2010. On the other hand, the decrease in grass pollen concentration might also be associated with increased precipitation in the spring-time as grasses bloom mainly in May and June, the months with the highest amount of precipitation, and precipitation substantially reduces airborne pollen quantity by both rain-out and wash-out mechanisms. However, no statistically significant association between Poaceae SPIn and precipitation was observed in the present study. On the other hand, some other researchers, e.g., Spieksma et al. (2003), Lindt et al. (2016), Ruiz-Valenzuela & Aguilera (2018), observed no significant trend in Poaceae pollen season intensity, over the long-term study period.

The descending trend observed for *Artemisia* SPIn can be explained by (1) the shortening of *Artemisia* pollen season, (2) the lack of available water during the hottest summer period or (3) the disappearance of fallow areas (former habitats of *Artemisia* species) due to their regular reaping and mowing or in-building. Besides, a significant negative association was observed between *Artemisia* SPIn and the mean

June–October daily air temperatures. A few studies have examined trends in *Artemisia* pollen season intensity over time, and related these to the trends in temperature over the same periods. Similarly to our results, a significant decrease in the *Artemisia* pollen season intensity over time associated with the increase in the mean July–September daily minimum temperatures was observed in Poznań (Bogawski et al., 2014), the area with similar climatic conditions than in Bratislava. Contrary to our results, in Thessaloniki, the area characterized by warm Mediterranean climate Damialis et al., (2007) observed trends towards increasing intensity in *Artemisia* pollen season over the period 1987–2005. Mentioned researchers associated the increasing patterns of airborne pollen abundance with higher pollen production rather than longer seasons. In contrast, a significant shortening of *Artemisia* pollen seasons accompanied by the decrease in SPIn was observed in our study.

5 Conclusion

Pollen seasons of *Alnus*, Poaceae, and *Artemisia* allergenic taxa in Bratislava changed during the 18 years; however, the trends of these changes are not uniform across all analysed pollen types. The pollination period now ends earlier for *Artemisia*, lasts shorter for Poaceae and *Artemisia*, and reaches the peak earlier for *Alnus* and *Artemisia*. As regards the intensity of pollen seasons, a significant rising trend in *Alnus* peak value and declining trends in Poaceae and *Artemisia* SPIn and peak values were observed over the study period. Furthermore, significant relationships were observed between several pollen season features of analysed taxa and some of the temperature and/or precipitation trends considered. It has to be emphasized, however, that the results of the correlation analyses are only an indication but this cannot be considered yet a clear proof of the assumed causal relationship. The present study shows similarities as well as differences with other studies that can be attributed mainly to different both geographical location and availability of pollen data time series. As a summary, it is possible to affirm that, the shifts in several features of pollen seasons of analysed taxa seem to reflect the recent change in air temperature and/or precipitation. However, the reasons for the trend towards a decrease in Poaceae and *Artemisia*

pollen season intensity cannot be explained unambiguously by the present study.

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Declarations

Conflict of 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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