



Do the threats of alder and birch allergenic pollen differ within an urban area?

Katarzyna Borycka, Idalia Kasprzyk*

University of Rzeszów, Department of Ecology and Environmental Biology, 4 Żelwerowicza St., 35-601 Rzeszów, Poland

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ABSTRACT

Currently, the increasing frequency of inhalant allergy is often linked to the urbanization effect. The pollen forecasts for a given city are most often prepared using data from one aerobiological station. However, there is evidence that the pollen concentrations in the air might differ depending on the city area and the height of the pollen trap. This study evaluated the spatial differences in the daily concentrations of alder and birch pollen grains in an urban area in relation to the proximity of the pollen sources and meteorological parameters. Pollen grains were sampled in Rzeszów in 2014–2016 by three volumetric traps located at the roof and nose levels in two city areas that differed in the numbers of alder and birch trees. The daily pollen concentrations were categorized into three allergy symptom thresholds. The relationship between the daily pollen concentrations and meteorological variables was examined using a redundancy analysis and circular statistics. There were spatial differences in the pollen season intensity and, to a lesser extent, the variability in its course. Generally, higher concentrations were registered at the roof level and in the city suburbs than at the nose level and in the downtown area where alder and birch trees were less numerous. Despite the spatial variability of the pollen concentrations and the differences in the proximity and abundance of pollen sources, the risks for allergy sufferers were similar throughout the city. It was concluded that the main cause of this phenomenon is the high dispersal abilities of *Alnus* and *Betula* pollen grains. Although temperature seems to be a crucial factor that influences the airborne pollen of both taxa, several weather variables were found to have complex impacts on the daily concentrations.

1. Introduction

The increasing frequencies of allergic respiratory diseases are often linked to urbanization effects (Šauliė et al., 2016). The reason might be not only exposure to air pollution components themselves (especially PM_{2.5}) but also the interactions between the particulate matter and a surface of pollen grains (Sénéchal et al., 2015). People living in urban areas are more affected by pollen-induced allergies than those living in rural environments (Timm et al., 2016), and some studies have suggested that long-term exposure to traffic-related air pollutants results in increased risks of plant pollen sensitivity (Wyler et al., 2000). Currently, widening urban green spaces is of particular interest when a majority of the population lives in cities, as green spaces improve the quality of life by directly influencing the health and well-being of the population as well as by improving air quality and microclimate conditions (Cariñanos and Casares-Porcel, 2011). Urban greenery is the most important source of pollen, and allergenic plant species can constitute up to two-thirds of urban greenery and therefore negatively

affect human health (Cariñanos et al., 2017).

The standard aerobiological monitoring for pollen-induced allergy prediction usually involves one volumetric spore trap per city, which is situated in the centre of the city in most cases (Nowosad et al., 2015; Rojo et al., 2015). However, there is evidence that the pollen concentrations in the air might differ depending on the city area (Rodríguez-Rajo et al., 2010; Fernández-Rodríguez et al., 2014a) as well as the height of the pollen trap (Speksma et al., 2000; Fernández-Rodríguez et al., 2014b). These differences might be caused by variations in the topoclimate, local topography, land use arrangements and street canyon configurations (Gonzalo-Garijo et al., 2006; Peel et al., 2014), which determine the air movement (Berkowicz et al., 1996) and influence the pollen transport and deposition within a city (Peel et al., 2014). The concentration altitudes are also strongly influenced by the proximity and abundance of local pollen sources (Cariñanos et al., 2002; Nowak et al., 2012; Fernández-Rodríguez et al., 2014a, b). The heights of plants that release pollen and the pollen dispersal abilities (Speksma et al., 2000; Rodríguez-Rajo et al., 2010) must also be

* Corresponding author.

E-mail addresses: katarzyna.a.borycka@gmail.com (K. Borycka), idalia@univ.rzeszow.pl (I. Kasprzyk).

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considered. The pollen of some taxa disperse in the air easily and despite the dilution of the grains, their concentrations could remain high in areas far from the source of release (Gonzalo-Garijo et al., 2006). The pollen of other taxa with low dispersal abilities fall rapidly and act only locally near the source of release (Cariñanos et al., 2002; Nowak et al., 2012; Alcázar et al., 2016).

The issue that is important to allergy sufferers is that pollen traps are most often located on roofs to reflect the regional aerobiological situation. However, some studies have indicated different pollen concentrations at the nose level than at the roof level (Tormo Molina et al., 2013; Peel et al., 2014; Alcázar et al., 2016). Consequently, the thresholds for provoking allergy symptoms that were distinguished based on roof level concentrations (de Weger et al., 2013) do not reflect the true danger for allergy patients. This aspect is very rarely studied and should be considered when preparing pollen forecasts.

Among the many allergenic pollen types, the tree taxa *Alnus* and *Betula* are characterized by the high clinical relevance of their allergens (Šauliune et al., 2016). The *Alnus* and *Betula* species are among the most frequent in urban spaces (Cariñanos and Casares-Porcel, 2011; Kuchcik et al., 2016) and have some of the highest allergenicity indexes (Cariñanos et al., 2017). Moreover, their abundance in Polish broad-leaved forests is among the highest in Europe (Skjøth et al., 2008). Alder and birch pollen grains are small (in average 20–25 µm) (Rantio-Lehtimäki, 1995); therefore, they easily move throughout an urban space because of their high dispersal abilities.

The main research problem is the spatial differentiation of the daily concentrations of allergenic alder and birch pollen grains in an urban area in relation to the proximity of the pollen sources. For this reason, we conducted aerobiological monitoring in two city areas and at two heights and estimated the abundances of *Alnus glutinosa* and *Betula pendula* trees. It has been assumed that significant differentiations between stations would not exist throughout the pollen season, but the pollen concentrations would be higher in the areas where the pollen sources are more numerous. Are there local differences in the aero-allergen risks for citizens? This problem was examined by evaluating the number of days with concentrations above the threshold values at the roof and nose levels and in two city areas. Furthermore, this research aimed to examine the comprehensive influence of meteorological parameters on the daily pollen concentrations.

2. Materials and methods

2.1. Study area

The study was carried out in Rzeszów, which is a middle-size city in southeast Poland (50°01'45"N, 22°00'57"E; Fig. A1). For most of the year, the region is influenced by polar-maritime and polar continental air masses (Woś, 2002). In 1997–2016, the coldest month in Rzeszów was January with a mean temperature of -2.0 °C, and the warmest month was July with a mean temperature of 19.6 °C. The mean annual temperature was 8.9 °C. Over this period, the total mean precipitation was approximately 700 mm, with minimum values in January and February (37 and 35 mm, respectively) and maximum values in July (119 mm) (Tutiempo Network, 2017).

We located two sampling stations that were approximately 3 km apart in the downtown area and the city suburbs (Fig. 1). The downtown is a densely built-up area where blocks of flats and industrial buildings predominate. There are small groups of ornamental trees within the estates, and single trees or formed hedges are along the streets. There are more green spaces in the city suburbs than in the centre. Forests predominated by silver birch occur on the surrounding slopes. In addition, black alder and willow trees are numerous on small brooks. Single-family houses with gardens are the predominant buildings in this area.

A. glutinosa (L.) Gaertn. (black alder) and *Betula pendula* Roth. (silver birch) trees were frequently noted in the area of study (Borycka

et al., 2017a). Silver birch is often planted due to aesthetic values, fast growth and small environmental requirements. It is frequent in urban parks, in urban forests, in a densely built-up area, as well as along the streets. Black alder prefers moist ground, so in contrast to the birch, it is not typical urban tree and is not planted in the city. However, a large part of the Rzeszów area is located in the Wisłok valley, which makes the groundwater level high. Moisture conditions favor the occurrence of black alder, especially besides the small flows that are numerous in the city suburbs. Thus it can be considered as often found in the city, although it is rare in a built-up area. It was estimated that the number of black alder trees in the 1 km buffer around the aerobiological stations in the city suburbs was approximately 220 individuals, and they usually form dense groups near the brooks. No black alder trees were noticed in the downtown area. According to the estimation downtown, there were 580 trees of silver birch, and they grew predominantly as solitaires or in small groups (up to 25 individuals). In the suburbs, approximately 1800 individuals were found in the forms of small forests (groups of hundreds of individuals) or as small groups or hedges (Fig. 1).

2.2. Aerobiological data

The objective of the study was to measure the airborne pollen grains of *Alnus* and *Betula*. The pollen grains were sampled by three Hirst's type volumetric spore traps in the period from 2014 to 2016. One trap was located downtown at the roof level at 12 m a.g.l. (AS 1), and two others were located in the city suburbs: one at roof level at 12 m a.g.l. (AS 2) and the second at nose level at 1.5 m a.g.l. (AS 3). The arrangement of the experiment allowed us to compare samples from two different sites in the city (horizontal gradient) and two different heights at the same site (vertical gradient). Because of technical problems, we obtained aerobiological records for alder from only two stations (AS 1 and AS 2). The aerobiological sampling as well as the preparation of microscopic slides and the counting of grains were done according to the procedures described by Stach and Kasprzyk (2005). The pollen grains were identified to the genus level (*Alnus* and *Betula*). For further analysis, the raw data were converted to daily concentrations per cubic metre (pollen grains·m⁻³). The main pollen season (MPS) was determined according to criterion: the threshold values for allergy symptoms (de Weger et al., 2013). We assumed that the *Alnus* MPS began on the first day when the average daily pollen concentration reached the threshold value of 45 pg·m⁻³, and the MPS ended on the last day at this value. For *Betula*, we assumed that the threshold value was 30 pg·m⁻³. In 2016, three week after the end of the *Betula* pollination period (Borycka et al., 2017a) the concentrations substantially increased but as we earlier proved it was the result of long-distance transport (Borycka et al., 2017b). Therefore we did not take into consideration these days. We also distinguished the peak pollen dates (the day with the maximum concentration value in a year) and calculated SPIn index (the seasonal pollen integral; the sum of the average daily concentrations during the MPS - Galán et al., 2017). We also counted the number of days per year when the average daily concentrations exceeded the thresholds for allergy symptoms. Three threshold values were considered: no symptoms when the concentrations are below 45 and 30 pg·m⁻³ for alder and birch, respectively; 45–100 pg·m⁻³ for alder and 30–100 pg·m⁻³ for birch for the first symptoms; and above 100 pg·m⁻³ for both species for severe symptoms (de Weger et al., 2013).

2.3. Meteorological data

The meteorological station was situated in the city suburbs near AS 3 (Fig. 1). The following parameters were analysed: * minimum, maximum and mean temperature - T_{min}, T_{max}, T_{mean} (°C); * mean relative humidity - H (%); * total precipitation - P (mm); * actual sunshine duration - I (sh⁻¹), and * prevailing wind direction WD (°).

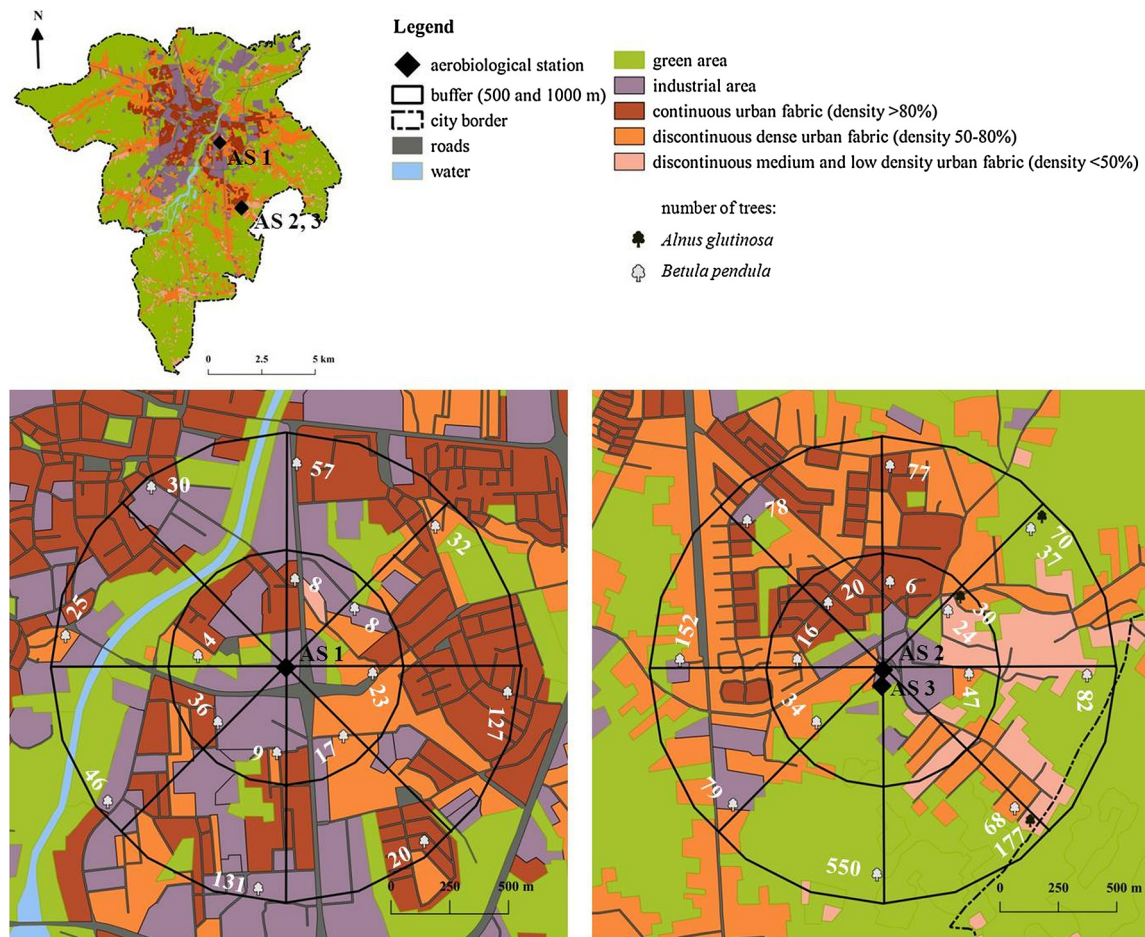


Fig. 1. Location of aerobiological against land use types.

2.4. Statistical analysis

The relationship between the daily pollen concentrations and meteorological variables was examined by means of redundancy analysis (RDA) using CANOCO 5.0. The RDA was preceded by a detrended correspondence analysis (DCA) to estimate the gradient length (multiples of the standard deviation - SD). For all ordination analyses, the aerobiological records were transformed into three categories according to the threshold values (see Section 2.2.): 1 - no allergic symptoms, 2 - first symptoms, 3 - severe symptoms. All weather variables used in the analysis were daily averages. The results were illustrated on the plots, where marks (circles and diamonds) correspond the pollen concentrations in a given day, and the larger their size, the higher the concentration. The stations were presented as black arrows and the meteorological parameters as white arrows. The longer white arrows the stronger relationships among weather parameter and pollen concentrations. The significance of each meteorological variable was tested using an F-test at the $\alpha \leq 0.05$ significance level. Wind direction is a circular variable so it cannot be use in RDA analysis. The influence of this parameter on the pollen concentrations was detected by the circular-linear correlation according to the formula described by Zar (1999).

The normality of the daily concentration values was checked by a Shapiro-Wilk test. The frequency distributions of the data were not normal; thus, the nonparametric Spearman correlation coefficient was used to determine whether synchronization of the daily pollen concentrations between the aerobiological stations existed (significance level $\alpha \leq 0.001$). That test was done using Statistica 13.0 software.

3. Results

3.1. The course and intensity of pollen seasons - spatial differentiation

In Rzeszów, the earliest start date of the *Alnus* MPS in the period from 2014 to 2016 was on 9th February, and the latest start date was on 28th February (Table 1). The end of the MPS ranged from 15th March to 30th March. The start dates were characterized by slightly higher variability than the end dates, and the differences between the years were 19 and 15 days, respectively. The MPS lasted from 22 to 51 days. The earliest peak pollen concentrations occurred on 23rd February, and the latest occurred on 13th March. The start, the end and the length of the MPS as well as the peak days were strongly synchronized between the two stations in all study years. The greatest difference was in 2016 when the seasons were very irregular at both sites (Fig. 2A). While the MPS in 2016 started on the same day at the two stations, the end of the MPS differed by 5 days; thus, the length of the MPS was longer at AS 2. The difference among the peak dates was 19 days. On the day with the maximum concentration at AS 2, the concentration at AS 1 was also very high but not the highest. On the day with the maximum concentration at AS 1, the concentration at AS 2 was also very high and was the second highest value of the year (Fig. 2A).

The SPIn values varied from 2931 to 13096 pg-day·m⁻³; the highest value occurred in 2016, and the lowest occurred in 2015. The seasonal peak values varied from 522 to 1404 pg·m⁻³. Although the average daily concentrations clearly differed between stations, the synchronization of the course of the MPS was very high. The Spearman correlation coefficients ranged from 0.9207 to 0.8069 (Table A1(A)). The daily concentrations, SPIn and peak values obtained from the roof level were

Table 1

The descriptive characteristics of the *Alnus* main pollen season; AS1- pollen trap located downtown at the roof level, AS 2- pollen trap located at the roof level in suburbs; MPS- the main pollen season; SPIn- the seasonal pollen integral.

year	station	MPS				seasonal peak	
		start	end	SPIn [pollen·day·m ⁻³]	length [days]	date	concentration [pollen grains·m ⁻³]
2014	AS 1	14.02	15.03	6847	30	10.03	795
	AS 2	15.02	15.03	10914	29	10.03	1346
2015	AS 1	28.02	21.03	2931	22	11.03	603
	AS 2	28.02	21.03	3660	22	8.03	522
2016	AS 1	9.02	25.03	8388	46	13.03	1013
	AS 2	9.02	30.03	13096	51	23.02	1404

generally higher in the city suburbs (AS 2) than in the city centre (AS 1) with the lowest differences in 2014 (Figs. 2 and A2(A), Table 1). During the MPS, higher daily concentrations at AS 1 occurred for only a few days from 5 days in 2014 to 8 days in 2015.

In 2014–2016, the earliest start date of the *Betula* MPS was on 29th March, and the latest start date was on 13th April (Table 2). The earliest end of the MPS occurred on 30th April, and the latest occurred on 7th May. The start dates were characterized by greater variability than the end dates, and the differences between the years were 15 and 9 days, respectively. Nevertheless, the MPS dates were almost identical at each station in any given year. The highest difference of 8 days was noted for the end of the MPS in 2014. The length of the MPS was the parameter with the greatest variability among years. The MPS lasted from 18 to 40 days. The earliest peak pollen concentrations occurred on 6th April, while the latest peak concentrations occurred on 23rd April, and the date was the same for all stations in only 2014. There was a 7-day shift in the dates with the peak pollen concentrations between stations in 2015 and 2016 (Fig. 2B).

The SPIn values strongly differed and reached 2842 to 42927 pg·day·m⁻³, with the highest values in 2016 and the lowest values in 2015. The seasonal peak values varied from 496 to 9908 pg·m⁻³. The average daily concentrations were significantly correlated between stations at the roof level as well as between stations at the roof and nose levels in the suburbs. The Spearman correlation coefficients between AS 1 and AS 2 were from 0.9656 to 0.8815, and the coefficients between AS 2 and AS 3 were from 0.9888 to 0.8834 (Table A1(B)). As in the case

for *Alnus*, the daily concentrations and SPIn values obtained from the roof level were generally higher in the city suburbs (AS 2) than in the city centre (AS 1) with the exception of 2015 (Figs. 2B and A2(B), Table 2). In the vertical gradient (Figs. 2B and A2(C), Table 2), higher concentrations were noted at the roof level than at the nose level but also with the exception of 2015. In this year, the SPIn values were almost equal, and there were more days with higher daily concentrations at the nose level than at the roof level.

The number of days per year with average daily concentrations above the thresholds for allergy symptoms strongly differed among the years. The number of days above the thresholds ranged from 16 to 32 days for *Alnus* (Fig. 3A) and from 17 to 39 days for *Betula* (Fig. 3B). For any given year, the differences between the stations were small. The highest difference for alder was noted in 2016 when the number of days above the threshold was 4 days higher at AS 2 than at AS 1. In 2014, the days above the threshold for birch were 5 days more at AS 2 than at AS 3 and 11 days more at AS 2 than at AS 1. Noticeable differences appeared one year when we differentiated between the two thresholds levels for alder. In 2015, although the number of days with daily concentrations above the thresholds for allergy symptoms was equal at both stations, 6 more days with concentrations of 45–100 pg·m⁻³ were registered at AS 1 than at AS 2 and 6 more days with concentrations above 100 pg·m⁻³ were registered at AS 2 than at AS 1. In the case of both species, 2015 was the least severe for allergy sufferers.

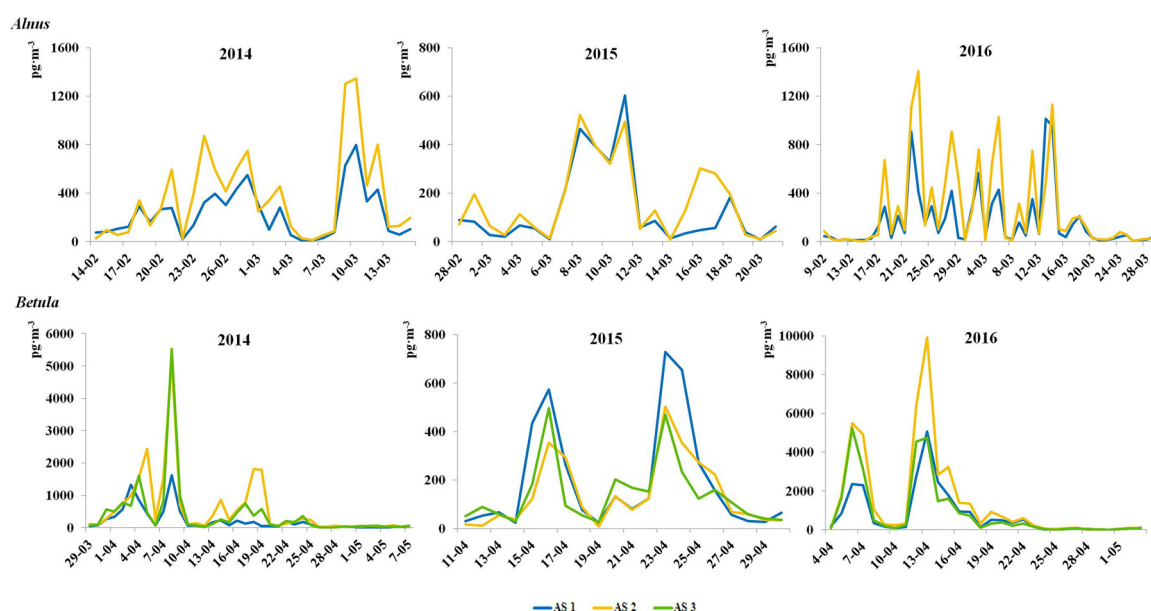


Fig. 2. The daily concentrations of the *Alnus* and *Betula* airborne pollen in 2014–2016 in Rzeszów; AS1- pollen trap located downtown at the roof level, AS 2- pollen trap located at the roof level in suburbs, AS 3- pollen trap located at 1.5 m a.s.l. in suburbs.

Table 2

The descriptive characteristics of the *Betula* main pollen season; AS1- pollen trap located downtown at the roof level, AS 2- pollen trap located at the roof level in suburbs, AS 3- pollen trap located at 1.5 m a.s.l. in suburbs, MPS- the main pollen season; SPIn- the seasonal pollen integral.

year	station	MPS				seasonal peak	
		start	end	SPIn [pollen·day·m ⁻³]	length [days]	date	concentration [pollen grains·m ⁻³]
2014	AS 1	29.03	29.04	8485	32	8.04	1623
	AS 2	29.03	7.05	22512	40	8.04	5160
	AS 3	29.03	7.05	16383	40	8.04	5517
2015	AS 1	11.04	30.04	3877	20	23.04	728
	AS 2	13.04	30.04	2847	18	23.04	503
	AS 3	11.04	30.04	2842	20	16.04	496
2016	AS 1	4.04	3.05	22824	30	13.04	5058
	AS 2	4.04	3.05	42927	30	13.04	9908
	AS 3	4.04	3.05	26922	30	6.04	5225

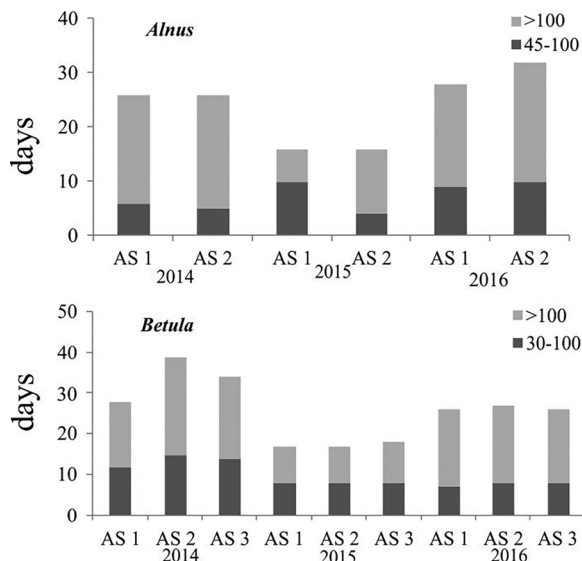


Fig. 3. The frequency of days with average daily *Alnus* (A) and *Betula* (B) pollen concentrations above the thresholds for allergy symptoms - comparison of two (A) or three (B) stations; AS1- pollen trap located downtown at the roof level, AS 2- pollen trap located at the roof level in suburbs, AS 3- pollen trap located at 1.5 m a.s.l. in suburbs.

3.2. Daily pollen concentrations - spatial differentiation and the impacts of weather

The comparison of the days with different average daily pollen concentrations expressed as categories between stations and in relation to the weather parameters were summarized in a RDA (Fig. 4A–C). The duration of MPS is longer than the pollination period therefore in the RDA plots the days of the MPS that overlapped with the pollination period are marked by circles. The diamonds in these figures indicate the days of the MPS when the trees did not pollinate in the study area but the pollen was registered in the air. The larger the size of the marks, the greater the pollen grains concentrations.

It was noted that the highest pollen concentrations of both taxa occurred in time when trees shed the pollen intensively. In the days outside of the *Alnus* pollination period, the daily concentrations were always below 100 pg·m⁻³ (Fig. 4A). For *Betula*, the pollen grain concentrations outside of the pollination period were often between 30–100 pg·m⁻³, and there were a few days with concentrations above 100 pg·m⁻³, especially in 2016. For birch, there were more days with concentrations between 30–100 pg·m⁻³ in 2014 than in other years. There were more days with concentrations between 30–100 pg·m⁻³ outside of the pollination period and slightly more days with

concentrations above 100 pg·m⁻³ during the pollination period at AS 2 and AS 3 than at AS 1 (Fig. 4B). Such substantial differences did not appear in other years and never in the case of alder. According to the first RDA axis, the course and intensity of the *Alnus* MPS were similar at the two stations (Fig. 4A). In the case of *Betula*, the course and intensity of the MPS were most similar between stations in 2015. In 2014 and 2016, AS 1 slightly stood out from AS 2 and AS 3 according to the first RDA axis.

The RDA revealed that temperature and relative humidity might be the most significant meteorological parameters that influenced the dynamics and intensity of the alder MPS. In 2014, the statistically significant parameters were mean humidity (Hmean), minimum temperature (Tmin) and maximum temperature (Tmax), and in 2015, they were Tmax and Hmean. In 2016, the percentage of explained variance was very low and none of the parameters were statistically significant at the $\alpha \leq 0.05$ level. Tmax and Tmean, as well as I had similar directions of correlation, and in 2014 and 2015, the increase of these parameters coincided with the increase in the number of days with high concentrations. The influence of Hmean and P was opposite (Fig. 4A). Taking into account three years, except Tmean all meteorological parameters were statistically significant. The impact of P and I were the strongest, but the direction of the correlations were opposite. Although for each year the most meteorological parameters were statistically significant, the cumulative percentage of the explained variance was low (from 15.03%–44.6%), of which the minimum input was the second axis (Table 3).

According to the RDA results, the main parameter that influenced the dynamics and intensity of the birch MPS might be temperature. Tmin was statistically significant in 2014, Tmax was statistically significant in 2015, and Tmean was statistically significant in 2016. The percentage of explained variance was extremely low and none of the meteorological parameters were statistically significant for all years together (Table 3). As in the case of alder, Tmax, Tmean and I had similar directions of correlation with the concentrations, while Hmean and P exhibited opposite directions (Fig. 4B and C). The Hmean exhibited the same direction of correlation as Tmax and Tmean in only 2014; however, its significance was lower. The increase in the number of days with higher concentrations usually coincided with the increases in Tmax, Tmean and I as well as the decrease of P; however, this correlation is not as clear as in the case of alder (Fig. 4B and C). In all cases the contributions of the second and third axes to the explained variance were minimal, which means that there is only a gradient along the first axis (Table 3).

The impact of wind direction on the daily pollen concentrations was weak or not significant what was confirmed by the circular-linear correlation coefficient r^2 . This coefficient was significant only for alder for AS 2 in 2014 (Fig. 5). In most cases the shapes of pollen roses and wind roses were different (Figs. 5 and A3).

4. Discussion

4.1. Spatial differentiation of the main pollen season course

In Poland, the timing of the start and end periods of the alder MPS are strongly differentiated (Rodríguez-Rajo et al., 2010; Piotrowska-Weryszko, 2013; Puc and Kasprzyk, 2013) because of the unstable weather conditions during the pollination period (Borycka et al., 2017a). Every few years, delays in the alder MPS and the peak of the pollen concentrations are registered in Poland; the MPS lasts until the last half of April and the peak day falls in the third quarter of March (Piotrowska-Weryszko, 2013; Nowosad et al., 2015). In 2014–2016, this delay was not registered in Rzeszów as the MPS fell in February and March and the peak concentrations occurred in the first or second quarters of March. In 2016, the season was extremely long; however,

this is not unusual in the Polish climate (Piotrowska-Weryszko, 2013). In Poland, the birch MPS usually begins in April and lasts until the beginning of May (Rodríguez-Rajo et al., 2010; Grewling et al., 2012), and this is in accordance with our results. While the among years differences in pollen season dates may be large, in a given year the concentration of birch pollen exceeds the threshold value ($30 \text{ pg}\cdot\text{m}^{-3}$) in similar time. In 2015 and 2016, in Rzeszów and in several cities in southern Poland the pollen concentration exceeded $30 \text{ pg}\cdot\text{m}^{-3}$ almost in the same day (Rapiejko et al., 2015; Weryszko-Chmielewska et al., 2016). In summary, in 2014–2016, the *Alnus* and *Betula* MPSs were typical according to studies in other Polish cities in different years and for other regions with temperate climates (Nowosad et al., 2015; Šauliune et al., 2016).

Few studies have compared the pollen seasons of *Alnus* or *Betula* at different sites within the same city. We found only one study in Poland

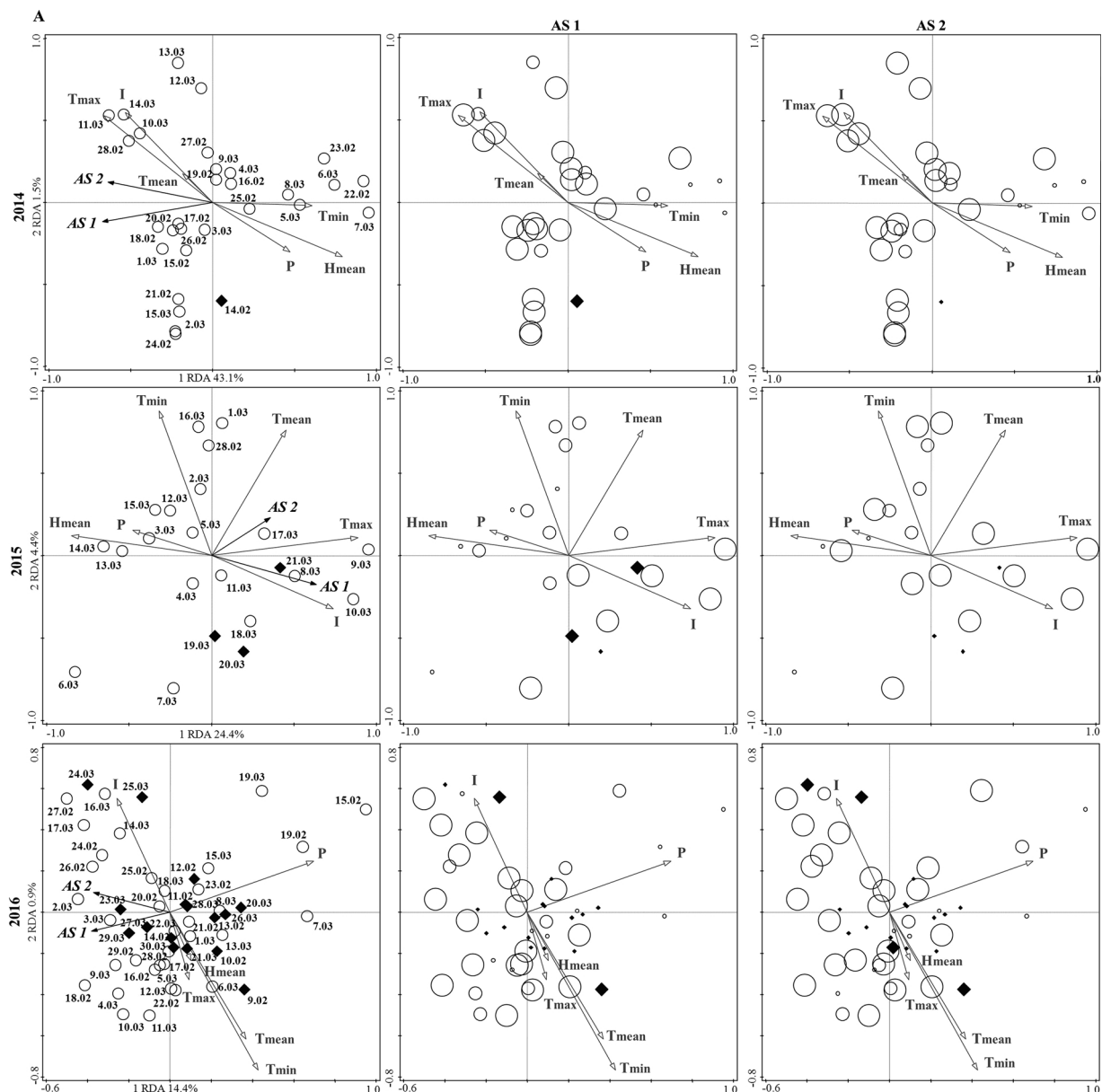


Fig. 4. RDA ordination diagrams based on the average daily concentrations of *Alnus* (A) and *Betula* (B) pollen grains in each study year and in 2014–2016 (C); triplot diagrams present the relationships between meteorological variables, aerobiological stations (AS 1–3) and daily pollen concentrations; biplot diagrams for AS 1–3 separately that present the differentiation in the daily concentrations (in three categories) in relation to meteorological variables; Tmax - maximum daily temperature, Tmin - minimum daily temperature, Tmean - mean daily temperature, Hmean - mean daily relative humidity, I - sunshine duration; P - total daily precipitation; circles - days during the pollination period, diamonds - days outside of the pollination period; the sizes of the circles and diamonds reflect the three categories of the concentrations.

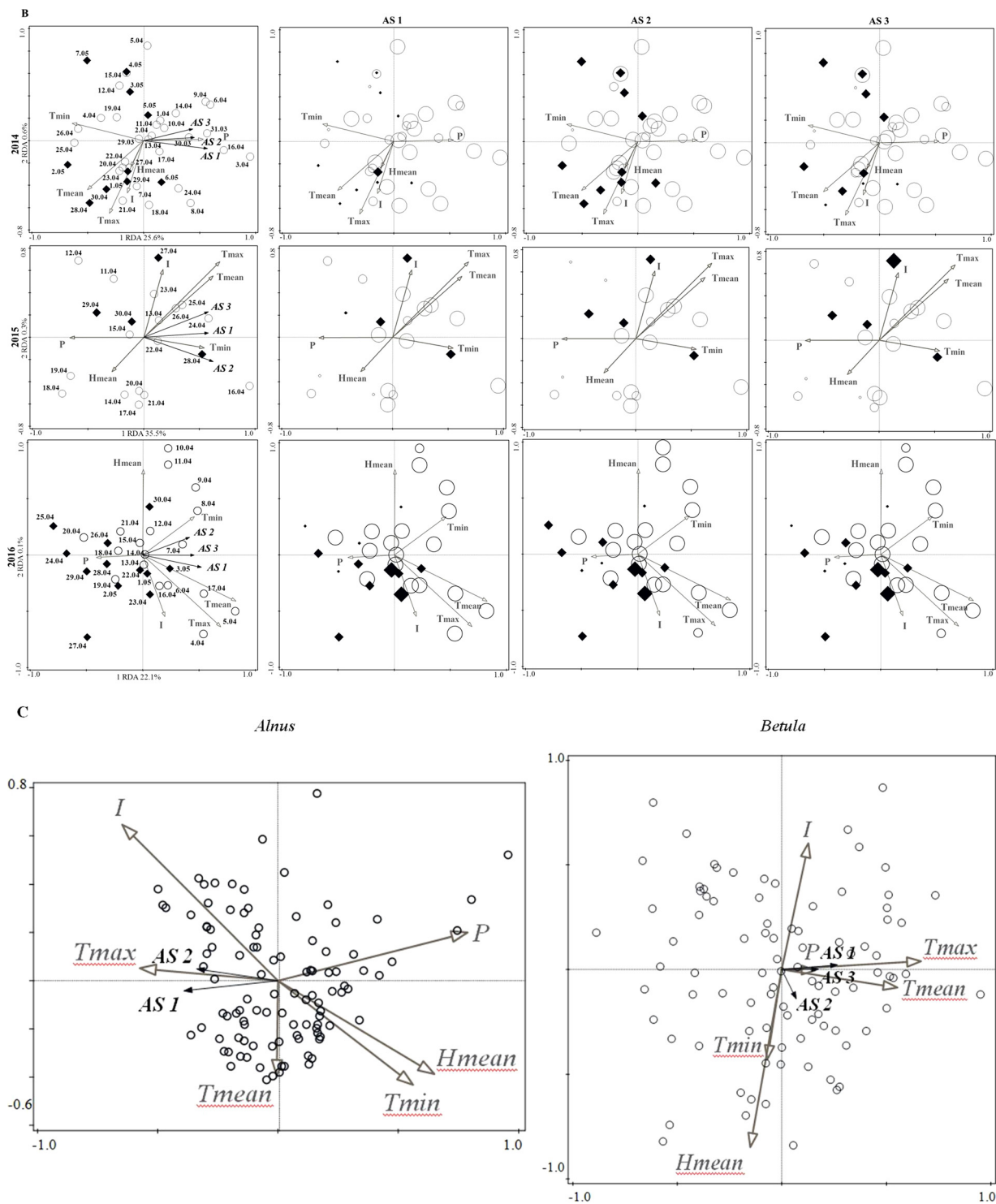


Fig. 4. (continued)

(Poznań, West Poland), and the authors obtained high synchronization in the horizontal gradient of the dates of the seasons for both species (Rodríguez-Rajo et al., 2010), which is in accordance with our results. In general, only a 1–2 day shift occurred in Rzeszów. The maximum concentrations of birch pollen occurred on the same day at the roof level. High synchronization of the pollen season course over a horizontal gradient was found for other arboreal and herbaceous taxa by

Gonzalo-Garijo et al. (2006); Rodríguez-Rajo et al. (2010) and Velasco-Jiménez et al. (2013). The course of the pollen season over a vertical gradient was studied by Rantio-Lehtimäki et al. (1991), who indicated a 10–20 day shift between the start, end and length of the MPSS of *Alnus* and *Betula* as well as for a few herbaceous species. In our research, the differences were of little significance and occurred for only the *Betula* peak days in the two study years. Moreover, high the Spearman

Table 3

Summary of the most important RDA results; *explained variation was presented only for the axes that were significant in the model, **significance of the variables that were statistically significant ($\alpha = 0.05$).

year	<i>Alnus</i>					<i>Betula</i>					
	explained variation (cumulative %)*		variable significance**			explained variation (cumulative %)*			variable significance**		
	Axis 1	Axis 2	explained data variance (%)	p-value		Axis 1	Axis 2	Axis 3	explained data variance (%)	p-value	
2014	43.13	44.60	Hmean	27.0	0.004	25.62	26.24	26.50	Tmin	10.5	0.042
			Tmax	19.4	0.006						
			Tmin	15.8	0.03						
2015	24.36	28.71	Tmax	19.2	0.018	35.51	38.79	39.91	Tmax	18.2	0.050
			Hmean	17.5	0.042						
2016	14.14	15.03	variables not statistically significant			22.06	23.22	23.30	Tmean	15.3	0.024
2014–2016	13.38	13.59	P	8.3	0.004	4.00	4.54	4.60	variables not statistically significant		
			I	5.7	0.012						
			Hmean	5.7	0.014						
			Tmax	4.4	0.032						
			Tmin	4.2	0.022						

correlation coefficients confirm the high synchronization of the daily pollen concentrations between all stations for both species for both the vertical and horizontal gradients, which was also obtained by Fernández-Rodríguez et al. (2014a,b).

4.2. Spatial differentiation of daily pollen concentrations

The seasonal pollen concentrations were found to be much more

differentiated over a horizontal gradient than the course of the season (Fernández-Rodríguez et al., 2014a). Some authors noted greater differences for herbaceous than arboreal species (Spijksma et al., 2000; Rodríguez-Rajo et al., 2010). The study by Fernández-Rodríguez et al. (2014a) showed no significant differences in the mean concentrations of *Alnus* pollen at two sites with different abundances of pollen sources, which was not in agreement with our findings. In general, the SPIn and peak values were approximately two-thirds higher in the suburbs than

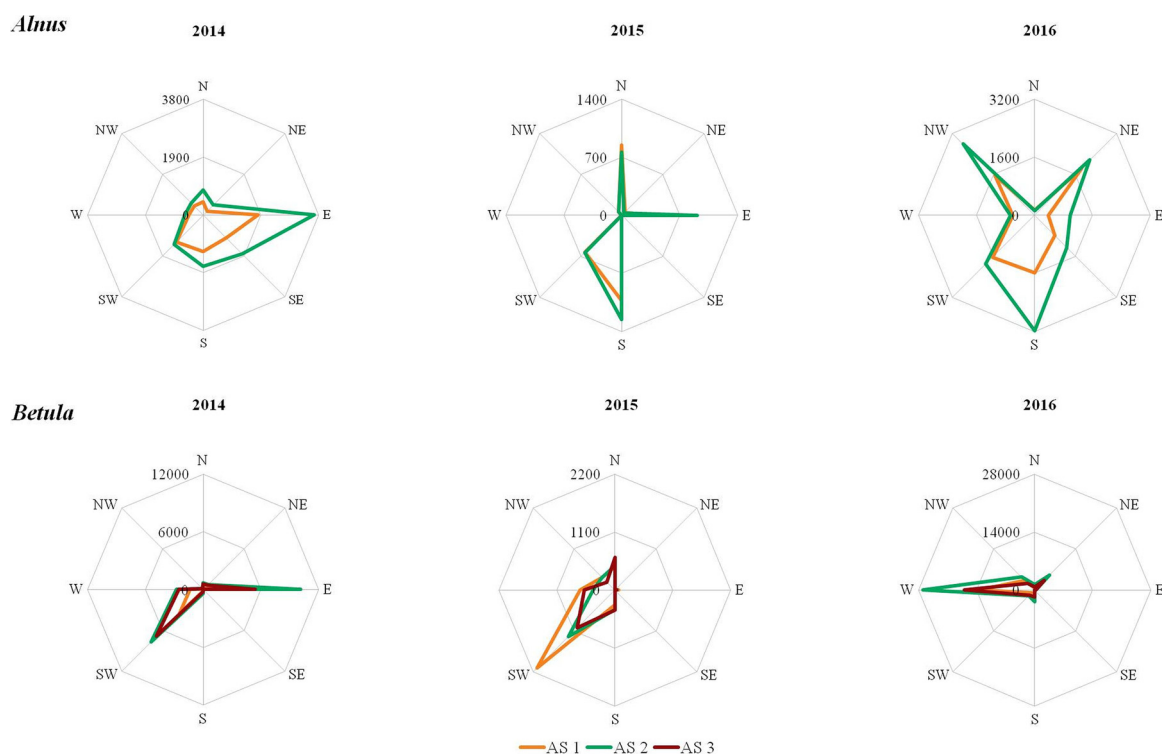


Fig. 5. Pollen roses for *Alnus* (A) and *Betula* (B) daily pollen concentrations in relation to predominant wind direction in 2014–2016 years (see scale); concentrations were expressed as $\text{pg}\cdot\text{m}^{-3}$; r^2 - circular-linear correlation coefficient for each station.

in downtown for alder, and two times higher (or more) in the suburbs than in downtown for birch. Many authors have highlighted that the SPIn and peak values appeared to be higher for most pollen types in the city suburbs than in the centre where pollen sources are usually less abundant (Gonzalo-Garijo et al., 2006; Rodríguez-Rajo et al., 2010). Our study also indicated higher daily concentrations in the suburbs where more alder and birch trees were found than in downtown.

Generally, the studies that compared the daily pollen concentrations as well as the SPIn values over a vertical gradient indicated that the concentrations decreased with height. This pattern is typical for herbaceous species (Rantio-Lehtimäki et al., 1991; Spieksma et al., 2000; Tormo Molina et al., 2013). The results on arboreal species obtained by many authors are very different and not always compatible (Tormo Molina et al., 2013; Fernández-Rodríguez et al., 2014b). Rantio-Lehtimäki et al. (1991) stated that the daily *Alnus* and *Betula* pollen concentrations did not differ between the roof and nose levels. Similar results were obtained by Spieksma et al. (2000), who found that the birch concentrations were two-fold higher at the nose level than at the roof level, but this result was not found for alder pollen. Our results for birch partially agree with the previous study – we indicated only slight variability in the daily concentrations but also reported 25–50% lower SPIn values at the nose than at the roof level over two study years.

The variability in the pollen concentrations within the cities seems to be shaped primarily by the urban topography, particularly the configuration of the street canyons and the density and height of buildings (Peel et al., 2014). Dense urban structure favours low wind speeds (Kuchcik et al., 2016), which might cause the increased pollen concentrations within buildings. In contrast, dense urban structure may also reinforce air turbulence (Berkowicz et al., 1996), which helps remove pollen. It is important if the main pollen sources are situated in the city centre or more peripherally (Gonzalo-Garijo et al., 2006) and if they are arranged as greenery next to streets, hedges, and lawns or form large, concentrated pollen emission sources such as in parks or urban forests (Cariñanos and Casares-Porcel, 2011). In our case, the urban forests growing in the suburbs are important alder and birch pollen sources for the whole city, and their proximities were reflected in the greater pollen concentrations at the stations located near the urban forests than at the downtown station. It cannot be excluded that the pollen in the city centre originated from the peri-urban forests, as many authors highlight the important role of wind direction and wind speed with respect to the location of pollen sources (Rojo et al., 2015). The lack of correlation between daily pollen concentrations and wind direction confirmed that in Rzeszów pollen of both taxa might originate from different directions. *A. glutinosa* and *Betula* sp. are common in the city as well as in SE Poland.

4.3. Avoiding allergy risks in urban areas

Birch trees are intensively used as greenery in many European cities. They occur in parks and urban forests, are planted along the streets and are major pollen producers, which results in serious problems for people with allergies (Cariñanos and Casares-Porcel, 2011; Cariñanos et al., 2017). A study carried out by Kuchcik et al. (2016) revealed that different birch species and cultivars are more often planted within new housing estates than within older estates built a few decades ago in Warsaw (the largest city in Poland). Our results show that birch trees occur throughout the city independently of the urban arrangement.

In the urban area, pollen grains are transported above the roof level or within the street canyons defined by the buildings (Peel et al., 2014). The types of pollen that are released or deposited at low levels are

transported upward by the wind vortexes in the street canyons (Berkowicz et al., 1996). However, the vertical and horizontal dispersion of grains might be hindered by unfavourable weather conditions and buildings that form continuous barriers (Berkowicz et al., 1996; Peel et al., 2014). Consequently, the pollen concentrations differ depending on the monitoring site, but the frequency of the days with concentrations above the allergy threshold values might be similar in many city districts, which is crucial information for allergy sufferers.

Some authors claim that one monitoring station per city with uniform vegetation and topography is sufficient for allergy prevention (Velasco-Jiménez et al., 2013), but others suggest wider aerobiological monitoring networks (Gonzalo-Garijo et al., 2006). In our opinion, a minimum of two aerobiological traps within the same city would be helpful, but their usefulness depends on the dispersal ability of the dominant pollen grains, which is a crucial issue that must be taken into account if we want to interpolate the data from one station to a larger area.

The comparison of data from two stations located in different city districts in Poznań revealed that the majority of the *Platanus* pollen falls within 400 m from its source, and the allergy risk information from one station did not reflect the situation throughout the city (Nowak et al., 2012). Similar results were obtained for *Ligustrum* (Cariñanos et al., 2002) and *Citrus* (Alcázar et al., 2016) pollen in Spain. The pollen concentrations of these taxa presented a risk for allergy sufferers only when they were near the plants. This phenomenon was named ‘proximity pollinosis’ (Cariñanos and Casares-Porcel, 2011). In such case, standard aerobiological monitoring does not always fulfil its task, since high concentrations of clinical relevance are noted at only the nose level and in only the area near the pollen sources (Cariñanos et al., 2002). The lack of a clear relationship between the pollen calendar for a city/region and the prevalence and severity of pollen allergies could make it difficult to determine the aetiology of inhalant allergies. This finding was noticed by Yamamoto et al. (2015) who emphasises the need for personal pollen monitoring.

Our results indicated that in the case of pollen types with high dispersal abilities, such as alder and birch, the number of days when the concentrations were above the allergy thresholds was similar at all stations, and the similarity in the number of days was independent of the proximity and abundance of the pollen sources. Therefore, avoiding alder and birch pollen allergy risks is not as easy as in the case of pollen grains from entomophilous plants and large-size grains. Rodríguez-Rajo et al. (2010) registered approximately the same number of days with concentrations up to $50 \text{ pg} \cdot \text{m}^{-3}$ over three study years in the city centre and suburbs. Therefore, it could be concluded that the ability to spread even over long distances of these pollen types are the main determinant of their slight spatial differentiations in concentrations.

4.4. The impact of weather on daily pollen concentrations

The results of the RDA indicated that temperature, as well as humidity and precipitation, impacted the daily concentrations of *Alnus* pollen grains, while only temperature seemed to have a significant influence on the concentrations of *Betula* pollen grains. The increases in temperature and actual sunshine duration were connected with the increases in the daily pollen concentrations, while the increases in relative humidity and precipitation were related to decreases in the daily pollen concentrations. A similar relationship was obtained by Rojo et al. (2015) for different wind-pollinated species.

Winter returns often appear during the alder pollination period (Borycka et al., 2017a), which disturbs the pollen release. Those days

are usually linked with snow or rainfall, increases in humidity, and decreases in temperature; therefore, all of those parameters might influence the daily pollen concentrations. Earlier studies conducted in two Polish cities revealed the influence of the mean and maximum daily temperature on the daily concentrations of alder pollen (Puc and Kasprzyk, 2013). Several aerobiological studies have indicated the great impact of temperature on the daily birch pollen concentrations as well as the course of the MPS (Piotrowska and Kaszewski, 2009; Grewling et al., 2012), which is in accordance with our results.

The impact of precipitation on airborne pollen is substantial but not clearly defined. Many aerobiological studies have indicated the crucial impact of precipitation on the daily pollen concentrations because of the wash-out effect (Rojo et al., 2015). A connection between a decrease in the number of days with high pollen concentrations and an increase in precipitation was clearly visible in Rzeszów in all years. In contrast, Puc and Kasprzyk (2013) stated that precipitation had no impact on the daily concentration of alder pollen during three study years. Grewling et al. (2012) stated that precipitation during the *Betula* pollen season had a significant influence on the decrease of the daily concentrations but only for the season with low intensity. We suppose that the impact of temperature on birch pollen concentrations is more significant than the impact of precipitation. During the birch pollination period, high precipitation events were usually showers that ended rapidly within a few hours and allowed warming to return (meteorological data - Tutiempo, 2017); therefore, pollination was not interrupted for an entire day. Moreover, spring rain might have convective origin and be connected with an increase in pollen concentrations in the first two hours of rainfall (Norris-Hill and Emberlin, 1993). During the alder pollination period, convective rain does not usually appear

because of the weak heating of the lower layer of the troposphere (Woś, 2002).

5. Conclusions

Based on the results, it can be concluded that there are spatial differences in aerobiological phenomena over horizontal gradient for *Alnus* and over horizontal and vertical gradient for *Betula*, even within a medium-sized city. These differences are related primarily to the intensity of the pollen season and, to a lesser extent, to the variability in the course of the pollen season. Despite the spatial variability of the pollen concentrations, the risks for allergy sufferers were similar throughout the city, and one station per medium-sized city such as Rzeszów would be enough to monitor the risks of aeroallergens. However, that recommendation applies to only *Alnus* and *Betula* pollen, as other pollen types with different dispersal abilities might show different spatial variabilities. Because of the enormous production of pollen grains by alders and birches as well as the ability of the pollen to spread over long distances, the high concentrations in the atmosphere may originate from local sources or from outside the city from broad-leaved forests where these species are important components. Bearing it in mind, it is difficult to locate an area in the city that is safe for allergy sufferers. The relationships between the daily *Alnus* and *Betula* pollen concentrations and weather variables are not clear enough to provide recommendations for avoiding concentrations that are risky for allergy sufferers. Although temperature seems to be a crucial factor for both taxa, the weather variables were found to have complex impacts on daily concentrations. The continuation of the research will allow verification of these conclusions.

Appendix A



Fig. A1. Location of Rzeszów in Poland and Europe.

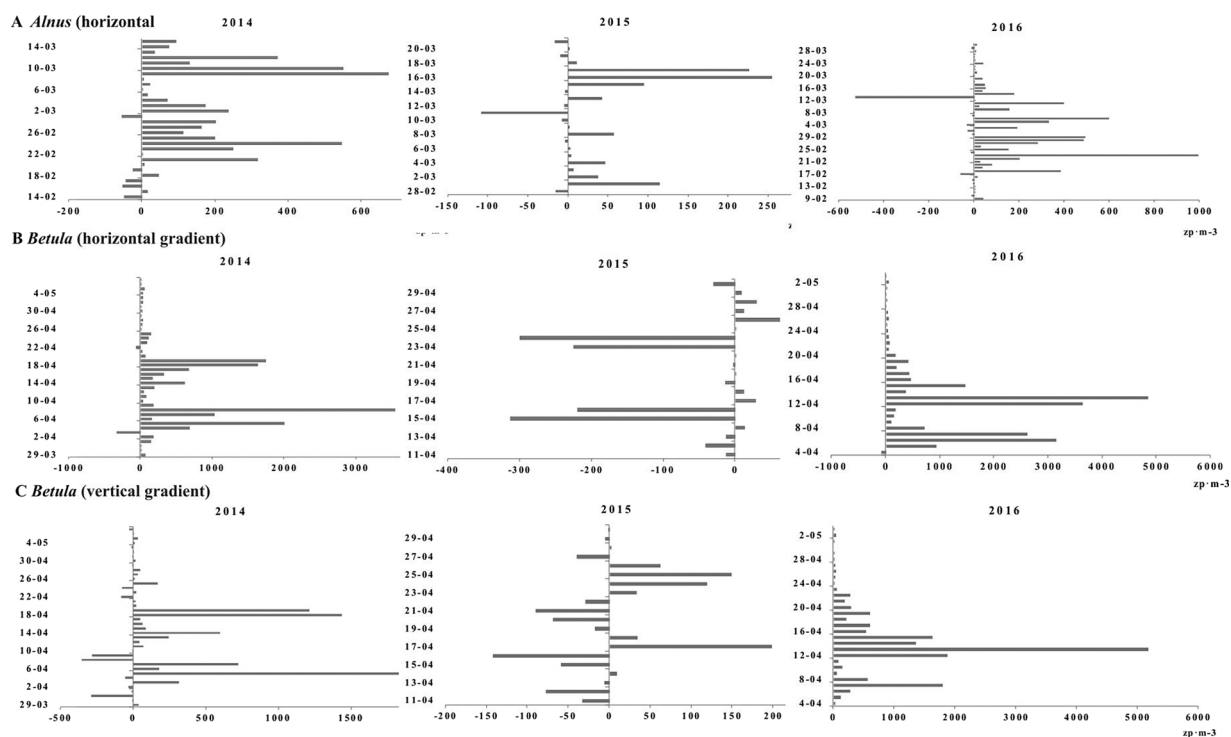


Fig. A2. The differences in the average daily concentrations of pollen grains: (A). *Alnus* between AS 1 and AS 2 (horizontal gradient); (B). *Betula* between AS 1 and AS 2 (horizontal gradient); (C). *Betula* between AS 2 and AS 3 (vertical gradient); the bars on the right side indicate an advantage of the concentrations at AS 2.

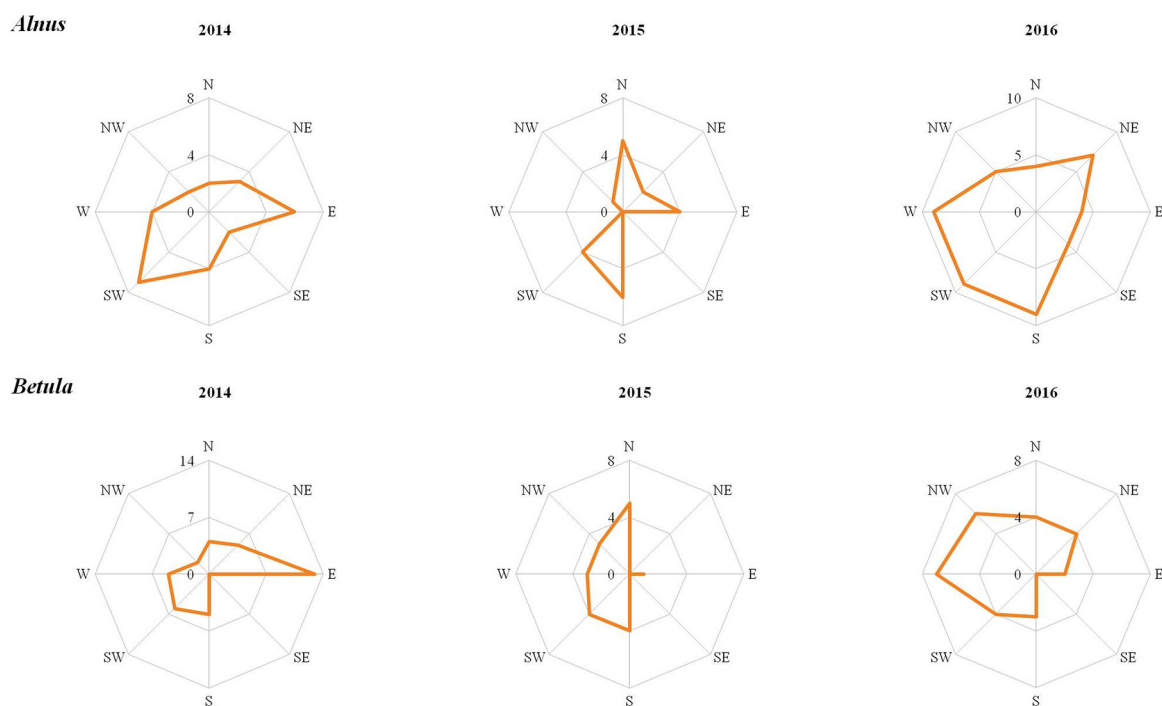


Fig. A3. Prevailing wind directions during the main pollen season of *Alnus* (A) and *Betula* (B) in Rzeszów in 2014–2016 years.

Table A1

Spearman correlation coefficients as a measure of the synchronization of the daily *Alnus* (A) and *Betula* (B) pollen concentrations between the aerobiological stations; significance level $\alpha = 0.001$.

(A)				
			AS 2	
AS 1	2014			0.9158
	2015			0.8069
	2016			0.9207
	2014–2016			0.8855
(B)				
		AS 1	AS 2	AS 3
2014	AS 1		0.8815	0.9077
	AS 2	0.8815		0.8993
	AS 3	0.9077	0.8993	
2015	AS 1		0.9139	0.8812
	AS 2	0.9139		0.8334
	AS 3	0.8812	0.8334	
2016	AS 1		0.9656	0.9648
	AS 2	0.9656		0.9888
	AS 3	0.9648	0.9888	
2014–2016	AS 1		0.8815	0.9077
	AS 2	0.8815		0.8993
	AS 3	0.9077	0.8993	

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