



Detecting distant sources of airborne pollen for Poland: Integrating back-trajectory and dispersion modelling with a satellite-based phenology

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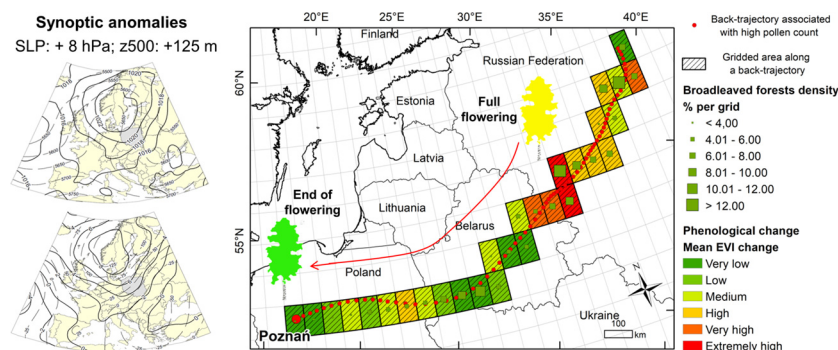
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HIGHLIGHTS

- Airborne birch pollen transport from distant sources occurred almost every year.
- Long-distant transport (LDT) episodes occurred mainly in the first fortnight of May.
- A high pressure centre over Scandinavia favoured the LDT of birch pollen to Poland.
- Potential pollen source areas were located primarily in western Russia.
- LDT caused a clinically relevant extension of the birch pollen season in Poland.

GRAPHICAL ABSTRACT



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ABSTRACT

Airborne pollen might be transported over thousands of kilometres, which has important ecological, evolutionary and clinical consequences. The long-distance transport (LDT) of birch (*Betula* sp.) pollen has been described in detail for northern Europe. However, a comprehensive analysis of this transport from other European regions is lacking. This study focused on the post-seasonal LDT of birch pollen to Poland (central Europe), with special attention paid to determining potential source areas of pollen and describing the causal mechanism favouring LDT episodes.

Pollen monitoring (1997–2016) was conducted in Poznań and Rzeszów (500 km away from each other) using volumetric traps. The LDT episodes were characterized by analysing the (1) bi-hourly backward air mass trajectories using the Hybrid Single Particle Lagrangian Integrated Trajectory model (HYSPPLIT); (2) sea level pressure (SLP) and 500 hPa geopotential height (z500) anomalies; and (3) patterns of the Enhanced Vegetation Index to determine the birch flowering time along the moving air mass trajectories. The potential locations of birch populations within broadleaved forests were estimated with GLOBCOVER data. Finally, the movement of pollen emitted from potential source areas was simulated using the HYSPPLIT dispersion model.

LDT episodes were mainly recorded in the first fortnight of May. The main source areas of pollen to Poland were western Russia, Belarus and to a lesser extent the eastern Baltic republics and the Scandinavian Peninsula. In most cases, a high-pressure centre located over Scandinavia and an elevated z500 over Germany–Denmark–Sweden favoured pollen transport. On average, the post-seasonal LDT episodes of birch pollen to Poland occur almost

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every year (Poznań) or every second year (Rzeszów). The episodes are highly variable in time; thus, the pollen concentration may unexpectedly cause allergy symptoms in sensitized patients. In some cases, these episodes may be extremely severe, thereby prolonging and strengthening the exposure to birch pollen allergens.

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1. Introduction

Pollen recorded at aerobiological monitoring sites might originate from local sources (micro- or local-scale transport) or is transported with air masses from distant areas (regional or long-range transport) (Belmonte et al., 2008; Grewling et al., 2016; Siljamo et al., 2008; Skjøth et al., 2007; Sofiev et al., 2006). Continental and intercontinental pollen transport, which can span several thousands of kilometres, has been observed around the globe (Kellogg and Griffin, 2006; Rousseau et al., 2004; Sofiev et al., 2013). For example, pollen grains of European trees have been detected in Arctic regions (Rousseau et al., 2004), whereas pollen originating from the Sahara Desert has been recorded in Caribbean islands (Monteil, 2008). The ability of pollen to be transported over long distances may have important ecological and evolutionary consequences, including reproductive assurance against fragmentation or colonization, metapopulation connectivity, and the enhancement of the response to selection (Kremer et al., 2012; Robledo-Arnuncio, 2011; Rousi et al., 2011). Significant effective pollen flow from large populations of Scots pines located 100 km away from isolated stands has been observed in the Iberian Peninsula (Robledo-Arnuncio, 2011). Additionally, viable and germinable pine (*Pinus* sp.) pollen transported from distant areas has been recorded in Scandinavia (Lindgren et al., 1995).

The dispersion ability of pollen grains is not only an important factor in the interpretation of pollen records in forensic, palaeobotanical and phytogeographical analyses (Belmonte et al., 2008; Jackson and Lyford, 1999; Ranta et al., 2008), it may also have important clinical implications. Pollen grains are considered one of the main causes of allergic diseases affecting millions of people around the world (D'Amato et al., 2007). Although the role of the long-distance transport (LDT) of pollen in inducing new sensitization is disputable (Cecchi et al., 2010; Wallin et al., 1991), it has been shown that the LDT of ragweed pollen grains still possess reactive allergens and hypothetically may cause allergic reactions in sensitized subjects (Grewling et al., 2016). It should be stressed that the LDT of pollen may markedly modify pollen season dynamics and affect the length and severity of the pollen season (Siljamo et al., 2008; Skjøth et al., 2007; Sofiev et al., 2006). In Denmark, the LDT of birch (*Betula* sp.) pollen has been recorded in high quantities before the flowering of local trees, while olive (*Olea* sp.) pollen grains originating from southern Spain have been observed in Portugal after the flowering of local trees (Galán et al., 2013; Skjøth et al., 2007). In addition, pollen allergens may even affect people living in areas outside the distribution range of certain plant species, as shown for ragweed (*Ambrosia* sp.) pollen transported from southeastern Europe to Scandinavia, where these species do not occur (Grewling et al., 2016; Šikoparija et al., 2013).

To correctly determine the source areas of pollen, several factors should be analysed, including phenological records (time of flowering), species distribution, surface meteorological conditions and large-scale synoptic data (García-Mozo et al., 2017; Izquierdo et al., 2017). The analysis of the synoptic configuration of the pressure and geopotential fields, as well as the determination of air-mass flows, is useful for the study of the LDT phenomenon (Bogawski and Bednorz, 2016; Izquierdo et al., 2017). On the other hand, it has been shown that large-scale atmospheric circulation patterns, such as the North Atlantic Oscillation, may influence the LDT of pollen grains (Izquierdo et al., 2015). Similarly, turbulent vertical mixing (Sofiev et al., 2006) and upward and downward air motions (Rousseau et al., 2004) might strongly

affect the movement of airborne pollen grains. Overall, specific synoptic conditions must occur in the source area and along the air mass pathway to facilitate the atmospheric transport of pollen (Šikoparija et al., 2013).

The LDT of birch pollen has been comprehensively analysed for northern Europe, e.g., in Denmark (Skjøth et al., 2007), Finland (Siljamo et al., 2008; Sofiev et al., 2006), Sweden (Wallin et al., 1991), Lithuania (Veriankaite et al., 2010) and Russia (Siljamo et al., 2008). In these areas, the LDT of birch pollen is observed before the flowering of local trees and originates mainly from central Europe, e.g., Poland and Germany (Skjøth et al., 2007). In contrast, the mechanism of birch pollen transport over central or western Europe is less studied and requires further attention. The first indications that large amounts of *Betula* pollen might occur in Poland after the main pollen season have been highlighted by Stach and Silny (1999). However, this analysis was based on a single episode and included only wind direction analysis. Therefore, we conducted the current study to comprehensively investigate the frequency and magnitude of post-seasonal LDT episodes of birch pollen to Poland with special attention on the meteorological conditions associated with LDT events. Considering that dense birch forests are much more common in Scandinavia, western Russia and the Baltic States than in Poland (Beck et al., 2016), we hypothesized that these regions might be potential sources of the *Betula* pollen transported to Poland. In addition, as the birch trees in northern Europe pollinate with a delay of a few weeks in comparison with the birch trees in Poland, i.e., mainly in May (Karlsen et al., 2009; Siljamo et al., 2008; Wallin et al., 1991), we focused only on LDT episodes that occurred after the flowering period of local trees (Beck et al., 2016). Thus, this study aimed to (1) estimate the impact of the LDT of pollen on the dynamics of pollen seasons with a 20-year dataset (1997–2016), (2) describe the general synoptic conditions related to these episodes, (3) determine the potential source areas of birch pollen transported to Poland, and (4) develop a novel method for detecting distant sources of pollen and predicting their impact on the pollen level in the receptor area.

2. Material and methods

2.1. Study area

The study was carried out in two cities in Poland (central Europe), i.e., Poznań (52.46°N, 16.92°E) and Rzeszów (50.04°N, 21.99°E), located approximately 500 km away from each other. Poznań is situated in western Poland in the lowland region and has an area of 261.91 km², while Rzeszów (116.36 km²) is located in the foothills at approximately 210 m a.s.l. in southern Poland (CSO, 2015). Both the Atlantic and continental air masses influence weather in Poland. Poznań has a temperate continental climate with polar marine air, while Rzeszów is more frequently influenced by polar continental air masses (Woś, 2010). Two birch species, i.e., *Betula pendula* (silver birch) and *B. pubescens* (downy birch), occur widely in Europe, and the whole area of Poland is included in their natural distribution range (Beck et al., 2016). Silver birch is far more common than downy birch, occupying approximately 7.4% of forests in Poland (FDB, 2014). In addition, *B. pendula* is frequently planted in cities and is abundant in urban parks, along streets, and within housing estates (Borycka et al., 2017; Grewling et al., 2012; Jackowiak, 1993). In Poland, the highest daily *Betula* pollen

concentrations are recorded in the middle of April when the birch trees usually flower (Grewling et al., 2012; Kasprzyk, 2016).

2.2. Pollen record

Aerobiological sampling was conducted from 1997 to 2016 using Hirst-type volumetric spore traps (Hirst, 1952). In both cities, traps were located in the city centres at 30 m a.g.l. in Poznań (P) and at 12 m a.g.l. in Rzeszów (R). The monitoring was performed following the recommendations of Galán et al. (2014). *Betula* pollen grains were counted and identified at a genus level using 400× light microscopy. The pollen data were expressed as the mean bi-hourly and mean daily pollen concentrations per 1 m³ of the air (pollen·m⁻³). Note: due to technical problems from 5 to 8 May 2006, the birch pollen data from Rzeszów are missing.

The birch pollen database was screened in order to select the potential episodes of LDT. We focused on episodes that were registered in the May–June period (after the local flowering of birch in Poland; Bogawski et al., 2019) with daily values above 30 pollen·m⁻³, i.e., the threshold value above which the first clinical reactions are believed to occur (De Weger et al., 2013). These episodes were characterized by a sharp increase in the daily pollen level and were followed by days with very low pollen concentrations. To better separate the post-seasonal long-distance transport episodes from the main pollen season (MPS), we calculated the basic characteristics of the MPS using the R software (R Core Team, 2018) and *Aerobiology* R package (Rojo et al., 2019). We provided the mean and standard deviation values for the start, end, peak date, pollen season length, pre-peak and post peak period length and annual pollen total (Table S1). The MPS start and end were defined using a logistic model based on the cumulative, sigmoidal pollen curve (Ribeiro et al., 2007). This method proved to be reliable for different pollen types and is useful for interregional comparisons (Ribeiro et al., 2007; Cunha et al., 2015). By calculating the derivatives (in this case, the 4th derivative), this method is able to detect the inflection points in the cumulative pollen curve and therefore to correctly indicate the primary changes in the pollen concentration at the beginning and the end of the MPS. The end date of the MPS was directly used in detecting post-seasonal LDT birch pollen episodes. Each increase in the pollen concentration > 30 pollen m³ occurring after the MPS end date was considered a possible LDT episode. Ultimately, five post-seasonal episodes with elevated birch pollen concentrations were chosen and investigated in detail: 2–4 June 1997 in Poznań (1st episode), 14–16 May 1998 in Poznań (2nd episode), 12 May 2000 in Poznań and Rzeszów (3rd episode), 5–12 May and 9–13 May 2006 in Poznań and Rzeszów, respectively (4th episode), and 1–9 May and 3–8 May 2016 in Poznań and Rzeszów, respectively (5th episode).

2.3. Atmospheric circulation patterns

The atmospheric circulation patterns during the selected LDT episodes were classified using the ‘environment to circulation’ approach, i.e., a specific set of environmental criteria for a particular phenomenon (Dayan et al., 2012; Yarnal, 1993). Thus, to reveal the large-scale pressure patterns that control the possibility of a LDT pollen influx to Poland, we analysed mean sea level pressure (SLP) and 500 hPa geopotential height (z500), which were expressed in hPa and m a.s.l., respectively. The data were extracted from the NCEP/NCAR reanalysis data (Kalnay et al., 1996). The spatial resolution of all NCEP/NCAR reanalysis data used here was 2.5° × 2.5°, extending from 35° to 70°N and from 20°W to 40°E (as in Bogawski and Bednorz (2016)).

The composite maps of SLP and z500 were constructed for every LDT episode. Next, these maps were related to the long-term (years 1997–2016) mean values of the SLP and z500 for the first fortnight of May (described in Supplementary Materials), i.e., the period when almost all of the selected LDT episodes occurred. Finally, anomaly maps

were produced showing differences between the pressure patterns of LDT episodes and the long-term mean.

2.4. Back-trajectory analysis

To determine the post-seasonal LDT pathways of birch pollen transport to Poland, the backward air mass trajectories were calculated using the Hybrid Single Particle Lagrangian Integrated Trajectory model (HYSPLIT) (Rolph et al., 2017; Stein et al., 2015). Back trajectories were computed using the vertical velocity field from meteorological data (model vertical velocity). Global Data Assimilation System (GDAS) meteorological data of 1° × 1° spatial resolution were used from April 2005 onwards, and NCEP/NCAR reanalysis data with a 2.5° × 2.5° spatial resolution were used to 2004. To analyse the movements of the air masses, we selected two starting heights of back-trajectories: 500 m and 2500 m above ground level (a.g.l.). The trajectories were calculated bi-hourly up to 72 h back in time starting from the last day of the LDT episode. From these, we selected trajectories associated with different bi-hourly pollen concentration levels (compared with the daily threshold of 30 pollen·m⁻³) at the destination sites: extremely high (>2000 pollen·m⁻³), very high (1000–2000 pollen·m⁻³), high (500–1000 pollen·m⁻³), medium (200–500 pollen·m⁻³), low (80–200 pollen·m⁻³), and none or scarce (<80 pollen·m⁻³).

All the back-trajectories calculated for the post-seasonal LDT of birch pollen episodes in 1997–2016 were used in the cluster analysis. We calculated the frequency of trajectories attributed to each cluster (%) showing also the dominant four directions associated with the elevated post-seasonal birch pollen concentration. A specific method of Sirois and Bottenheim (1995) was used to calculate an angle-based distance matrix considering distances between each pair of back-trajectories, separately for Poznań and Rzeszów. This method is reliable when the direction of trajectories is important in the clustering. All the calculations were performed in the R software (R Core Team, 2018) and *openair* R package (Carslaw and Ropkins, 2012). The results from the cluster analysis were plotted on a map formatted using ArcGIS (ESRI) software.

2.5. Birch populations inventory

A simple approximation was performed to create the birch population inventory map, which is used as base map for trajectories to identify the potential birch pollen source areas. Broadleaved forests are the primary sources of birch pollen in northern, eastern and northeastern Europe (Atkinson, 1992; Siljamo et al., 2008; Sofiev et al., 2006). Therefore, a map of broadleaved forests for central and northern Europe was created based on 300 m-resolution GLOBCOVER data (Bicheron et al., 2008). Extracted broadleaved forest data were then aggregated to a 1° × 1° resolution to meet the accuracy of the GDAS meteorological data used to calculate the trajectories. The potential birch population inventory was presented in this gridded form. To provide additional information, we presented the EUFORGEN distribution map of *Betula pendula* Roth., one of the two species that contribute the most to the European birch pollen pool (EUFORGEN, 2009).

2.6. Phenological timing

Due to the lack of available phenological data for selected episodes in the source area, we used satellite imagery (Karlsen et al., 2009; Khwarahm et al., 2017) and selected the Enhanced Vegetation Index (EVI) to estimate the time of birch flowering along particular air mass trajectories. Similar to Karlsen et al. (2009), we assumed that differences in the timing of the development of birch male flowers and leaf-bud burst were negligible. Therefore, by observing the most rapid increase in the EVI values in spring, we could attribute the timing of flowering to a particular 16-day period.

EVI data were obtained from the Land Processes Distributed Active Archive Center (LP DAAC) website (<https://lpdaac.usgs.gov/>). The

dataset used in this study was the MYD13C1 acquired by the MODIS sensor aboard the Aqua satellite (heliosynchronous orbit, afternoon overpass between 13.00 and 14.00 local time) in spring months. The dataset (version 6) comprises 13 science dataset layers, with EVI as the second layer. The spatial and temporal resolutions were 5.6 km and 16 days, respectively. The raw data retrieved were also transformed using an appropriate scale factor (Didan et al., 2015):

$$EVI = EVI_{raw} \cdot Sc_F$$

where EVI_{raw} is the value of the digital number obtained directly from the MODIS MYD 13C1 dataset and Sc_F is a scale factor; in this case, $Sc_F = 0.0001$.

For clarity and brevity, the EVI pattern was constructed only for two episodes, i.e., episodes in 2006 and 2016, characterized by the most distinct LDT of birch pollen to Poznań and Rzeszów. The EVI was determined in three control points for each city. The first control point reflected the spring phenology in the vicinity of pollen stations (central and southeastern Poland), the second control point was located in the middle of a particular trajectory (Lithuania, Belarus) and the third control point was located at the end of the trajectory (Russia). As 16-day intervals occurred between the phenological data acquisitions, we could indicate which 16 day-period was characterized by the most rapid increase in EVI in these three mentioned areas. The period with the most rapid EVI increase can be attributed to the intensive spring vegetation development and thus flowering.

2.7. Simulation of pollen dispersal from potential sources

The potential source areas of LDT pollen recorded at Poznań and Rzeszów were identified based on the (1) back-trajectory routes, (2) potential locations of birch populations within broadleaved forests and (3) spatial shifts of the land surface phenology data (Fig. 1). The movement of pollen emitted from these areas during selected LDT episodes was simulated using the HYSPLIT dispersion model (Rolph et al., 2017; Stein et al., 2015).

We calculated the forward HYSPLIT dispersion of particles with a settling velocity of $0.027 \text{ m} \cdot \text{s}^{-1}$, which is the value for birch pollen according to Jackson and Lyford (1999). To ensure compatibility with the back-trajectory analysis, the simulations were performed using GDAS $1^\circ \times 1^\circ$ resolution meteorological data. The source term parameters were as follows: the particle release starting time was set according to the back-trajectory time (separately for each specific case), and the release top and bottom were set to 30 m (maximum birch height following Atkinson (1992)) and 0 m, respectively, meaning that the pollen release could occur from whole birch trees. Although birch pollen can be released from the anthers over twelve hours of daylight daily, we limited this time for presentation clarity, and the release duration parameter was set to 6 h. Runtime parameters, i.e., the total duration of the simulation, were set to 84 h, with an averaging period of 3 h and a top of averaged layer of 100 m a.g.l. Similarly, as with the EVI patterns, the simulations were calculated for the two episodes with the most distinct LDT of birch pollen observed both in Poznań and Rzeszów, i.e., 2006 and 2016.

3. Results

The post-seasonal LDT of birch pollen was detected over 15 years (Poznań) and 8 years (Rzeszów) during a 20-year study period (Fig. 2). On average, the number of days with post-seasonal LDT pollen were higher in Poznań (3.25 days per year and a maximum of 15 days in 2006) than in Rzeszów (1.45 days per year and a maximum of 10 days) (Fig. S1). In addition, the time when the LDT birch pollen episodes occur was highly variable, and although LDT events typically occurred between day of year (DOY) 121 and 138 (first fortnight of May), they could be recorded even in the beginning of June (DOY 152–155). During

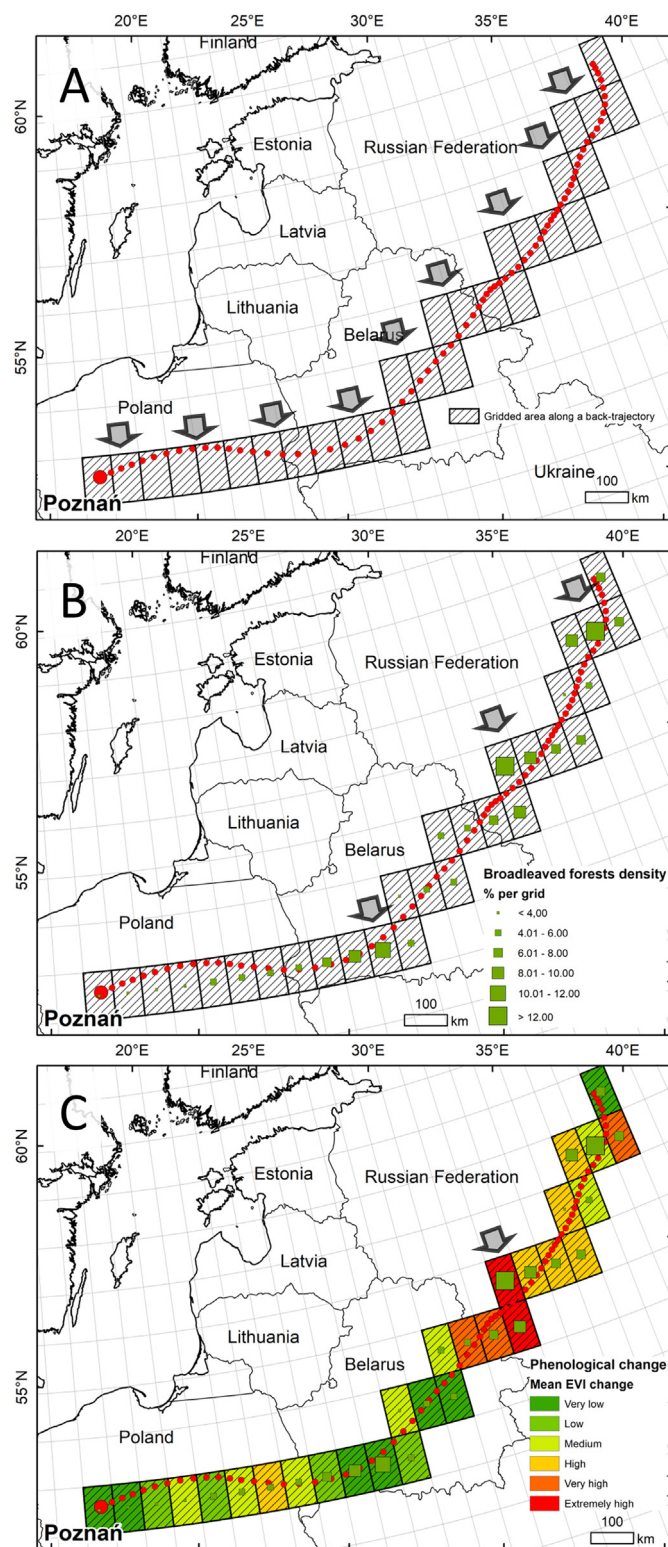


Fig. 1. Three stage procedure of the selection of potential LDT birch pollen sources for the dispersion simulation: 1st stage - selection of raster cells located along the back-trajectory (red points) associated with a high bi-hourly pollen count (A), 2nd stage - selection of raster cells with a high density of broad-leaved forests (B), 3rd stage - selection of raster cells with the highest shift in remote sensing phenology (EVI values between two satellite image acquisitions, before and after the episode examined) (C). Raster cells meeting all the 3 criteria were indicated as potential birch pollen source regions for Poznań. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

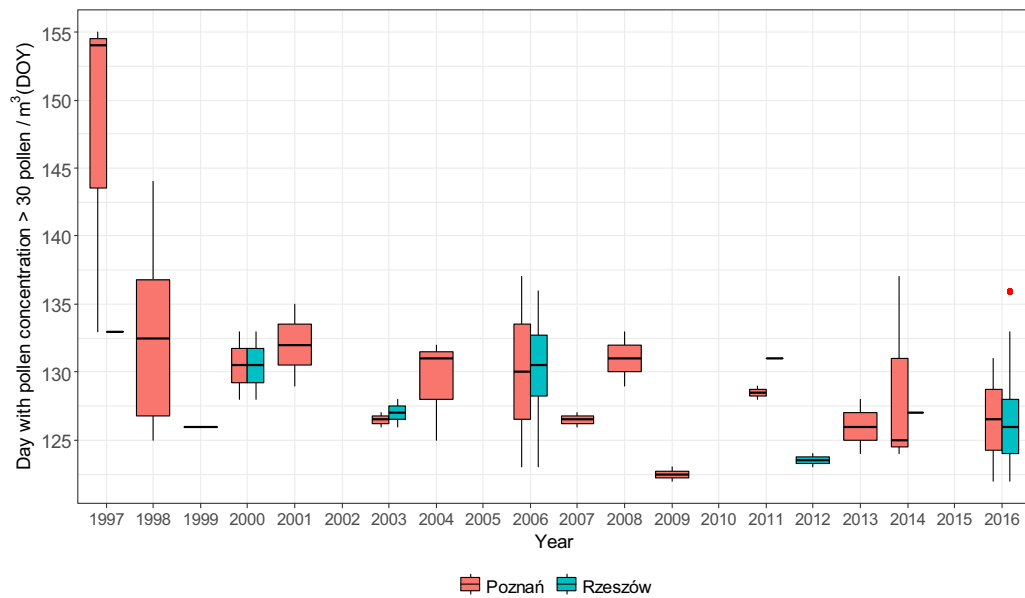


Fig. 2. Temporal range of clinically relevant (daily concentrations $>30 \text{ pollen} \cdot \text{m}^{-3}$), post-seasonal birch pollen episodes in Poznań and Rzeszów during the 20-year period.

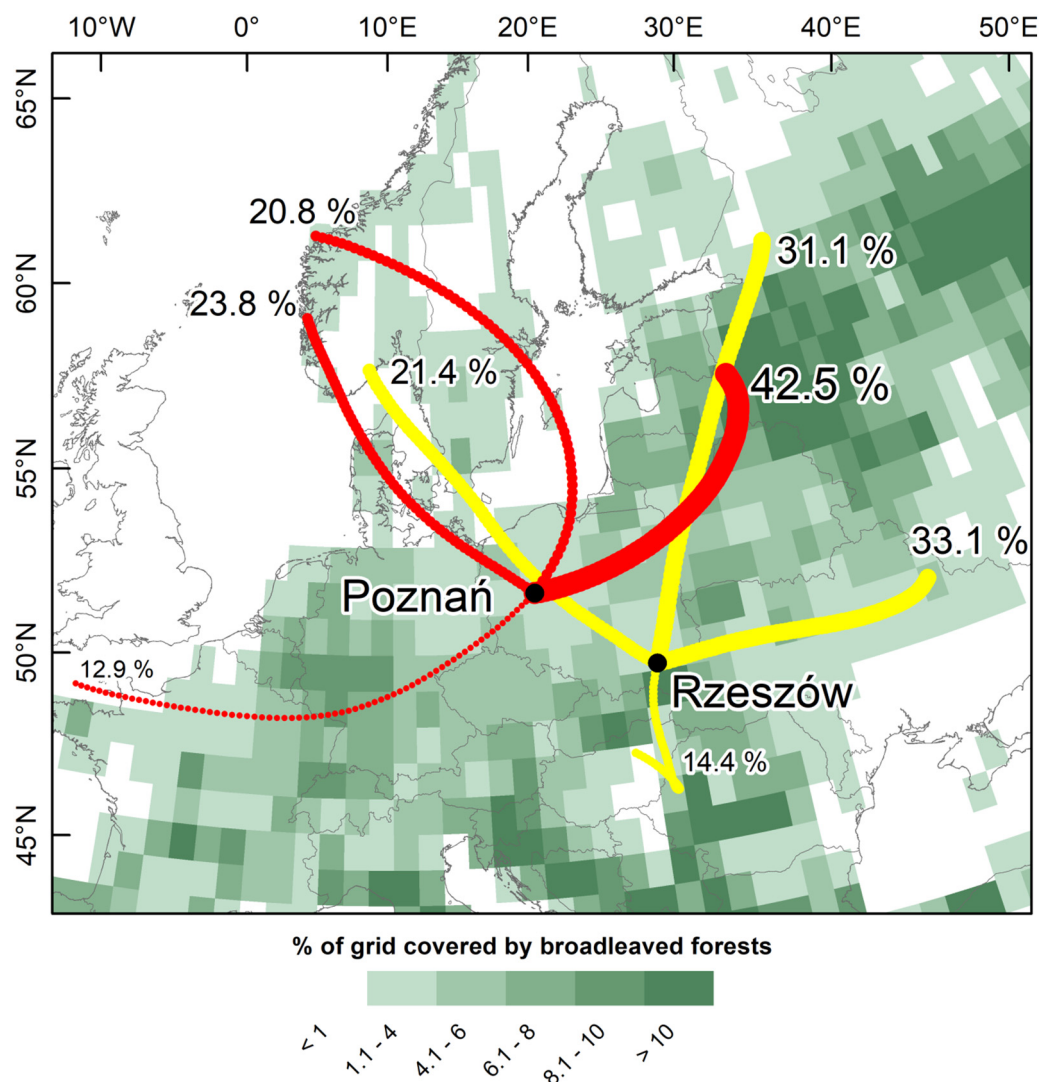


Fig. 3. Cluster analysis for back-trajectories associated with the post-seasonal birch pollen concentration $> 30 \text{ pollen} \cdot \text{m}^{-3}$ for Poznań and Rzeszów (1997–2016).

Table 1
Main characteristics of selected post-seasonal *Betula* pollen LDT episodes in Poznań and Rzeszów in relation to the peak of MPS; MPS - main pollen season (local flowering of birch).

Year	City	Peak date of MPS [date]	Peak of MPS [pollen·m ⁻³]	LDT episode [date]	Diff. between MPS peak date and the start of LDT episode [days]	Peak of LDT episodes [pollen·m ⁻³]	LDT peak percentage of MPS peak [%]	Number of days with conc. above allergy thresholds [days]	
								30 pollen·m ⁻³	80 pollen·m ⁻³
1997	Poznań	2nd May (122 DOY ^a)	1365	2–4th June (153–155 DOY)	31	121	8.9	2	1
1998	Poznań	24th April (114 DOY)	1025	14–16th May (134–136 DOY)	20	109	10.6	2	1
2000	Poznań	18th April (109 DOY)	1306	12th May (133 DOY)	24	122	9.3	1	1
	Rzeszów	24th April (115 DOY)	2186	12th May (133 DOY)	18	53	2.4	1	0
2006	Poznań	22nd April (112 DOY)	2167	5–12th May (125–132 DOY)	13	1308	60.4	11	9
	Rzeszów	23rd April (113 DOY)	2347	9–13th May (129–133 DOY)	17	295	12.6	5	5
2016	Poznań	11th April (102 DOY)	2569	1st–9th May (122–130 DOY)	20	606	23.6	9	8
	Rzeszów	13th April (104 DOY)	5058	3rd–8th May (124–129 DOY)	20	1454	28.7	6	5

^a DOY – day of year counted from 1st January.

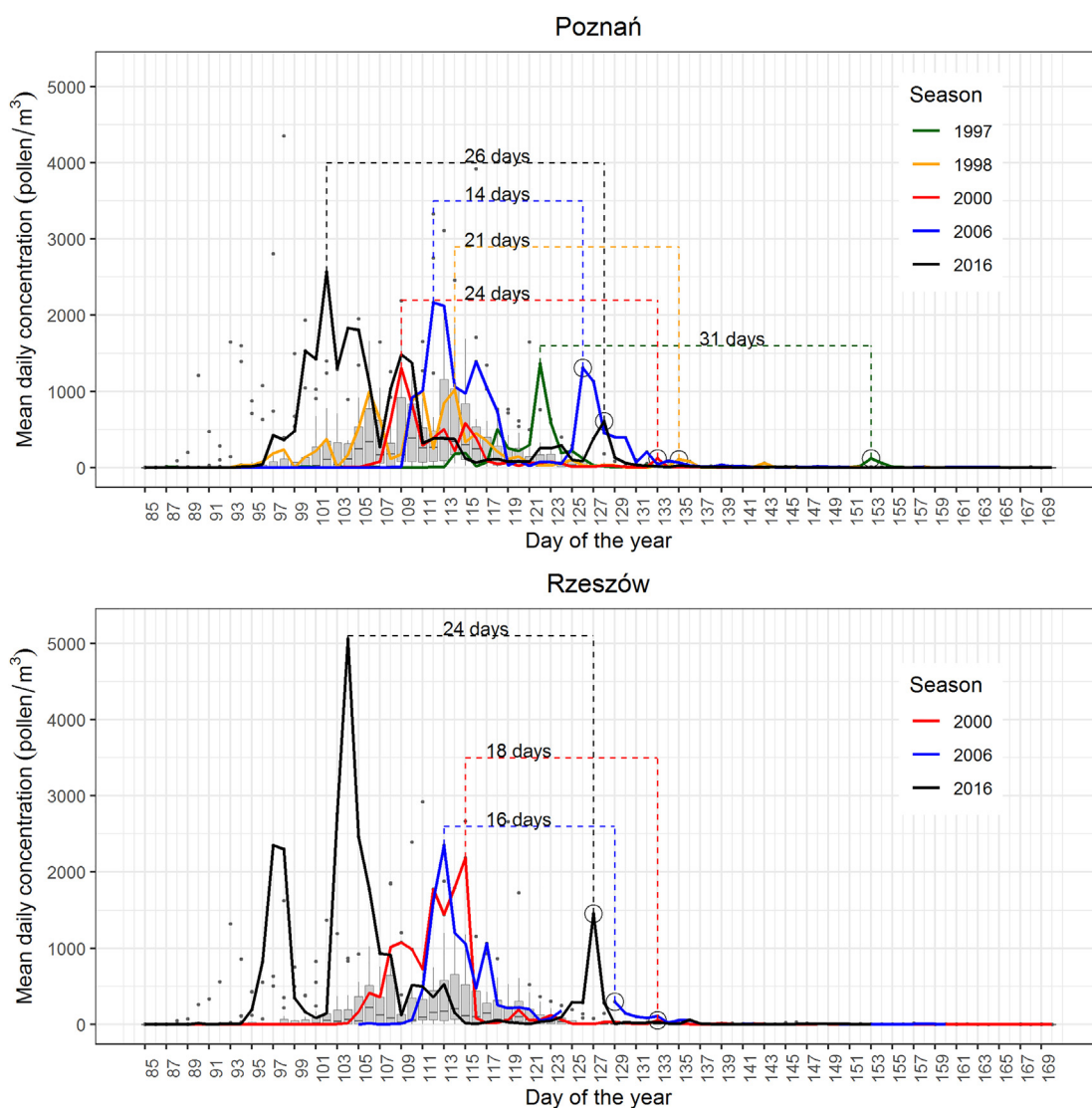


Fig. 4. Daily concentrations of *Betula* pollen during LDT episodes in Poznań and Rzeszów on the background of mean daily concentrations in the period 1997–2016 without years with LDT episodes (grey boxplots).

post-seasonal days with clinically relevant birch pollen concentrations (>30 pollen·m⁻³), air masses flowed primarily from the northeast (42.5% for Poznań and 31.1% for Rzeszów), north (20.8% for Poznań) and northwest (23.8% for Poznań, 21.4% for Rzeszów) to Poland (Fig. 3, Table S2) suggesting that these directions are mainly responsible for the LDT of birch pollen to Poland and central Europe. However, it is interesting that air masses from the east substantially contribute to the post-seasonal birch pollen increase in Rzeszów (33.1%). It is likely that Rzeszów also receives birch pollen from the Carpathian Mountains

located south of the city (14.4%) (Fig. 3). From all the recorded episodes of the LDT of birch pollen, we selected the five most distinct episodes to (1) reveal the synoptic conditions favouring LDT, (2) identify the location of the main potential sources of LDT birch pollen, and (3) simulate the paths taken by a pollen cloud emitted from the potential source regions.

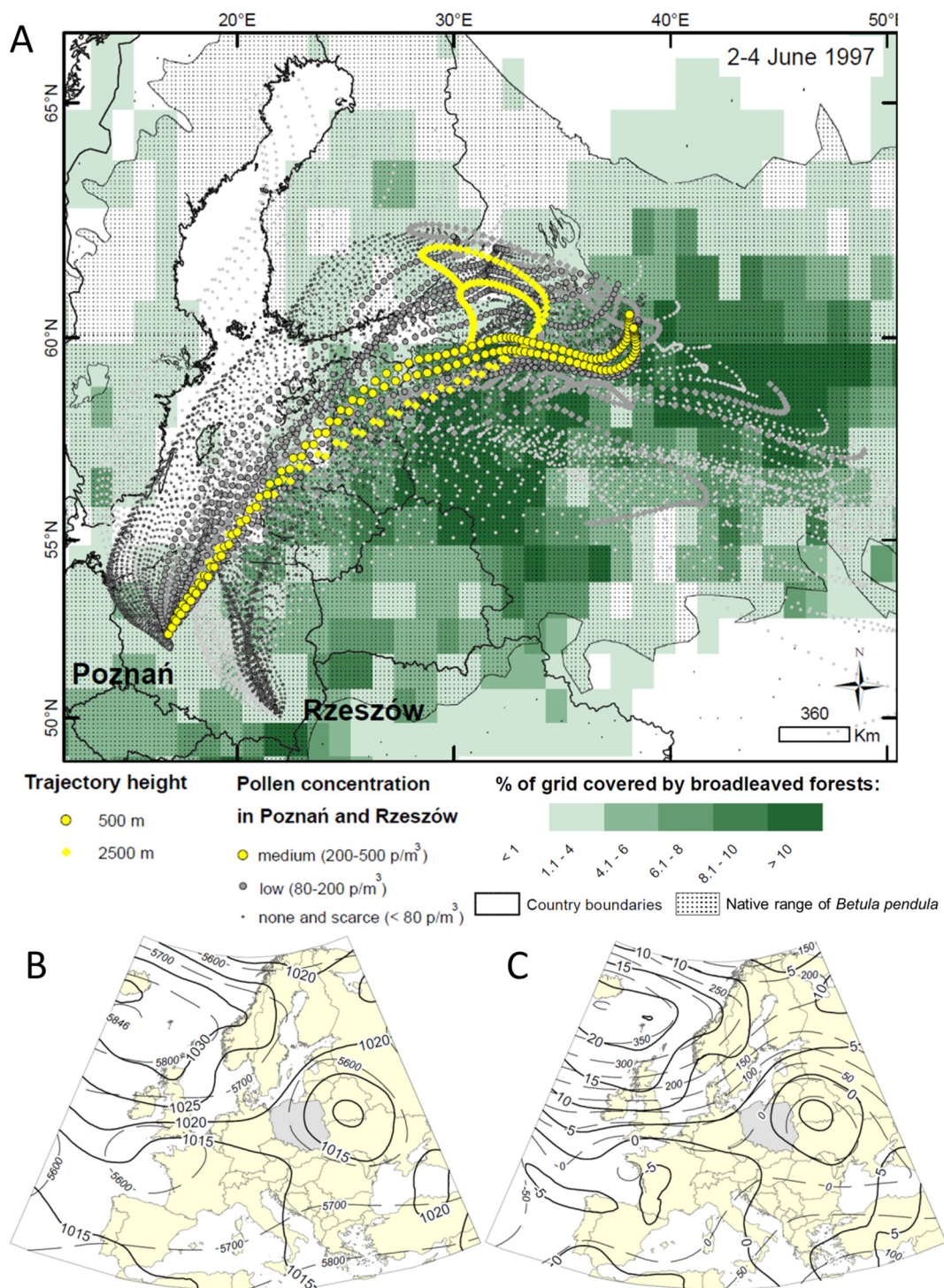


Fig. 5. Seventy-two-hour back-trajectories calculated for Poznań and Rzeszów during the LDT episode in 2–4 June 1997 (A), the mean synoptic pattern (B) and the anomaly map (C) for these days. Solid contours denote the atmospheric pressure (hPa), and the dashed contours denote the 500 hPa geopotential height (m a.s.l.)

3.1. First episode (2–4 June 1997 in Poznań)

On 2 June (DOY 153), a distinct increase in the birch pollen level from 0 to $121 \text{ pollen} \cdot \text{m}^{-3}$ was observed in Poznań but not in Rzeszów (Table 1, Fig. 4). Air masses flowed to Poznań from western Russia and passed through Estonia, Latvia and Lithuania (Fig. 5A). On this date, the air masses arrived over Rzeszów from lower latitudes. In addition, the back-trajectories associated with the highest bi-hourly pollen concentrations showed descending air movement towards Poznań but upward air movement towards Rzeszów (Fig. S2). An extremely elevated

atmospheric pressure anomaly (higher than +20 hPa) was recorded in northern Europe, and it forced the eastern air flow in central Europe (Fig. 5B,C).

3.2. Second episode (14–16 May 1998 in Poznań)

On the 15 May (DOY 135), the mean daily pollen level peaked at $109 \text{ pollen} \cdot \text{m}^{-3}$ (Table 1, Fig. 4). On this date, the air masses originating from central Sweden and Norway lowered in height and arrived over Poznań and Rzeszów (Fig. 6A, Fig. S2). Positive SLP and z500 anomalies (up to

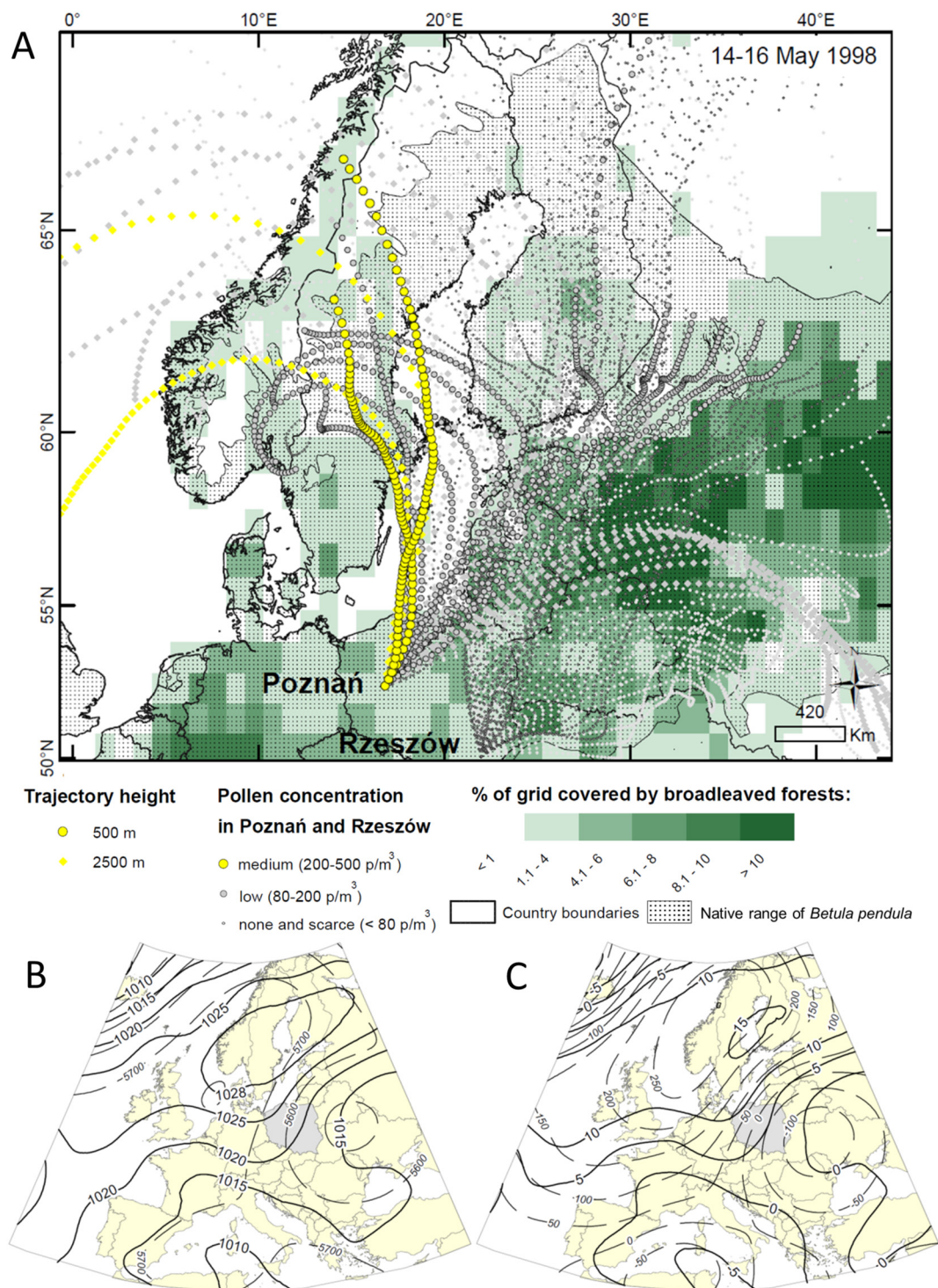


Fig. 6. Seventy-two-hour back-trajectories calculated for Poznań and Rzeszów during the LDT episode in 14–16 May 1998 (A), the mean synoptic pattern (B) and the anomaly map (C) for these days. Solid contours denote the atmospheric pressure (hPa), and the dashed contours denote the 500 hPa geopotential height (m a.s.l.)

+15 hPa and 250 m, respectively) were noted in northern Europe (Fig. 6B,C), although they were slightly lower than that of the 1st episode.

3.3. Third episode (12 May 2000 in Poznań and Rzeszów)

A distinct increase in the birch pollen level occurred on 12 May (DOY 133), when the mean daily pollen level peaked at 122 pollen·m⁻³ in Poznań and 53 pollen·m⁻³ in Rzeszów (Table 1, Fig. 4). Air mass influxes in Poznań and Rzeszów had similar directions. Specifically, the

air masses that originated from the Atlantic Ocean and then passed over the Scandinavian Mountains and Sweden sharply descended towards Poznań and Rzeszów (Fig. 7A, Fig. S2). Such air mass movement was caused by extremely high negative SLP and z500 anomalies over the British Isles (−25 hPa (SLP) and −400 m (z500)) and a strong pressure gradient in northwestern and central Europe (Fig. 7B,C).

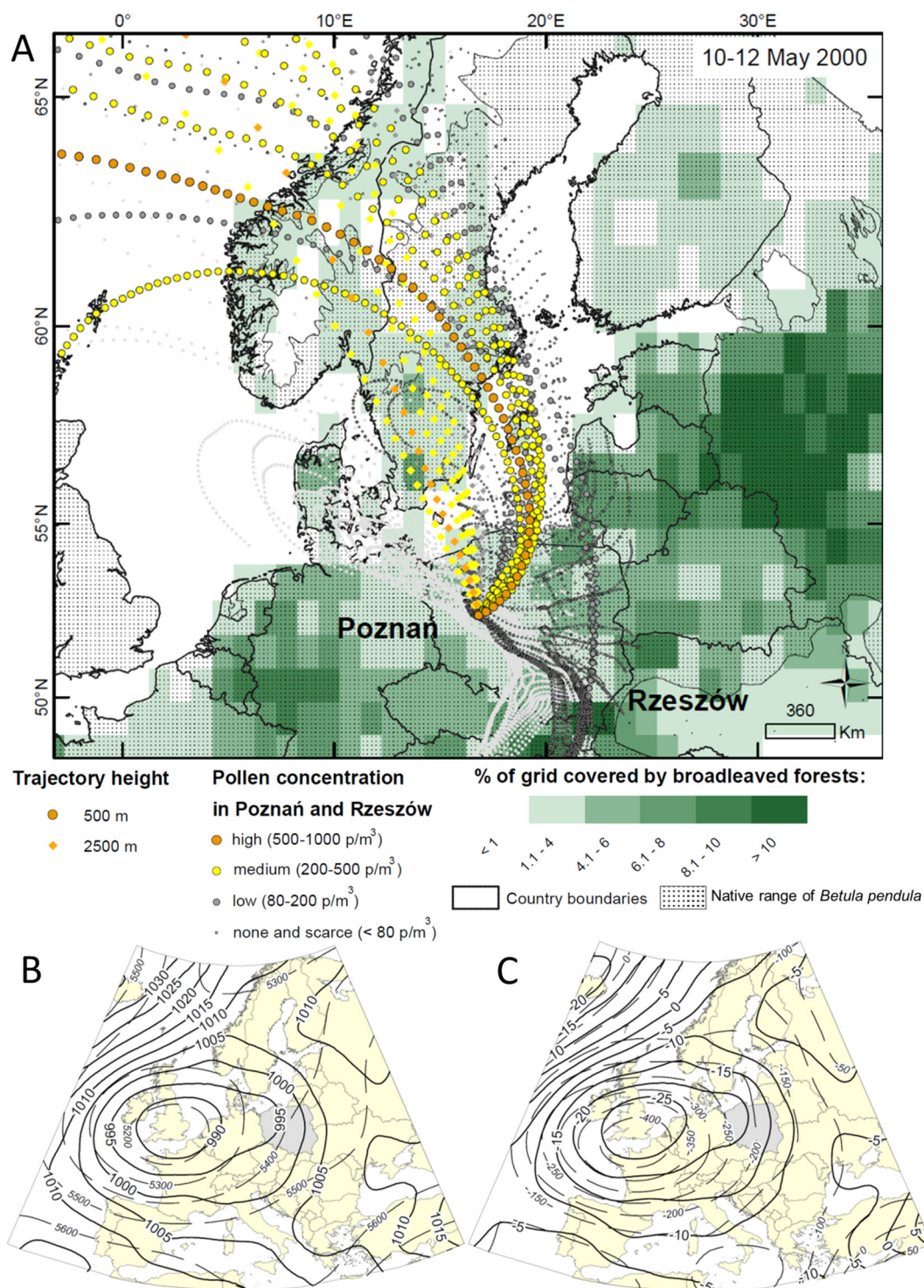


Fig. 7. Seventy-two-hour back-trajectories calculated for Poznań and Rzeszów during the LDT episode in 10–12 May 2000 (A), the mean synoptic pattern (B) and the anomaly map (C) for these days. Solid contours denote the atmospheric pressure (hPa), and the dashed contours denote the 500 hPa geopotential height (m a.s.l.)

3.4. Fourth episode (5–12 May 2006 in Poznań and 9–13 May 2006 in Rzeszów)

In Poznań, the increase in the LDT birch pollen level started on 5 May (DOY 125) (Table 1, Fig. 4). Within two days, the mean daily pollen

concentration peaked from 56 to over 1300 pollen · m⁻³. During this period, the air masses moved from central European Russia through Lithuania and Belarus to Poland (Fig. 8). At this time (between 1 and 17 May 2006), a sharp increase in EVI values (exceeding 0.3–0.4) was observed over large areas in Lithuania, Belarus and western Russia,

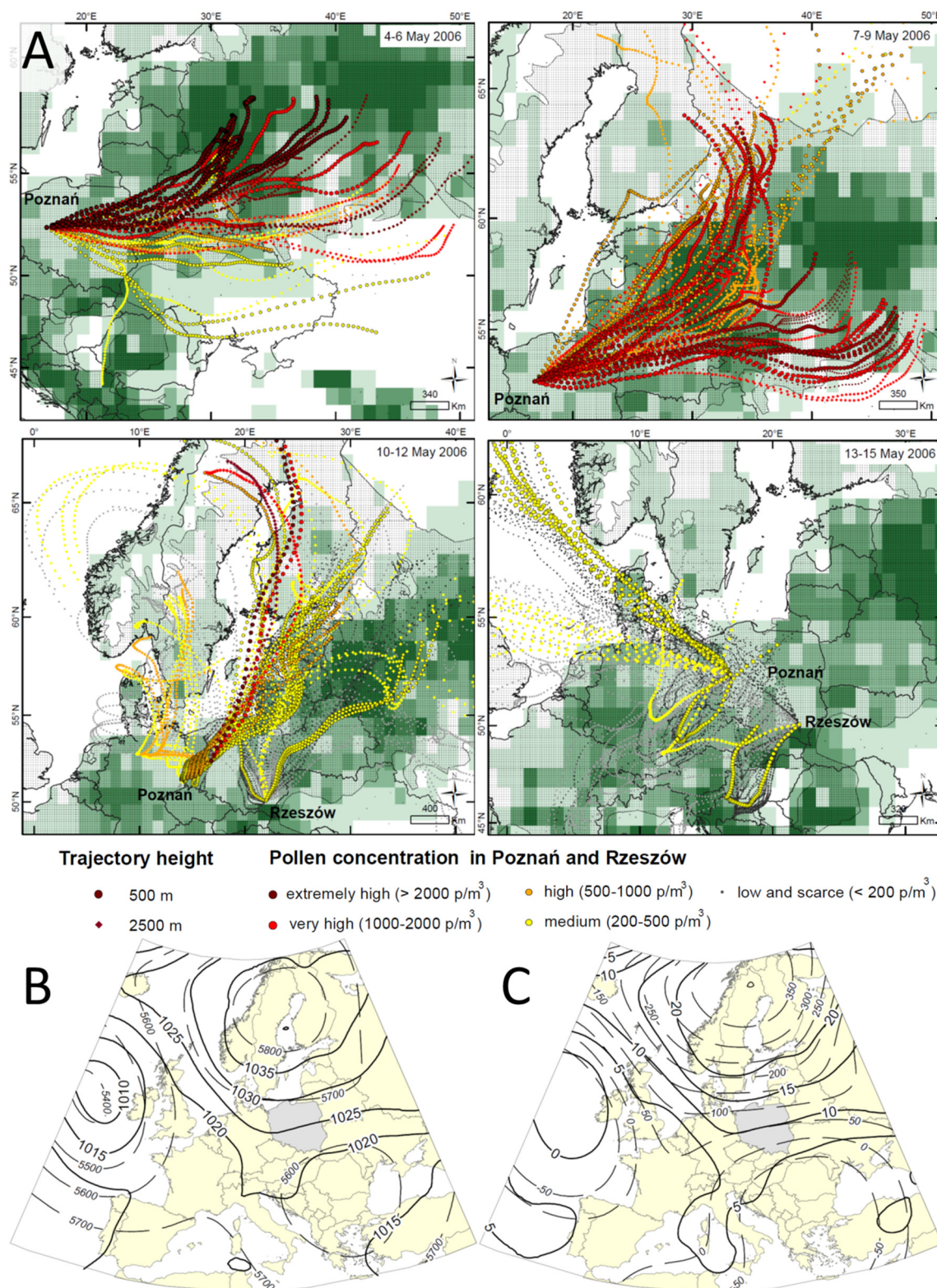


Fig. 8. Seventy-two-hour back-trajectories calculated for Poznań and Rzeszów during the LDT episode in 4–15 May 2006 (A), the mean synoptic pattern (B) and the anomaly map (C) for these days. Solid contours denote the atmospheric pressure (hPa), and the dashed contours denote the 500 hPa geopotential height (m a.s.l.)

which indicated that birch pollen emissions were already possible from these countries (Fig. 10).

On 9–10 May (DOY 128–129), at least two different potential sources of pollen for Poznań and one potential pollen source for Rzeszów were detected. First, the pollen cloud emitted from western Russia reached Poznań and Rzeszów almost simultaneously on 9 May, and it was reflected in the bi-hourly pollen counts (sharp increases at 6.00 and 8.00 UTC in

Poznań, and 8.00 and 12.00 UTC in Rzeszów) (Table S3, Fig. 11). However, a much lower magnitude pollen level was observed in Rzeszów compared with Poznań, which might be related to the upward air movement recorded at this time in Rzeszów but not in Poznań, where height-stable air flow was observed (Fig. S2). Interestingly, on 10 May (0.00–6.00 UTC), a sharp increase in the pollen count was recorded in Poznań. The simulation of pollen dispersion showed that this pollen cloud was emitted

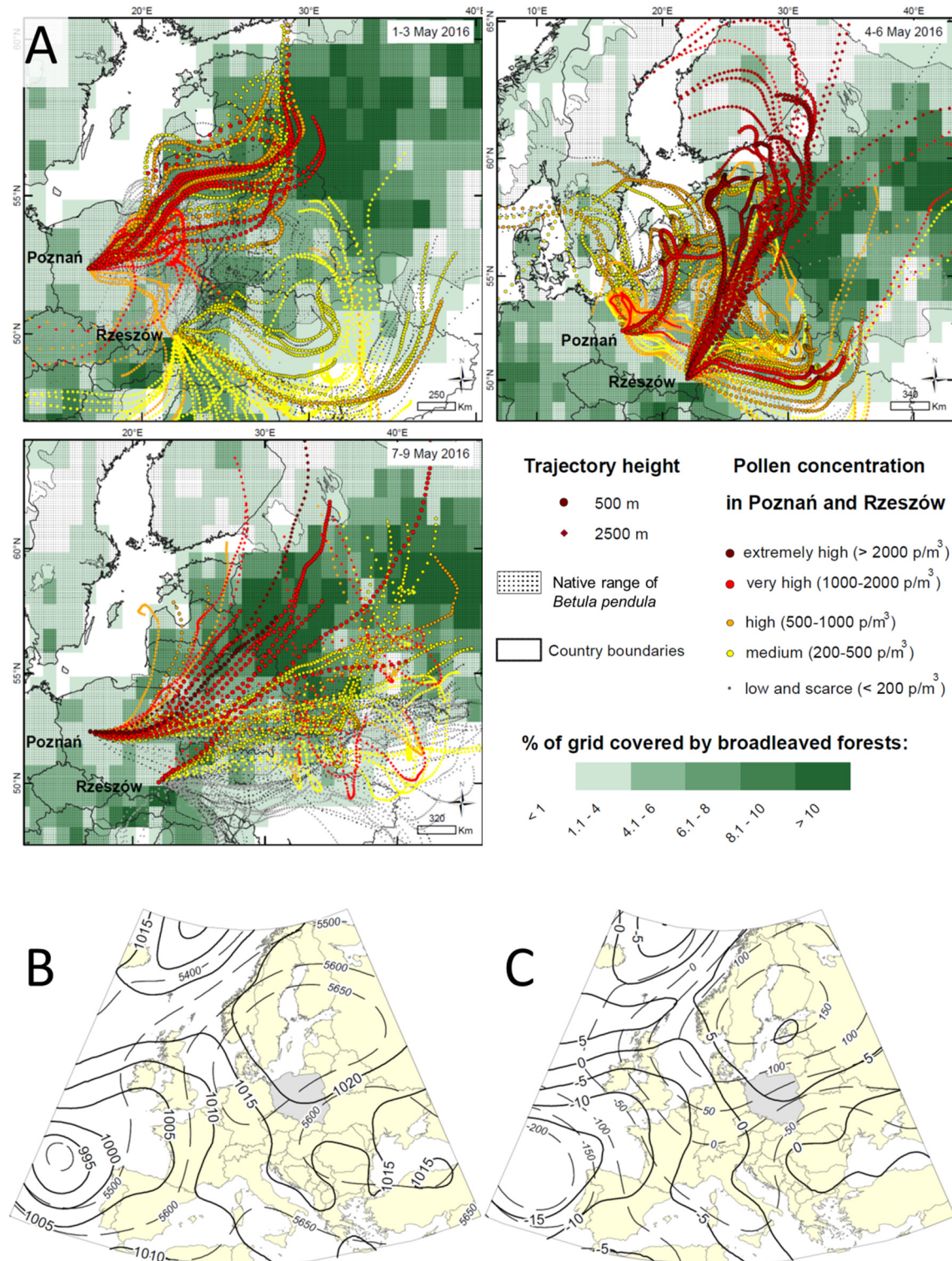


Fig. 9. Seventy-two-hour back-trajectories calculated for Poznań and Rzeszów during the LDT episode in 1–9 May 2016 (A), the mean synoptic pattern (B) and the anomaly map (C) for these days. Solid contours denote the atmospheric pressure (hPa), and the dashed contours denote the 500 hPa geopotential height (m a.s.l.)

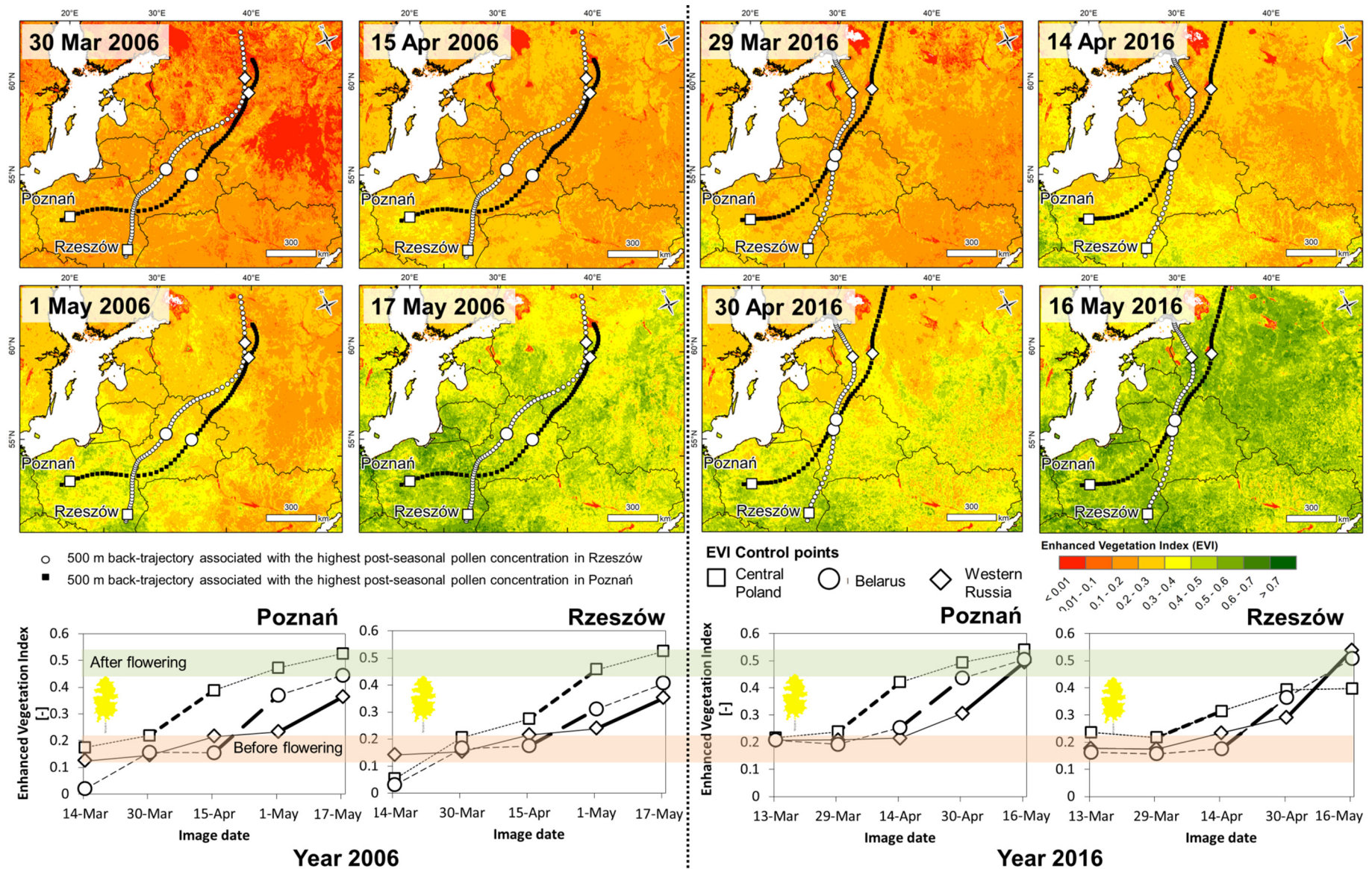


Fig. 10. Enhanced Vegetation Index (EVI) pattern in spring (March–May), Central and Eastern Europe, and years 2006 and 2016. Maps: changes in the EVI in spring shown over the area surrounding the back-trajectories associated with the highest post-seasonal concentrations of birch pollen in Poznań and Rzeszów. Three control points for the detailed EVI analysis were selected along each trajectory: at the beginning in Poland (square), in the middle in Belarus (circle) and at the end in Russia (diamond). Charts: the EVI for the control points was analysed in details. Low EVI values occur generally before intensive plant development and thus before flowering in spring (light orange horizontal bar). High EVI values occur when the leaves are already well developed, which is after the flowering period (green horizontal bar). The bold line on the charts indicates the period when the EVI increases most rapidly, which is attributed to the intensive spring vegetation development and thus flowering. Example: in the first chart (Poznań 2006), the bold line indicates that flowering occurred between 30 March and 15 April in Central Poland (square), between 15 Apr and 1 May in Belarus and between 1 and 17 May in western Russia. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

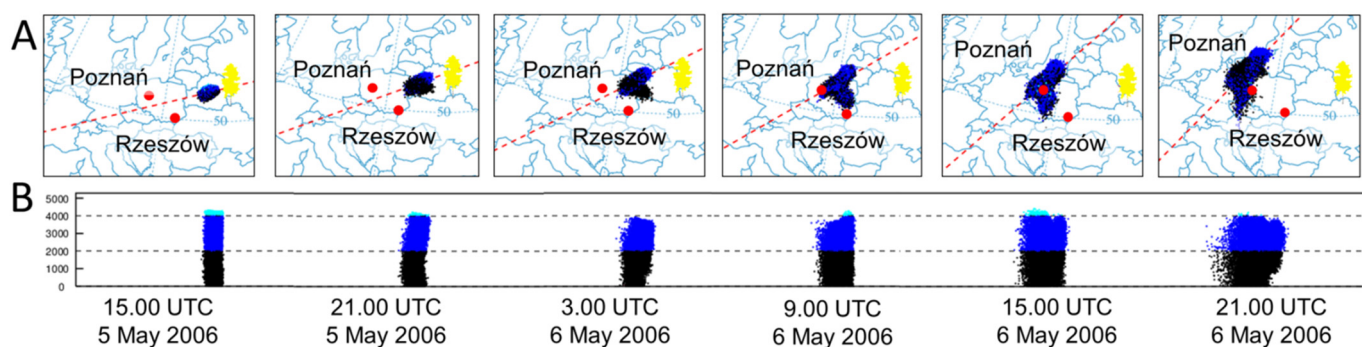
in southern Finland and then dispersed over 2000 m a.g.l. (Fig. 11). The daily concentrations remained high (above 80 pollen·m⁻³) until 12 May (DOY 132) in Poznań and 13 May (DOY 133) in Rzeszów, when the air mass directions completely changed and flowed from the North Sea and Denmark (Fig. 8).

3.5. Fifth episode (1–9 May 2016 in Poznań and 3–8 May 2016 in Rzeszów)

A sudden increase in the birch pollen concentration was observed in Poznań on 1–3 May 2016 (DOY 122–124, especially between 12 and 18 UTC on DOY 123) when the air masses arrived from Estonia, Latvia, Lithuania and northern Belarus (Table 1, Table S3, Fig. 4, Fig. 9). In these areas, the EVI values started distinctly increasing in the second part of April (reaching up to 0.4 on 30 April) (Fig. 10). This finding

Simulation 1.

LDT birch pollen reached Poznań on 6 May 2006 and this was confirmed by the increase in recorded bi-hourly pollen concentrations (from 1225 pollen m⁻³ at 3.00 to 3060 pollen m⁻³ at 9.00). Pollen data from Rzeszów were lacking for this day.



Simulation 2.

LDT birch pollen emitted from Eastern Belarus reached Poznań and Rzeszów almost simultaneously on 9 May 2006. Bi-hourly pollen concentration increased from 560 pollen m⁻³ at 6.00 to 780 pollen m⁻³ at 12.00 in Poznań and from 230 pollen m⁻³ at 8.00 to 690 pollen m⁻³ at 12.00 in Rzeszów). Then, a pollen cloud from southern Finland reached only Poznań on 10 May 2006 (bi-hourly pollen concentration increased from 530 pollen m⁻³ at 0.00 to 3470 pollen m⁻³ at 6.00).

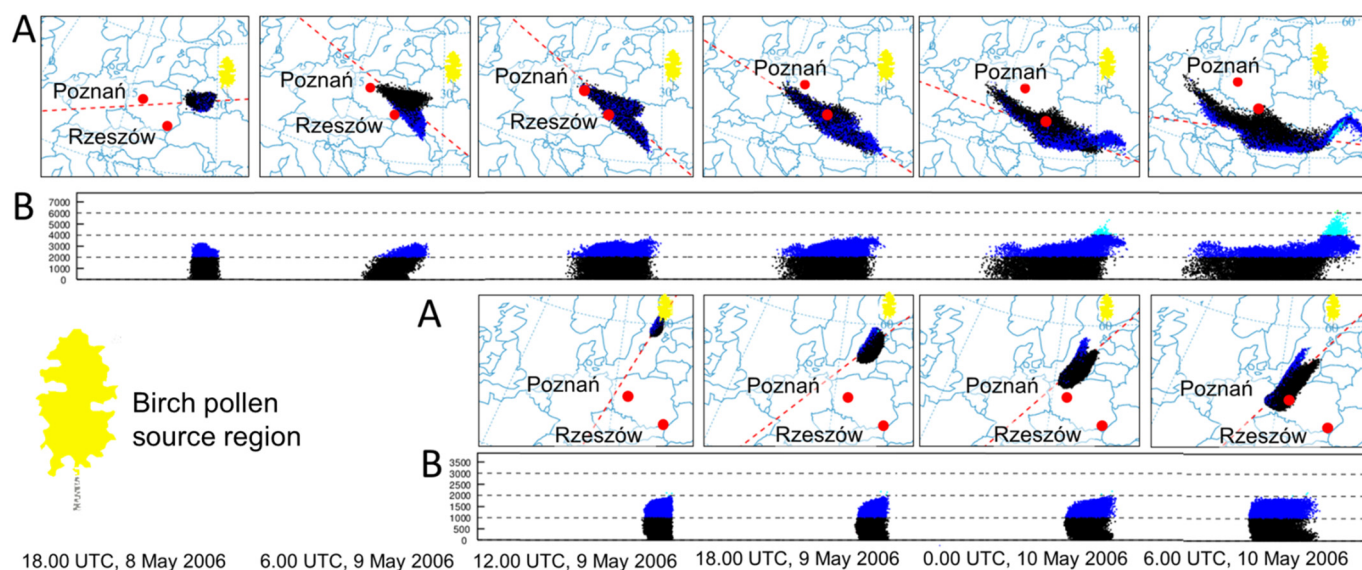
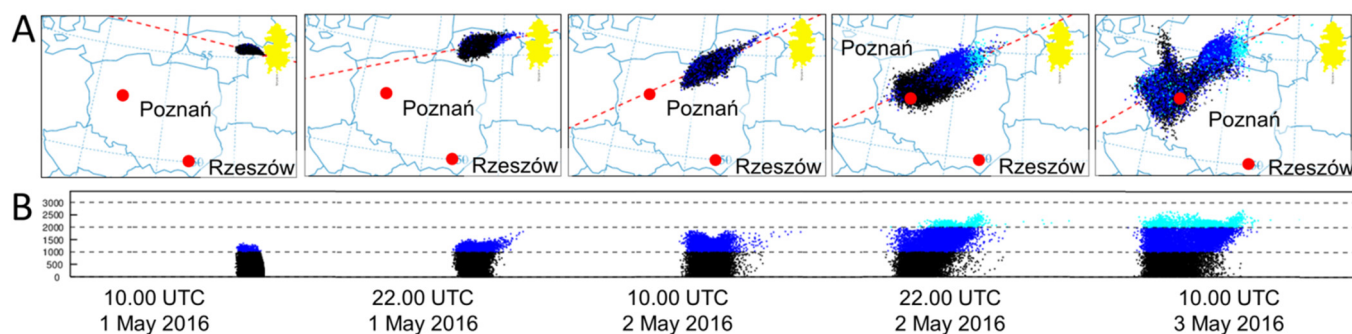


Fig. 11. Simulations of pollen dispersal from a potential source areas (indicated by yellow birch tree) in 2006. Two different long distance transport possibilities (1 and 2) are presented. A – horizontal position of the particles simulating the pollen cloud dispersal over Europe; the time and date are given below the maps. The blue lines denote the country boundaries. B – vertical position of the pollen cloud across the red dashed line (expressed in meters above ground level) for the same time and date as the simulated horizontal position. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

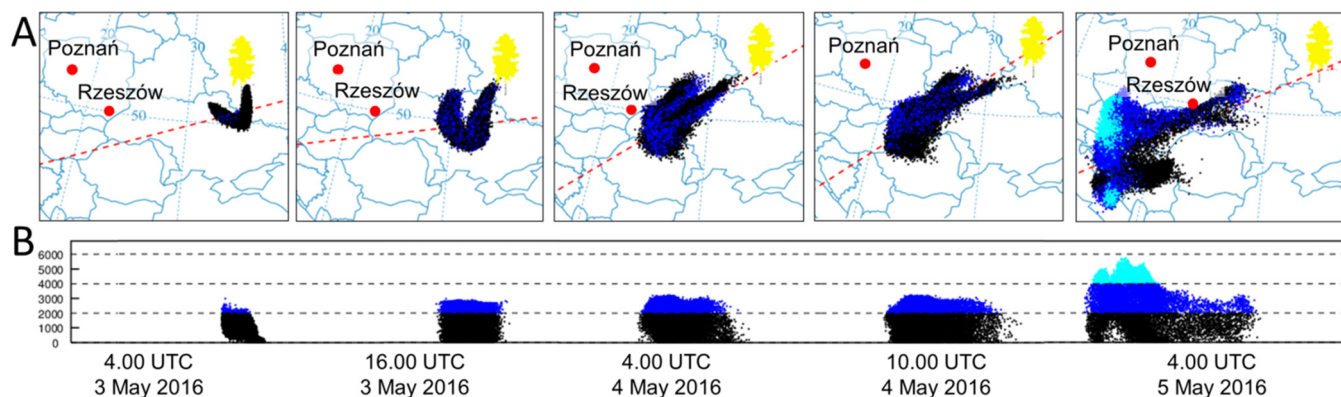
Simulation 3.

LDT birch pollen from northern Belarus reached only Poznań on 2 May 2016 and this was confirmed by the increase in recorded bi-hourly pollen concentrations (from 190 pollen m^{-3} at 10.00 to 1260 pollen m^{-3} at 22.00)



Simulation 4.

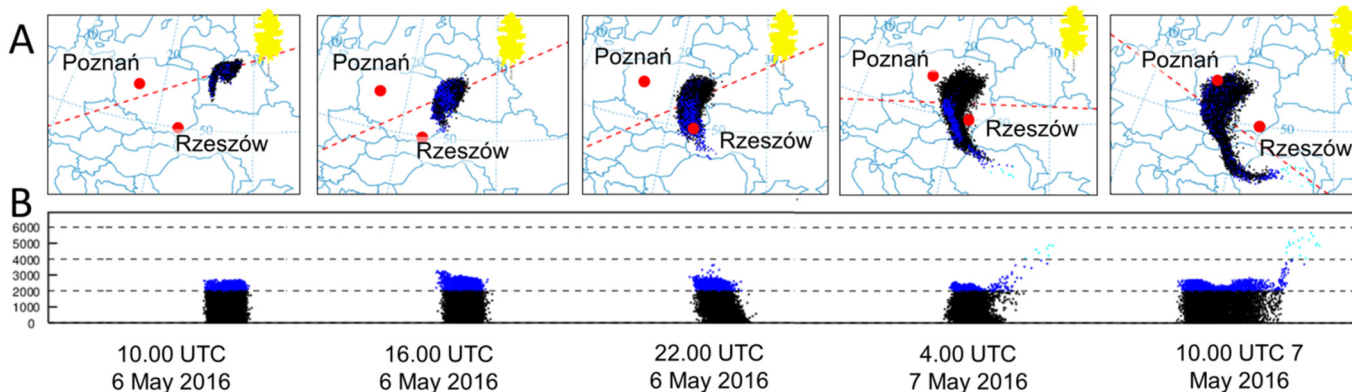
LDT birch pollen from western Russia reached only Rzeszów on 4 May 2016 and this was confirmed by the increase in recorded bi-hourly pollen concentrations (from 486 pollen m^{-3} at 4.00 to 1080 pollen m^{-3} at 10.00)



Simulation 5.

LDT birch pollen from western Russia reached Rzeszów on 6 May 2016 and this was confirmed by the increase in recorded bi-hourly pollen concentrations (from 1800 pollen m^{-3} at 16.00 to 2030 pollen m^{-3} at 22.00).

Then, the same pollen cloud moved further and reached Poznań at 10.00 on 7 May 2016. This was confirmed by the increase in bi-hourly pollen concentrations (from 540 pollen m^{-3} at 4.00 to 2250 pollen m^{-3})



indicates that the birch pollen release started in the second part of April. However, the distinct increase in EVI values continued in these areas in the first half of May, which indicates that the pollen was probably shed also between 1 and 16 May, especially in the first days of May. The dispersion simulation showed that the potential pollen cloud dispersed over 2500 m a.g.l. and reached Poznań between 10 and 22 UTC on 2 May, which was reflected in an increase in the bi-hourly pollen count between 12 and 18 UTC (Fig. 12, Table S3). On these days, Rzeszów was under the influence of air masses originating from Ukraine, Hungary and Romania and the concentrations of birch pollen were markedly lower in Rzeszów than in Poznań (Fig. 4, Fig. 9). An increase in the pollen level in Rzeszów was observed on 3 May when air masses arrived from southern Finland, the Baltic countries, western Russia and Belarus, where a sudden increase in the EVI values (up to 0.4) was recorded this time (Fig. 9, Fig. 10).

On 4–6 May (DOY 125–127), air masses mainly from Lithuania and southern Sweden descended to Poznań (Fig. 9). The simulated pollen cloud from western Russia reached Rzeszów on 4 May (between 4 and 10 UTC) (Fig. 12). The highest daily pollen concentration ($1454 \text{ pollen} \cdot \text{m}^{-3}$) was recorded on 6 May (max bi-hourly pollen count reached $4968 \text{ pollen} \cdot \text{m}^{-3}$ at 8.00 UTC), and it was related to air masses originating from western Russia (Table S2, Fig. 9). Poznań was reached by the same pollen cloud a one day later at between 4.00 and 10.00 UTC on 7 May (DOY 128). The pollen concentration was high until the evening hours, while in Rzeszów, this concentration was markedly lower at that time (Table S3, Fig. 12).

4. Discussion

4.1. Frequency and intensity of the episodes

During the 20-year study period, episodes of the LDT of birch pollen to Poland were observed almost every year, with some episodes lasting several days and being extremely severe from a clinical point of view. In Finland and Denmark, the pre-seasonal episodes of LDT of *Betula* pollen occurred with similar periodicity (Mahura et al., 2007; Ranta et al., 2008; Siljamo et al., 2008; Skjøth et al., 2007), while in Sweden, only four episodes were registered during a 12-year period (Wallin et al., 1991). The severity of the LDT episodes in Finland might be extremely high, could reach as much as $5000 \text{ pollen} \cdot \text{m}^{-3}$ per day and account for >30% of the annual pollen sum (Ranta et al., 2008; Siljamo et al., 2008; Sofiev et al., 2006). During some years, due to the scarce flowering of local birch trees, the contribution of LDT pollen could be even higher (Ranta et al., 2006). Elevated levels of LDT birch pollen exceeding several hundred $\text{pollen} \cdot \text{m}^{-3}$ have also been frequently observed in Sweden (Wallin et al., 1991), Lithuania (Veriankaite et al., 2010), Russia (Siljamo et al., 2008), and Denmark (Skjøth et al., 2007). Sporadically, much higher concentrations of LDT birch pollen have been recorded in Sweden and Russia (up to $1.200 \text{ pollen} \cdot \text{m}^{-3}$ and $5.000 \text{ pollen} \cdot \text{m}^{-3}$, respectively) (Wallin et al., 1991; Siljamo et al., 2008). Our results showed that in Poland, generally lower concentrations of LDT birch pollen ranging from 30 to 200–300 $\text{pollen} \cdot \text{m}^{-3}$ per day were observed during the investigated episodes. In 2006 and 2016, the daily concentrations exceeded $1.300 \text{ pollen} \cdot \text{m}^{-3}$, indicating that extremely high concentrations of birch pollen transported over long distances might also occur in Poland. However, considering that birch forests (pollen source area) in northern and eastern Europe are much larger than those in central and western Europe (Beck et al., 2016), it is surprising that the frequency and the intensity of post-seasonal birch LDT episodes in Poland (receiving pollen from northern

Europe) were not distinctly higher than the pre-seasonal LDT episodes in northern Europe (receiving pollen from central Europe).

Notably, due to the high and clinically relevant intensity of the investigated LDT pollen episodes, these events might be a real threat to people suffering from allergies. The transport of birch pollen from distant sources to Poland is possible for a long time after the flowering of local trees and may even occur as late as June. During LDT episodes, sensitized patients are often unprepared and may unexpectedly develop allergy symptoms (Wallin et al., 1991). The co-occurrence of post-seasonal episodes of *Betula* pollen LDT with pollen released by late flowering allergenic species, e.g., oak (*Quercus* sp.), plane tree (*Platanus* sp.) and grasses (Poaceae), could be another clinical problem (De Weger et al., 2013). It has been shown that the concomitant exposure to many aeroallergens could cause a severe allergy response, which might be especially important for polysensitized patients (Bousquet et al., 1991). In contrast, post-seasonal LDT events have rather negligible effects on eco-evolutionary processes when considering impacts on intra-population genetic variability. It has been shown that only the pre-seasonal transport of pollen can increase gene exchange when the transport occurs during the phenological window formed by female flowers receptivity and before local pollen production (Rousi et al., 2011). The post-seasonal transport of pollen to Poland typically occurs from two to four weeks after the local birch flowering, while birch female flower receptivity persists approximately one week (Sarvas, 1952).

4.2. Sources of *Betula* pollen transported to Poland

Based on back-trajectory modelling, pollen dispersion analyses, land surface phenology changes and the birch forest distribution in central and northern Europe, we estimated that the main sources of *Betula* pollen transported to Poznań and Rzeszów were located in western Russia (Fig. 1, Fig. 3), Belarus, and, to a lesser extent, the eastern Baltic republics and the Scandinavian Peninsula. During certain episodes, a more specific pollen origin could be determined, e.g., areas located to the north from Smolensk City in 2006 and areas between Pskov and Tver cities (Russia) in 2016. The comprehensive analysis conducted in this study allowed the previous hypothesis about the origin of LDT of birch pollen to Poland to be verified. Stach and Silny (1999) reported that, during the LDT episode in 1997, the birch pollen arrived at Poznań from Sweden, as very high concentrations of pollen were measured in Poznań at that time. However, the current study revealed that the main source area was located in western Russia. On the other hand, our analysis confirmed the findings of Siljamo et al. (2008), who noted that, in 2006, almost the whole of Europe (as far as Iceland) was in the range of a birch pollen cloud transported from Russia.

The different proximities of source areas may partially explain the differences in the intensity and frequency of LDT episodes experienced in Poznań and Rzeszów. Generally, the post-seasonal transport of birch pollen was recorded more often and had a higher magnitude in Poznań than in Rzeszów (Fig. S1). Compared to Rzeszów, Poznań is approximately 500 km farther north, so pollen transported from the Scandinavian Peninsula may reach Poznań earlier and more easily than Rzeszów, e.g., in the episodes of 1998 and 2000. In addition, Poznań is located in a lowland region without distinct orographic obstacles that can hinder the transport and deposition of pollen, as was shown in detail for the Iberian Peninsula (Belmonte et al., 2008; García-Mozo et al., 2017; Izquierdo et al., 2017). In contrast, Rzeszów is situated in an upland region not far from the Carpathian Mountains. The upward movement of air masses (Fig. S2) forced by that massive orographic barrier might prevent pollen deposition in the city. To explain regional

Fig. 12. Simulations of pollen dispersal from potential source areas (indicated by a yellow birch tree) in 2016. Three different long-distance transport possibilities (1 and 2) are presented. A – horizontal position of the particles simulating the pollen cloud dispersal over Europe; the time and date are given below the maps. Blue lines denote the country boundaries. B – vertical position of the pollen cloud across the red dashed line (expressed in meters above ground level) for the same time and date as the simulated horizontal position. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(e.g., topographic) differences in the atmospheric transport of the particles, mesoscale models such as MM5 or WRF should be applied (Belmonte et al., 2008; Hernández-Ceballos et al., 2014).

In addition, we examined the altitude changes of the selected trajectories during the movement of air masses towards Poznań and Rzeszów. It has previously been shown that the air mass trajectory height is important for explaining the peculiarities of pollen transport processes (García-Mozo et al., 2017; Rousseau et al., 2004). Based on the results of previous studies (Izquierdo et al., 2017; Rousseau et al., 2004; Veriankaite et al., 2010), we focused on only two trajectory heights: 500 m a.g.l. and 2500 m a.g.l. However, the cross-section of the simulated birch pollen cloud showed that pollen might frequently reach an altitude of 4000 m. Our analysis revealed distinct differences in the behaviour of the selected trajectories approaching Poznań and Rzeszów. For instance, during the episode in 2006, the movement of the 500 m a.g.l. trajectory associated with the highest concentration of LDT birch pollen was height-stable towards Poznań. In contrast, a strong decrease in the trajectory height (the trajectory almost reached the ground height) followed by a distinct increase was observed during the movement of the pollen towards Rzeszów, which might explain the lower concentrations of birch pollen observed in this city. On the other hand, during the LDT episode of 2016, when similar high concentrations of pollen were registered in both cities, only slight variations in the vertical movements of air mass trajectories were observed.

4.3. Synoptic pattern favouring pollen transport

During all the examined episodes, the synoptic situation considerably differed from the multiannual mean synoptic pattern observed in the first fortnight of May over Europe, i.e., an Azores High and Icelandic Low (see Fig. S3 for more information). When the post-seasonal transport of *Betula* pollen was recorded in Poland, the high-pressure system, reaching 1022 hPa in the centre, was located over Scandinavia and northwestern Russia. According to the Hess-Brezowsky Grosswetterlagen classification, the dominant circulation types were High Scandinavia-Iceland (23 HNFZ and 22 HNFA) and Scandinavian High (21 HFZ and 20 HFA) (James, 2007). These synoptic patterns are usually associated with dry air influxes, less cloudiness and high solar radiation in Poland (Bogawski and Bednorz, 2016; Werner and Gerstengarbe, 2010). The Z500 pattern clearly indicates southwestern air movement in the middle troposphere over central Europe. Moreover, during one of the episodes (3rd episode in 2000), a strong low-pressure system over the British Isles governed synoptic conditions in central Europe. This pattern characterized by a high SLP gradient and extremely low position of z500 over the British Isles is called the Low over the British Isles (28 TB) (Werner and Gerstengarbe, 2010). This example indicates that although the LDT episodes of birch pollen to Poland is mainly observed during high positive SLP anomalies over Scandinavia and northern Russia, post-seasonal birch pollen transport may also be sporadically experienced during different synoptic situations.

The mean maximum SLP and z500 positive anomalies during the examined LDT episodes reached 8 hPa and 125 m over Norway and Sweden. Distinctly higher anomalies, e.g., 20 hPa over Scandinavia in 2006, were recorded during particular episodes. In contrast, negative SLP anomalies were observed over western Europe (−25 and −15 hPa in 2000 and 2016, respectively). Clearly, both negative and positive anomalies located over different areas (western and northern Europe, respectively) could be associated with elevated birch pollen counts in Poland. The anomaly analyses precisely localized places where the pressure field mostly deviated from the mean, and the SLP pattern controls the most important surface conditions, i.e., wind direction and velocity (Izquierdo et al., 2017). As the z500 is used to describe airflows in the middle troposphere (Bogawski and Bednorz, 2016), this parameter may be extremely useful in explaining the transport mechanisms of airborne pollen (García-Mozo et al., 2017; Hernández-Ceballos et al., 2014; Izquierdo et al., 2017). Hernández-Ceballos et al. (2014) and

Izquierdo et al. (2017) highlighted that a strong pressure gradient is favourable for pollen transport, as it is associated with higher wind speeds. Our results showed that a SLP gradient of approximately 5 hPa (the episodes in 1997 and 2016) between Poland and the pollen source area is sufficient for LDT. Interestingly, the largest anomalies (both SLP and z500) did not occur over Poland itself, but, on average, occurred over Norway and Sweden. In addition, anomalies could be equal to zero over Poland (SLP: 1997; z500: all episodes except 2000), but the atmospheric circulation pattern over Europe could still favour the LDT of pollen to Poland.

5. Conclusions

This is the first study to comprehensively explain the mechanism underlying the post-seasonal LDT of birch pollen to central Europe. We documented that the main source areas for the post-seasonal LDT of *Betula* pollen to Poland are located in Belarus and western Russia and to a lesser extent the eastern Baltic republics and the Scandinavian Peninsula. The LDT pollen reached Poznań more frequently than Rzeszów because of the different topographies of both regions and the proximities of pollen sources. In most cases, the high-pressure centre located over Scandinavia (mean anomaly +8 hPa) and elevated 500 hPa geopotential height over Germany-Denmark-Sweden (mean anomaly up to +125 m) favoured pollen transport. Importantly, the LDT episodes of birch pollen to Poland might be extremely severe, thereby prolonging and strengthening the exposure to birch allergens in receptor areas. Although the post-seasonal LDT of *Betula* pollen can be expected almost every year in Poznań and every second year in Rzeszów, the timing of these episodes is extremely variable (from beginning of May to beginning of June). Thus, by affecting birch pollen-sensitized patients in unforeseen periods, post-seasonal LDT episodes may have important clinical implications. In addition, we proposed a novel approach for detecting sources of LDT pollen. Specifically, we integrated an air mass back-trajectory model, pollen dispersal process simulation, and synoptic pattern analysis with a satellite-based phenological study.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2019.06.348>.

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Supplementary Materials

Detecting distant sources of airborne pollen for Poland: integrating back-trajectory and dispersion modelling with a satellite-based phenology

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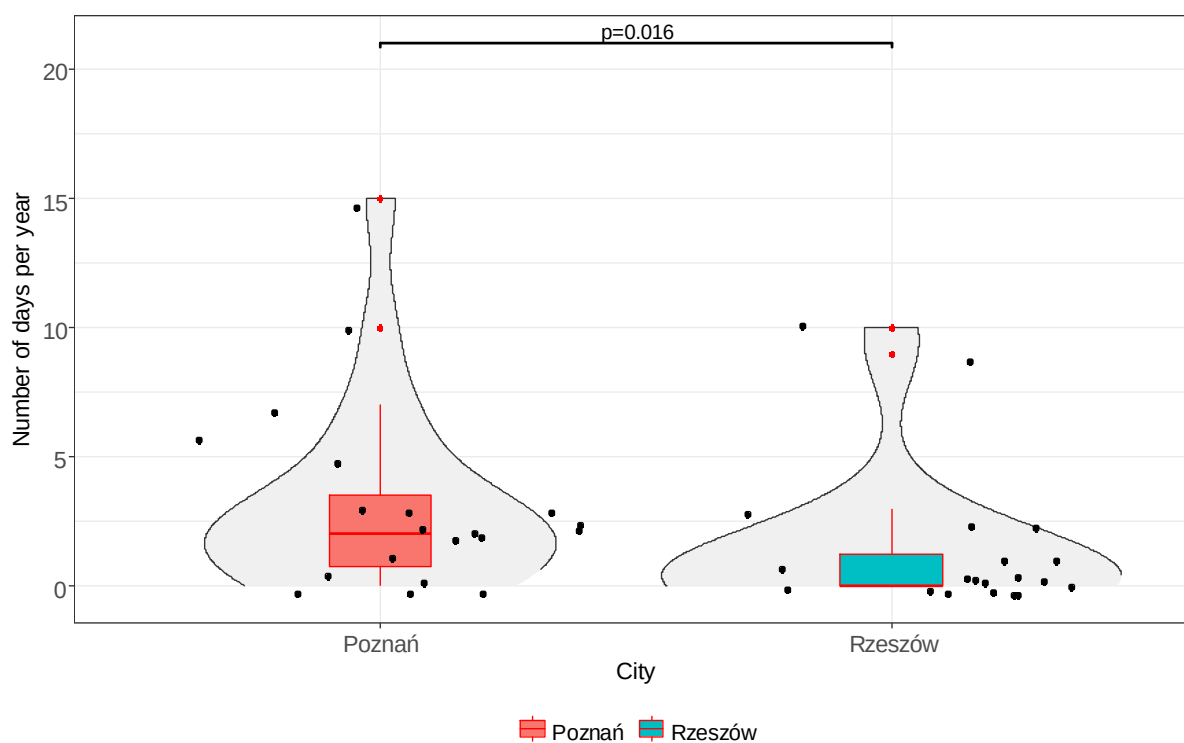


Figure S1. Number of days with pollen concentration > 30 pollen m3 recorded after the local pollen season.

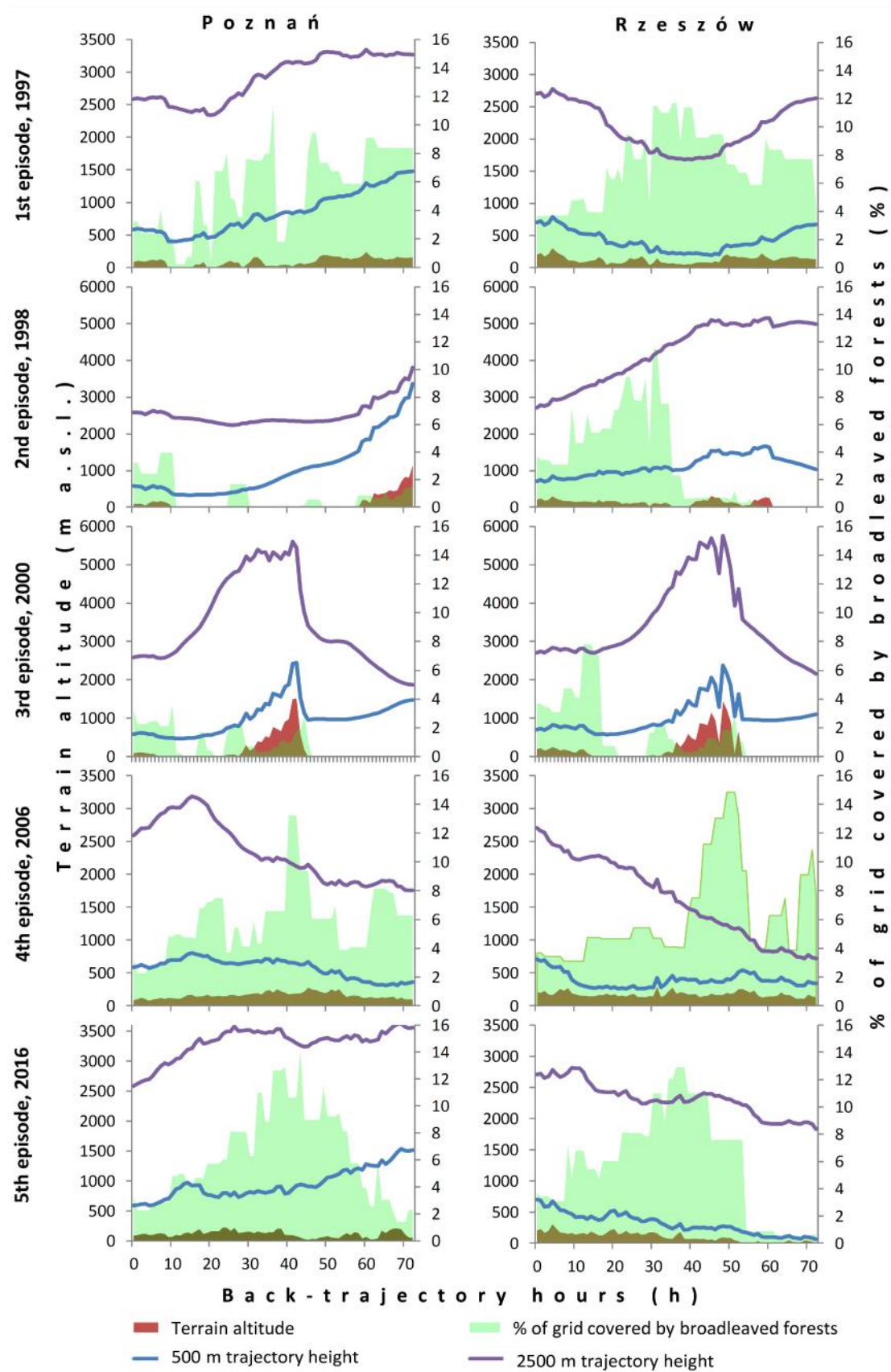


Figure S2: The vertical movement of 72-hour back-trajectories (started at 500 and 2500 m) associated with the highest LDT pollen concentration during the particular episode recorded at Poznań and Rzeszów. The terrain altitude and the density of broadleaved forest are indicated.

Long-term mean of atmospheric circulation pattern

The multiannual mean synoptic situation over Europe observed in the first fortnight of May can be described by a high-pressure system located over Azores and two lower pressure areas located south of Iceland and south-east of Turkey. Mean 500 hPa geopotential height (z500) gradually declined from south to north. A high-pressure system reaching 1022 hPa in the centre was located over Scandinavia determining north-eastern flow of air masses in the lower troposphere to Poland. Z500 pattern clearly indicates on south-western air movement in the middle troposphere over Central Europe.



Figure S3. General synoptic maps for Europe in 1997-2016: A – Mean sea level pressure (SLP [hPa]; solid line) and 500 hPa geopotential height (Z500 [m a.s.l.]; dashed line) in the first fortnight of May, B – Mean SLP and Z500 during post-seasonal birch pollen LDT episodes, C – Anomalies of SLP and Z500 in relation to the mean values for appropriate period (showed in A).

Table S1. Summary of Main Pollen Season Parameters in Poznań and Rzeszów

City	Descriptive statistics	Pollen season start date (day of year)	Peak date (day of year)	Pollen season end date (day of year)	Pollen season length (days)	Pre-peak period length (days)	Post-peak period length (days)	Annual pollen total (pollen m ³)
Poznań	Mean	103.50	110.75	118.05	15.55	8.25	7.30	11067
	Standard deviation	7.00	6.58	5.53	4.21	2.63	3.64	6577
Rzeszów	Mean	103.35	109.70	117.70	15.35	7.35	8.00	7696
	Standard deviation	7.67	6.50	5.53	4.92	3.07	5.02	6190

Table S2. List of days with post-seasonal birch pollen concentration $> 30 \text{ pollen} \cdot \text{m}^{-3}$ in a 20-year period in Poznań and Rzeszów. Air mass inflow directions and suggestions for potential source region of birch pollen has been indicated. Days with southern and western (W, SW, S, SE) inflow directions were most likely not connected with long distance transport. Higher birch pollen concentration on these days might be explained by redeposition of local pollen or the late-flowering of markedly less common *Betula pubescens*.

City	Day of year	Date	Back-trajectory (air mass flow) direction	Potential source region (other sources)
Poznań	132	12 May 1997	S-SW	Denmark, southern Sweden
Poznań	153	02 June 1997	N-NE	Western Russia, Finland
Poznań	154	03 June 1997	N-NE	Western Russia, Finland
Poznań	124	04 May 1998	N-NW	Southern Sweden, Lithuania
Poznań	125	05 May 1998	N-NW	Denmark, southern Norway
Poznań	128	08 May 1998	W-SW	Redeposition, <i>Betula pubescens</i>
Poznań	135	15 May 1998	N-NE	Scandinavia, western Russia
Poznań	136	16 May 1998	N-NE	Scandinavia, western Russia
Poznań	143	23 May 1998	N-NW	Sweden, Norway
Poznań	125	05 May 1999	N	Denmark, Sweden, Lithuania, northern Poland
Poznań	128	07 May 2000	N-NE	Lithuania, Sweden
Poznań	133	12 May 2000	N	Sweden, Norway
Poznań	128	08 May 2001	N	Sweden
Poznań	129	09 May 2001	NNE	Finland
Poznań	130	10 May 2001	NE	Baltic countries, western Russia
Poznań	131	11 May 2001	NNW	Sweden, Norway
Poznań	132	12 May 2001	NNW	Sweden, Norway
Poznań	133	13 May 2001	NNW	Sweden, Norway
Poznań	134	14 May 2001	N	Sweden
Poznań	125	05 May 2003	W-SW	Redeposition, <i>Betula pubescens</i>
Poznań	126	06 May 2003	W-SW	Redeposition, <i>Betula pubescens</i>
Poznań	125	04 May 2004	W-SW-S	Redeposition, <i>Betula pubescens</i>
Poznań	131	10 May 2004	N-NE-E	Belarus, Baltic countries, western Russia, southern Finland,
Poznań	132	11 May 2004	N-NE-E	Belarus, Baltic countries, western Russia, southern Finland,
Poznań	122	02 May 2006	S	Redeposition, <i>Betula pubescens</i>
Poznań	123	03 May 2006	SE-E	Belarus, Russia
Poznań	124	04 May 2006	E	Belarus, Russia
Poznań	125	05 May 2006	E	Belarus, Russia
Poznań	126	06 May 2006	E	Belarus, Russia
Poznań	127	07 May 2006	E-NE	Belarus, Russia, Lithuania, Latvia
Poznań	128	08 May 2006	E-NE	Belarus, Russia, Lithuania, Latvia
Poznań	129	09 May 2006	E-NE	Belarus, Russia, Lithuania, Latvia
Poznań	130	10 May 2006	N-NE	Lithuania, Latvia, Estonia, Finland, Sweden, Denmark
Poznań	131	11 May 2006	N-NE	Lithuania, Latvia, Estonia, Finland, Sweden, Denmark
Poznań	132	12 May 2006	N-NE	Lithuania, Latvia, Estonia, Finland, Sweden, Denmark
Poznań	133	13 May 2006	NW	Redeposition, <i>Betula pubescens</i>
Poznań	134	14 May 2006	NW	Denmark, Norway
Poznań	135	15 May 2006	NW	Denmark, Norway
Poznań	136	16 May 2006	W	Redeposition, <i>Betula pubescens</i>
Poznań	139	19 May 2006	W	Redeposition, <i>Betula pubescens</i>
Poznań	125	05 May 2007	N	Sweden, Norway
Poznań	126	06 May 2007	N	Sweden, Norway
Poznań	129	08 May 2008	N	Sweden, Norway
Poznań	133	12 May 2008	N	Sweden, Norway

Poznań	121	01 May 2009	NE	Baltic countries, Belarus, western Russia
Poznań	122	02 May 2009	NE	Baltic countries, Belarus, western Russia
Poznań	127	07 May 2011	N-NE	Baltic countries, Sweden
Poznań	128	08 May 2011	NE-E	Baltic countries, Belarus, Russia
Poznań	123	03 May 2013	NE-NW	Northern Poland, Lithuania, Denmark
Poznań	124	04 May 2013	NE-NW	Northern Poland, Lithuania, Latvia, Denmark
Poznań	125	05 May 2013	NE-NW	Denmark, southern Sweden
Poznań	126	06 May 2013	NE-NW	Denmark
Poznań	127	07 May 2013	NE-NW	Belarus, Denmark
Poznań	123	03 May 2014	N-NW	Sweden, Norway, Denmark
Poznań	124	04 May 2014	N-NW	Sweden, Norway, Denmark
Poznań	136	16 May 2014	NE-W	Lithuania, Latvia, Sweden, Norway
Poznań	122	01 May 2016	NE-E	Lithuania, Belarus, western Russia
Poznań	123	02 May 2016	NE-E	Lithuania, Belarus, western Russia
Poznań	124	03 May 2016	NE-E	Lithuania, Belarus, western Russia
Poznań	125	04 May 2016	NE	Lithuania, Latvia, Belarus
Poznań	126	05 May 2016	NE	Lithuania, Latvia, Belarus
Poznań	127	06 May 2016	NE	Lithuania, Latvia, Belarus
Poznań	128	07 May 2016	NE-E	Belarus, Russia
Poznań	129	08 May 2016	NE-E	Belarus, Russia
Poznań	130	09 May 2016	NE-E	Belarus, Russia
Poznań	131	10 May 2016	NE-E	Belarus, Russia
Rzeszów	133	13 May 1997	S-SW	Redeposition, <i>Betula pubescens</i> , mountains
Rzeszów	128	07 May 2000	N-NW	Sweden, Norway, Denmark, Lithuania
Rzeszów	133	12 May 2000	N	Sweden, Norway, Denmark
Rzeszów	126	06 May 2003	S-W	Redeposition, <i>Betula pubescens</i> , mountains
Rzeszów	127	07 May 2003	S-W	Redeposition, <i>Betula pubescens</i> , mountains
Rzeszów	128	08 May 2003	S-W	Redeposition, <i>Betula pubescens</i> , mountains
Rzeszów	123	03 May 2006	E	Belarus, western Russia
Rzeszów	124	04 May 2006	NE-N	Belarus, western Russia
Rzeszów	128	09 May 2006	NE-N	Belarus, western Russia
Rzeszów	129	10 May 2006	NE-N	Belarus, western Russia
Rzeszów	130	11 May 2006	NE-N	Belarus, western Russia,
Rzeszów	131	12 May 2006	NE-N	Belarus, western Russia
Rzeszów	132	13 May 2006	NE-N	Latvia, Lithuania, Estonia, Finland, Sweden
Rzeszów	133	14 May 2006	NE-N	Finland, Sweden
Rzeszów	135	15 May 2006	N-NW	Denmark, <i>Betula pubescens</i> ?
Rzeszów	136	16 May 2006	N-NW	Denmark, <i>Betula pubescens</i> ?
Rzeszów	131	11 May 2011	NE-N	Western Russia, Belarus, Finland
Rzeszów	123	02 May 2012	S	Redeposition, <i>Betula pubescens</i> , mountains
Rzeszów	124	03 May 2012	S	Redeposition, <i>Betula pubescens</i> , mountains
Rzeszów	127	07 May 2014	N-NW	Norway, Sweden, Denmark
Rzeszów	122	01 May 2016	S-SE	Redeposition, <i>Betula pubescens</i> , mountains
Rzeszów	123	02 May 2016	S-SE	Redeposition, <i>Betula pubescens</i> , mountains
Rzeszów	124	03 May 2016	S-SE	Redeposition, <i>Betula pubescens</i> , mountains
Rzeszów	125	04 May 2016	NE	Latvia, Lithuania, Estonia, Belarus, western Russia
Rzeszów	126	05 May 2016	NE	Latvia, Lithuania, Estonia, Belarus, western Russia
Rzeszów	127	06 May 2016	NE	Latvia, Lithuania, Estonia, Belarus, western Russia
Rzeszów	128	07 May 2016	NE	Belarus, western Russia
Rzeszów	133	12 May 2016	SE	Redeposition, <i>Betula pubescens</i> , mountains
Rzeszów	136	15 May 2016	NW	Denmark, Norway, Sweden

Table S3. Bi-hourly pollen concentrations during five selected episodes

Poznań, 1997, episode 1												
Bi-hourly period (UTC)	24.00-2.00	2.00-4.00	4.00-6.00	6.00-8.00	8.00-10.00	10.00-12.00	12.00-14.00	14.00-16.00	16.00-18.00	18.00-20.00	20.00-22.00	22.00-24.00
1997-06-01	41	20	0	0	0	0	20	0	0	82	122	102
1997-06-02	102	204	224	61	143	61	163	163	102	82	41	41
1997-06-03	61	122	61	61	143	41	41	20	41	61	20	20
1997-06-04	0	20	41	41	0	20	0	0	20	0	0	
Poznań, 1998, episode 2												
Bi-hourly period (UTC)	24.00-2.00	2.00-4.00	4.00-6.00	6.00-8.00	8.00-10.00	10.00-12.00	12.00-14.00	14.00-16.00	16.00-18.00	18.00-20.00	20.00-22.00	22.00-24.00
1998-05-14	20	0	20	102	0	20	0	0	20	20	0	266
1998-05-15	184	204	123	20	184	82	82	123	20	20	0	82
1998-05-16	20	164	143	102	184	184	61	61	20	0	0	
Poznań, 2000, episode 3												
Bi-hourly period (UTC)	24.00-2.00	2.00-4.00	4.00-6.00	6.00-8.00	8.00-10.00	10.00-12.00	12.00-14.00	14.00-16.00	16.00-18.00	18.00-20.00	20.00-22.00	22.00-24.00
2000-05-11	19	19	19	19	0	39	58	58	39	0	39	19
2000-05-12	78	388	737	349	252	407	271	136	116	97	78	39
2000-05-13	19	0	0	19	0	19	0	19	0	0	0	
Rzeszów, 2000, episode 3												
Bi-hourly period (UTC)	24.00-2.00	2.00-4.00	4.00-6.00	6.00-8.00	8.00-10.00	10.00-12.00	12.00-14.00	14.00-16.00	16.00-18.00	18.00-20.00	20.00-22.00	22.00-24.00
2000-05-11	0	0	0	0	0	0	14	14	7	0	7	5
2000-05-12	14	50	58	158	58	86	65	65	50	36	0	8
2000-05-13	22	7	14	50	22	29	14	7	0	0	0	

Table S3 cont. Bi-hourly pollen concentrations during five selected episodes

Poznań, 2006, episode 4												
Bi-hourly period (UTC)	24.00-2.00	2.00-4.00	4.00-6.00	6.00-8.00	8.00-10.00	10.00-12.00	12.00-14.00	14.00-16.00	16.00-18.00	18.00-20.00	20.00-22.00	22.00-24.00
2006-05-04	63	21	42	32	116	169	201	211	158	95	190	84
2006-05-05	137	137	243	95	211	306	961	1425	908	475	940	2344
2006-05-06	1225	2260	2608	3062	2175	1880	5617	4065	2703	1890	1563	1521
2006-05-07	1679	1045	2460	2450	1890	1404	2091	2545	2745	3221	4034	1056
2006-05-08	781	1035	686	1267	1214	919	993	866	824	697	591	1088
2006-05-09	1436	560	1014	1193	781	771	496	517	591	612	528	813
2006-05-10	496	3474	1774	655	380	211	327	285	443	412	275	264
2006-05-11	137	116	201	53	74	84	116	127	116	95	190	201
2006-05-12	243	634	792	771	517	433	370	433	222	222	158	42
2006-05-13	42	137	222	116	127	74	127	63	106	11	0	0
2006-05-14	42	32	42	53	201	180	243	232	327	370	486	348
2006-05-15	317	127	201	116	84	53	116	63	32	32	84	
Rzeszów, 2006, episode 4												
Bi-hourly period (UTC)	24.00-2.00	2.00-4.00	4.00-6.00	6.00-8.00	8.00-10.00	10.00-12.00	12.00-14.00	14.00-16.00	16.00-18.00	18.00-20.00	20.00-22.00	22.00-24.00
2006-05-05	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
2006-05-06	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
2006-05-07	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
2006-05-08	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
2006-05-09	no data	no data	no data	234	689	520	234	169	169	91	195	286
2006-05-10	351	208	221	13	0	130	130	117	117	65	104	117
2006-05-11	39	39	143	143	143	169	130	130	65	39	117	52
2006-05-12	65	91	91	91	208	130	117	91	39	0	52	52
2006-05-13	91	39	78	52	169	169	169	286	182	39	0	39
2006-05-14	26	13	13	12	18	67	43	24	6	61	37	49
2006-05-15	55	49	37	104	49	92	73	49	37	31	61	

Table S3 cont. Bi-hourly pollen concentrations during five selected episodes

Poznań, 2016, episode 5												
Bi-hourly period (UTC)	24.00-2.00	2.00-4.00	4.00-6.00	6.00-8.00	8.00-10.00	10.00-12.00	12.00-14.00	14.00-16.00	16.00-18.00	18.00-20.00	20.00-22.00	22.00-24.00
2016-05-01	95	85	53	551	1579	890	1102	816	371	297	318	488
2016-05-02	413	180	64	191	360	148	265	594	943	1261	1251	1367
2016-05-03	1442	1336	806	869	562	85	307	117	11	11	74	85
2016-05-04	0	74	138	106	11	32	85	254	615	668	360	265
2016-05-05	191	201	244	53	64	138	64	148	212	201	201	541
2016-05-06	1654	859	647	615	901	1336	700	413	403	541	678	763
2016-05-07	541	901	1039	1972	2258	1919	1579	1060	1283	806	477	413
2016-05-08	201	170	138	127	180	339	413	371	445	265	201	85
2016-05-09	64	74	106	95	106	180	170	191	159	106	95	
Rzeszów, 2016, episode 5												
Bi-hourly period (UTC)	24.00-2.00	2.00-4.00	4.00-6.00	6.00-8.00	8.00-10.00	10.00-12.00	12.00-14.00	14.00-16.00	16.00-18.00	18.00-20.00	20.00-22.00	22.00-24.00
2016-05-01	11	32	216	33	44	54	33	141	76	64	216	346
2016-05-02	248	98	22	98	54	22	54	227	22	0	22	33
2016-05-03	97	54	54	87	195	108	270	583	324	151	356	508
2016-05-04	540	486	324	1080	1080	864	497	681	475	227	292	260
2016-05-05	194	486	767	648	918	637	734	648	206	465	831	2420
2016-05-06	3424	2549	4374	4968	3521	2927	3165	1890	1728	2030	1901	1242
2016-05-07	1448	1393	637	389	421	260	356	270	130	76	64	43
2016-05-08	11	11	0	11	11	11	54	11	0	11	0	11
2016-05-09	22	0	32	65	108	119	98	86	43	33	33	