ACTA UNIVERSITATIS LODZIENSIS
Folia Geographica Physica 23, 2024: 61–88, https://doi.org/10.18778/1427-9711.23.06
KATEDRA GEOGRAFII FIZYCZNEJ
Uniwersytet Łódzki

Margarita Zalinian

Uniwersytet Łódzki, Szkoła Doktorska Nauk Ścisłych i Przyrodniczych
E-mail: *margarita.zalinian@edu.uni.lodz.pl*

Extreme events in pollen concentration in Poznań, Poland: seasonality, trends and health impact

Ekstremalne zdarzenia w stężeniu pyłków w Poznaniu, Polska: sezonowość, trendy i wpływ na zdrowie

Abstract Aerobiology studies the biological particles in the air that affect human health, especially plant pollen that causes allergies. The purpose of this study is to describe and examine the pollen seasons of the following plants: plantain (*Plantago sp.*), mugwort (*Artemisia sp.*), alder (*Alnus sp.*), birch (*Betula sp.*), grasses (*Poaceae sp.*), and hazel (*Corylus sp.*) during the period 1996–2021. The results show that each species experiences unique pollen seasons that are influenced by weather patterns. By comprehending these patterns, pollen thresholds essential for controlling pollen allergies and reducing negative health effects can be established.

Keywords Aerobiology, pollen season, extreme pollen events, allergy, pollen thresholds.

Zarys treści Aerobiologia bada cząstki biologiczne w powietrzu, które wpływają na zdrowie człowieka, w szczególności pyłki roślin wywołujące alergie. Celem tego badania jest opisanie i zbadanie sezonów pyłkowych następujących roślin: babka lancetowata (*Plantago sp.*), bylica pospolita (*Artemisia sp.*), olcha (*Alnus sp.*), brzoza (*Betula sp.*), trawy (*Poaceae sp.*) oraz leszczyna (*Corylus sp.*) w okresie 1996–2021. Wyniki pokazują, że każda z tych roślin ma unikalne sezony pyłkowe, które są zależne od warunków pogodowych. Zrozumienie tych wzorców umożliwia ustalenie progów pyłkowych niezbędnych do kontrolowania alergii pyłkowych i ograniczenia negatywnych skutków zdrowotnych.

Słowa kluczowe Aerobiologia, sezon pyłkowy, ekstremalne wydarzenia pyłkowe, alergia, progi pyłkowe.

1. Introduction

The term "aerobiology" was coined in the 1930s to describe the interdisciplinary field of studying the pathways of biological particles (bacteria, viruses, algae, spores, pollen, and other biological matter) that enter and impact living organisms, as well as their behavior in the atmosphere (Bovallius, Roffey 1987). Pollen grains, primarily produced by wind-pollinated plants, are particularly interesting due to their abundance and allergenic properties (Sofiev, Bergmann 2013).

Modern aerobiology is an active discipline that uses cutting-edge techniques and methodologies to study and identify various airborne particles and infectious agents, allowing disease tracking (Fernstrom, Goldblatt 2013). The wide range of aerobiological observations includes the etiology of various diseases caused by plant pollen allergens, fungal spores, bacteria, viruses, urinary proteins from laboratory and farm animals, and organic particles emitted by industrial processes (Myszkowska 2020).

Airborne particles, which are released from substrates, plants, or the environment, are transported into the atmosphere by turbulence and air currents; the concentration of particles in the air and the ground depends on various factors, including the properties of the particles themselves, such as mass, size, pollen wall structure, and shape, the emission rate of particles from the source over a given period, and atmospheric conditions (Bovallius, Roffey 1987).

Pollen is one of the most common types of airborne particles, serving as a carrier for the male gametes required for sexual reproduction in flowering and cone-producing plants (Charles, Craigie 2008). The stamen, the male part of a flowering plant, produces pollen, which is made up of an anther and a filament (Hoen 1999; Punt *et al.* 2007).

Pollen grains have a tough outer wall (exine) made of an anomalous substance called sporopollenin. The pollen grain wall is extremely resistant to water loss and environmental damage, primarily used to prevent damage and dehydration during air travel (Emberlin 2003). The chemical stability of sporopollenin provides significant environmental resilience, allowing pollen grains to survive for millions of years in sedimentary rocks (Edlund *et al*. 2004).

Original article; Received: 18.12.2024; Revised: 7.02.2025; Accepted: 10.02.2025

Pollen grains may also contain inner walls called intine, which are structurally similar to other plant cells. Pollen grains are classified by their size, shape, number of openings (apertures), and surface texture (sculpture). These unique characteristics of pollen grains enable their use in identifying and classifying plants at the family and species levels (Hoedemaekers *et al.* 2015).

Pollen grains vary in size, from 6 µm in forget-me-nots (*Myosotis sp.*) to over 100 µm in plants like pumpkin (*Cucurbita pepo*) and fir (*Abies alba*). Pollen grains range between 10–70 µm in diameter. Pollen size frequently correlates with pollination vector, with the smallest grains being wind-borne and the largest being animal or water-borne pollen. Pollen grains can be spherical, ovoid, triangular, or disc-shaped. They can also be stretched and flattened, resulting in a wide range of variations on these basic geometric patterns.

Furthermore, pollen grains contain a wide range of proteins, only a small portion of which are allergenic to humans. Allergenic proteins can be found in several parts of the pollen grain, including the exine (in the surface depression), the intine (which is primarily concentrated near the germopore), and the cytoplasm (Emberlin 2003).

This complex structure of pollen grains plays an important role in the pollination process where pollen grains are transported from the stamen to the stigma, which is the part of the pistil where pollen should land and develop a pollen tube (Charles, Craigie 2008).

Pollination is facilitated by various vectors, including wind, animals, and water (Piotrowska, Weryszko-Chmielewska 2003). Zoophilous plants, which rely on animal pollination, have evolved mechanisms such as color and scent to attract specific insects that aid in the pollination process, establishing a symbiotic relationship between the plant and the insect (Frenguelli 2003a). These plants usually have heavy pollen, making them very attractive to bees and other insects (Salo *et al*. 2014). Insects are the most common live vector pollinators, but mammals, birds, and sometimes reptiles also play a role as animal pollinators (Ratto *et al*. 2018). Bird pollination is particularly significant in tropical and subtropical regions and typically exhibits larger, more robust structures, vivid colors, lack of scent, abundant nectar, and sticky pollen (Britannica 2020; Belavadi 2013). Although pollen grains of animal-pollinated plants can become airborne, they are generally present in the air in smaller quantities (Piotrowska, Weryszko-Chmielewska 2003).

Water pollination is a comparatively uncommon phenomenon in nature, and to facilitate this process, flowers, and pollen have undergone specific adaptations to allow them to float effectively; for example, the stigmas of water-pollinated plants are simple and rigid (USDA 2020). Wind-pollinated plants produce a large quantity of pollen to enhance the likelihood of some grains reaching the female flowers and achieving pollination (Frenguelli 2003a). This type of pollination primarily occurs in plants found in temperate climates. Wind-pollinated flowers have a relatively simple structure, with few perianths, no odor, and no nectar (Culley *et al*. 2002).

The influence of pollen on the emergence and severity of allergic disorders depends on various factors. These factors include the duration of exposure, which is directly linked to the length of the pollen season and the time spent in allergenic environments. Another factor is the intensity of exposure, which is determined by the concentration of pollen in the atmosphere. These aforementioned factors exhibit significant geographic and temporal variations, resulting in differences in the frequency of allergic disorders associated with pollen across different locations and periods (ECHO 2023). Longer and more intense pollen seasons increase the potential exposure to pollen allergens, thereby worsening the clinical symptoms in sensitive individuals (Myszkowska 2020). The term “pollen season intensity” is used to express the amount of pollen grains present in the air (Sofiev, Bergmann 2013). The dynamics of the pollen season and its annual variability depend on the behavior of plants, particularly concerning the start of the season and its intensity (Myszkowska, Majewska 2014).

The pollen season in a specific area is closely linked to the local flowering season. For pollen to be present in the air, it must be produced and emitted by mature flowers beforehand. However, pollen seasons and flowering seasons typically do not completely align. This misalignment can be attributed to various factors, such as the influence of intervening winds that facilitate the mid and long-range transportation of pollen and the impact of adverse weather conditions (e.g., rain) (Sofiev, Bergmann 2013).

To ensure accurate modeling and forecasting, it is critical to understand the processes and mechanisms by which meteorological factors influence the spatiotemporal variation of pollen concentrations (Frenguelli 2003a).

Environmental factors, particularly weather conditions, influence the onset, duration, and intensity of pollen seasons, which can have an impact on the quality of life for allergy sufferers (Belavadi 2013; Sofiev, Bergmann 2013). For example, temporary environmental conditions such as humidity influence the timing of flowering and pollen release. To create meaningful predictive models, it is necessary to consider year-to-year variations and assess the factors influencing all relevant processes and species differences (Britannica 2023). Furthermore, elevated concentrations of carbon dioxide (CO_2) in the atmosphere have the potential to stimulate plant growth and, as a result, increase pollen and allergen levels in the atmosphere. This increases the risk of allergic reactions (Ziska *et al.* 2019; Climate Central 2023).

Every year, numerous plant species release pollen into the atmosphere, but only a small number of plants cause most allergic disorders (Lo *et al*. 2019). The botanical families that frequently contain the most problematic plants for allergy sufferers are *Poaceae* (grasses), *Betulaceae*, *Asteraceae*, *Oleaceae*, *Cupressaceae*, and *Fagaceae* (Jager 2003). Pollen has a significant impact on human health, particularly in allergic diseases of the nose, eyes, and bronchi (Fernstrom, Goldblatt 2013). Pollen sensitization increases the risk of developing allergic asthma.

The allergenic proteins in pollen grains are the primary cause of allergic reactions. They act on allergic individuals' respiratory tracts, causing allergy symptoms (Rapiejko *et al*. 2022).

Asthma is a chronic condition that is extremely common and poses a significant public health risk. Its prevalence varies around the world, with asthma affecting more than 5% of all populations studied. This condition affects people of all ages, but it is especially common in children, adolescents, and adults, often during their most productive years (Emberlin 2003). Asthma not only impairs many aspects of a person's daily life, such as work or school performance and productivity, but it can also be fatal if not treated (Global Atlas of Asthma 2013).

One of the most fascinating and dangerous types of asthma is "thunderstorm asthma" (D'Amato *et al*. 2021). It occurs when airborne grass pollen accumulates in conjunction with favorable meteorological conditions for thunderstorm formation. During a thunderstorm, these pollen grains are lifted into the air currents, causing them to swell and eventually rupture after absorbing water. This causes the release of particulates containing pollen allergens. The wind can propel these tiny particles downward, allowing them to be easily ingested and infiltrate the respiratory system. Individuals are most susceptible to thunderstorm-induced asthma during the pre-rainy and windy seasons, which are primarily in spring and early summer. Notably, it can affect people who haven't already been diagnosed with asthma (RACGP 2023).

Identifying and avoiding allergy triggers is an important step toward preventing and treating allergies. Avoiding allergen exposure is often the first and most important step in managing allergic diseases (Strzelczyk *et al*. 2020). Successful allergen avoidance necessitates a multifaceted approach that includes education (understanding the sources and behavior of airborne pollen), regular hygiene practices (for both the body and clothing), and the use of physical barriers (Martynov *et al*. 2015). Despite the significant importance of pollen thresholds in allergies, specifically the levels above which the first symptoms occur, there still exist many gaps in our knowledge. While most studies have concentrated on investigating the prevalence of allergies to various pollen species, understanding the threshold at which sensitization occurs remains elusive. Moreover, there is considerable variation in the identified pollen thresholds for symptom manifestation across different studies (Sofiev, Bergmann 2013).

The physiological basis for the development of symptoms in allergic individuals is the increased sensitivity of their mucosa to allergens (Sterk *et al*. 1993). In addition, seasonal variations in allergen load and air pollution are associated with increased responsiveness. In terms of seasonal variations in threshold level, pre- and post-season exposure to relatively lower pollen concentrations may result in allergic responses at a lower threshold (Cheung *et al*. 2003).

The wide range of factors influencing pollen's health effects has hampered efforts to establish a direct relationship between pollen and symptom severity. However, several studies have reported the pollen levels at which symptoms appeared (Sofiev, Bergmann 2013). Despite this, a consensus on threshold levels is still required for the scientific and medical communities and patients seeking a better understanding of the relationship between pollen concentration and personal risk (Guerrero-Rascado 2022).

One solution is to designate days with extreme concentrations of pollen grains. Under high or very high pollen concentrations in the air, the allergic response in sensitive patients is very intense, which is frequently associated with exacerbation of symptoms (Myszkowska 2020). For allergy sufferers, periods of extremely high pollen concentrations become critical, significantly increasing the number of hospital visits for emergencies (Hanslik *et al*. 2001). Thus, extreme pollen events (EPEs) could be defined as all episodes or events of atmospheric pollen that, due to their magnitude, low frequency, and consequences, can have a significant impact on the population and the environment (Carinanos *et al*. 2022).

The research area is located in Poznań, with a population of ~550,000, which is the capital of Wielkopolska, an agricultural region in midwestern Poland (CSO 2011). Poznań features warm summers and cold winters due to its temperate continental climate. Mean January and July temperatures in Poznań are −1.0°C and 18.0°C, respectively, and mean annual precipitation is approximately 550 mm (1971–2000 average). Prevailing winds are from a westerly direction (mainly southwest) (Woś 2010).

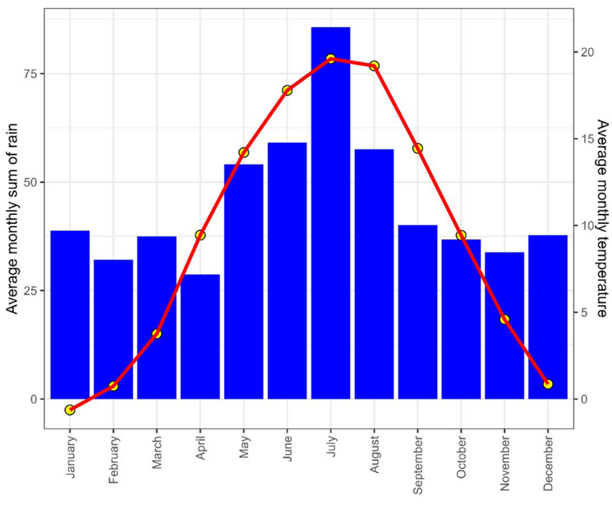


Fig. 1. Climatic conditions in Poznań for the period 1995–2021

Rys. 1. Warunki klimatyczne w Poznaniu w okresie 1995–2021

2. Materials and methods

Six plant taxa, namely hazel (*Corylus sp.*), birch (*Betula sp.*), alder (*Alnus sp.*), grasses (*Poaceae*), plantain (*Plantago sp.*), and mugwort (*Artemisia sp.*), have been included in the analysis. These taxa are considered important sources of allergenic pollen in Poland (ECAP 2023). Detailed characteristics of the selected plants are described below.

2.1. Hazel (*Corylus sp.*)

Kingdom:	*Plantae*	Allergenicity:	High
Order:	*Fagales*	Pollen season:	Spring
Family:	*Betulaceae*	Type:	Tree and shrub
Genus:	*Corylus*	Sub-type:	Deciduous

Plant

Male inflorescences

Pollen grain

Fig. 2. Table with taxonomy of genus *Corylus* and general appearance of *C. colurna* (photo: https://www.vdberk.pl/drzew/corylus-colurna/), male inflorescences and pollen grains of *C. avellana*

Rys. 2. Tabela z taksonomią rodzaju *Corylus* oraz ogólny wygląd *C. colurna* (fot. https://www.vdberk.pl/drzew/corylus-colurna/), kwiatostany męskie i ziarna pyłku *C. avellana*

The hazel tree is a deciduous plant from the *Betulaceae* family. It is distinguished by its multi-stemmed shrub or small tree form, which ranges in height from 3 to 8 meters. Hazel trees are widely distributed throughout Europe, Asia, and North Africa, and they are valued for both their ornamental value and their edible nuts (Svenning 2002). Hazels are widely grown in Poland, with the highest concentrations in the central and southeastern macroregions (Puc 2007).

Hazel produces slender catkins containing pollen, and female flowers grow separately on the branches. Wind pollinates the flowers, which produce a large amount of pollen in spring or even winter (Taylor *et al*. 2007). Corylus pollen grains are generally isopolar, suboblate to oblate, or oblate-spheroidal, with three pores. Corylus pollen grains typically measure 20–25 µm in length and 26–28 µm in width (Palynological Database 2023).

Hazels are a rich source of tree pollen allergens, which cause symptoms of spring inhalant allergy. Among all allergenic plants, hazel pollen appears the earliest during the growing season (Rapiejko *et al*. 2022). Pollen grains are an important source of tree pollen allergens in northern temperate regions (Pigg *et al*. 2003). The percentage of patients sensitized to hazel (positive skin prick test, SPT) varied from 7.4% in Portugal and 11.9% in France to 35.9% in Germany and 49.4% in Denmark. Poland's share is 22.3%, which is consistent with the European average of 22.8% (Heinzerling *et al*. 2009). The prevalence of clinically relevant hazel sensitization in people with inhalation allergies varied from 3.2% in Portugal and 7.4% in France to 32.4% in Germany and 37.8% in Denmark. In Poland, the percentage was 13.3%, while the European average was 17% (Rapiejko *et al*. 2022). According to Tomalak *et al*. (2010), hazel pollen can cross-react with birch, alder, hornbeam, and hop beam pollen allergens.

2.2. Alder (*Alnus sp.*)

Kingdom:	*Plantae*	Allergenicity:	High
Order:	*Fagales*	Pollen season:	Spring
Family:	*Betulaceae*	Type:	Tree
Genus:	*Alnus*	Sub-type:	Deciduous

Plant

Male inflorescences

Pollen grains

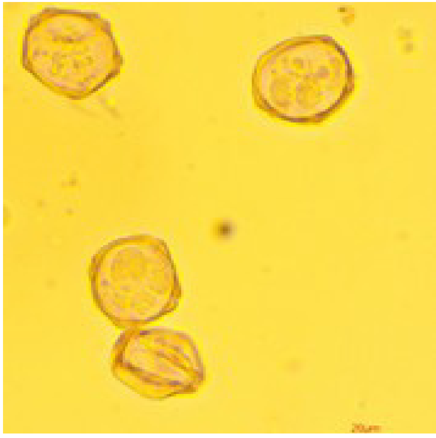


Fig. 3. Table with taxonomy of genus *Alnus* and general appearance of *A. glutinosa*, male inflorescences and pollen grains of *A. glutinosa*

Rys. 3. Tabela z taksonomią rodzaju *Alnus* oraz ogólny wygląd *A. glutinosa*, kwiatostany męskie i ziarna pyłku *A. glutinosa*

The Alder genus is part of the *Fagales* order and *Betulaceae* family. The alder, a rapidly growing deciduous tree commonly found near bodies of water, plays an important role in ecosystem restoration and soil enrichment due to its nitrogen-fixing capabilities. Flowering occurs before the leaf buds open, typically between January and April, depending on latitude and elevation (Gilman and Watson 1993; Biedermann *et al*. 2019). *A. glutinosa*, or black alder, grows throughout Poland, except in high-altitude areas. Alder *A. incana* is less common and is found mainly in the mountains and is an early flowering tree (Zając and Zając 2001).

Alnus pollen grains range from oblate-spheroidal, with 4–5 pores. Pollen grains range in size between 19–21 x 23–30 µm (Palynological Database 2023). *Alnus sp.* is well-known for its high allergenicity, with pollen being a common trigger for allergies in susceptible individuals. People who have been exposed to one type of alder pollen are more likely to be exposed to pollen from other types of alder trees. In northern temperate regions, alder is a major source of tree pollen allergens. In 14 European countries, the percentage of patients sensitized to alder ranged from 3.1% to 47.0%, while the percentage of patients with clinically relevant symptoms varied from 2.3% to 36.2% (Heinzerling *et al*. 2009). In Poznań, the symptoms of patients with positive SPT to *Alnus* pollen allergens were: 51% pollinosis, 43% atopic dermatitis, 4% asthma, 1% chronic urticaria, and 1% eczema (Smith *et al*. 2007).

2.3. Birch (*Betula sp.*)

Kingdom:	*Plantae*	Allergenicity:	Moderate
Order:	*Fagales*	Pollen season:	Winter–Spring
Family:	*Betulaceae*	Type:	Tree
Genus:	*Betula*	Sub-type:	Deciduous

Plant

Male inflorescences

Pollen grains

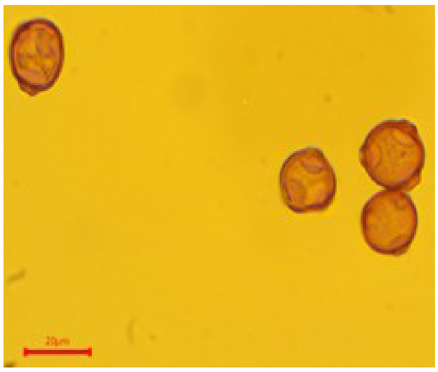


Fig. 4. Table with taxonomy of genus *Betula* and general appearance of *B. pendula*, male inflorescences and pollen grains of *B. pendula*

Rys. 4. Tabela z taksonomią rodzaju *Betula* oraz ogólny wygląd *B. pendula*, kwiatostany męskie i ziarna pyłku *B. pendula*

The birch is a wind-pollinated tree of medium size, reaching heights of up to 30 meters. A birch tree is characterized by its smooth, variegated or white bark that is rich in resin and bears horizontal pores, known as lenticels. This type of bark tends to peel horizontally, especially on young trees, in thin sheets. On mature tree trunks, the dense and deeply grooved bark fractures into asymmetrical plates (Britannica 2020). The floral structures take the form of cone-shaped catkins. Birch trees flower in the late spring season (Schmitz *et al*. 2013). In Poznań the birch pollen season occurs predominantly in April and the beginning of May (Grewling *et al*. 2012). According to empirical research, a single catkin from the silver birch tree has the capacity to yield an average of 1.66 million pollen grains (Ranpal *et al*. 2022).

The pollen of the birch tree is characterized by small grain size, with a maximum axis dimension exceeding 20–25 µm. It has a spheroidal morphology and three distinctive protruding pores (Kubik-Komar *et al*. 2018). Birch pollen is the primary and prevalent cause of seasonal allergies in the regions of Central and Northern Europe. The prevalence of sensitization to birch pollen allergies in European countries has been reported to range from 8% to 16% (Biedermann *et al*. 2019). In Poland, a positive SPT was observed in 14% of the whole population (Samoliński *et al*. 2014).

2.4. Grasses (*Poaceae sp.*)

Kingdom:	*Plantae*	Allergenicity:	Very high
Order:	*Cyperales*	Pollen season:	Spring–Autumn
Family:	*Poaceae*	Type:	Grass
Genus:	–	Sub-type:	Annual

Grass

Inflorescences

Pollen grains

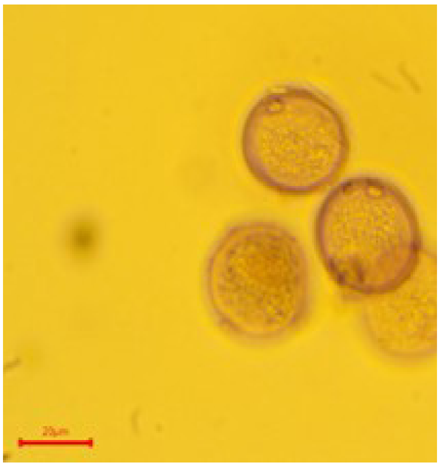


Fig. 5. Table with taxonomy of genus *Dactylis* and general appearance of grasses, inflorescences and pollen grains of *Dactylis glomerata*

Rys. 5. Tabela z taksonomią rodzaju *Dactylis* oraz ogólny wygląd traw, kwiatostany i ziarna pyłku *Dactylis glomerata*

Grasses (*Poaceae*) are wind-pollinated plants that are widely distributed in all types of environments, ranging from tropical to polar habitats. In Poland, there are more than 300 grass species, with the most common genera being *Festuca*, *Dactylis*, *Phleum*, *Poa*, and *Bromus*. Apart from wild species, grasses are widely cultivated, such as wheat and corn (Falkowski 1982). Many grasses grow in compact, long-lasting tussocks with heights ranging from 20 to over 100 centimeters (Míka *et al*. 2002).

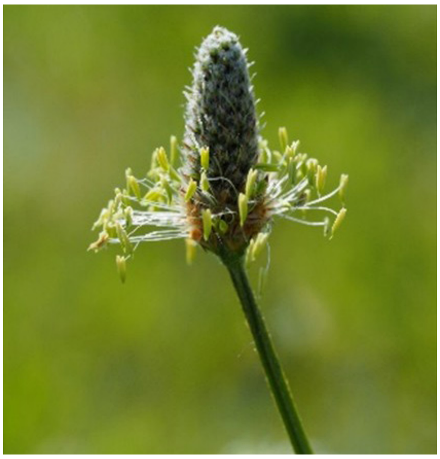
In Poland, the grass pollen season occurs mainly from May to August, with the highest pollen concentration in June and July. Grass pollen seasons in Poland are definitely more stable than tree pollen seasons (Myszkowska *et al*. 2014). Grass pollen grains have a spherical, oval, or ellipsoid shape with only one round pore covered with the exine operculum. The pollen grain size ranges from 25–40 µm in wild species to 75–100 µm in maize (Palynological Database 2023). Grass pollen is the most common cause of respiratory allergies and is associated with more than 50% of allergic rhinitis cases. Grass exhibits a remarkably high level of allergenicity, often triggering severe allergic reactions in susceptible individuals (Calderon and Brandt 2008).

2.5. Plantain (*Plantago sp.*)

Kingdom:	*Plantae*	Allergenicity:	Moderate
Order:	*Plantaginales*	Pollen season:	Spring–Summer
Family:	*Plantaginaceae*	Type:	Weed
Genus:	*Plantago*	Sub-type:	Annual

Plant

Inflorescences



Pollen grains

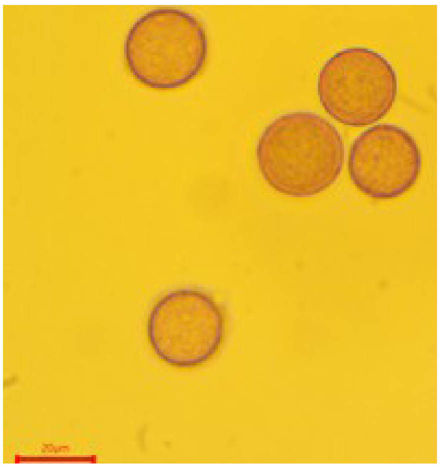


Fig. 6. Table with taxonomy of genus *Plantago* and general appearance of *P. major*, inflorescences and pollen grains of *P. lanceolata*

Rys. 6. Tabela z taksonomią rodzaju *Plantago* oraz ogólny wygląd *P. major*, kwiatostany i ziarna pyłku *P. lanceolata*

The botanical genus *Plantago*, also known as plantain, originated in Europe but has since spread widely throughout the world, achieving cosmopolitan status. Its distribution is primarily found in temperate regions (Holm *et al*. 1977). The *Plantago* species thrives in areas with significant disturbances and has a high tolerance for waterlogging and soil compaction. In Poland, there are over ten plantain species, the most common of which are *P. lanceolata*, *P. media*, and *P. major*. *Plantago major*, a perennial herb, is well known for its medicinal properties and is used to treat a variety of ailments (Choudhary *et al*. 2014). This species is distinguished by leaves with a broadly rounded or cordate base, flower spikes with broadly round-ovate sepals, and ovoid fruits that split at or just below the center (Britannica 2020).

Plantain produces numerous spheroidal pollen grains with 7–9 pores, each measuring 25–30 µm in diameter. These grains have a scabrate sexine with an undulating, densely granular surface (Duke 2001). *Plantago* is a genus of plants with varying levels of allergenicity, with some species known to elicit allergic reactions in people who are sensitive to pollen or other plant allergens. According to Samoliński *et al*. (2014), approximately 8.6% of the Polish population reacts positively to Plantago pollen through SPT. Plantain pollen season in Poland typically begins in May and lasts until September (Dąbrowska-Zapart *et al*. 2018).

2.6. Mugwort (*Artemisia sp.*)

Kingdom:	*Plantae*	Allergenicity:	Severe
Order:	*Asterales*	Pollen season:	Summer–Autumn
Family:	*Asteraceae*	Type:	Weed
Genus:	*Artemisia*	Sub-type:	Perennial

Plant

Inflorescences

Pollen grains

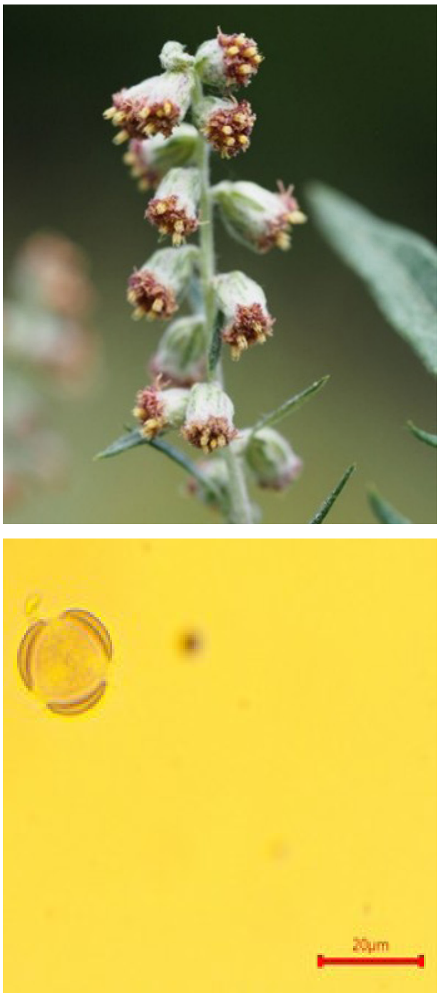


Fig. 7. Table with taxonomy of genus *Artemisia* and general appearance of *A. campestris*, inflorescences and pollen grains of *A. vulgaris*

Rys. 7. Tabela z taksonomią rodzaju *Artemisia* oraz ogólny wygląd *A. campestris*, kwiatostany i ziarna pyłku *A. vulgaris*

Artemisia sp., also known as mugwort, is a perennial weed from the *Asteraceae* family. This genus has 57 species and is found throughout the north temperate regions of Asia, North America, and Europe. The most common *Artemisia* species in Europe are *A. vulgaris* (mugwort), *A. campestris*, and *A. absinthium* (Tutin *et al.* 1972). Common mugwort typically grows to a height of 1 to 2 meters. It thrives best in a variety of soil conditions, from poor to moderately fertile, but prefers well-drained soils with dry to medium moisture levels. Furthermore, it has strong spreading tendencies in the landscape. The flowers themselves are disc-shaped, yellowish to reddish brown, and without petals. Usually blooms in late summer or early fall (Farooq 2016).

Artemisia sp. is well-known for its high allergenicity, owing to its potent pollen, which can cause severe discomfort and respiratory symptoms such as allergic rhinitis, conjunctivitis, and asthma. Mugwort's small pollen grains are a primary trigger for allergic reactions in late summer and autumn in Europe, affecting approximately 10–14% of pollinators (Wopfner *et al*. 2005; Heinzerling *et al*. 2009). Mugwort allergy has been reported in several European regions, as well as in Asia, particularly China and Korea (Barney and Di Tommaso 2003). In Poznań, the prevalence of sensitization to *Artemisia* pollen exceeded 10.5% (Grewling *et al*. 2018).

2.7. Collection of pollen data

From 1996 to 2021, daily pollen data were collected using a Hirst volumetric sampler (Hirst 1952) in Poznań's city center at an altitude of 33 meters above ground level. The Hirst volumetric trap is a popular tool in the field of aerobiology for collecting and monitoring airborne pollen samples. It is critical to understand the distribution and seasonality of pollen, as well as its effects on human health and the environment. A vacuum pump draws in the air sample at a rate of 10 liters per minute, and impaction deposits the pollen grains on a tape. Consequently, the trap samples 0.6 cubic meters of air per hour, resulting in a total of 14.4 cubic meters every day (Stach 2003; Levetin 2004).

After one week of impaction exposure, the tape was removed, and microscope slides were prepared for pollen grain enumeration. The samples were examined under a light microscope at a magnification of 400x. The count of pollen grains is not a cumulative value for the entire sampling surface; rather, it is calculated statistically. There are four main pollen-counting methods: tangent fields, vertical lines, random fields, and horizontal lines. The latter methods were used in this study. In short, during the examination, the sample was scanned by observing four horizontal lines, which allowed for the recording of variations over 24 hours, following the direction of the rotating sampling tape (Frenguelli 2003b). The pollen count for each sample was expressed as the daily average of pollen grains per cubic meter of air (pollen/day/m^3).

Fig. 8. Hirst-type pollen trap located at the studied site (dormitory Eskulap)

Rys. 8. Pułapka pyłkowa typu Hirst zlokalizowana na badanym stanowisku (akademik Eskulap)

2.8. Collection of weather data

Meteorological data, i.e. monthly mean temperature (°C) and monthly sum of rain (mm), used in the study were recorded from 1995 to 2021 by the station located at Ławica Airport (52°25 N, 16°49 E), situated 4.25 km west of the pollen-monitoring site at Esculap. The data were obtained using R package "imgw" (https://github.com/bczernecki/imgw).

2.9. Statistical analysis

Statistical analyses are crucial for examining the pollen season and understanding pollen data distribution. The following characteristics were analyzed: (1) Pollen Season Duration (determined using the 90% method (Nilsson and Persson 1981), where the season starts when 5% of the total pollen is collected and ends at 95%); (2) Pollen Season Intensity (measured by the sum of daily average pollen concentrations, providing a comprehensive assessment of pollen load from the season's start to end); (3) Peak Pollen Concentration (maximum daily pollen concentration and the day of the seasonal peak were recorded for each year from 1996–2021); (4) Extreme Pollen Events (calculated using the 95th, 97th, and 99th percentiles for different pollen taxa, indicating periods of exceptionally high pollen concentrations).

Data related to the start, end, and peak days of the pollen season are converted to the day of the year from 1 January (DOY). Variations of all the characteristics of the pollen season are presented by the following statistical parameters: mean (M), maximum (MAX), and minimum (MIN) values. In addition, simple linear regression analysis was used to describe trends in the chosen characteristics of the pollen seasons. The following statistics are shown: the slope of the regression and the probability level (p). All calculations were carried out using R software (package *tidyverse*, *AeRobiology*, *readxl*, *openxlsx*).

3. Results

3.1. Weather data

During the study period, monthly mean temperatures increased significantly in June (+0.12°C per year), September (+0.08°C per year), November (+0.12°C per year), and December (+0.15°C per year). Only in May was there a slight downward trend, which was not statistically significant (Fig. 9). The mean monthly rainfall data did not show as dramatic changes as the temperature data, but a decreasing trend was observed for the majority of the months (66.6%) – Fig. 10. This trend was most noticeable between February and May, as well as July and October. The most significant decrease in monthly rainfall total occurred in September, at a rate of −1.15mm/year (p-value = 0.051).

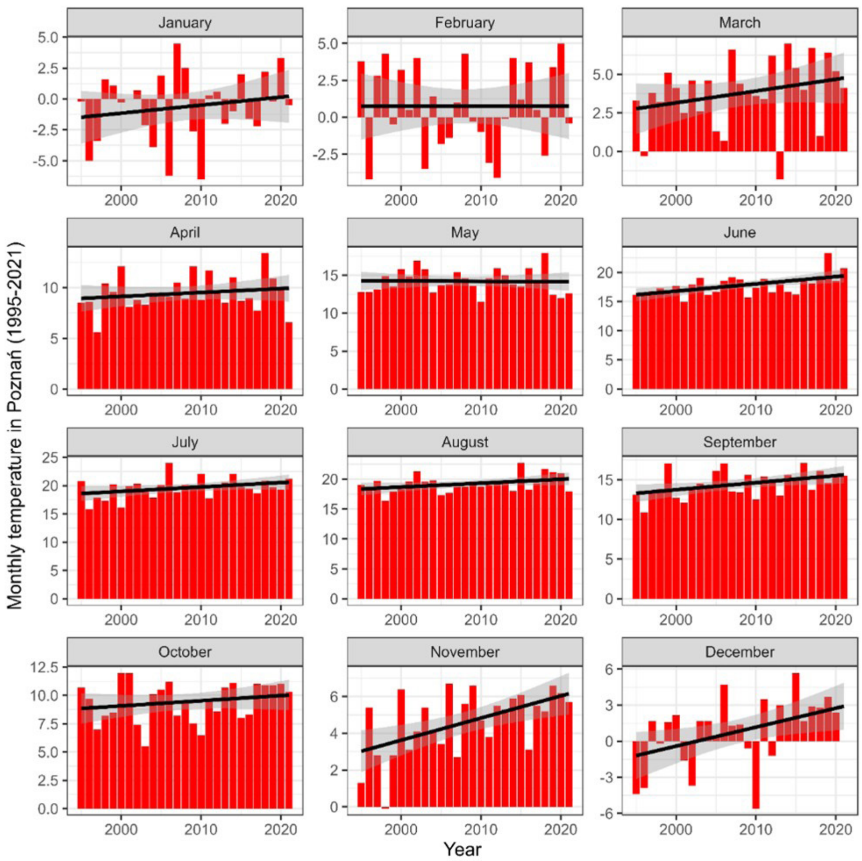


Fig. 9. Variation in average monthly temperature in Poznań during the studied period

Rys. 9. Zmienność średniej miesięcznej temperatury w Poznaniu w badanym okresie

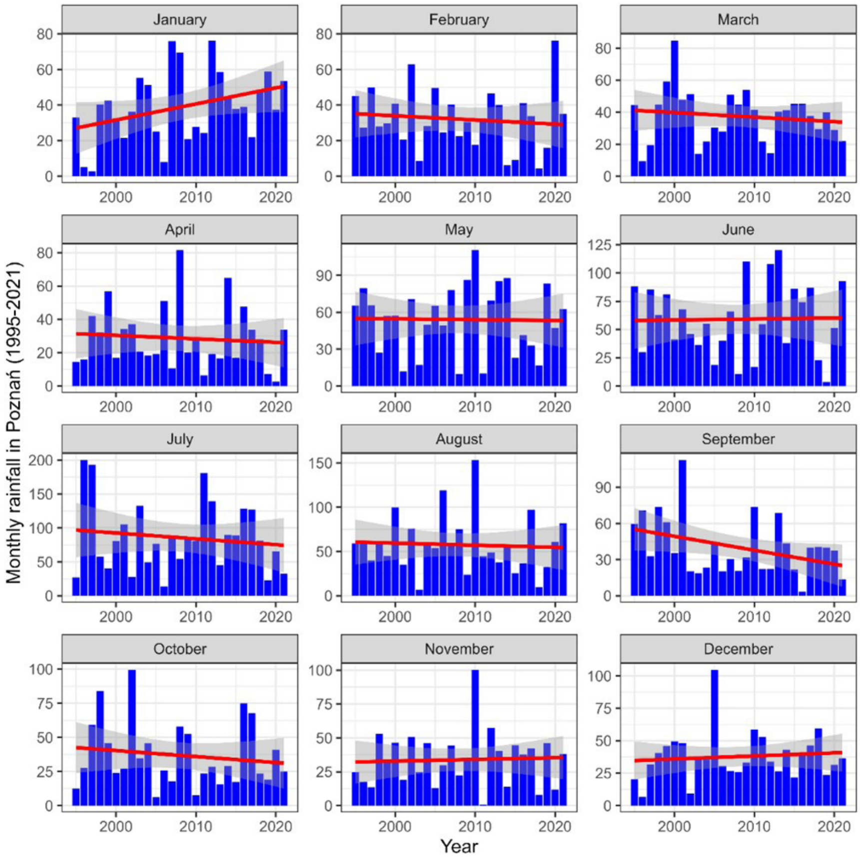


Fig. 10. Variation in the monthly sum of rain in Poznań during the studied period

Rys. 10. Zmienność miesięcznej sumy opadów w Poznaniu w badanym okresie

3.2. *Corylus* (hazel) pollen season

The average hazel pollen season began 41 DOY (11th of February) and ended 94 DOY (3rd of April). The average duration of pollen season was 53 days, but it ranged from 19 (in 2006) to 94 days (in 1996). During the study period, the highest seasonal sum of hazel pollen was recorded in 2019 (731 pollen), and the lowest was in 2000 (103 pollen). The average maximum daily pollen concentration was 60 pollen/m^3/day. The peak day typically occurred near the end of February (Fig. 11).

Several statistically significant trends emerged during the hazel pollen season between 1996 and 2021 (Fig. 12). For example, pollen seasons ended earlier each year (−1.32 days per year; p = 0.04517). Similarly, the peak dates of pollen season were significantly earlier (9–0.33 days/year; p = 0.527). Furthermore, the intensity of pollen season changed dramatically during the study period, indicating a significant increase. The number of days with extremely high pollen concentrations ranged from 1 to 9 (for the 95% method) to only 3 (for the 99% method). The 95% method resulted in a significant increase ($p < 0.05$) in the number of extreme events observed during the study period (Fig. 13).

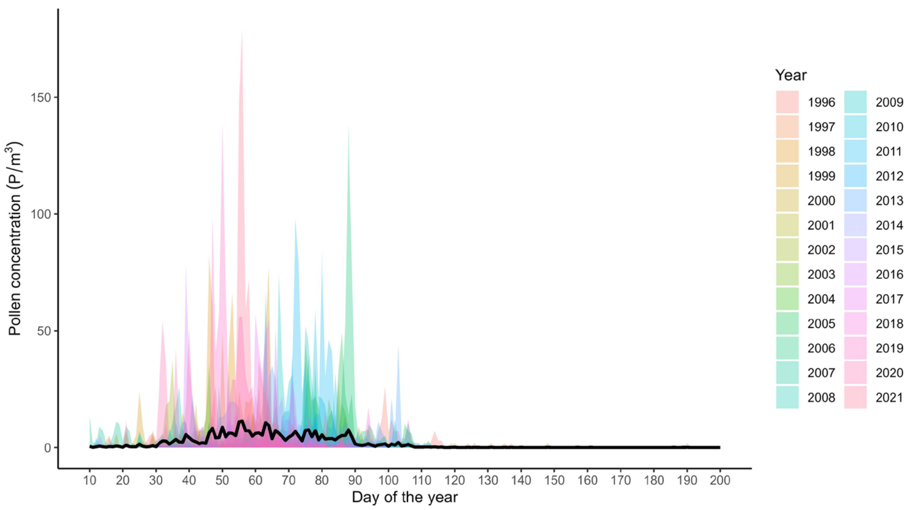


Fig. 11. Pollen seasons of *Corylus* in Poznań between 1996–2021

Rys. 11. Sezony pyłkowe *Corylus* w Poznaniu w latach 1996–2021

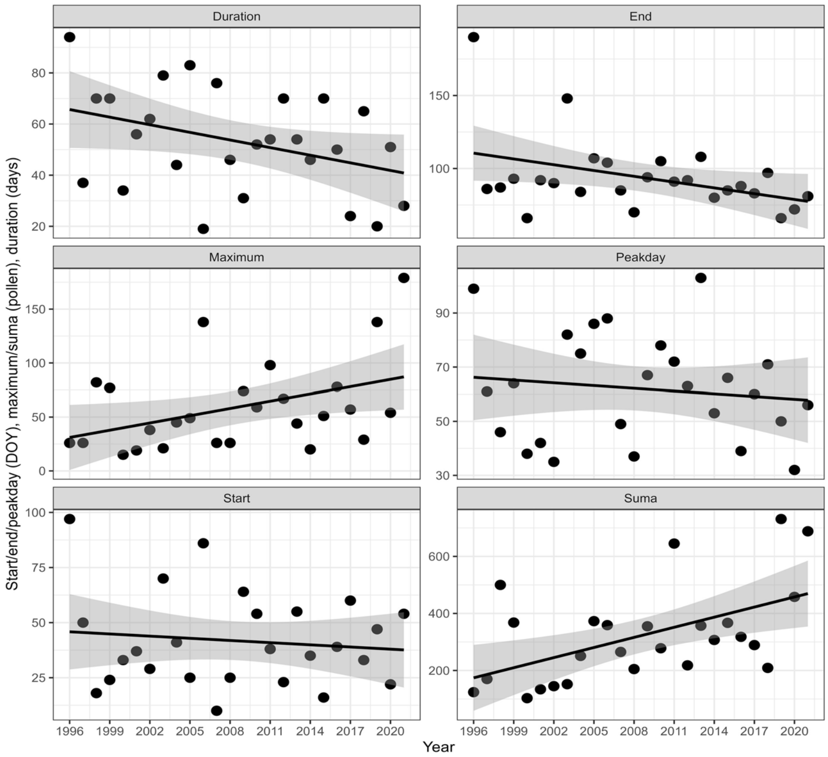


Fig. 12. Temporal changes in the main characteristic of hazel pollen seasons in Poznań between 1996–2021

Rys. 12. Zmiany czasowe głównych charakterystyk sezonów pyłkowych leszczyny w Poznaniu w latach 1996–2021

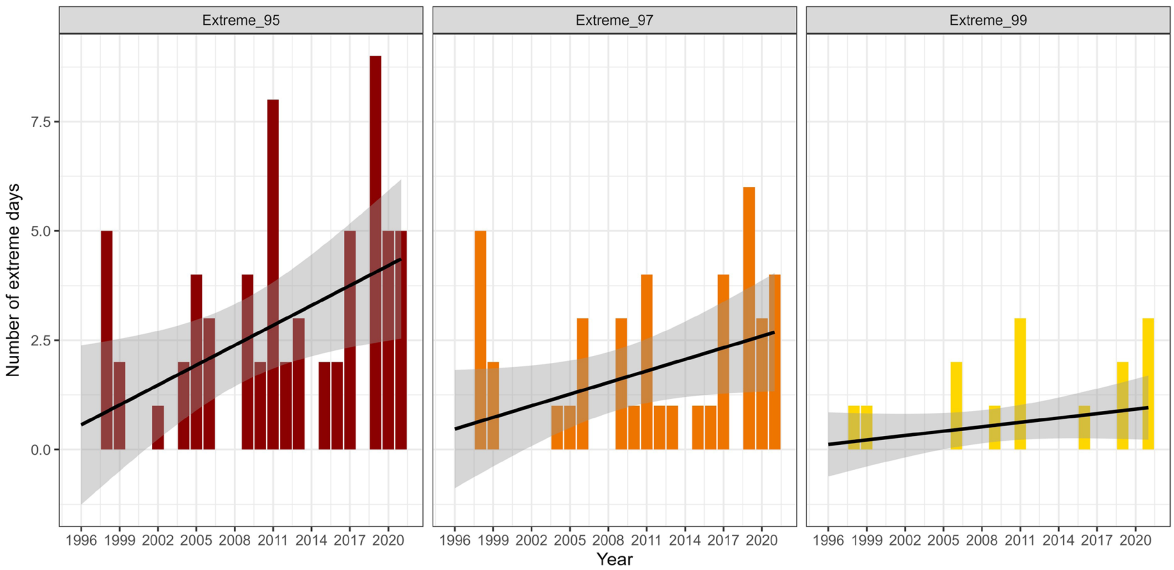


Fig. 13. Variation in the extreme days (95%, 97%, and 99%) of daily hazel pollen concentration in Poznań between 1996–2021

Rys. 13. Zmienność ekstremalnych dni (95%, 97% i 99%) dobowego stężenia pyłku leszczyny w Poznaniu w latach 1996–2021

3.3. *Alnus* (alder) pollen season

The average alder pollen season begins 56 DOY (25th of February) and ends 88 DOY (29th of March). The average duration of pollen season was 34 days, but it ranged from 15 (in 2010) to 65 days (in 2002). During the study period, the highest seasonal sum of alder pollen was recorded in 2019 (20860 pollen), and the lowest was in 2002 (715 pollen). The average maximum daily pollen concentration was 927 pollen/m^3/day. The peak day typically occurred near the end of February (Fig. 14). There were no statistically significant trends in the duration of the alder pollen season or in EPEs (Fig. 15). The most significant change (p value = 0.084) was observed with regard to pollen season intensity, which increased at a rate of 21 pollen per year.

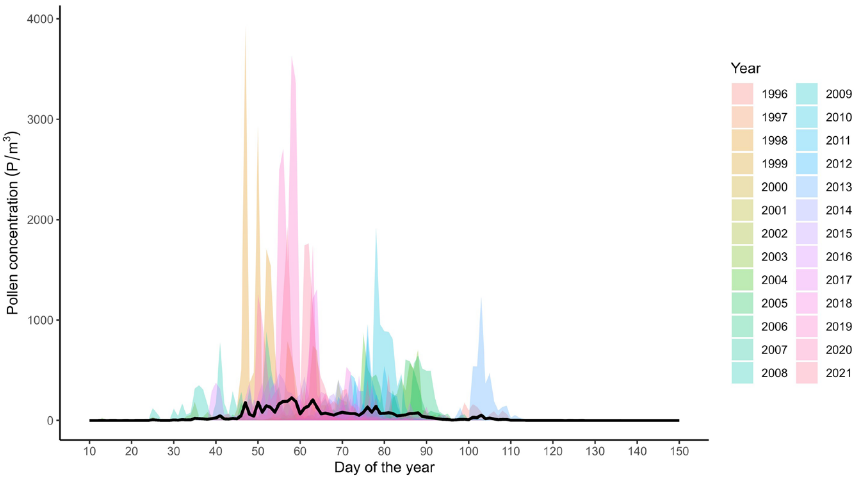


Fig. 14. Pollen seasons of *Alnus* in Poznań between 1996–2021

Rys. 14. Sezony pyłkowe *Alnus* w Poznaniu w latach 1996–2021

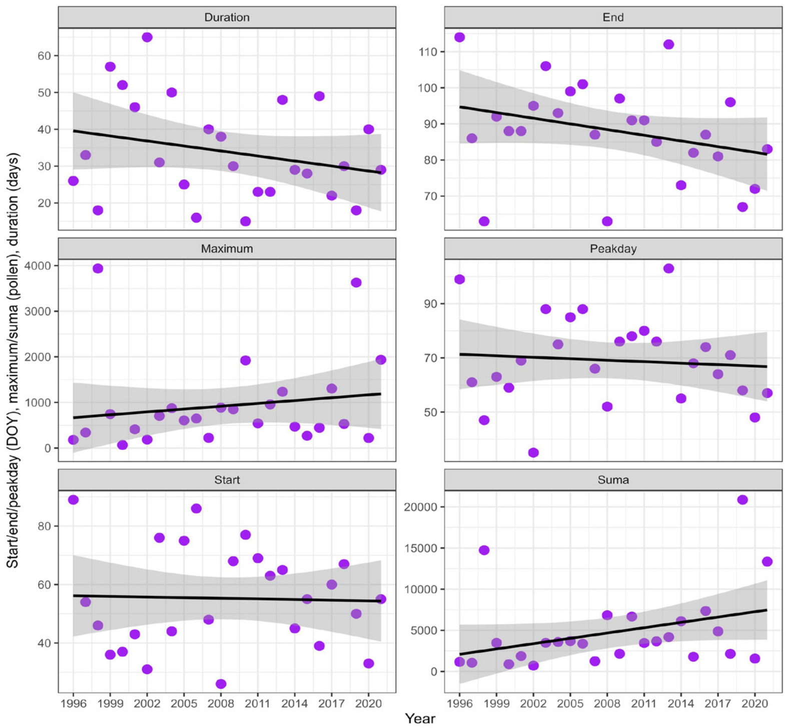


Fig. 15. Temporal changes in the main characteristic of alder pollen seasons in Poznań between 1996–2021

Rys. 15. Zmiany czasowe głównych charakterystyk sezonów pyłkowych olszy w Poznaniu w latach 1996–2021

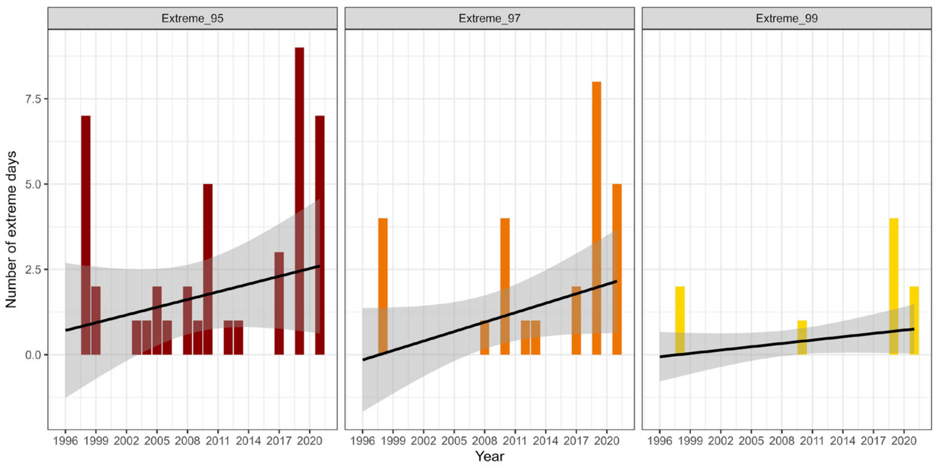


Fig. 16. Variation in the extreme days (95%, 97%, and 99%) of daily alder pollen concentration in Poznań between 1996–2021

Rys. 16. Zmienność ekstremalnych dni (95%, 97% i 99%) dobowego stężenia pyłku olszy w Poznaniu w latach 1996–2021

3.4. *Betula* (birch) pollen season

Birch pollen seasons typically begin at 103 DOY (12th of April) and end at 119 DOY (29th of April). The average duration of pollen season was 26 days, but it ranged from 15 (in 2013) to 40 days (in 1997 and 1998). During the study period, the highest seasonal sum of birch pollen was recorded in 2019 (26996 pollen), and the lowest was in 2002 (1713 pollen). The average maximum daily pollen concentration was 1953 pollen/m^3/day. The peak day was usually around the middle of April (17th April) (Fig. 17).

Several statistically significant trends emerged during the birch pollen season from 1996 to 2021 (Fig. 18). For example, pollen seasons begin earlier each year (−0.38 day/year; p = 0.033). Similarly, the end and peak dates of pollen season were significantly earlier (−0.48 day/year; p = 0.0087 and −0.49 day/year; p = 0.006846, respectively). In contrast, the intensity and duration of the pollen season did not change significantly over the study period.

The number of days with high pollen concentrations ranged from 1 to 5 (for the 95% method) to only 2 days (for the 99%). There were no statistically significant increases ($p < 0.05$) in the number of extreme events during the studied period (for all applied methods) (Fig. 19).

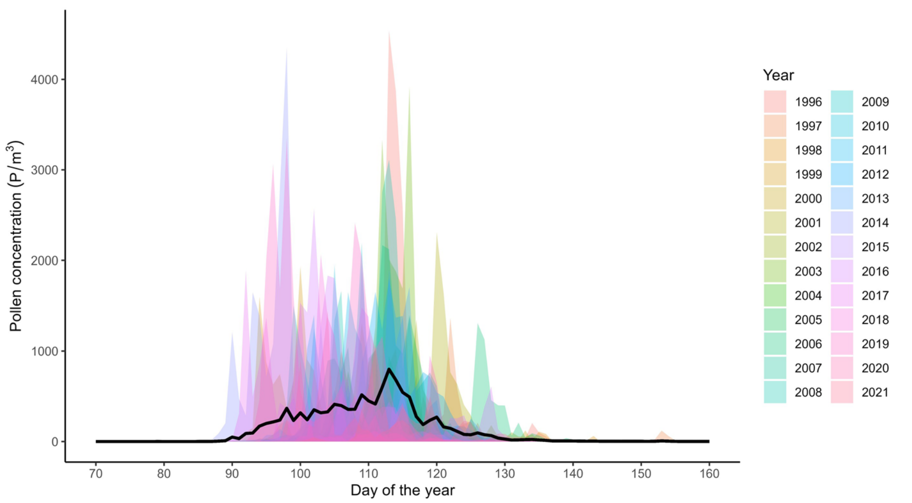


Fig. 17. Pollen seasons of *Betula* in Poznań between 1996–2021

Rys. 17. Sezony pyłkowe *Betula* w Poznaniu w latach 1996–2021

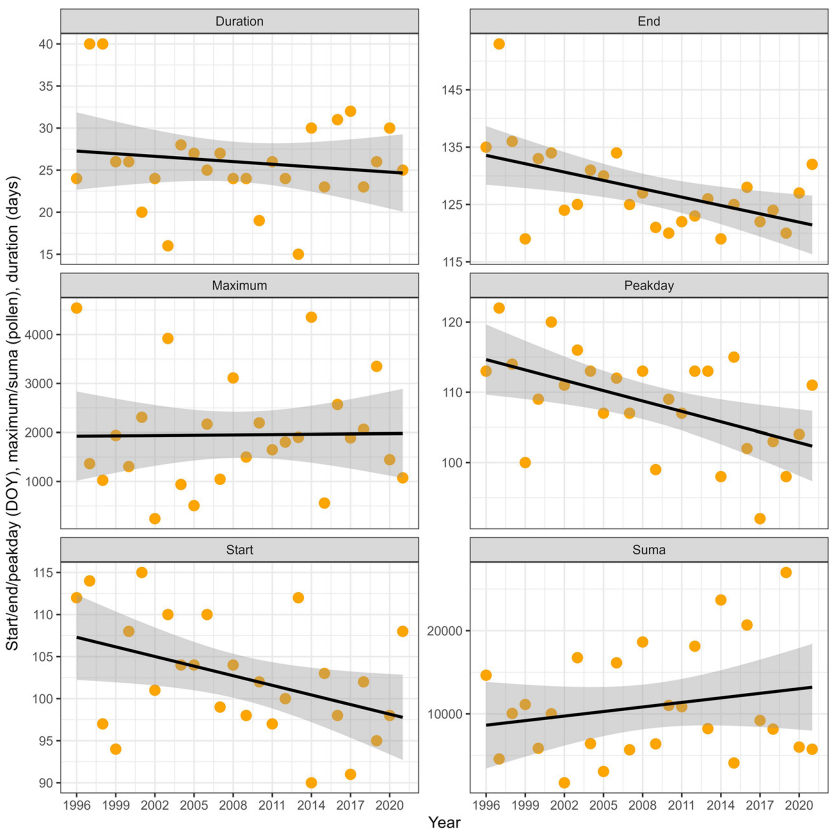


Fig. 18. Temporal changes in the main characteristic of birch pollen seasons in Poznań between 1996–2021

Rys. 18. Zmiany czasowe głównych charakterystyk sezonów pyłkowych brzozy w Poznaniu w latach 1996–2021

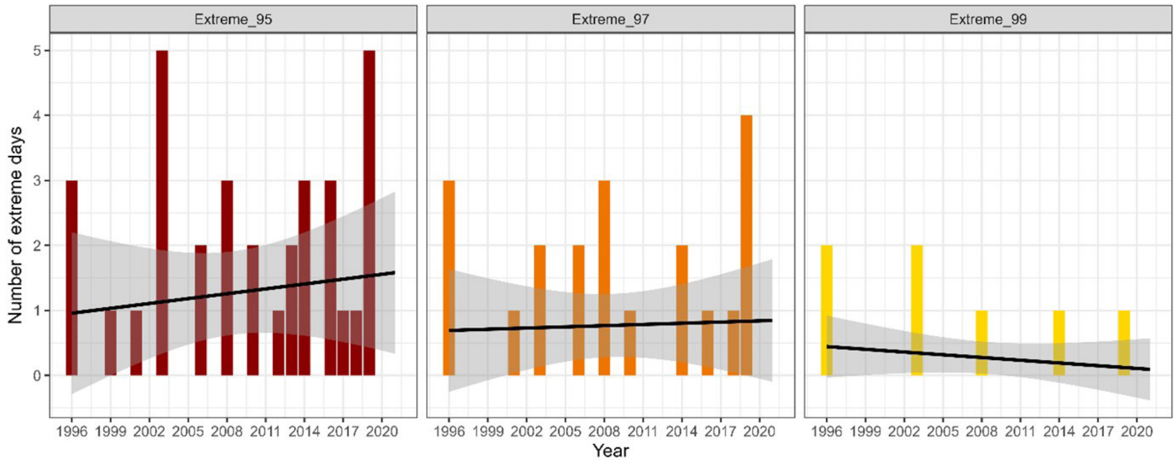


Fig. 19. Variation in the extreme days (95%, 97%, and 99%) of daily birch pollen concentration in Poznań between 1996–2021

Rys. 19. Zmienność ekstremalnych dni (95%, 97% i 99%) dobowego stężenia pyłku brzozy w Poznaniu w latach 1996–2021

3.5. Grass pollen season

On average, the grass pollen season began at 149 DOY (29th of May) and ended at 244 DOY (1st of September). The average duration of pollen season was 96 days, but it ranged from 66 days (in 1999) to 113 days (in 2020). During the study period, the highest seasonal sum of grass pollen was recorded in 1997 (6652 pollen), and the lowest was in 2000 (2075 pollen). The average maximum daily pollen concentration was 213 pollen/m^3/day. The peak day typically occurred around the beginning of July (Fig. 20).

Several statistically significant trends in the grass pollen season from 1996 to 2021 were observed (Fig. 21). For example, each year, pollen seasons ended earlier (−1.04 day/year; p = 0.0009), resulting in a 1.179-day shorter pollen season duration. There were also significant changes in the amount of grass pollen in the air, with both pollen season intensity and daily maximum pollen concentration decreasing significantly (−56 and −7 pollen/year, respectively). The number of days with extreme pollen concentration values decreased significantly over the study period (for all methods used). This decrease is especially visible in the 95% method, where the number of EPEs fell from more than ten in the middle of the 1990s to only 1–3 by the end of the study period (Fig. 22).

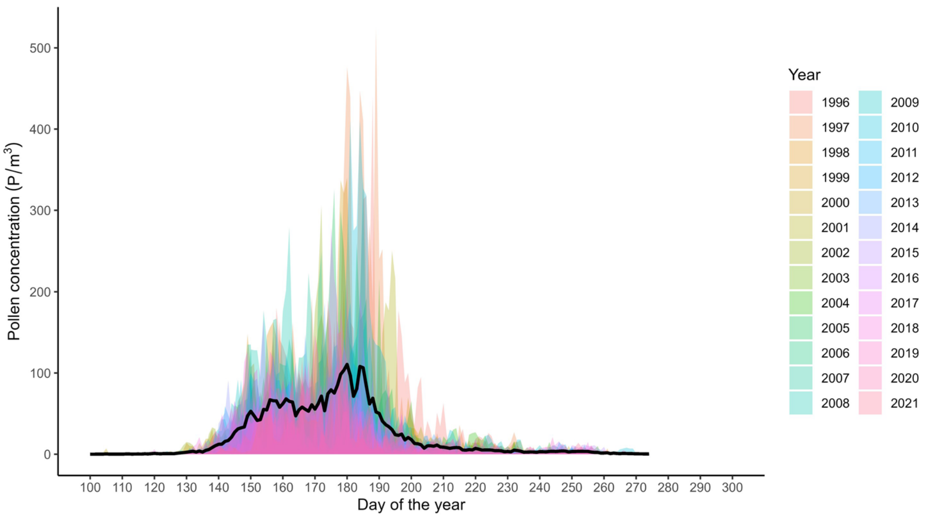


Fig. 20. Pollen seasons of grass in Poznań between 1996–2021

Rys. 20. Sezony pyłkowe traw w Poznaniu w latach 1996–2021

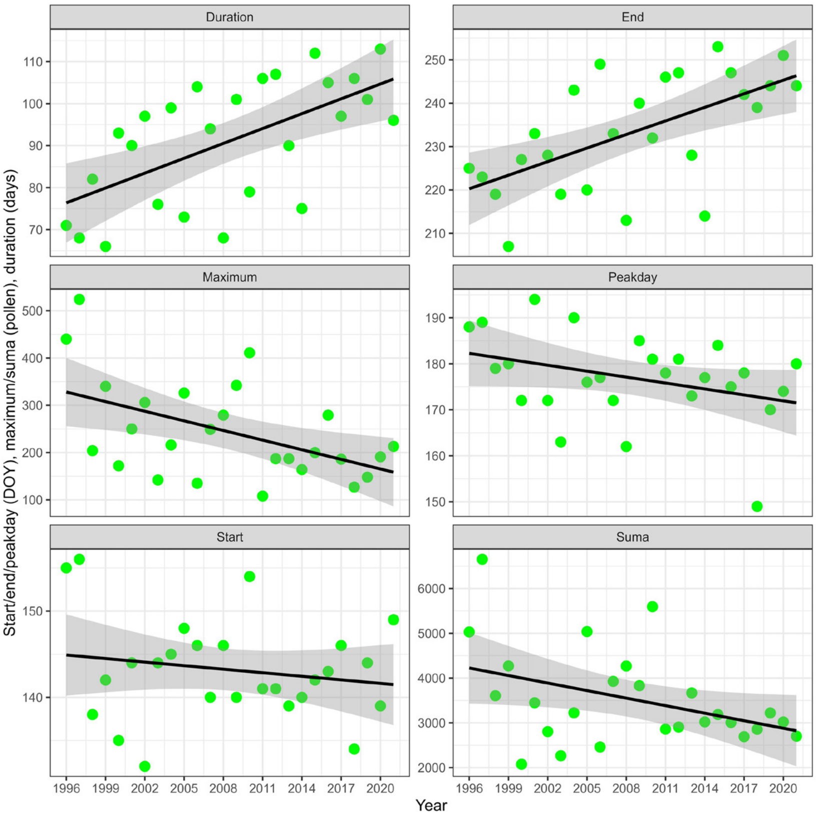


Fig. 21. Changes in the main characteristic of grass pollen seasons in Poznań (1996–2021)

Rys. 21. Zmiany głównych charakterystyk sezonów pyłkowych traw w Poznaniu (1996–2021)

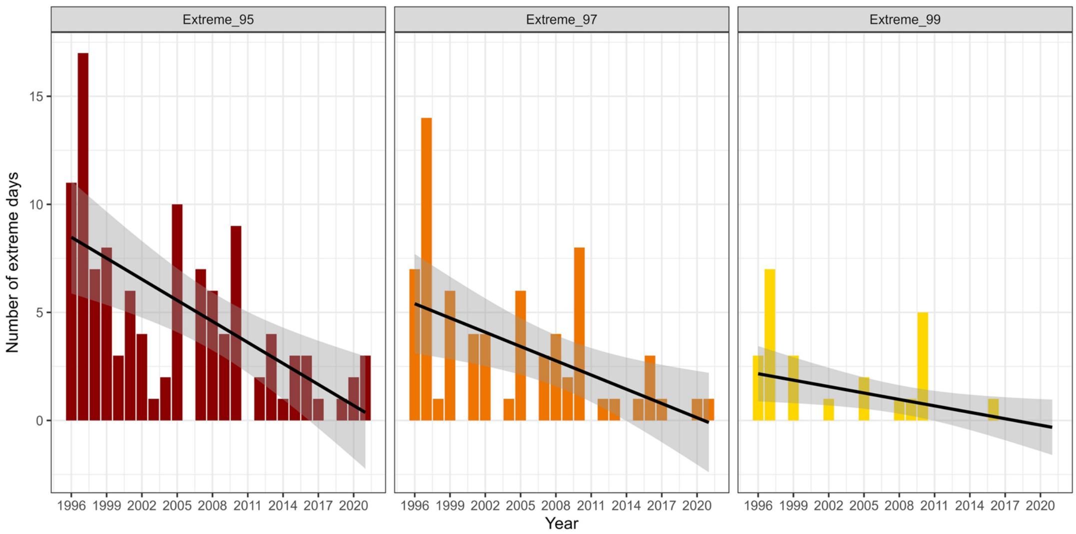


Fig. 22. Variation in the EPEs of grass in Poznań between 1996–2021

Rys. 22. Zmienność ekstremalnych epizodów pyłkowych (EPE) traw w Poznaniu w latach 1996–2021

3.6. *Plantago* (plantain) pollen season

On average, the plantain pollen season began at 147 DOY (27th of May) and ended at 252 DOY (9th of September). The average duration of pollen season was 106 days, but it ranged from 81 (in 1997) to 146 days (in 2002). During the study period, the highest seasonal sum of plantain pollen was recorded in 2015 (313 pollen) and the lowest in 1996 (36 pollen). The average maximum daily pollen concentration was 9 pollen/m^3/day. The peak day usually fell around the beginning of July (Fig. 23). Only one statistically significant change occurred during the plantain pollen season. Specifically, the intensity of the pollen season increased by 8 pollen per year ($p = 0.0001$) (Fig. 24). Currently, the seasonal sum of pollen is almost 300% higher than 25 years ago. Also, the number of days with extreme values of pollen concentration statistically increased for the 95% method (p-value = 0.018), reaching 17 days in 2015 (Fig. 25).

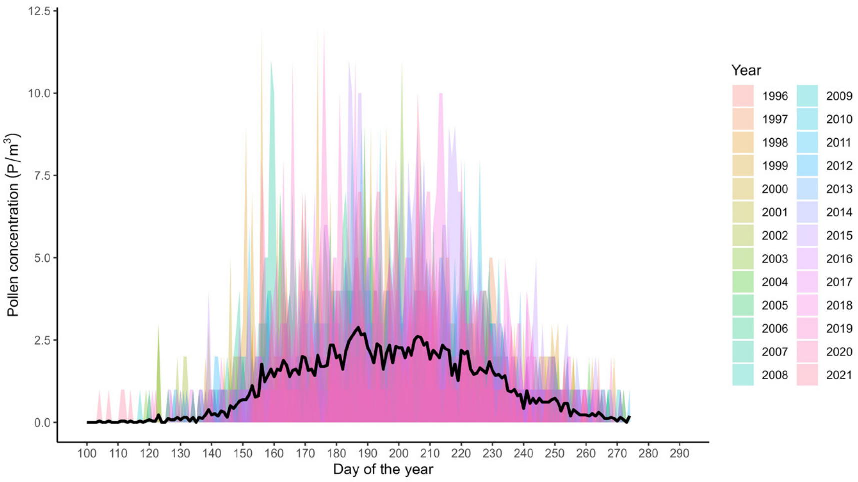


Fig. 23. Pollen seasons of *Plantago* in Poznań between 1996–2021

Rys. 23. Sezony pyłkowe *Plantago* w Poznaniu w latach 1996–2021

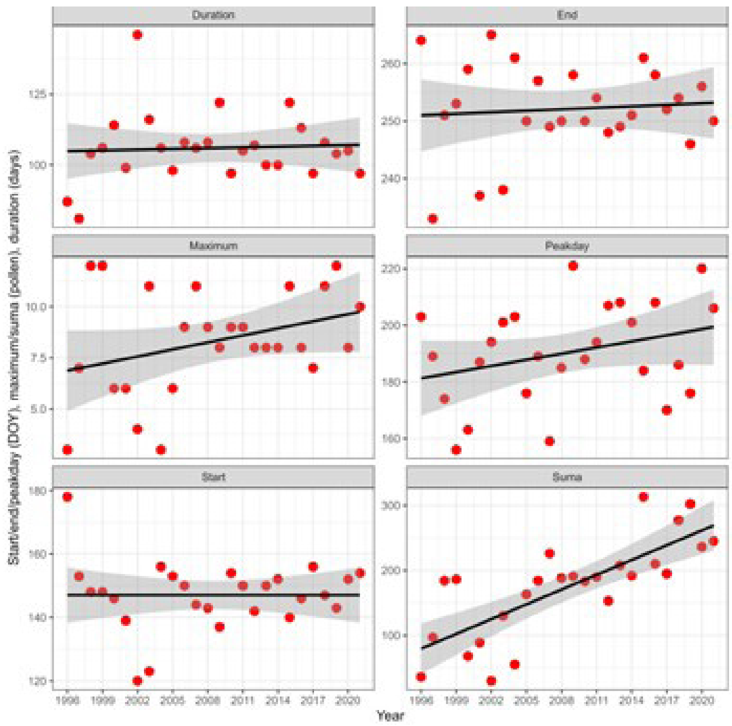


Fig. 24. Temporal changes in the main characteristic of plantain pollen seasons in Poznań between 1996–2021

Rys. 24. Zmiany czasowe głównych charakterystyk sezonów pyłkowych babki w Poznaniu w latach 1996–2021

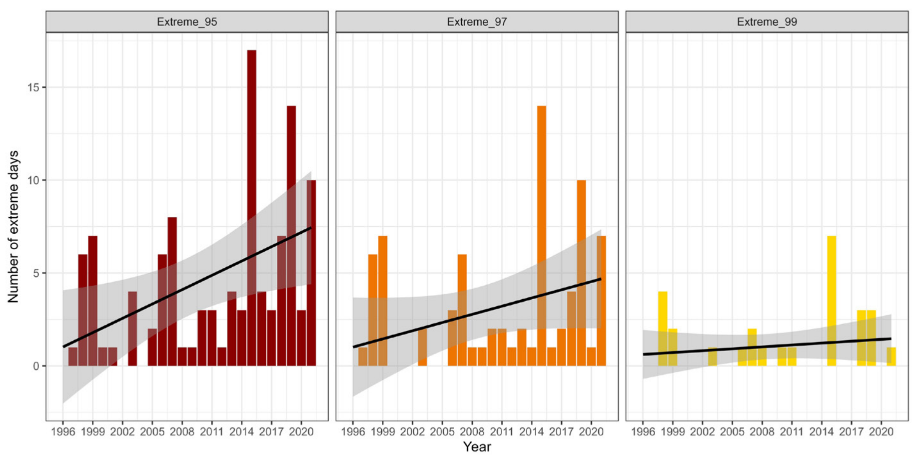


Fig. 25. Variation in the EPEs of *Plantago* in Poznań between 1996–2021

Rys. 25. Zmienność ekstremalnych epizodów pyłkowych (EPE) babki w Poznaniu w latach 1996–2021

3.7. *Artemisia* (mugwort) pollen season

The average mugwort pollen season begins at 202 DOY (21st of July) and ends at 247 DOY (4th of September). The average duration of pollen season was 46 days, but it ranged from 25 (in 1996) to 72 days (in 2006). During the study period, the highest seasonal sum of mugwort pollen was recorded in 1996 (3302 pollen) and the lowest in 2002 (377 pollen). The average maximum daily pollen concentration was 114 pollen/m³/day. The peak day is usually around the beginning of August (Fig. 26). From 1996 to 2021, two statistically significant trends in mugwort pollen production were observed (Fig. 27). The intensity and seasonal peak of the pollen season decreased significantly during the study period (−49 pollen/year and −6 pollen/year, respectively). Furthermore, the number of EPEs for all three methods has significantly decreased (Fig. 28).

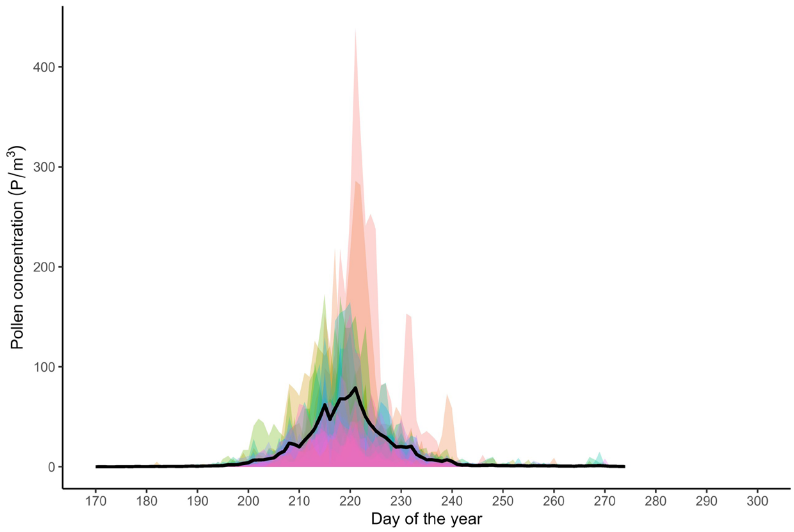


Fig. 26. Pollen seasons of *Artemisia* in Poznań between 1996–2021

Rys. 26. Sezony pyłkowe *Artemisia* w Poznaniu w latach 1996–2021

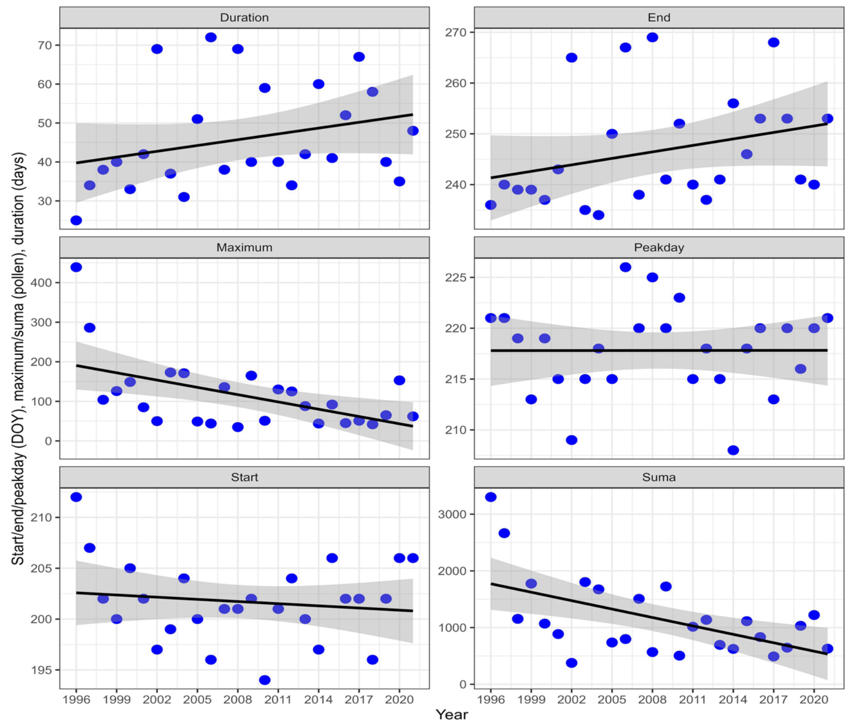


Fig. 27. Changes in the main characteristic of mugwort pollen seasons in Poznań (1996–2021)

Rys. 27. Zmiany głównych charakterystyk sezonów pyłkowych bylicy w Poznaniu (1996–2021)

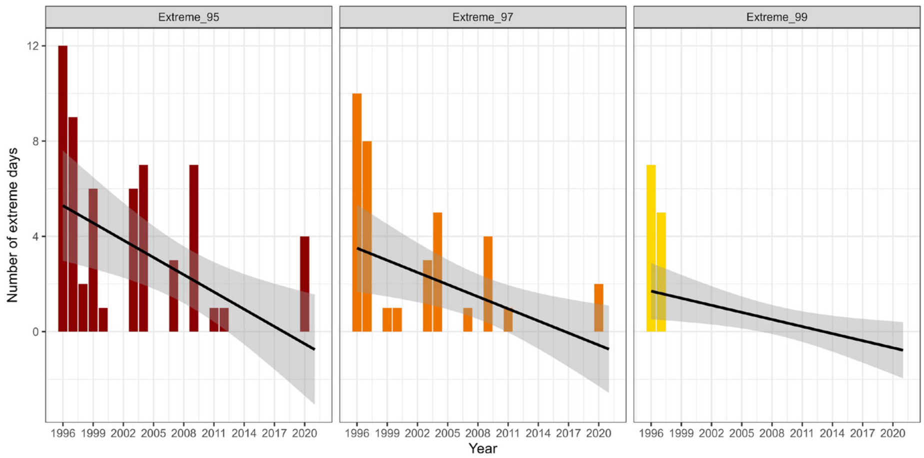


Fig. 28. Variation in the EPEs of *Artemisia* in Poznań between 1996–2021

Rys. 28. Zmienność ekstremalnych epizodów pyłkowych (EPE) bylicy w Poznaniu w latach 1996–2021

4. Discussion

This study revealed that the recent changes in the timing of pollen seasons for allergenic species in Poznań varied depending on the analyzed taxa. The most significant changes were observed concerning grasses, birch, and plantain pollen seasons. In all cases, the pollen season for these three taxa started and ended significantly earlier. The only taxon that did not show any temporal changes was *Alnus*. The intensity of the pollen season significantly increased for *Corylus* and *Plantago*, while it decreased significantly for grass and mugwort. The last two taxa pollinate in the summer, suggesting that recent temperature increases and lower rainfall in this period result in plant drying and reduced pollen production. This hypothesis was previously suggested with weeds and grasses in Poznań (Bogawski *et al*. 2014).

The dramatic changes in pollen season intensity are also evident in terms of EPEs. Such events for grasses and mugwort are becoming increasingly rare, which is good news for allergy patients. However, the number of EPEs is increasing for *Plantago sp*., indicating that pollen grains from these taxa may become problematic soon, especially in urban environments. This trend is also evident in the overall characteristics of the pollen season of plantain, which have become much more intense (300%) compared to just 25 years ago.

When seeking the underlying causes of the observed changes in pollen season characteristics, one should first and foremost consider the impact of recent climate changes (Ziska *et al*. 2019). All vital processes in living organisms, including flowering and pollination, are tuned to specific climatic ranges. The optimal amplitude of this range varies among the plant species adapted to different climate regimes (Britannica 2020). Temperature, rainfall, and relative humidity are important for pollen production and release (Savitsky 2002). Plants exposed to elevated temperatures flower earlier with a clear temperature-driven extension of the growing season. This lengthening of the growing season might also account for observed increases in productivity (IPCC 2007). Increased pollen and flower production is also favored by higher rainfall before inflorescence production, pollen formation, and pollen liberation (Damialis *et al*. 2011). On the other hand, rainfall typically reduces concentrations of pollen grains in the atmosphere. The distribution of rainfall during the day may be an important factor in the interpretation of pollen data. For example, most grasses release pollen in the morning; thus, rainfall during that time would result in lower pollen concentrations throughout the day, whereas morning dryness followed by afternoon rain would result in higher or moderate average daily concentrations (Emberlin 2003).

The relationship between meteorological factors and pollen concentrations has been extensively studied in the literature (Sofiev and Bergmann 2013). Estimating statistically significant correlations between daily pollen concentrations and daily weather factors is of great practical importance (Guerrero-Rascado 2022). The analysis of climate data from Poznań, specifically the daily mean temperature and rainfall, reveals that these two parameters have undergone significant changes in the past few decades, with the most notable shifts occurring during the summer and winter months. For example, the average monthly temperature in June has increased by 3.3°C over the study period, whereas in September, there has been an increase of 2.4°C accompanied by a simultaneous decrease in rainfall of 31 mm. These substantial climate changes have had a weakening effect on the pollen production of grass and mugwort, but not on plantain. Recently, it has been shown that *Plantago lanceolata* is resistant to climate change by having large degrees of genetic variation despite not being influenced by changes in population and dispersal (Smith *et al*. 2022).

In general, it is suggested that recent climate change has resulted in the acceleration and lengthening of pollen seasons, as well as an increase in their intensity. This may potentially exacerbate allergic reactions and respiratory health issues for individuals sensitive to pollen allergens (Damialis *et al*. 2019). The results of this study have shown that these general trends are not universal and may vary significantly depending on local changes in climate. For instance, in Poznań, there is a more visible impact of climate on summer pollinating species compared to spring pollinating species. In some cases, recent climate changes have likely resulted in a decrease in pollen season intensity (such as mugwort and grass), while in others, it has made the pollen season more severe (e.g., hazel). This also applies to other characteristics of the pollen season, including its start, end, and duration.

Additionally, other factors, such as increased concentrations of carbon dioxide (CO_2), can have an impact on the intensity of pollen seasons (Ziello *et al*. 2012). Elevated CO_2 concentrations can stimulate photosynthesis in many plants, particularly when an excess of nutrients, such as nitrogen, is available. Consequently, an increase in CO_2 concentration might influence the pollen load in a specific region. Research has demonstrated that rising CO_2 levels can affect both the quantity of pollen produced per plant and the allergenic properties of the pollen grains themselves (Sofiev and Bergmann 2013). For example, a doubling of atmospheric CO_2 concentration led to a 61% increase in ragweed pollen production (Wayne *et al*. 2002). Furthermore, ragweed plants cultivated under elevated CO_2 levels produce pollen that elicits stronger allergic lung inflammation (Rauer *et al*. 2020). However, since the changes in EPEs in Poznań do not show consistent patterns across all studied taxa, it is plausible to suggest that CO_2 is not the decisive factor in this phenomenon. Other factors, such as weather conditions or land-use changes (Adams-Groom *et al*. 2022), are likely to be more significant.

In summary, the analysis of pollen seasons and EPEs in this study has revealed which pollen taxa may increase in importance for pollen allergies. It is evident that EPEs for *Plantago* and *Corylus* have dramatically increased during the studied period, and allergies to these two genera should be increasingly monitored. On the other hand, allergenic plants as important as grass and mugwort pollen show a notable decreasing trend with pollen season intensity, which may bring relief to allergic individuals.

5. References

Adams-Groom B., Selby K., Derrett S., Frisk C.A., Pashley C.H., Satchwell J., King D., McKenzie G., Neilson R. 2022. Pollen season trends as markers of climate change impact: *Betula*, *Quercus* and *Poaceae*. Science of the Total Environment 831: Article 154882.

Agache I., Akdis C.A. (Eds.). 2021. Global atlas of asthma (2nd ed., Vol. 1). European Academy of Allergy and Clinical Immunology. Retrieved from https://www.eaaci.org

Barney J., Di Tommaso A. 2003. The biology of Canadian weeds. 118. *Artemisia vulgaris* L. Canadian Journal of Plant Science 83(1): 205–215.

Belavadi V. 2013. Insect pollination manual (eBook). Bangalore, India.

Biedermann T., Winther L., Till S.J., Panzner P., Knulst A., Valovirta E. 2019. Birch pollen allergy in Europe. Allergy 74(7): 1237–1248.

Bogawski P., Grewling Ł., Nowak M., Smith M., Jackowiak B. 2014. Trends in atmospheric concentrations of weed pollen in the context of recent climate warming in Poznań (Western Poland). International Journal of Biometeorology 58(8): 1759–1768.

Bovallius A., Roffey R. 1987. Aerobiology and the spread of microbial diseases. Defence Science Journal 37(2): 185–204.

Britannica. 2020. 2023. https://www.britannica.com

Calderon M., Brandt T. 2008. Treatment of grass pollen allergy: Focus on a standardized grass allergen extract – Grazax®. Therapeutics and Clinical Risk Management 4(6): 1255–1260.

Carinanos P., Guerrero-Rascado J.L., Valle A.M., Cazorla A., Titos G., Foyo-Moreno I., Alados-Arboledas L., Díaz de la Guardia C. 2022. Assessing pollen extreme events over a Mediterranean site: Role of local surface meteorology. Atmospheric Environment 272: 118928.

Central Statistics Office. 2011. Census 2011 results. Data.gov.ie. https://data.gov.ie/dataset/census-2011-results

Charles M., Craigie R. 2008. Methods and theory in Quaternary palynology. Food and Energy 2.

Cheung D., Dick E., Timmers M. 2003. Rhinovirus inhalation causes long--lasting excessive airway narrowing in response to methacholine in asthmatic subjects in vivo. American Journal of Respiratory and Critical Care Medicine 152(5): 1490–1496.

Choudhary N., Siddiqui M.B., Bi S., Khatoon S. 2014. Effect of seasonality and time after anthesis on the viability and longevity of Cannabis sativa pollen. Palynology 38(2): 235–241.

Climate Central. (n.d.). Pollen season & climate change. Retrieved from https://www.climatecentral.org/climate-matters/pollen-season-climate-change

Culley T.M., Weller S.G., Sakai A.K. 2002. The evolution of wind pollination in angiosperms. Trends in Ecology & Evolution 17(8): 361–369.

D'Amato G., Annesi-Maesano I., Urrutia-Pereira M., Del Giacco S., Rosario Filho N.A., Chong-Neto H.J., Sole D., Ansotegui I., Cecchi L., Sanduzzi Zamparelli A., Tedeschini E., Biagioni B., Murrieta-Aguttes D., D'Amato M. 2021. Thunderstorm allergy and asthma: State of the art. Multidisciplinary Respiratory Medicine 16(1): 806.

Damialis A., Fotiou C., Halley J.M. *et al*. 2011. Effects of environmental factors on pollen production in anemophilous woody species. Trees 25: 253–264.

Damialis T., Traidl-Hoffmann C., Treudler R. 2019. Climate change and pollen allergies. In Biodiversity and health in the face of climate change: 47–66.

Dąbrowska-Zapart K., Chłopek K., Malkiewicz M. 2018. Analysis of the plantain pollen season in selected Polish cities in 2018. Alergoprofil 14(4): 96–100.

Duke J.A. 2001. Plantago major, [in:] Handbook of phytochemical constituents of GRAS herbs and other economic plants. CRC Press: 471.

Edlund A.F., Swanson R., Preuss D. 2004. Pollen and stigma structure and function: The role of diversity in pollination. The Plant Cell 16 Suppl 1: S84–S97. https://doi.org/10.1105/tpc.015800. Epub 2004 Apr 9. PMID: 15075396; PMCID: PMC2643401.

Emberlin J. 2003. Aerobiology, aerodynamics and pollen sampling. Postępy Dermatologii i Alergologii 20(4): 196–199.

European Climate and Health Observatory. (n.d.). European Climate and Health Observatory. European Environment Agency. Retrieved August 30, 2024, from https://climate-adapt.eea.europa.eu/en/observatory

Falkowski M. 1982. Trawy polskie. Państwowe Wydawnictwo Rolnicze i Leśne.

Farooq A. 2016. Mugwort (*Artemisia vulgaris*) oils, [in:] Essential oils in food preservation, flavor and safety. Elsevier: 573–579.

Fernstrom A., Goldblatt M. 2013. Aerobiology and its role in the transmission of infectious diseases. Journal of Pathogens 13: 493960.

Frenguelli G. 2003a. Pollen structure and morphology. Postępy Dermatologii i Alergologii 20(4): 205–207.

Frenguelli G. 2003b. Basic microscopy, calculating the field of view, scanning of slides, sources of error. Postępy Dermatologii i Alergologii 20(4): 208–210.

Gilman E.F., Watson D.G. 1993. *Acacia farnesiana*. Sweet Acacia. USDA, Forest Serv., Fact Sheet ST-5. http://hort.ifas.ufl.edu/trees/acafara.pdf

Global Atlas of Asthma. 2013. https://eaaci.org

Grewling Ł., Jackowiak B., Nowak M., Uruska A., Smith M. 2012. Variations and trends of birch pollen seasons during 15 years (1996–2010) in relation to weather conditions in Poznań (Western Poland). Grana 51(4): 280–292.

Grewling Ł., Jenerowicz D., Bogawski P., Smith M., Nowak M., Frątczak A., Czarnecka-Operacz M. 2018. Cross-sensitization to Artemisia and Ambrosia pollen allergens in an area located outside of the current distribution range of Ambrosia. Advances in Dermatology and Allergology XXXV(1): 83–89.

Guerrero-Rascado J.L. 2022. Assessing pollen extreme events over a Mediterranean site: Role of local surface meteorology. IISTA--CEAMA.

Hanslik T., Boelle P.Y., Flahault A. 2001. The control chart: An epidemiological tool for public health monitoring. Public Health 115(4): 277–281.

Healthcare Services Group, Inc. (n.d.). ECAP. 2023. Retrieved 20th of February 2025. https://www.hcsgcorp.com/ecap23/

Heinzerling L., Burbach G., Edenharter G. *et al*. 2009. GA2LEN skin test study I: GA2LEN harmonization of skin prick testing: Novel sensitization patterns for inhalant allergens in Europe. Allergy 64(10): 1498–1506.

Hirst J.M. 1952. An automatic volumetric spore trap. Annals of Applied Biology 39(2): 257–265.

Hoedemaekers K., Derksen J., Hoogstrate S.W., Wolters-Arts M., Oh S.-A., Twell D., Mariani C., Rieu I. 2015. BURSTING POLLEN is required to organize the pollen germination plaque and pollen tube tip in Arabidopsis thaliana. New Phytologist 206(1): 255–267.

Hoen P. 1999, April 16. Glossary of pollen and spore terminology. Second and revised edition (P. Hoen, Ed.). Retrieved July 21, 2014 from Laboratory of Palaeobotany and Palynology.

Holm L.G., Plucknett D.L., Pancho J.V., Herberger J.P. 1977. The world's worst weeds: Distribution and biology. University Press of Hawaii.

https://github.com/bczernecki/imgw

https://www.vdberk.pl/drzew/corylus-colurna/

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, H.L. Miller (Eds.)]. Cambridge University Press.

Jager S. 2003. Plant taxonomy and nomenclature. Postępy Dermatologii i Allergologii 20(4): 218–226.

Kubik-Komar A., Kubera E., Piotrowska-Weryszko K. 2018. Selection of morphological features of pollen grains for chosen tree taxa. Biology Open 7(5).

Levetin E. 2004. Methods for aeroallergen sampling. Current Allergy and Asthma Reports 4(5): 376–383.

Lo F., Bitz C.M., Battisti D.S. *et al*. 2019. Pollen calendars and maps of allergenic pollen in North America. Aerobiologia 35: 613–633.

Martynov A.I., Ilyina N.I., Luss L.V., Martynov A.A., Fedoskova T.G., Andreev I.V. 2015. Peculiarities of pollen characteristics in the regions of chemical factor. Russian Allergology Journal 6: 12–16.

Míka V., Kohoutek A., Odstrčilová V. 2002. Characteristics of important diploid and tetraploid subspecies of Dactylis from the point of view of forage crop production. Rostlinná výroba 48(6): 243–248.

Myszkowska D. 2020. Aerobiological studies – Current state and future challenges. Alergoprofil 16(1): 8–14.

Myszkowska D., Majewska R. 2014. Pollen grains as allergenic environmental factors: A new approach to forecasting pollen concentration during the season. Annals of Agricultural and Environmental Medicine 21(4): 681–688.

Nilsson S., Persson S. 1981. Tree pollen spectra in the Stockholm region (Sweden), 1973–1980. Grana 20: 179–182.

Palynological Database. 2023. https://www.paldat.org

Pigg K.B., Manchester S.R., Wehr W.C. 2003. Corylus, Carpinus, and Palaeocarpinus (*Betulaceae*) from the Middle Eocene Klondike Mountain and Allenby Formations of Northwestern North America. International Journal of Plant Sciences 164(5): 807–822.

Piotrowska K., Weryszko-Chmielewska E. 2003. Pollen count of selected taxa in the atmosphere of Lublin using two monitoring methods. Annals of Agricultural and Environmental Medicine 10(1): 79–85.

Puc M. 2007. The effect of meteorological conditions on hazel and alder pollen concentration in the air of Szczecin. Acta Agrobotanica 60(2): 65–70.

Punt W., Hoen P.P., Blackmore S., Nilsson S., Le Thomas A. 2007. Glossary of pollen and spore terminology. Review of Palaeobotany and Palynology 143(1–2): 1–81.

RACGP. 2023. 2023 triennium. Royal Australian College of General Practitioners. Retrieved February 20, 2023 from https://www.racgp.org.au/education/professional-development/cpd/2023-triennium

Ranpal S., Sieverts M., Wörl V., Kahlenberg G., Gilles S., Landgraf M. *et al*. 2022. Is pollen production of birch controlled by genetics and local conditions? International Journal of Environmental Research and Public Health 19(13): 8160.

Rapiejko P., Jurkiewicz D., Lipiec A. 2022a. Very high birch pollen concentration in the air in selected Polish cities in 2022 – Clinical implications. Otolaryngologia Polska 76(6): 30–36.

Rapiejko J., Malkiewicz M., Puc M. 2022b. Hazel pollen in the air of selected Polish cities in 2022. Alergoprofil 18(2): 20–26.

Ratto F., Simmons B.I., Spake R., Zamora-Gutierrez V., McDonald M.A., Merriman J.C., Tremlett C.J., Poppy G.M., Peh K.S.-H., Dicks L.V. 2018. Global importance of vertebrate pollinators for plant reproductive success: A meta-analysis. Frontiers in Ecology and the Environment 16(2): 82–90.

Rauer D., Gilles S., Wimmer M., Frank U., Mueller M. *et al*. 2020. Ragweed plants grown under elevated CO_2 levels produce pollen which elicits stronger allergic lung inflammation. Allergy 76(6): 1718–1730.

Salo P., Arbes S., Jaramillo R., Calatroni A., Weir C., Sever M., Hoppin J., Rose K., Liu A., Gergen P., Mitchell H., Zeldin D. 2014. Prevalence of allergic sensitization in the United States: Results from the National Health and Nutrition Examination Survey (NHANES) 2005–2006. Journal of Allergy and Clinical Immunology 134(2): 350–359. https://doi.org/10.1016/j.jaci.2013.12.1071

Samoliński B., Raciborski F., Lipiec A., Tomaszewska A., Krzych-Fałta E., Samel-Kowalik P., Walkiewicz A., Lusawa A., Borowicz J., Komorowski J., Samolińska-Zawisza U., Sybilski A.J., Piekarska B., Nowicka A. 2014. Epidemiologia chorób alergicznych w Polsce (ECAP). Polish Journal of Allergology 1: 10–18.

Savitsky E. 2002. Ecology and distribution of pollen of allergenic plants. Allergy, Asthma & Immunology Research 14(2): 168–181.

Schmitz R., Ellert U., Kalcklösch M., Dahm S., Thamm M. 2013. Patterns of sensitization to inhalant and food allergens: Findings from the German Health Interview and Examination Survey for Children and Adolescents. International Archives of Allergy and Immunology 162(3): 263–270.

Smith M., Emberlin J., Stach A., Czarnecka-Operacz M., Jenerowicz D., Silny W. 2007. Regional importance of *Alnus* pollen as an aeroallergen: A comparative study of *Alnus* pollen counts from Worcester (UK) and Poznań (Poland). Annals of Agricultural and Environmental Medicine 14: 123–128.

Smith M., Matavulj P., Mimić G., Panić M., Grewling Ł., Šikoparija B. 2022. Why should we care about high temporal resolution monitoring of bioaerosols in ambient air? Science of The Total Environment 826: 154231.

Sofiev M., Bergmann C. 2013. Allergenic pollen: A review of the production, release, distribution, and health impacts. Springer.

Stach A. 2003. The use of Hirst volumetric trap, preparation of drums and slides. Advances in Dermatology and Allergology / Postępy Dermatologii i Alergologii 20(4): 246–249.

Sterk P., Fabbri L., Quanjer P. 1993. Airway responsiveness: Standardized challenge testing with pharmacological, physical, and sensitizing stimuli in adults. European Respiratory Journal 6: 53–83.

Strzelczyk Z., Roszkowski M., Feleszko W., Krauze A. 2020. Avoidance of allergens as an environmental method in the prevention of inhaled allergy symptoms. Journal Name 48(6): 745–752.

Svenning J. 2002. A review of natural vegetation openness in north-western Europe. Biological Conservation 104(2): 133–148.

Taylor P., Jacobson K., House J. 2007. Links between pollen, atopy, and the asthma epidemic. International Archives of Allergy and Immunology 144: 162–170.

Tomalak M., Rossi E., Ferrini F., Moro P.A. 2010. Negative aspects and hazardous effects of forest environment on human health, [in:] Forests, trees and human health. Springer Netherlands: 77–124.

Tutin T.G., Heywood V.H., Burges N.A., Moore D.M., Valentine D.H., Walters S.M., Webb D.A. 1972. *Flora Europaea*. Vol. 3: *Diapensiaceae* to *Myoporaceae* (pp. 370, maps I–V). Cambridge University Press.

United States Department of Agriculture. 2020. U.S. Forest Service. Retrieved from https://www.fs.fed.us

Wayne P., Foster S., Connolly J., Bazzaz F., Epstein P. 2002. Production of allergenic pollen by ragweed (*Ambrosia artemisiifolia* L.) is increased in CO_2-enriched atmospheres. Annals of Allergy, Asthma & Immunology 88(3): 279–282.

Wopfner N., Gadermaier G., Egger M., Asero R., Ebner C., Jahn-Schmid B., Ferreira F. 2005. The spectrum of allergens in ragweed and mugwort pollen. International Archives of Allergy and Immunology 138(4): 337–346.

Zając A., Zając M. 2001. Atlas rozmieszczenia roślin naczyniowych w Polsce. Wydawnictwo Naukowe, Kraków.

Ziello C., Sparks T.H., Estrella N., Belmonte J., Bergmann K.C., Bucher E., Brighetti M.A., Damialis A., Detandt M., Galán C., Gehrig R., Grewling L., Gutiérrez Bustillo A.M., Hallsdóttir M., Kockhans-Bieda M.C., De Linares C., Myszkowska D., Pàldy A., Sánchez A., Smith M., Thibaudon M., Travaglini A., Uruska A., Valencia-Barrera R.M., Vokou D., Wachter R., de Weger L.A., Menzel A. 2012. Changes to airborne pollen counts across Europe. PLoS One 7(4): e34076. https://doi.org/10.1371/journal.pone.0034076

Ziska L.H., Makra L., Harry S.K., Bruffaerts N., Hendrickx M. *et al.* 2019. Temperature-related changes in airborne allergenic pollen abundance and seasonality across the Northern Hemisphere: A retrospective data analysis. The Lancet Planetary Health 3(3): e124-e131.

Supplementary materials

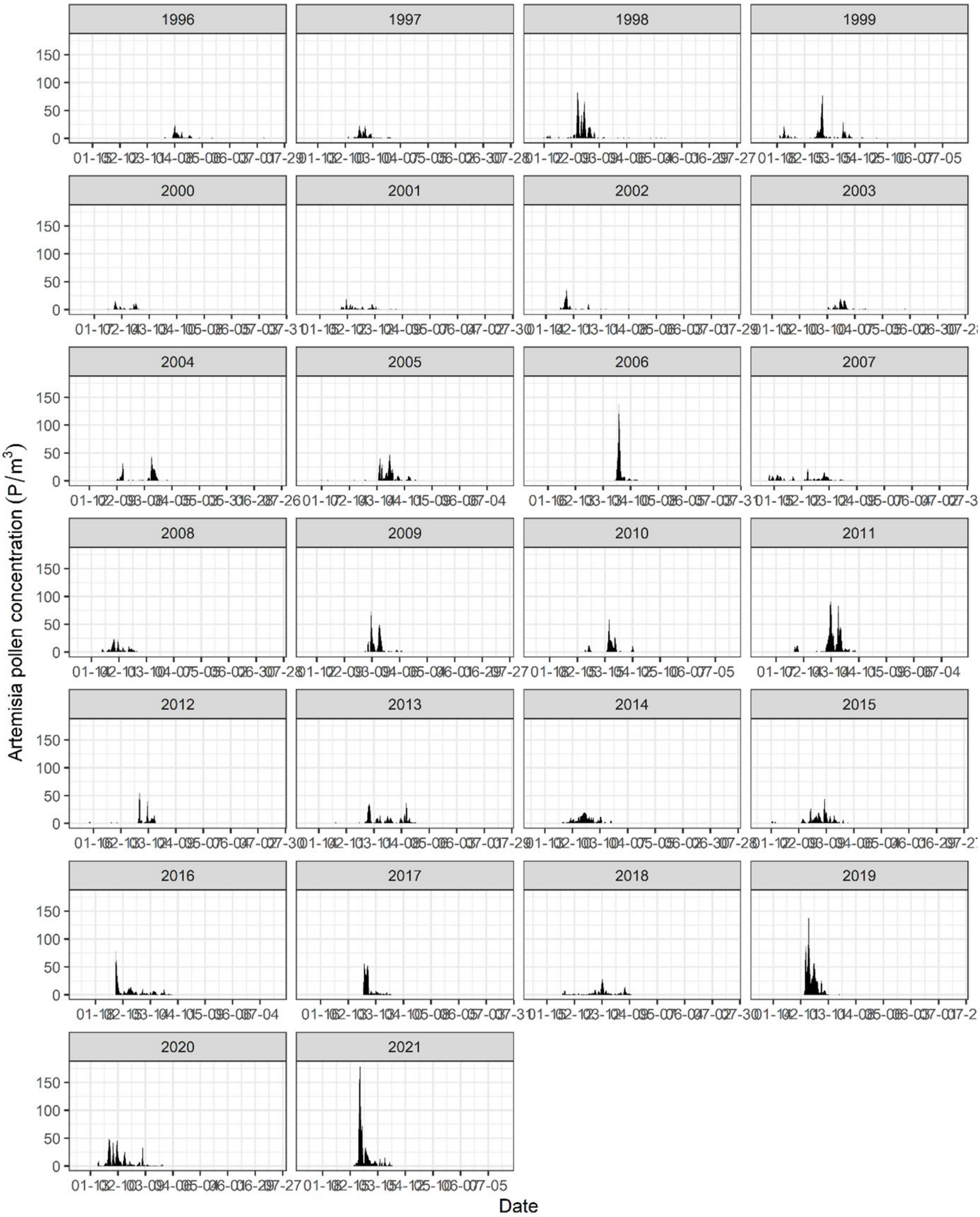


Fig. S1. The course of pollen seasons of *Corylus* in Poznań between 1996–2021

Rys. S1. Przebieg sezonów pyłkowych *Corylus* w Poznaniu w latach 1996–2021

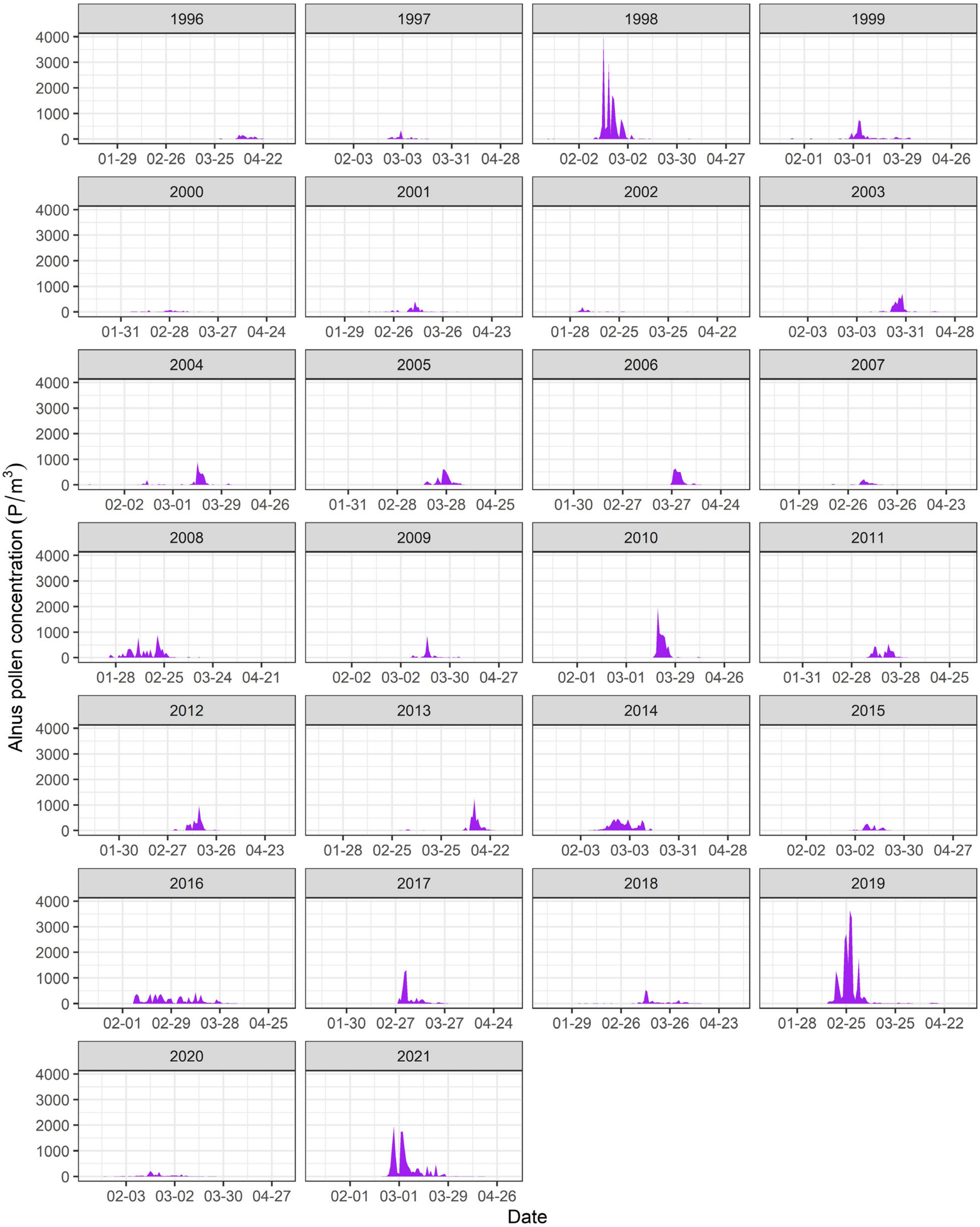


Fig. S2. The course of pollen seasons of *Alder* in Poznań between 1996–2021

Rys. S2. Przebieg sezonów pyłkowych olszy w Poznaniu w latach 1996–2021

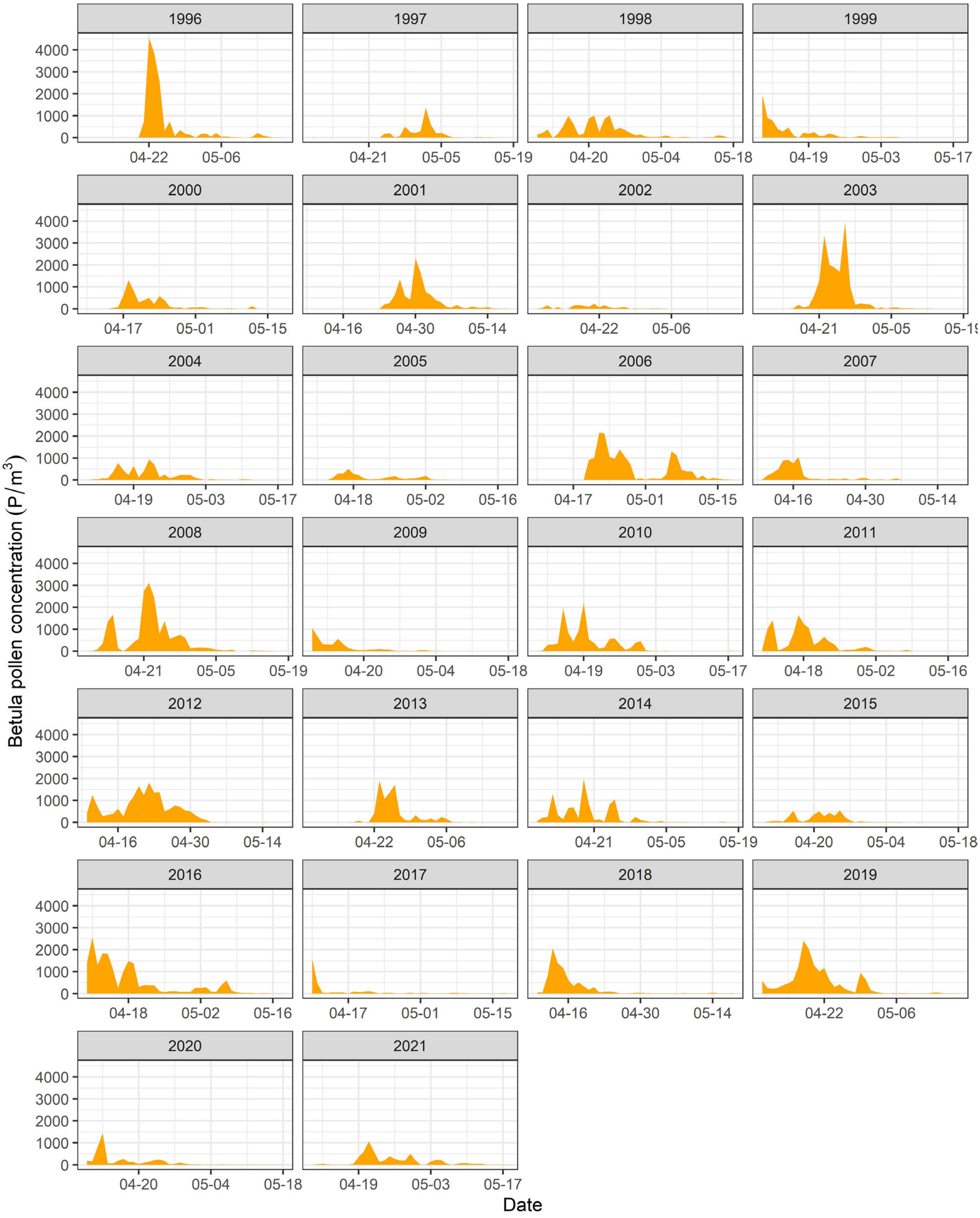


Fig. S3. The course of pollen seasons of *Betula* in Poznań between 1996–2021

Rys. S3. Przebieg sezonów pyłkowych *Betula* w Poznaniu w latach 1996–2021

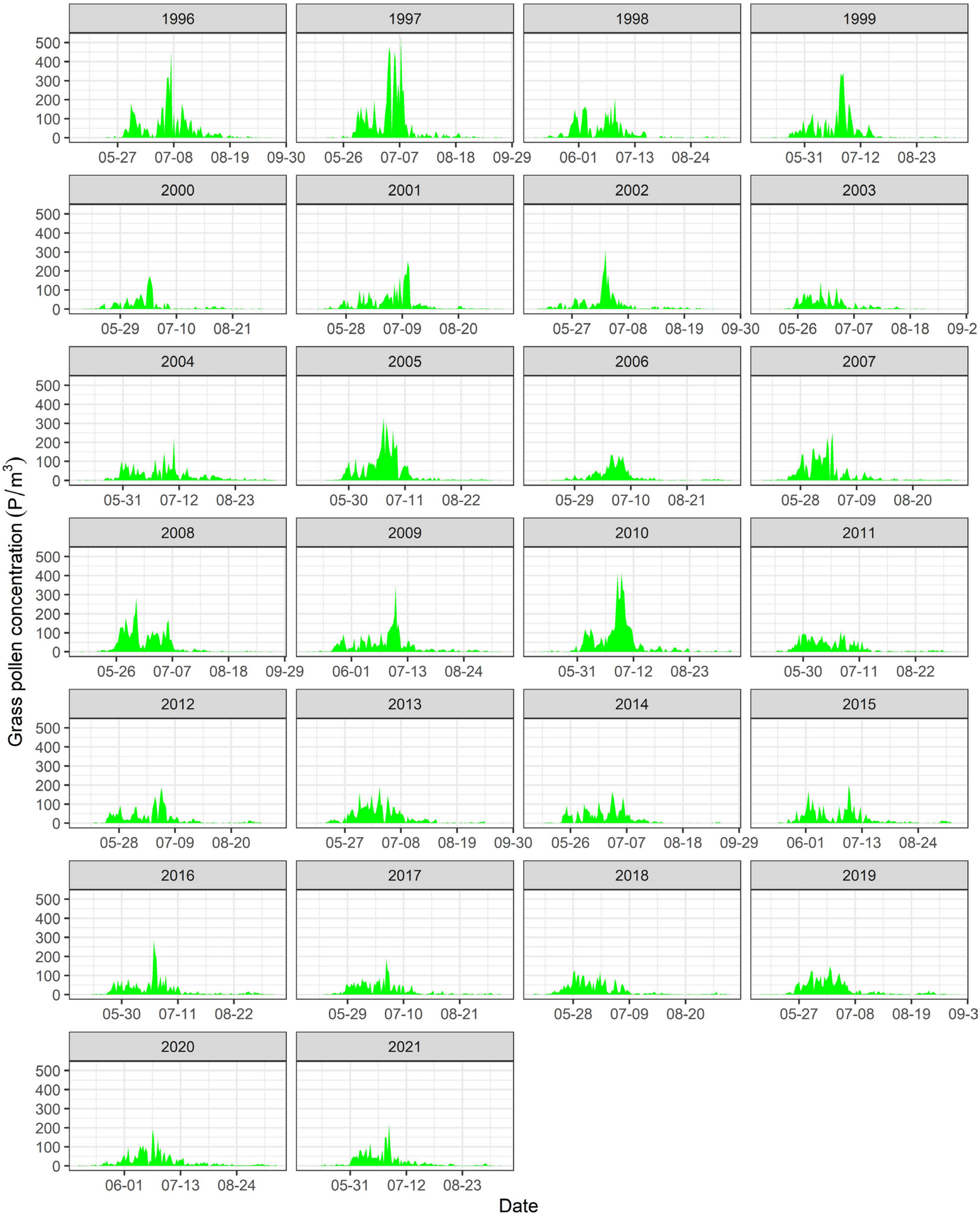


Fig. S4. The course of pollen seasons of grasses in Poznań between 1996–2021

Rys. S4. Przebieg sezonów pyłkowych traw w Poznaniu w latach 1996–2021

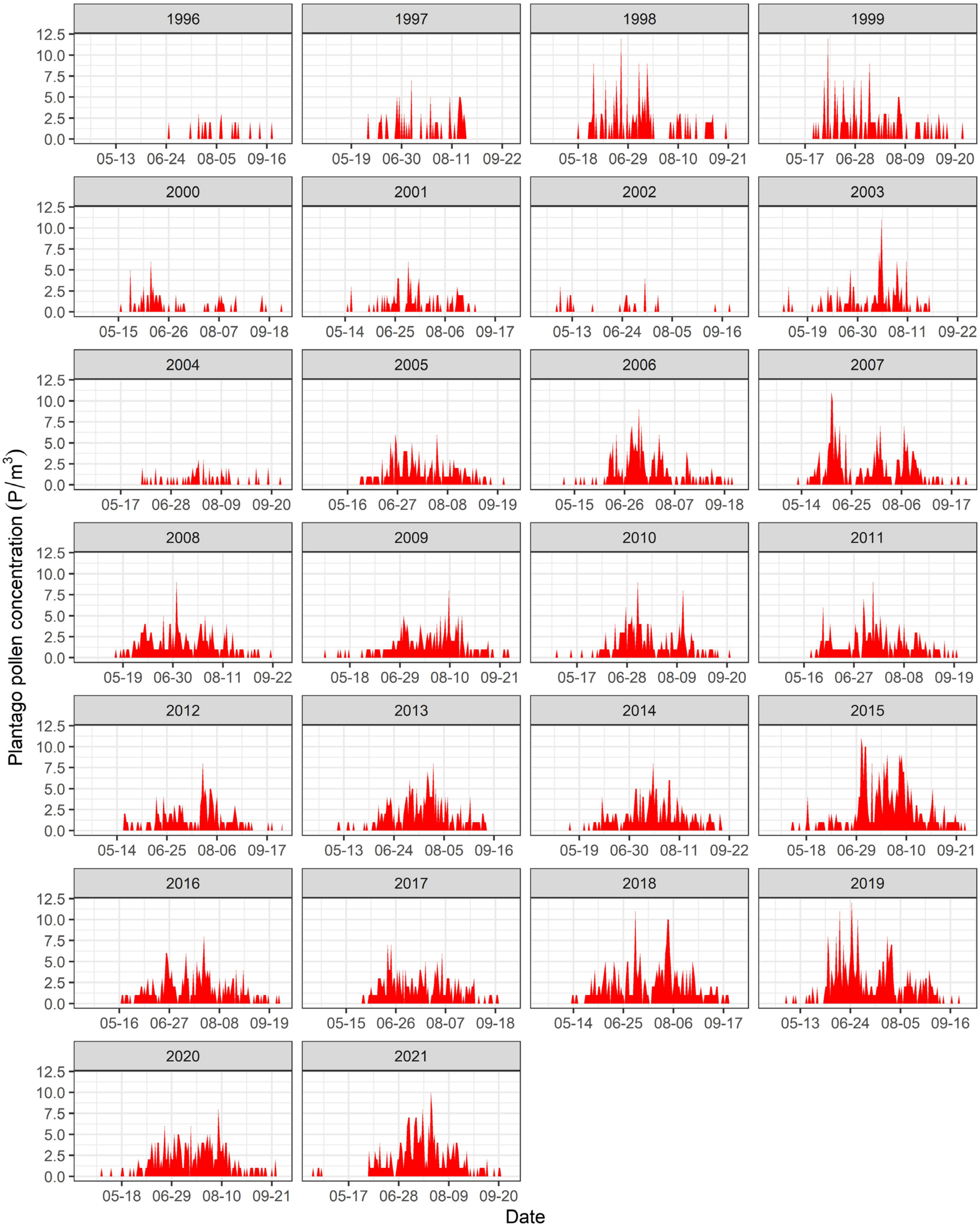


Fig. S5. The course of pollen seasons of *Plantago* in Poznań between 1996–2021

Rys. S5. Przebieg sezonów pyłkowych *Plantago* w Poznaniu w latach 1996–2021

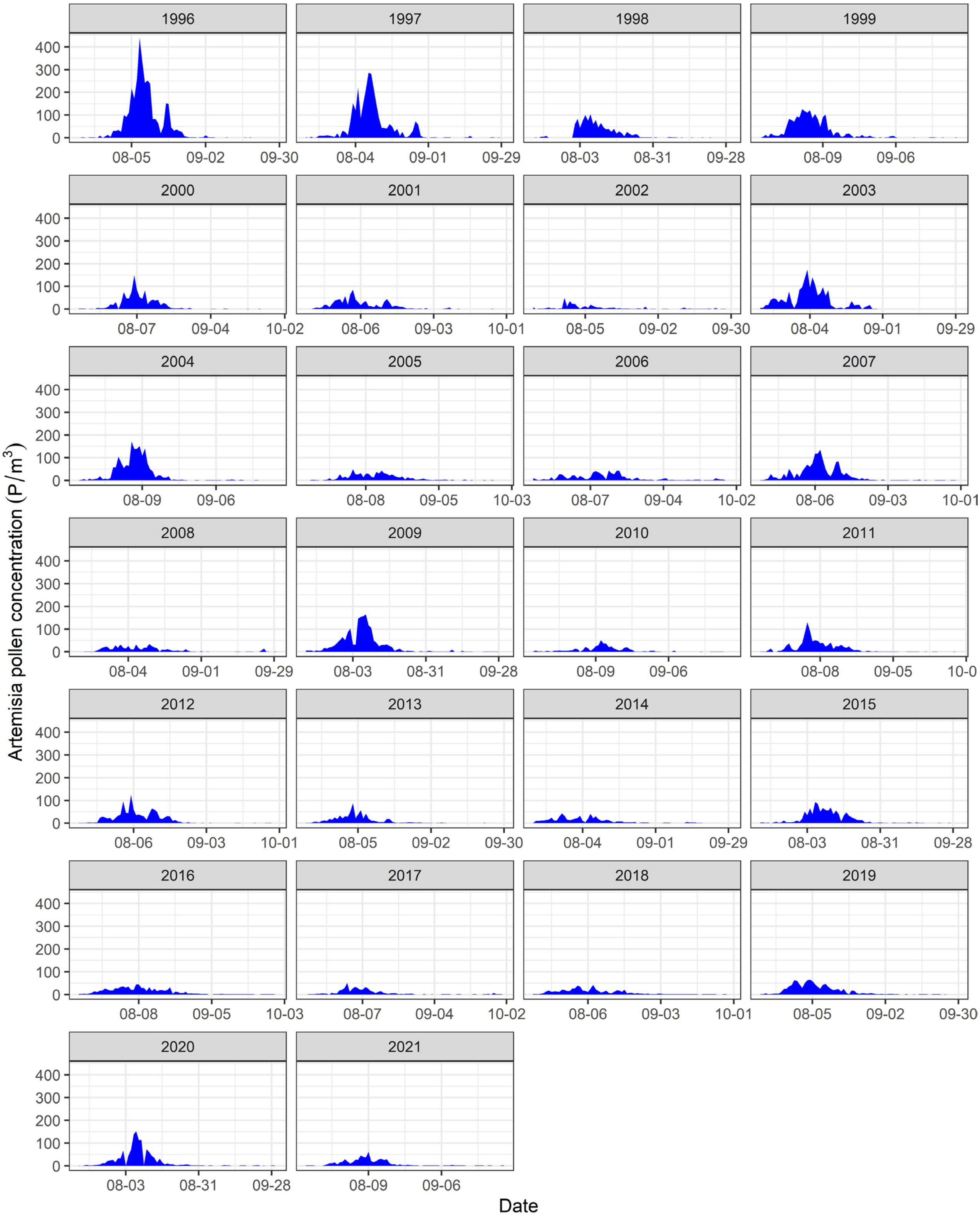


Fig. S6. The course of pollen seasons of *Artemisia* in Poznań between 1996–2021

Rys. S6. Przebieg sezonów pyłkowych bylicy pospolitej w Poznaniu w latach 1996–2021

Table S1. Changes in monthly sum of rain and monthly mean temperature in Poznań between 1995–2021 (the statistically significant trends are bolded in red color)

Tabela S1. Zmiany miesięcznej sumy opadów i średniej miesięcznej temperatury w Poznaniu w latach 1995–2021 (istotne statystycznie trendy zaznaczono na czerwono)

Month	Factor	Slope	p-value	Factor	Slope	p-value
January	Temperature	0.06508	0.3527	Rainfall	0.9031	0.06338
February		0.00116	0.9872		−0.2321	0.5909
March		0.07637	0.1590		−0.2834	0.4951
April		0.03871	0.3671		−0.2079	0.6645
May		−0.00329	0.9333		−0.0668	0.9250
June		**0.12399**	**0.0022**		0.0866	0.9154
July		0.07808	0.0758		−0.8599	0.5097
August		0.06502	0.0650		−0.2358	0.7746
September		**0.08919**	**0.0195**		−1.1589	0.0512
October		0.04554	0.3016		−0.4395	0.4691
November		**0.12057**	**0.0028**		0.1258	0.8078
December		**0.15788**	**0.0186**		0.2355	0.6206