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Pollen exposure and asthma-related outpatient emergency treatments: A multicenter time series analysis using automated pollen monitoring in Bavaria, Germany

Matteo Boser [a,b,*], Athanasios Damialis [c], Christoph Knote [d], Monika Seemann [a,b], Claudia Traidl-Hoffmann [a,b,e], Maria P. Plaza [a,b]

[a] Institute of Environmental Medicine and Integrative Health - Environmental Medicine, Faculty of Medicine, University of Augsburg and University Hospital of Augsburg, Augsburg, Germany
[b] Institute of Environmental Medicine, Environmental Health Center, Helmholtz Zentrum München, Neuherberg, Germany
[c] Terrestrial Ecology and Climate Change, Department of Ecology, School of Biology, Faculty of Sciences, Aristotle University of Thessaloniki 546 36 Thessaloniki, Greece
[d] Chair of Model-Based Environmental Exposure Science, Environmental Health Sciences Institute, Faculty of Medicine, University of Augsburg, Augsburg, Germany
[e] Christine Kühne Center for Allergy Research and Education (CK-CARE), Davos, Switzerland

A R T I C L E I N F O

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A B S T R A C T

Airborne pollen is a key driver of allergy-induced asthma exacerbations. Its relevance is expected to further increase due to climate change, which influences pollen season timing, intensity, and allergenicity. However, taxon-specific asthma risks associated with pollen exposure remain insufficiently quantified.

We considered asthma-related outpatient emergency treatments (ICD-10: J45, J46) from the Bavarian Association of Statutory Health Insurance Physicians (KVB) in three metropolitan areas: Augsburg, Munich, and Nuremberg. Daily pollen concentrations for the taxa Alnus, Betula, Corylus, and Poaceae were obtained from the electronic Pollen Information Network (ePIN). We employed a multicenter time-series analysis using quasi-Poisson regression with Distributed Lag Non-Linear Models (DLNMs) to account for non-linear and delayed effects. Pollen effects were modelled at low, medium and high exposure levels. We adjusted for seasonality, public holidays, day of the week and potential confounders such as temperature, relative humidity and air pollution. We estimated taxon-specific attributable fractions (AFs) to assess the asthma burden during the pollen season.

High Betula concentrations were associated with an increased risk of asthma treatments (RR: 1.64, 95% CI [1.41,1.90]), while Poaceae showed significant effects at medium (RR: 1.19, 95% CI [1.03,1.38]) and high concentrations (RR: 1.41, 95% CI [1.17,1.70]). While the effect of Betula was strongest on the day of exposure, the Poaceae effect peaked on day two after exposure. During the respective pollen season, AFs for Betula varied from 10.24% (95% CI [1.01,18.50]) in Augsburg to 17.75% (95% CI [9.72,24.80]) in Nuremberg, while the respective AFs for Poaceae ranged between 14.25% (95% CI [4.46,22.84]) in Munich and 18.84% (95% CI [7.21,28.88]) in Augsburg.

Betula and Poaceae pollen contribute substantially to asthma-related outpatient emergency treatments in Bavaria, especially during the main pollen season. Our findings underscore the importance of automated, real-time pollen monitoring to support targeted public health interventions and timely warning systems.

1. Introduction

Asthma affects approximately 260 million adults worldwide, according to an assessment based on the Global Burden of Disease, Injuries, and Risk Factors Study (GBD) of 2021 (Oh et al., 2025). Although global prevalence decreased between 1990 and 2021, asthma remains the second leading cause of mortality among chronic respiratory diseases and leads to increased healthcare costs and a reduced quality of life (Yuan et al., 2025). In Germany, estimates for the prevalence of asthma range between 6.0% (Khan et al., 2025) and 8.0% (Heidemann et al., 2021), with women more frequently affected than men (Heidemann et al., 2021; Steppuhn et al., 2017).

* Corresponding author.
E-mail address: matteo.boser@med.uni-augsburg.de (M. Boser).

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Environmental factors, such as extreme meteorological conditions, airborne pollen and air pollutants are recognized as critical triggers that exacerbate asthma symptoms and influence disease progression (Damialis et al., 2019; Anenberg et al., 2020). Both extreme cold and heat can increase the risk of asthma exacerbations, hospitalizations, and respiratory-related deaths, especially among vulnerable groups such as children, older adults, and individuals with chronic conditions (Han et al., 2023). High levels of humidity have also been linked to an increased risk for asthma exacerbations (Romaszko-Wojtowicz et al., 2025). Air pollution is another well-established environmental risk factor for asthma, with numerous epidemiological studies demonstrating associations between exposure to air pollutants and increased asthma-related incidence, emergency room visits, hospitalizations, and symptom severity (Perez et al., 2013; Guarnieri and Balmes, 2014; Tiotiu et al., 2020; Zhou et al., 2024; Altman et al., 2023; Pini et al., 2022). Air pollutants can penetrate deeply into the respiratory tract, inducing oxidative stress, inflammation, and epithelial barrier dysfunction (Cooper and Loxham, 2019; De Grove et al., 2018; Kayalar et al., 2024), mechanisms central to the pathogenesis of asthma. Airborne pollen is another, often-overlooked environmental trigger, particularly during the main pollen season. Elevated pollen concentrations have been linked to asthma exacerbations (Annesi-Maesano et al., 2023; Katz et al., 2024; Lappe et al., 2023; Shrestha et al., 2021; Zhaobin et al., 2024), allergic rhinitis (Damialis et al., 2019; Holzmann et al., 2025; Luyten et al., 2024; Tameeris et al., 2023; Zhaobin et al., 2024), and other respiratory conditions, leading to increased healthcare utilization (Idrose et al., 2022). Furthermore, exposure to pollen in childhood has been associated with the development of asthma, which often persists into adulthood (Lindqvist et al., 2024; Stanescu et al., 2024). In central Europe, *Alnus, Betula, Corylus,* and Poaceae are among the most relevant pollen taxa for human health, and have been linked to asthma exacerbations and other adverse health outcomes (Beutner et al., 2021; Biedermann et al., 2019; Guilbert et al., 2018; Höflich et al., 2021; Osborne et al., 2017).

The interplay between pollen and other environmental stressors is complex and not fully understood. There is growing evidence that air pollution can enhance pollen allergenicity (Frank and Ernst, 2016). Pollutants such as ozone and nitrogen dioxide can modify pollen proteins, making them more potent triggers for allergic reactions (Sedghy et al., 2018; Venkatesan et al., 2024). Temperature fluctuations and high humidity can alter pollen dispersal patterns and pollutant concentrations, further complicating the exposure landscape and intensifying respiratory risks (Schramm et al., 2021). The additional strain on the human immune system caused by extreme temperatures or humidity can subsequently exacerbate respiratory and allergic symptoms, and increase vulnerabilities (Boser et al., 2025; Han et al., 2023; Wang et al., 2025). Moreover, extreme weather events, such as thunderstorms, have been associated with asthma outbreaks, a phenomenon referred to as *thunderstorm asthma* (Straub et al., 2022; Thien et al., 2018).

Climate change is expected to continually increase the global prevalence of asthma, particularly by intensifying exposure to environmental triggers (Agache et al., 2024; Bielory et al., 2012; Calderon et al., 2012; Luschkova et al., 2022; Ziska, 2021). Increasing greenhouse gas emissions and anthropogenic pollutant levels can aggravate the symptoms of pollen allergy in sensitized individuals, while shifts in meteorological conditions and air quality have been linked to increased respiratory mortality (Li et al., 2015; Silva et al., 2017). In addition to causing heat stress on the human body, global warming can also affect airborne pollen concentrations and their seasonality. Rising temperatures, altered precipitation patterns and increased atmospheric CO_2 levels can contribute to shifted season onsets, more intensive peaks and higher pollen concentrations (Anderegg et al., 2021; Rojo et al., 2021; Zhang and Steiner, 2022; Ziska et al., 2019; Ziska, 2021). As climate change drives an upsurge in both air pollutants and aeroallergen levels, their combined effects are expected to intensify respiratory health risks, as individuals are exposed for extended periods and at higher intensities. Additionally, climate change can create favorable conditions for invasive species, such as the highly allergenic ragweed, to spread in Europe (Lake et al., 2017) and alter the dominant ecological niches.

Compared with other environmental exposures, such as temperature, humidity and air pollution, the effects of airborne pollen on human health have received far less research attention. Although multiple studies have found significant relationships between specific pollen taxa and asthma-related health outcomes (Cole et al., 2026; Guilbert et al., 2018; Katz et al., 2024; Lappe et al., 2023; Osborne et al., 2017; Zhaobin et al., 2024), the existing evidence is heterogeneous and limited (Annesi-Maesano et al., 2023). In a recent *meta*-analysis investigating asthma risk from pollen exposure, the authors urge caution “due to the low number of studies and their heterogeneity”, thereby underscoring the need for more research in this area (Annesi-Maesano et al., 2023). Differences in pollen taxa abundances and varying sensitization rates across populations at the studied locations additionally complicate the picture. Further, pollen concentration measurements are prone to error and uncertainty. Traditional Hirst-type (Hirst, 1952) pollen traps have provided reliable long-term data and remain the reference method for aerobiological monitoring. However, they require manual counting by experts, which introduces unavoidable time delays and limits the ability to provide real-time information. Automated pollen monitoring systems complement these traditional methods by enabling continuous, near-real-time tracking, thereby potentially supporting early warning strategies that allow susceptible individuals and health systems to take proactive measures (Plaza et al., 2026). Incorporating this data into health surveillance could improve our ability to effectively prevent or mitigate asthma exacerbations and other adverse health outcomes associated with pollen exposure. As of now, most studies that investigated the effects of pollen exposure on human health relied on traditional, Hirst-type data (Guilbert et al., 2018; Katz et al., 2024; Osborne et al., 2017), while evidence for the potential of automated pollen monitoring in the context of health impact studies remains scarce.

In this study, we aim to address this research gap by quantifying the taxon-specific impacts of airborne pollen on asthma-related outpatient emergency treatments in Bavaria, Germany, using exposure data from automated pollen monitors in three metropolitan areas.

2. Materials and methods

2.1. Location and data collection

This study employed a retrospective time series analysis to investigate the effects of airborne pollen concentrations on asthma-related outpatient emergency treatments between 2018 and 2024 in the three largest cities in Bavaria: Augsburg (pop.: 301,105 as of 31.12.2024), Nuremberg (pop.: 529,508 as of 31.12.2024) and Munich (pop.: 1,505,005 as of 31.12.2024) (German Federal Statistical Office, 2026). The following data sets were used for the analysis:

1. Three-hourly pollen concentrations ([grains/m^3]) from automated pollen monitors (BAA500, HUND GmbH). In Augsburg the device is run and maintained by the Institute of Environmental Medicine and Integrative Health at the University Hospital Augsburg (2018 – 2024, Lat.: 48.38, Lon.: 10.84), while the pollen data for Munich (2019 – 2024, Lat.: 48.13, Lon.: 11.56[1]) and Nuremberg (2020 – 2024, Lat.: 49.38, Lon.: 11.20) were retrieved from the electronic Pollen Information Network (ePIN) (Kutzora et al., 2025). For the ePIN data retrieval, we used the station IDs “DEMUNC” (Munich) and “DEFEUC” (Feucht, located southeast of Nuremberg). To enhance reproducibility we also retrieved the pollen classification algorithm

[1] The measurement device in Munich was moved at 03.08.2022 from “Biedersteiner Straße” (Lat.: 48.16, Lon.: 11.59) to “Thalkirchner Straße” (Lat.: 48.13, Lon.: 11.56).

for each measurement, as provided by ePIN. We calculated a daily average if at least one of the eight 3-hourly measurements was available; otherwise, we treated the data point as missing. Since this can introduce bias to the daily mean estimates, we additionally tested a minimum requirement of four measurements per day as part of the sensitivity analysis. Within this study, we focused on the pollen taxa *Alnus, Betula, Corylus* and Poaceae as they are among the most important allergenic taxa in central Europe, and have been linked to asthma exacerbations before (Beutner et al., 2021; Biedermann et al., 2019; Guilbert et al., 2018; Höflich et al., 2021; Osborne et al., 2017).

2. Daily routine data on outpatient emergency care provided by the Bavarian Association of Statutory Health Insurance Physicians (KVB) for the period 2018 – 2024. The KVB is an organization of practicing physicians and psychotherapists in Bavaria and represents the interests of its more than 30,000 members vis-à-vis policymakers, health insurance companies, and the public. As part of its legal mandate, the KVB bills statutory health insurance companies for outpatient services. The billing records used in this study are limited to outpatient emergency services and contain information on the patient's age, gender, place of residence (postal code) and the primary diagnosis (International Classification of Diseases, 10th revision (ICD-10), three-digit level) for each treatment. We considered cases with a primary asthma diagnosis (ICD-10: J45, J46) and the patient's place of residence (given as postal code) within a 25 km radius around the respective pollen monitor (Katz et al., 2024). Since a single measurement location can lead to substantial exposure misclassification, in particular in urban, highly heterogeneous environments, we tested the sensitivity of our results to the chosen radius probing values between 10 km and 40 km with a 5 km increment (Katz et al., 2024). We aggregated the individual entries of the included emergency treatments into a time series of daily case numbers.
3. Daily meteorological data publicly available from the Climate Data Center (CDC) of the German Weather Service (*Deutscher Wetterdienst,* DWD) (German Weather Service (DWD), 2026). This data included daily minimum, maximum and mean temperature ([°C]) and relative humidity ([%]). For each city, we chose the DWD measurement station closest to the pollen monitoring site: Augsburg (Station-ID: 00232, Lat.: 48.43, Lon.: 10.94), Munich (Station-ID: 03379, Lat.: 48.16, Lon.: 11.54), Nuremberg (Station-ID: 03668, Lat.: 49.50, Lon.: 11.05).
4. Daily air pollution data ([$\mu g/m^3$]) publicly available from the measurement archive of the Bavarian Environment Agency (Bayerisches *Landesamt für Umwelt*, LFU Bayern) (Bavarian Environment Agency (LfU), 2026), including PM10, PM2.5, O_3, NO and NO2. To facilitate better differentiation in the case of particulate matter, we calculated the coarse fraction (PM_{CF}) as the difference between PM10 and PM2.5. Since for all three study locations we had multiple measurement stations located within the considered 25 km radius around the pollen monitor, we averaged the measurements across the available sites. Not every station tracked all considered pollutants, so the number of sites used for averaging can vary by species and location.
5. Weekly epidemiological data including the incidence of seasonal influenza and COVID-19 at county level across Germany, publicly available from the Robert Koch Institute (RKI) database (Robert Koch Institute (RKI), 2025). For the analysis we considered the incidence in the urban districts of Augsburg, Munich and Nuremberg.

Missing values in pollen, meteorological and air pollution data were imputed via linear interpolation. When multiple measurement sites were available for air pollution, data imputation was applied to each station's data first before averaging across sites. For the often right-skewed pollen data, we tested the validity of the linear interpolation scheme employing two alternative approaches as part of the sensitivity analysis. First, we applied the linear interpolation on a $\log_{10}$ scale (Katz et al., 2024). Second, we used the interpollen function of the AeRobiology (Rojo et al., 2019) R-package with a moving average approach (int.method = 'movingmean'). We did not include other measurement stations from ePIN in our analysis due to the limited number of asthma cases within the considered 25 km radius. Maps with the locations of considered measurement devices and the included postal code regions can be found in the supplementary material (**Fig. S1**). Furthermore, we assessed multicollinearity of the involved exposure variables via a pairwise Spearman correlation analysis.

2.2. Time series analysis

A time series analysis was employed to estimate the exposure–response relationship between airborne pollen concentrations and asthma-related outpatient emergency treatments. Evidence from previous studies indicates that asthma symptoms can be delayed by several days after pollen exposure, while both the effect strength and lag structure can vary between taxa (Guilbert et al., 2018; Ito et al., 2015; Katz et al., 2024; Lappe et al., 2023; Osborne et al., 2017; Zhaobin et al., 2024). To appropriately capture these complex interactions, we used penalized Distributed Lag Non-linear Models (DLNMs) (Gasparrini et al., 2010, 2017), a well-established framework in the field of environmental epidemiology that allows for flexible modelling of potentially lagged and non-linear relationships. We implemented the model in R (Version 4.5.1) (R Core Team, 2025) as a GAM (Generalized Additive Model) using the libraries dlnm (Version 2.4.10) (Gasparrini, 2011) and mgcv (Version 1.9.3) (Wood, 2011). The model can be stated as:

$$\log E[Y_{t,loc}] = \text{intercept} + \text{loc} + \text{cbTemp} + \text{cbHumid} + \text{cbAlnus} + \text{cbBetula} + \text{cbCorylus} + \text{cbPoaceae} + \text{dow:loc} + \text{phday:loc} + \text{seasonality}(\text{doy}, \text{ns}(8\ \text{df}):\text{year:loc})$$

with the daily case count ($Y_{t,loc}$) at time *t* for a given location *loc.* To avoid overfitting in single locations, we used shared exposure cross-basis objects for pollen (*cbAlnus*, *cbBetula*, *cbCorylus*, *cb*Poaceae*)*, maximum daily temperature (cb_{Temp}) and daily relative humidity (cb_{Humid}) across the three study sites. This approach was preferred over a two-stage design (Gasparrini et al., 2015) due to the small number of locations and the limited informative value of potential *meta*-regression estimates. To estimate a shared exposure–response relationship, we combined the time series from the three locations into a single stacked dataset, ordered by location: Augsburg, Munich and Nuremberg. We inserted missing values exceeding the maximum lag period between the location-specific time series to prevent accidental leakage of lagged exposure across locations during cross-basis construction. For temperature, we used the maximum daily temperature (T_{Max}) since it better reflects the actual exposure during daytime, and tested minimum (T_{Min}) and mean (T_{Mean}) daily temperature as part of the sensitivity analysis. Furthermore, we introduced location-specific interaction terms for the day of the week (*dow:loc*), public holidays (*phday:loc*) and the seasonality component (*seasonality* (*doy, ns (8 df):year:loc*)) to account for variations in the temporal patterns across locations. The seasonality component consists of a natural spline function of the day of the year (*doy*) with eight degrees of freedom (*df*) and an additional interaction term for the year (*year*). The choice of eight degrees of freedom per year lies within the range of complexity considered an appropriate tradeoff between seasonality control and leaving enough information for the effect estimations (Bhaskaran et al., 2013; Gasparrini et al., 2010; Iñiguez et al., 2021; Wen et al., 2024). We tested the robustness of our results with respect to the degrees of freedom for the seasonality component as part of the sensitivity analysis. The model further included a shared intercept (*intercept*) and a location effect (*loc*). To account for potential overdispersion, a quasi-Poisson distribution was used. Since the four pollen taxa differ in seasonal onset and duration, we included the whole year's data in the analysis. By this approach, we aimed for more accurate estimations of the influence of control variables, such as day of the week and public holidays, as well as potential confounding effects.

2.3. Cross-basis parametrization

Following a recent nationwide study from England, we employed a strata-based approach to model the pollen effect (Cole et al., 2026). We derived the strata for each taxon from the percentiles in the observed in-season daily concentrations across the three study locations: *Reference* = [0, 10th), *Low* = [10th, 25th), *Medium* = [25th, 75th) and *High* = [75th, 100th]. To determine the in-season window for each taxon, we used the calculate_ps function of the AeRobiology (Rojo et al., 2019) R-package, defining the season around the peak (def.season = 'peak') and employing the 95-percentage method (Andersen, 1991), to obtain accurate, location-specific estimates for each pollen taxon's season start and end date. The strata-based approach was preferred over more complex parameterization approaches due to the higher numerical stability in face of zero-inflated and highly skewed exposure distributions, as often observed in raw pollen concentration data (Cole et al., 2026). We compared our effect estimates to the more common assumption of a linear relationship (Guilbert et al., 2018; Katz et al., 2024; Lappe et al., 2023; Osborne et al., 2017) and tested additional parameterizations after $\log_{10}$-transforming the daily pollen concentrations, including a linear function, a natural spline function with three knots (10th, 50th and 90th percentile of the in-season pollen concentrations) and a P-Spline (Eilers and Marx, 1996) with five degrees of freedom. The effect of temperature and relative humidity were modelled via a P-Spline with five degrees of freedom. For the lag dimensions of all involved cross-basis objects we used penalized splines with five degrees of freedom and a ridge penalty, imposing a decay towards the maximum lag value (Gasparrini et al., 2017; Obermeier et al., 2015). We specified a diagonal penalty matrix with entries $\mathbf{p} = [0,0,0,1,1]^T$. Following previous studies we chose a maximum lag of seven days for the pollen effects (Ito et al., 2015; Osborne et al., 2017; Sun et al., 2016) and used the same maximum lag for temperature and relative humidity, focusing on short-term effects. We extended the maximum lag to 10 and 14 days and implemented other lag-space parametrizations as part of the sensitivity analysis.

2.4. Relative risk at different exposure levels

We reported the pollen effect as the relative risk (RR) at different exposure levels compared to the *Reference*, based on the strata definitions given in Section 2.2.1. For temperature and relative humidity, we reported the relative risk at the 10*th* and 90*th* percentiles compared to the median, using the aggregated distribution across the three study sites. All estimated effects were reported with a 95% confidence interval based on a standard Wald test.

2.5. Attributable fraction

To assess the health burden associated with exposure to airborne pollen, we estimated the fraction of asthma treatments attributed to each taxon. To estimate attributable fractions (AFs) and attributable numbers (ANs), we followed the *backward perspective* approach (Gasparrini and Leone, 2014). The AF was calculated for each location separately, once within each taxon's season and once across the entire study period. In addition, the AF was calculated for each year separately, which allowed us to investigate the inter-annual variance in the estimated asthma burden associated with pollen exposure and facilitated a more detailed interpretation. We accounted for uncertainty in the AF estimations by calculating empirical confidence intervals using Monte Carlo simulations (N = 5000) (Gasparrini and Leone, 2014). For the calculation of the AF and AN, we used the R function attrdl from the FluMoDL (Lytras, 2019) (Version 0.0.3) library, which includes minor modifications to the initial implementation provided (Gasparrini and Leone, 2014) and allows the calculation of the AF over user-defined sub-periods.

2.6. Sensitivity analysis

We conducted an extensive sensitivity analysis to ensure the robustness of our findings, varying most modelling assumptions and including the air pollutants PM_{CF}, $PM_{2.5}$, O_3, NO and NO_2 as cross-basis objects, following the lag parameterization for pollen and meteorological parameters. In the variable dimension we tested two parameterizations: a simple linear relationship and a P-Spline with five degrees of freedom, as used for the meteorological variables in the main model. Weekly Influenza and COVID-19 incidences were included as linear control variables, to account for potential confounding. As additional steps, we separately excluded the years 2020 and 2021 from the analysis to rule out potential impacts of the early dynamics of the COVID-19 pandemic on our pollen effect estimates. We varied the complexity of the natural spline for seasonality and implemented an alternative seasonality control, employing categorical year-month strata (e.g., *2020: January*). The penalized spline in the lag dimension of the pollen cross basis objects was replaced by a bicubic spline with two equally spaced knots and by a simple linear function. To account for the potential influence of remaining autocorrelation in the model's residuals, we added the one-day lagged deviance residuals to the model (Bhaskaran et al., 2013). Furthermore, we fitted additional models for each taxon separately, constraining the study period to each taxon's typical seasonal extent: *Alnus* (January – March), *Betula* (March – May), *Corylus* (January – April), Poaceae (May – September). The degrees of freedom per year for the seasonality component were adjusted according to the season length: *Alnus* (2 *df*), *Betula* (2 *df*), *Corylus* (3 *df*), Poaceae (3 *df*).

The R code used for the analysis is available on the authors' GitHub page (see Data and Code Availability statement).

3. Results

3.1. Health data

Over the study period, a total of 4,164 (Augsburg), 13,379 (Munich) and 5,434 (Nuremberg) asthma-related outpatient emergency treatments were recorded by the KVB. In 2020, a strong decline in reported cases was observed, coinciding with the onset of the COVID-19 (SARS-CoV-2) pandemic (Fig. S2). While most cases were assigned the diagnosis J45 (*Asthma*), J46 (*Status Asthmaticus*) was rarely reported across all three locations. Patients aged 16 to 64 years accounted for the majority of cases, while women were slightly overrepresented (Table 1).

3.2. Taxon-specific pollen effects

From the considered pollen taxa, *Corylus* had the earliest season onset, followed by *Alnus, Betula* and Poaceae (Table S1, Table S2, Table S3). While the longest average season duration was observed for Poaceae with 97.3 (SD: 25.5) days, *Betula* had the shortest season with an average of 43.9 (SD: 18.5) days. The highest daily exposure was observed for *Betula* in Nuremberg on April, 7 2024, with 3624.21 pollen grains/m^3. Across the three study sites, the in-season IQR was highest for *Betula* (172.91 pollen grains/m^3) and lowest for Poaceae (27.25 pollen grains/m^3). The exposure strata based on percentiles covered the following ranges: *Low* (*Alnus*: [0, 3.49), *Betula*: [3.00, 10.30), *Corylus*: [0.79, 4.61), Poaceae: [0.43, 3.05)), *Medium* (*Alnus*: [3.49, 56.14), *Betula*: [10.30, 183.20), *Corylus*: [4.61, 51.40), Poaceae: [3.05, 30.31)) and *High* (*Alnus*: [56.14, 3353.72], *Betula*: [183.20, 3624.21], *Corylus*: [51.40, 2074.60], Poaceae: [30.31, 513.37]). The Spearman correlation analysis revealed a strong correlation between the taxa *Alnus* and *Corylus* (Spearman's $\rho = 0.73$) and between Poaceae and temperature (Spearman's $\rho > 0.60$) (Fig. S3). More descriptive statistics of the environmental exposures (Table S4), the different pollen exposure levels

Table 1
Descriptive table of the asthma-related KVB outpatient emergency treatment data in the three considered study locations.

	Study Period	Total	Gender			Age				Diagnosis	
			Female	Male	Other	0 – 5	6 – 15	16 – 64	≥ 65	J45	J46
Augsburg	2018–2024	4,164	2,190	1,973	1	209	429	2,925	606	4,106	58
Munich	2019–2024	13,379	7,247	6,128	4	1,356	1,202	8,882	1,939	13,221	158
Nuremberg	2020–2024	5,434	3,041	2,391	2	167	433	4,177	657	5,409	25

(Table S5) and information on the number of gaps (Table S6) are available in the supplementary material.

3.3. Cumulative effect

We observed a significantly elevated cumulative relative risk for asthma treatments after exposure to high concentrations of *Betula* (RR: 1.64 (95% CI [1.41, 1.90])), while for low and medium levels no statistically significant association was observed (Fig. 1). For Poaceae pollen medium (RR: 1.19 (95% CI [1.03, 1.38])) and high (RR: 1.41 (95% CI [1.17, 1.70])) levels of pollen concentration showed a significant effect, with an increasing risk at higher concentrations. There were no indications of substantial effects for *Alnus* or *Corylus* pollen (Fig. 1).

3.4. Lag structure

The effects of pollen on the daily number of asthma treatments exhibited taxon-specific lag patterns, as shown for high exposure levels in Fig. 2. High levels of *Betula* pollen led to a significantly increased relative risk, peaking on the day of exposure (RR: 1.24, 95% CI [1.06, 1.45]) and decaying after two days. For high levels of Poaceae pollen, there was a non-significantly decreased relative risk on the day of exposure, which was followed by a stronger, significant risk increase on day one to four, peaking at day two (RR: 1.13, 95% CI [1.06, 1.21]). In the case of medium exposure, Poaceae pollen exhibited a weaker, more delayed effect structure, with the highest risk on day four after exposure (**Fig. S4**). The respective plots for low and medium exposure levels of all considered taxa are available from the supplementary material (**Fig. S4** and **Fig. S5**).

3.5. Attributable fractions

Focusing on taxa with significant cumulative effects, we calculated the attributable fractions of asthma treatments for *Betula* and Poaceae pollen within each season and across the whole year. Within season, we observed significant AF estimates for *Betula* ranging from 10.24% (95% CI [1.01, 18.50]) in Augsburg and 13.61% (95% CI [5.83, 20.51]) in Munich to 17.75% (95% CI [9.72, 24.80]) in Nuremberg (**Fig. S6**). Also, for Poaceae pollen we observed significant AFs at all three study locations, with the highest value of 18.84% (95% CI [7.21, 28.88]) in Augsburg. For Munich and Nuremberg, we obtained AFs of 14.25% (95% CI [4.46, 22.84]) and 14.91% (95% CI [4.47, 24.09]), respectively (**Fig. S6**). The respective attributable fractions calculated over the whole year reached a maximum of 1.84% (95% CI [-0.03, 3.59]) for *Betula* in Munich and 6.18% (95% CI [1.70, 10.08]) for Poaceae in Augsburg (**Fig. S6**). Estimating the AFs for each year's season separately revealed high inter-annual variations for both *Betula* and Poaceae (Fig. 3). In Augsburg 2018, the fraction of asthma cases attributed to *Betula* pollen reached 22.06% (95% CI [13.13, 29.84]), while in 2023 we obtained a respective AF of 3.19% (95% CI [-8.24, 13.45]). In Munich, the highest fraction for *Betula* was observed in 2020 (31.94% (95% CI [22.95, 39.63])) and the lowest in 2023 (0.91% (95% CI [-7.03, 8.22])), while for Nuremberg, the respective AFs ranged from 27.08% (95% CI [18.26, 34.79]) in 2020 to 8.27% (95% CI [0.45, 15.42]) in 2023. For Poaceae pollen, the year 2023 showed the highest AFs of asthma cases for all three locations: 26.01% (95% CI [12.82, 36.94]) in Augsburg, 23.07% (95% CI [10.33, 33.70]) in Munich and 18.30% (95% CI [6.68, 28.16]) in Nuremberg. In 2021, we obtained the lowest AFs for Augsburg (6.84% (95% CI [-3.14, 15.63])) and Nuremberg (8.53% (95% CI [-0.69, 16.63])), while for Munich the lowest fraction was observed in 2022 with 11.36% (95% CI [2.63, 19.10]). The respective plots of the yearly attributable numbers are available in the supplementary material (**Fig. S7**).

3.6. Confounders

We found significant cumulative effects for both considered meteorological variables (**Fig. S8**). Relative to the median, heat (T_{Max} = 27.4 °C (90th perc.), RR: 0.94 (95% CI [0.84, 1.05])) had no significant effect, while cold (T_{Max} = 3.5 °C (10th perc.), RR: 0.87 (95% CI [0.78, 0.96])) was linked to a significantly reduced cumulative relative risk. On the other side, both humidity extremes were associated with an elevated relative risk, with a stronger effect for humid air (RH = 90% (90th perc.), RR: 1.13 (95% CI [1.03, 1.23])) than for dry air (RH = 57% (10th perc.), RR: 1.08 (95% CI [0.98, 1.18])). Adding air pollutants as part of the sensitivity analysis revealed a significant cumulative effect of $PM_{2.5}$

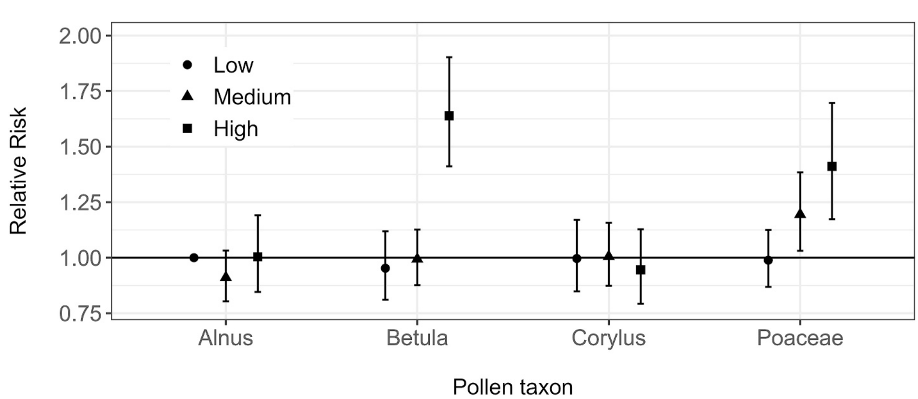

Fig. 1. Cumulative relative risk for asthma treatments at different exposure levels for the four considered taxa. Whiskers represent 95% confidence intervals.

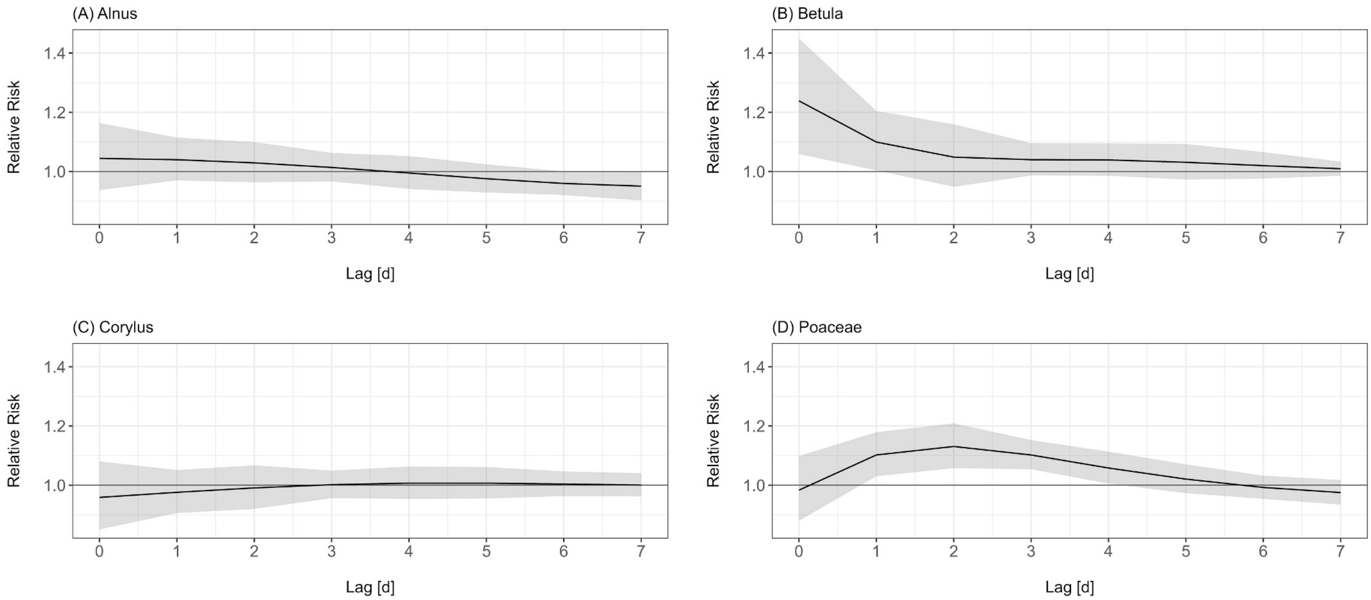

Fig. 2. Lag structure of the effect of high pollen exposure on asthma treatments reported as relative risk for the four considered pollen taxa Alnus (A), Betula (B), Corylus (C) and Poaceae (D). Shaded areas represent 95% confidence intervals.

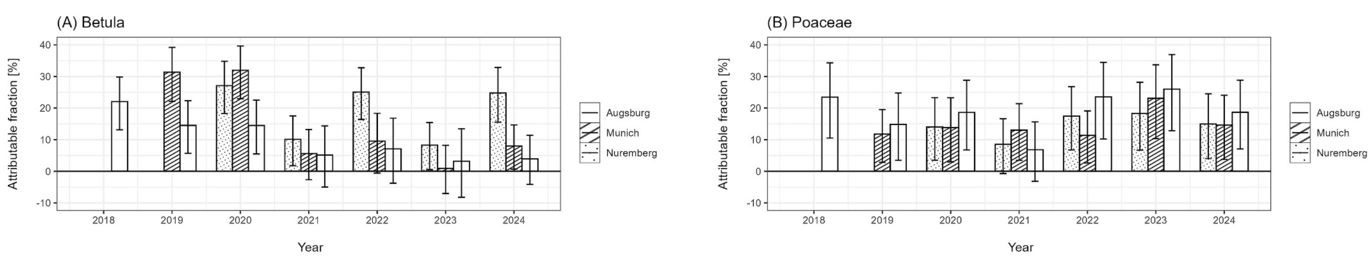

Fig. 3. Attributable fractions of asthma cases related to the exposure of Betula (A) and Poaceae (B) pollen within the respective season calculated for each year separately. Whiskers represent 95% confidence intervals.

on asthma treatments, whereas no substantial impact was observed for the other pollutants (**Table S7**). Assuming a linear effect structure, an IQR increase in $PM_{2.5}$ concentration (7.0 μg/m^3) was associated with a 11.45% (95% CI [6.39, 16.75]) increase in relative risk. This effect was confirmed by the non-linear parametrization via P-Splines, indicating a weaker effect for low concentrations of $PM_{2.5}$, accompanied by a stronger risk increase at high concentrations (**Fig. S9**).

3.7. Sensitivity analysis

Our results for the overall cumulative pollen effect are broadly consistent across varying modelling assumptions of the pollen effect, with only the two linear models showing noteworthy deviations (**Fig. S10**). The linear model on the $\log_{10}$-transformed data overestimated the effect for low levels of both *Betula* and Poaceae pollen. The linear model on the raw, untransformed data underestimated the effect at high *Betula* and Poaceae concentrations and stands out with very narrow confidence intervals. The influence of the different parameterizations on the pollen effect estimates is further illustrated in **Fig. S11** in the supplementary material, showing the relative risk over the exposure range for the different modelling choices. In the case of *Betula* pollen, the assumption of a linear relationship after $\log_{10}$-transformation, i.e., a convex relationship, yields a very strong effect for low exposure levels, disagreeing with all other tested parameterizations. For Poaceae pollen, on the other hand, all models except the linear relationship on the original pollen concentration scale agree on a sharp rise in effect strength at low exposures. Varying the radius around the pollen monitoring station for the included asthma treatments from 10 km to 40 km indicated slightly higher effect estimates for smaller radii, but had no substantial effects beyond that. (**Fig. S12**). Adding one-day lagged deviance residuals to account for the remaining autocorrelation in the residuals of the main model (**Fig. S13**) did not substantially alter our effect estimates. Due to the strong correlation between temperature and Poaceae pollen (Spearman's $\rho > 0.6$, **Fig. S3**), we additionally tested the robustness of our pollen effect estimates by removing the temperature cross-basis term (cb_{Temp}) from the main model. This and the remaining results of the sensitivity analysis showed that our results were robust under varying modelling choices and were also not altered substantially when including air pollutants and weekly influenza or COVID-19 incidence (**Table S8**, **Table S9**, **Table S10**, **Table S11**). The estimated in-season attributable fractions remained stable under the different parametrizations of the pollen effect, with the exception of the two linear parametrizations, which seem to overestimate ($\log_{10}$ scale of pollen exposure) and underestimate (original scale of pollen exposure) the attributions (**Table S12**).

4. Discussion

We analyzed the association between taxon-specific pollen exposure and asthma-related outpatient emergency treatments in Bavaria, Germany, between 2018 and 2024, including data from three metropolitan areas: Augsburg, Munich and Nuremberg. Using pollen concentrations from automated pollen monitors, we found statistically significant short-term effects on the daily number of asthma treatments for the pollen taxa

Betula and Poaceae, each with a distinct lag pattern. Our estimations of attributable fractions demonstrated that pollen exposure is associated with a substantial share of the observed asthma burden, in particular during the main pollen season and exhibits strong inter-annual variability.

4.1. Cumulative pollen effects

The observed significant impact of *Betula* pollen on asthma-related health outcomes is consistent with previous findings (Cole et al., 2026; Guilbert et al., 2018; Ito et al., 2015; Katz et al., 2024; Lappe et al., 2023). Guilbert *et al.* found a significant effect of *Betula* pollen on asthma-related hospital admissions in Brussels (Percentage change in RR per IQR-increase in *Betula* concentration (40 grains/m^3): 3.2% (95% CI [1.1, 5.3])) (Guilbert et al., 2018). Lappe *et al.* investigated emergency department visits for asthma and wheeze between 1993 and 2018 and found a percentage change in RR of 3.8% (95% CI [2.5, 5.0]) per standard deviation increase in *Betula* concentration (44.1 grains/m^3). A recent study by Cole *et al.*, who investigated the effect of tree pollen on asthma-related hospital admissions in a nationwide study in England based on concentrations modelled via SILAM (Sofiev et al., 2024), found significant effects for medium (RR: 1.041, (95% CI [1.019, 1.060])) and high levels (RR: 1.032, (95% CI [1.005, 1.060])) of *Betula* concentrations (Cole et al., 2026). The effect reported by Cole *et al.* for high levels of *Betula* pollen is clearly weaker compared with our RR estimate of 1.64 (95% CI [1.41, 1.90]) for high exposure. To facilitate a quantitative comparison with the effect estimates from Guilbert *et al.* and Lappe *et al.*, we used their reported percentage change in RR, to recalculate the RR at the median of our high exposure level strata for Betula (464.71 grains/m^3) with a reference of 0 grains/m^3. This yielded an RR of 1.44 for hospital admissions (Guilbert et al., 2018) and 1.48 for emergency department visits (Lappe et al., 2023), which is still weaker but of similar magnitude compared to our effect estimate.

The observed cumulative effect of Poaceae pollen on asthma treatments is in agreement with previous studies, which found an associated increased risk for asthma-related hospital admissions (Guilbert et al., 2018; Osborne et al., 2017). Also, a study by Sun *et al.* in Wake County, North Carolina, reported a significant effect of Poaceae pollen on asthma emergency department visits (Sun et al., 2016). Comparing the effect strength reported by Guilbert *et al.* (Percentage change in RR per IQR-increase in Poaceae concentration (12 grains/m^3): 5.9% (95% CI [0.0, 12.0])) (Guilbert et al., 2018) at the median of the high exposure strata for Poaceae (59.64 grains/m^3), yields a RR of 1.33, compared to our RR estimate of 1.41 (95% CI [1.17, 1.70]). Compared to the existing literature, our observed effect sizes for *Betula* and Poaceae pollen are relatively high, which could be related to the low-threshold health service outcome we considered, compared to, e.g., hospital admissions (Cole et al., 2026; Guilbert et al., 2018; Osborne et al., 2017) or emergency department visits (Lappe et al., 2023). Furthermore, each health outcome might represent different population subgroups, with distinct vulnerabilities. Moreover, the different sources of pollen concentration data could introduce additional bias (Maya-Manzano et al., 2023), in particular when comparing effect estimates at absolute pollen concentrations. While most studies used traditional Hirst-type pollen data (Guilbert et al., 2018; Ito et al., 2015; Katz et al., 2024; Osborne et al., 2017), Cole *et al.* relied on 10x10km gridded, modelled *Betula* pollen concentrations from SILAM (Cole et al., 2026). The comparison between studies from different geographical regions is further limited by variations in taxa abundances, sensitization rates among the studied populations and differences in healthcare management systems.

4.2. Taxon-specific lag pattern

The temporal structure of the *Betula* effect indicates an immediate impact after exposure, with the highest relative risk on the day of exposure. This aligns with previous studies, which also reported significant effects on days one and two after exposure to *Betula* pollen (Ito et al., 2015; Lappe et al., 2023). In London, elevated relative risks for asthma-related hospital admissions were reported on the day of exposure and the two days thereafter, though not significant (Osborne et al., 2017). Also, Cole *et al.* reported a significant effect for medium levels of Betula concentrations on day one after exposure (Cole et al., 2026). On the other hand, Katz *et al.* who investigated the effect of tree pollen on asthma-related emergency department visits in Texas, U. S. found the strongest effect at the maximum lag value of seven days (Katz et al., 2024). It should be noted that Katz *et al.* considered tree pollen as a group of taxa, with *Betula* playing only a minor role in the composition. The observed delayed effect structure for Poaceae pollen, peaking around days two to three after exposure, is in agreement with the results of Osborne *et al.*, who found a significantly increased risk at days four and five after exposure based on a linear pollen effect (Osborne et al., 2017). Based on pollen alert levels – similar to the exposure level definition used in our study – Osborne *et al.* found the effect peaking at day three for high and very high grass pollen concentrations. Also, Sun *et al.* reported an effect delayed up to several days (maximum at lag 2—4) for Poaceae pollen, while tree pollen had a more immediate effect (Sun et al., 2016). The delayed effects observed for Poaceae pollen may reflect both the taxonomic heterogeneity and prolonged flowering period of grasses, leading to sustained or cumulative exposure, whereas *Betula* pollen, originating from a single genus, exhibit a shorter and more concentrated season. Overall, the lag structures observed in our study are in good agreement with the existing literature, reinforcing the credibility of our results.

4.3. Attributable fractions

The estimated attributable fractions within the *Betula* pollen season ranging from 10.24% (95% CI [1.01, 18.50]) in Augsburg to 17.75% (95% CI [9.72, 24.80]) in Nuremberg align well with results from Katz *et al.*, who found attributable fractions of emergency department visits for tree pollen during March between 3.1% and 18.6%, with variations by location and age-groups (Katz et al., 2024). For Poaceae pollen, the range between 14.25% (95% CI [4.46, 22.84]) in Munich and 18.84% (95% CI [7.21, 28.88]) in Augsburg also appears in a plausible range, though we could not find comparable estimates in the literature. Our results indicate that *Betula* and Poaceae play an important role for the asthma burden, with estimated attributable fractions of similar magnitude within season. The wide confidence intervals in the AF estimations could partly be explained by the highly skewed distribution of observed pollen concentrations, particularly in case of *Betula*, with high exposure events being rare and rather abrupt. Longer time series could help reducing the uncertainty in effect estimates and thereby improving accuracy in the assessment of the pollen-related asthma burden, stressing the importance of long-term pollen monitoring. Our year-by-year analysis of the AFs highlighted the strong variations across seasons, with strong implications for potential asthma prevention and mitigation strategies. It should be noted that the asthma burden attributable to pollen exposure would likely be even higher for more specific diagnoses, such as allergic asthma (J45.0x). However, this could not be assessed with the given detail of the available health outcome data.

4.4. Influence of parametrization on effect estimates

Our study further highlights the importance of careful parametrization when modelling the effect of pollen exposure on human health. The often-skewed and zero-inflated distribution of the measured pollen concentrations can lead to substantial bias introduced by simple approaches, such as the assumption of a linear effect, as also discussed previously (Cole et al., 2026). Especially when the data is not log-transformed, rare events of extremely high exposure can lead to an over- or underestimation of the effect strength and the associated confidence intervals in the low to medium exposure range, in which most of the data points fall. As apparent from our comparison between different effect parametrizations (Fig. S10, Fig. S11), also the assumption of a linear effect on the log-transformed data, i.e., a concave effect can lead to either under- or overestimation of the effect strength, particularly at low exposure levels. Our results showed that effect structures can vary substantially for different taxa, requiring additional caution when assessing the plausibility of the found effects.

Confounders

The observed protective effects for both cold and heat are unexpected and should be interpreted with caution, since extreme temperatures were associated with adverse health effects, particularly on respiratory health (Boser et al., 2025; Han et al., 2023; Wen et al., 2024). It should be noted that the heat effect is statistically non-significant and hence provides no reliable evidence for a true association. We also cannot rule out that the observed cold and heat effects are the result of residual confounding, model misspecification or remaining seasonal patterns that were not fully captured by the seasonality component in our model. In addition, behavioral changes during cold spells and heat waves may play an important role, with people refraining from strenuous outdoor activities, which is a known trigger for asthma exacerbations. Given the strong correlation between temperature and Poaceae pollen (Spearman's $\rho > 0.6$, **Fig. S3**), we additionally removed the Poaceae pollen effect from the main model, leading to a slight reduction of the observed heat effect (RR: 0.94 (95% CI [0.84, 1.05]) (Main model) vs. RR: 0.96 (95% CI [0.86, 1.08]) (Without Poaceae pollen effect)), indicating a potential moderate interaction between those two exposures. In summary, our findings do not allow for drawing definitive conclusions on the role of temperature as a potential confounder, and the interpretation of the observed effects remains speculative.

In contrast, the effects for both dry and humid air confirm the importance of relative humidity as an important co-exposure. High and low relative humidity can lead to favorable conditions for bacterial and viral growth (Guarnieri et al., 2023). While breathing dry air can alter the nasal mucosa and lead to epithelial damage (Guarnieri et al., 2023), very humid air can be harder to breathe and have adverse effects on lung function (Lepeule et al., 2018). Although most studies controlled for meteorological variables, they did not report the observed effect estimates (Cole et al., 2026; Guilbert et al., 2018; Katz et al., 2024; Lappe et al., 2023; Osborne et al., 2017; Sun et al., 2016; Zhaobin et al., 2024), making a comparison with the existing literature difficult. The observed significant effect of $PM_{2.5}$ on the number of treatments aligns well with the established role of air pollution as a trigger of asthma exacerbations (Altman et al., 2023; Guarnieri and Balmes, 2014; Perez et al., 2013; Pini et al., 2022; Tiotiu et al., 2020; Zhou et al., 2024). Sensitivity analyses using a non-linear parameterization for air pollutants yielded consistent results, suggesting that the assumption of linearity did not substantially influence our conclusions.

5. Strengths and limitations

A strength of our study is its multi-centric approach, combining up to seven years of coherent daily airborne pollen concentrations with diagnosis-specific health outcomes from three densely populated metropolitan areas. The use of data from automated, standardized pollen monitors from the same manufacturer ensures a high comparability between the study sites and may significantly improve comparability across studies. Automated pollen monitors have the potential to become a crucial component of effective prevention, as they enable real-time monitoring of pollen concentrations and can thereby support timely warnings and information policies. However, evidence that automated pollen monitors are a reliable data source for health impact studies remains scarce. To our knowledge, this is the first study to directly link data from automated pollen monitors to health outcomes in a time series analysis approach, estimating taxon-specific exposure–response relationships. The location of the pollen monitoring sites near densely populated urban areas allowed us to include more than 20,000 asthma treatments in total, within a reasonable radius of 25 km (Pashley et al., 2009; Smith et al., 2026). The confirmed ICD-10 diagnoses of the considered outpatient emergency treatments are another strength, ensuring a high reliability of the health outcome data. As low-threshold health services, outpatient emergency treatments are likely to be more sensitive to short-term environmental exposures than hospital admissions or mortality data. This makes them a particularly suitable health outcome for assessing the pollen-related asthma burden, given that the majority of asthma cases are mild (Wang et al., 2023). Despite their mildness, these cases are of great importance, since also patients who were asymptomatic or had mild symptoms for a long time are nevertheless at risk of experiencing severe and life-threatening exacerbations (Wang et al., 2023). Furthermore, early treatment of asthma is a crucial cornerstone for effective prevention of more severe exacerbations, relieving burden from emergency departments and improving the quality of life of those affected by asthma (Skolnik et al., 2024).

Our analysis is limited by the availability of pollen data, forcing us to use inconsistent study periods for the three study locations. Further, the limited number of outpatient emergency treatments prevents the identification of vulnerable groups through stratified analyses by age, gender, or place of residence. In particular, the limited number of cases in Augsburg and Nuremberg impairs the statistical power of our analysis. We tried to account for this by estimating a single, shared exposure–response relationship across the three locations, intending to avoid overfitting. We are aware that this approach may introduce bias due to the assumption of a fixed effect and potentially masks local heterogeneity in the effect estimates. In addition, we cannot rule out bias due to the selection of urban study sites, with potential differences compared to rural areas remaining unclear. Furthermore, the COVID-19 (SARS-CoV-2) pandemic affects the consistency of the considered time series, introducing additional dynamics, which are difficult to model explicitly. Possible effects could be more hesitant healthcare-seeking behaviour due to lockdown policies and the recommended *social distancing* as well as diagnostic coding bias during the COVID-19 pandemic. Furthermore, spending less time outdoors could lead to a reduced overall exposure with airborne allergens. We have attempted to account for the additional dynamics introduced by COVID-19 implicitly, using a flexible natural spline function for seasonality modelling and tested the robustness of our results with respect to the degrees of freedom. Additionally, we added control variables for the COVID-19 and seasonal influenza incidence and separately excluded the years 2020 and 2021 from the analysis as part of the sensitivity analysis. Moreover, the daily numbers of asthma cases exhibit strong weekday patterns, with significantly higher numbers on the weekend. We accounted for this via a control variable for the day of the week but cannot rule out residual confounding. Another limiting factor is the accuracy of the three-digit ICD-10 codes, which do not allow for a more detailed differentiation between, e.g., allergic asthma (J45.0x) and non-allergic asthma (J45.1x). It must also be emphasized that the treatments considered in our study represent only a part of the overall asthma health burden, which ranges from family doctor visits over hospital admissions to fatal events. However, the significant associations found in our study suggest that the considered outpatient treatment setting plays an important role in the pollen-related asthma burden, also reflecting the often-neglected non-severe cases. In the context of exposure data, we must acknowledge that automated, real-time pollen monitoring is still under development, and thus, we cannot rule out inconsistencies in the pollen concentration data used in this study due to the usage of different pollen taxon classification algorithms. Furthermore, the measurement device in Munich was moved in August 2022, with potential measurement inconsistencies. It must also be admitted that the geographical scope of our study does not allow for drawing conclusions about other regions of the world.

6. Conclusion

Our study demonstrated significant associations between elevated levels of *Betula* and Poaceae pollen concentrations and asthma outpatient emergency treatments in Bavaria. The estimates of attributable fractions suggest a substantial asthma burden linked to *Betula* and Poaceae and revealed strong inter- and intra-annual variability, underscoring the importance of continuous monitoring and the preparedness of clinicians and patients, particularly during the main pollen season. By leveraging data from automated pollen monitors, we laid a foundation for future health impact studies on aeroallergens and strengthened confidence in this emerging technology. The combination of real-time measurements and reliable evidence on taxon-specific health impacts can substantially enhance early warning and prevention measures, ranging from improved healthcare resource management to accessible tools such as mobile apps targeted at allergy sufferers, providing guidance on timely pre-exposure medication. Future research could provide further evidence on automated pollen monitors as a reliable data source for health impact studies, investigate socio-economic vulnerabilities and contribute to a more comprehensive picture of the overall asthma burden associated with pollen exposure. In addition, studies are needed to clarify potential synergistic effects between pollen and other environmental stressors on human health, an issue of growing importance in times of climate change.

CRediT authorship contribution statement

Matteo Boser: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Athanasios Damialis:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Christoph Knote:** Writing – review & editing, Supervision, Methodology. **Monika Seemann:** Writing – review & editing, Funding acquisition, Conceptualization. **Claudia Traidl-Hoffmann:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Conceptualization. **Maria P. Plaza:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Formal analysis, Data curation, Conceptualization.

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Declaration of competing interest

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

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Ethical approval

The use of cumulated and anonymized outpatient emergency data was approved by the ethics committee of the medical faculty of Ludwig-Maximilians-University (LMU) in Munich, approval number 25-0422-KB.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2026.110426.

Data availability

I have shared the R code (attached as Research Data) to reproduce the workflow/analysis. Publicly available data sets were provided alongside the R code. Health data was simulated.

https://github.com/bosermat/2026_Pollen_Asthma_Bavaria

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