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Full length article

Tree pollen and asthma-related hospital admissions in England: a national case time series analysis

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ABSTRACT

Objective: Evidence linking pollen exposure to asthma exacerbations is limited and inconsistent across regions, pollen types, and age groups. We assessed the association between pollen concentrations and asthma-related hospital admissions across England at high spatial resolution.

Materials and methods: We use unplanned asthma admissions records (2008–2022) from Hospital Episode Statistics, linked to 10-km gridded data on alder and birch pollen. Tree pollen exposure was categorised as low, medium, or high. Age-specific case time series analyses were conducted using conditional Poisson regression, controlling for temperature and air pollutants ($PM_{2.5}$ and NO_2). Analyses were restricted to January–August, when tree pollen is present.

Results: Elevated asthma admission risk was associated with both pollen types, with a non-linear exposure–response that increased sharply at low levels and attenuated at higher exposures. For alder pollen, relative risks (RRs) across all ages were 1.014 (95%CI: 0.998, 1.031) for low, 1.026 (1.007, 1.046) for medium, and 1.019 (0.995, 1.044) for high exposure. For birch, RRs were 1.016 (0.996, 1.037), 1.041 (1.019, 1.06), and 1.032 (1.005, 1.060), respectively. Risks were mostly limited to children, with medium alder pollen exposure associated with RRs of 1.047 (0.993, 1.105) and 1.112 (1.066, 1.159), and birch with RRs of 1.131 (1.066, 1.201) and 1.079 (1.029, 1.131) in 0–4 and 5–14-year-olds, respectively. No evidence of association was found in older groups.

Conclusion: Moderate tree pollen levels are associated with increased asthma admissions in younger populations in England. Further work is needed to understand group and individual susceptibility.

1. Introduction

Asthma is one of the most prevalent chronic non-communicable diseases, affecting approximately 300 million people worldwide (Porsbjerg et al., 2023) and the second leading cause of mortality among chronic respiratory conditions (Yuan et al., 2025). According to The Global Asthma Report (2022), the estimated global prevalence of asthma is 9.1% among children, 11.0% among adolescents, and 6.6% among adults. However, the prevalence exhibits substantial variation across geographic regions. The United Kingdom (UK) ranks among the countries with the highest asthma prevalence worldwide. In England, recent harmonised analyses of longitudinal cohort data estimated the national asthma prevalence at 9.6%, corresponding to around 5.5 million individuals (Whittaker et al., 2025). Despite sustained efforts to mitigate its impact, asthma continues to impose a significant burden in the UK, with annual costs to the National Health Service (NHS) estimated to exceed £1.1 billion (Mukherjee et al., 2016).

Asthma is a heterogeneous respiratory condition characterised by recurrent bronchospasm, airway inflammation, and variable airflow limitation leading to symptoms such as wheezing, dyspnoea and cough (Yuan et al., 2025). Exacerbations – acute worsening of symptoms – are clinically important as they often require emergency care or

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hospitalisation (Skolnik et al., 2024). While the onset is usually rapid in children, it may develop over a week or more in adults (Papi et al., 2018).

Numerous environmental factors are known to exacerbate asthma symptoms. Among these, airborne allergens are recognised as critical triggers, especially in individuals with allergic sensitisation or an underlying atopic predisposition (Murrison et al., 2019). Tree pollen, a major aeroallergen, is an established risk factor for respiratory symptoms and is an important early-season trigger in temperate climates. A recent systematic review suggested that pollen exposure can be associated with moderate and severe asthma exacerbations, particularly among children and adolescents, with effects observed at short lags (Annesi-Maesano et al., 2023). However, existing studies exhibit substantial heterogeneity, particularly with respect to study design, population characteristics, assessed pollen taxa, spatial and temporal resolution, and specification of lag structures. In addition, studies have primarily been conducted in limited geographical areas, which may hinder generalisability to wider populations and often fail to adequately adjust for potential confounding (Annesi-Maesano et al., 2023). In light of the uncertainty regarding the population-level impact of pollen-related asthma outcomes, additional epidemiological studies are fundamental to estimate the potential strain posed on the public health system. No prior study has systematically quantified tree pollen-related asthma admissions across England using high-resolution exposure data.

In this contribution, we address this research gap by conducting a nationwide study examining the association between pollen exposure and asthma-related unplanned hospital admissions across England, using high-resolution modelled pollen data and state-of-the-art epidemiological methods.

2. Methods

2.1. Data

Data from different sources were gathered to assemble complete daily time series for each of the 33,775 lower layer super output areas (LSOAs) in England for the period 2008-2022. LSOAs are the second smallest UK census tracts, each with resident populations in the region of 1,000 to 3,000 individuals. All data were complete for the study period with no missing daily values for pollen, air pollution, temperature, or admissions across the spatial domain.

Information on daily unplanned hospital admissions for asthma (ICD10 code: J45) was retrieved from the Admitted Patient Care (APC) tables from the NHS Hospital Episode Statistics (HES, 2024) dataset accessed via DARS approval DARS-NIC-329869-Q9Z2Z-v0.6. Events were aggregated as daily counts for each LSOA, both for all ages and then stratified by specific age intervals (0-4, 5-14, 15-29, 30-44, 45-59, 60+), selected to give similar-sized groups.

Daily levels of pollen for different tree species were derived from the European Pollen Reanalysis (EPR) v.1.1 calculated by the SILAM (System for Integrated modeLling of Atmospheric composition, https://silam.fmi.fi) model, developed by the Finnish Meteorological Institute (FMI) (Sofiev et al., 2024). The EPR presents a 43 year-long reanalysis of pollen seasons for three major allergenic genera of trees in Europe: alder, birch, and olive. Driven by the European meteorological reanalysis ERA5, the atmospheric composition model SILAM predicted the flowering period and calculated the Europe-wide dispersion pattern of pollen for the years 1980–2022. The reanalysis used an extended 4-dimensional variational data assimilation of in-situ observations of aerobiological networks in 34 European countries to reproduce the interannual variability and trends of pollen production and distribution. The assimilation targeted the total pollen release during each flowering season represented via an annual correction factor to the mean pollen production. Detailed description of the modelling technology behind these data is presented in Sofiev et al. 2024. The analysis in this study was restricted to two pollen species, alder and birch, due to their prevalence in the UK. Average pollen concentration (counts/m^3) over the 10-km grid of the EPR was linked to each LSOA using area-weighted averages of the corresponding boundary polygon.

Daily levels of other environmental factors, specifically air pollutants and temperature, were gathered from 1-km gridded databases and similarly linked to each LSOA using area-weighted averages. Specifically, daily mean temperature was computed as the average between minimum and maximum provided by the HadUK-Grid database, developed by the UK Meteorological Office (Met Office 2024). Levels of fine particulate matter ($PM_{2.5}$) and nitrogen dioxide (NO_2) were produced by a hybrid ensemble machine learning model with an overall monitor-based cross-validated R^2 of 0.82 and 0.69, respectively (de la Cruz Libardi et al., 2024).

2.2. Analysis

The analysis followed a case time series design (Gasparrini, 2021), with cases represented by small geographical units (LSOAs). This approach allowed us to conduct a country-wide analysis whilst accounting for high-resolution differences in exposure in a computationally efficient design, taking advantage of the important spatial contrasts observed for pollen. Stratification by year and month was implemented for flexible control of LSOA-specific long-term and seasonal trends (Gasparrini, 2022). This stratification means all comparisons are made within the month-year time strata, providing automatic control for between-month and between-year differences.

We fitted a single conditional Poisson regression for all the 33,775 LSOA-level series, including the two tree pollen types, alder and birch. The analysis was restricted to the January-August period, during which these pollen types are present in the UK. Additional terms for daily average temperature and air pollution ($PM_{2.5}$ and NO_2) were included to control for potential co-pollutant confounding due to temporal correlations with pollen and known impacts on respiratory conditions. In addition, we controlled for day of the week and public holiday effects by including indicator variables in the model.

In the main model, we applied an exposure-response parameterisation based on three strata and a reference group. Due to the zero-inflated and right-skewed nature of the pollen distribution, a strata parameterisation was favoured to improve numerical stability and interpretability. Specifically, we used zero and very low pollen days as the reference, and we then defined low, medium, and high strata. These strata were selected to represent the full distribution of the pollen counts whilst retaining a sufficient number of LSOA-days in each strata for analysis (see Supplementary Fig. E1 in the Appendix). For alder, the reference days are those with less than one pollen particle per cubic meter, and for birch less than five. Low, medium and high pollen levels were defined as 1-5, 5-20 and more than 20 for alder and 5-50, 50-200 and more than 200 for birch. We estimated the acute effect of pollen on asthma-related hospital admissions, and therefore specified the exposure as a moving average of the current and previous day's pollen exposure.

Mean temperature was included in the model using a natural spline with three knots at the 10th, 75th and 90th LSOA-specific percentiles of the distribution for the full year. The maximum lag was chosen as three days, and the lag response was modelled as two strata for lags 0 and 1-3. Linear terms were included for the two-day moving average of each of NO_2 and $PM_{2.5}$ to capture the known short-term health effects of air pollution (Liu et al., 2019; Meng et al., 2021).

Sensitivity analysis explored the effect of using different strata definitions and extending the lag to 5 days. The alternative strata definitions are provided in Supplementary Tables E3 and E4. In addition, two alternative parameterisations of the exposure response were included. The first assumed a linear relationship, and the second a linear relationship after the exposure was log-transformed to account for the skewness of the pollen distributions, assuming a concave relationship. For these alternative parameterisations, the lag-response was modelled as in the main model. Model fit was evaluated via residual diagnostics and assessment of overdispersion in the quasi-Poisson model.

All data preparation and analysis was completed in R version 4.5.0 (R Core Team, 2025).

3. Results

3.1. Descriptive statistics

Table 1 contains summary statistics for the outcome, exposure and environmental confounders over the period 2008-2022 (January to August). During this period there were 437,543 unplanned asthma-related hospital admissions across England (mean 120 per day). Asthma hospitalisations occurred more often in young people, with 55,196 (13%) and 88,770 (20%) events in children aged 0-4 and 5-14, respectively.

Both alder and birch pollen showed zero-inflated and right skewed distributions, with medians of zero and maximum values exceeding 1,000 particles/m^3. The spatial distribution of pollen is similar for both pollen types as shown in Fig. 1, with higher average pollen levels in the North of the country. Discrete areas of elevated pollen are observed in the West Midlands for alder (Fig. 1A) and the North of England for birch (Fig. 1B).

3.2. Overall risk associations

Across the all-age pooled analysis, there is evidence of an effect of elevated pollen levels on asthma-related hospital admissions. The exposure response was characterised by an initial increase in risk at low and medium pollen levels, with suggestion of attenuation at high concentrations of pollen. For alder the relative risk (RR) for low concentrations is 1.014 (95% CI: 0.998, 1.031) and 1.026 (95% CI: 1.007, 1.046) for medium concentrations, falling to 1.019 (95% CI: 0.995, 1.044) for high concentrations. Similarly for birch there is an initial increase from low concetrations (RR: 1.016 (95% CI: 0.996, 1.037)) to medium concentrations (RR: 1.041 (95% CI: 1.019, 1.06)) followed by a drop in risk for high concentrations (RR: 1.032 (95% CI: 1.005, 1.060)).

Similar risks were observed for both pollen types, with some evidence of greater risk of asthma-related hospital admissions due to elevated birch pollen, although confidence intervals overlap (Fig. 2). This is likely due to overall higher birch concentrations.

3.3. Age-stratified risk associations

Young children exhibited the greatest risk of pollen-related hospital admission for asthma (Fig. 2). The highest RRs were found for birch in the 0-4 age group and, differently to the pooled model, the risk associated with birch pollen for 0–4-year-olds continued to increase with greater pollen exposure (low: 1.002 (95% CI: 0.947, 1.060); medium: 1.131 (95% CI: 1.066, 1.201); high: 1.196 (95% CI: 1.111, 1.289)). There were pronounced differences between pollen types in this age group with high alder concentrations associated with a significantly lower and non-statistically significant risk estimate (RR: 1.016 (95% CI: 0.951, 1.086)).

Conversly, for 5–14-year-olds, similar or higher risks were associated with alder pollen (high: 1.122 (95% CI: 1.065, 1.183)) compared to birch (high: 1.078 (95% CI: 1.014, 1.147)). Similarly to the all-ages model, there is a suggestion of risk attenuation at high concentrations. There was limited evidence of an association in the 15-29 age group for birch pollen and no evidence for an association with alder pollen.

We observed no evidence of an association between pollen levels and asthma-related hospital admissions for those aged 30 and above (Fig. 2).

3.4. Sensitivity analysis and robustness

The sensitivity analysis revealed that the linear model underestimated risk, whilst the main strata model, and log-transformed exposure model were broadly consistent – with the exception of some minor disagreement in the risk estimates for high exposures of alder (Supplementary Fig. E2). Different strata placement and an increased lag period (0-5 days) resulted in risk estimates within the confidence intervals of the presented model (Supplementary Figs. E3–E4). The lag-response varied across pollen types and strata with low precision, but generally indicated a relevant exposure window of 0-2 days (Supplementary Figs. E5-E6).

Each of the age-specific models converged and showed no evidence of overdispersion, with Pearson dispersion statistics close to one (all age: 0.988).

4. Discussion

This study evaluated the association between exposure to alder and birch pollen and risk of asthma-related hospital admission across England, using high-resolution pollen maps and state-of-the-art study designs and statistical methods. The analysis identified substantial evidence of increased risk in the 0–4, 5–14, and 15–29 age groups, as

Table 1
Summary statistics for each of the environmental variables for the study period (2008-2022), restricted to January through August.

Outcome						
Age group	0-4	5-14	15-29	30-44	45-59	60+
Observations	55,196	88,770	64,233	69,660	73,071	86,613
Exposures						
Alder pollen (particles/m^3)						
Distribution	Min	1st Qu.	Median	Mean	3rd Qu.	Max
	0.00	0.00	0.00	3.37	0.24	3211.76
Strata information	Reference	Low	Medium	High		
Range	0-1	1-5	5-20	20+		
Count	348,822	39,042	30,065	19,614		
Birch pollen (particles/m^3)						
Distribution	Min	1st Qu.	Median	Mean	3rd Qu.	Max
	0.00	0.00	0.00	17.98	0.01	5033.34
Strata information	Reference	Low	Medium	High		
Range	0-5	5-50	50-200	200+		
Count	379,572	23,673	21,864	12,434		
Confounders						
	Min	1st Qu.	Median	Mean	3rd Qu.	Max
PM$_{2.5}$ (μg/m^3)	0.28	6.50	8.65	10.69	12.37	92.00
NO$_2$ (μg/m^3)	0.18	10.54	16.47	19.82	25.52	142.32
Mean daily temperature (°C)	-9.48	6.71	11.10	11.12	15.77	31.38

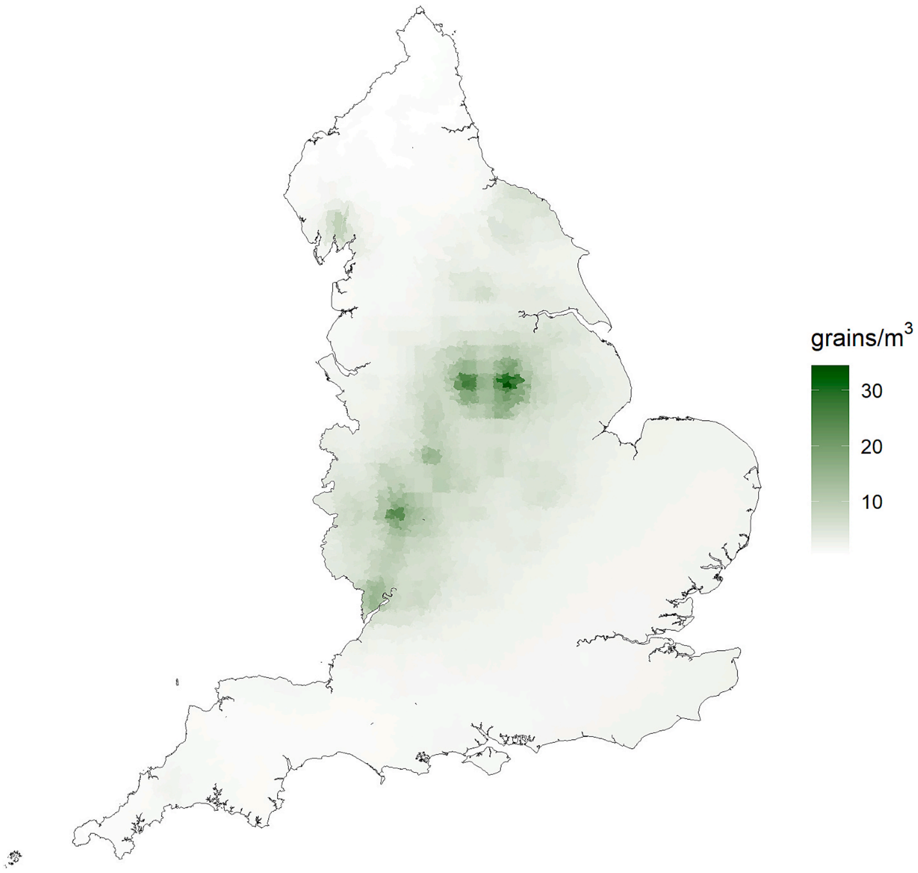

Fig. 1. Maps showing the spatial distribution of the average pollen concentration (particles per m^3) for A) alder and B) birch for the study period.

well as for the full population. In contrast, we found no evidence of increased risk of hospitalisation in the 30–44, 45–59, or 60+ age groups. Of the two pollen types, birch pollen had the strongest evidence of increased asthma-related hospital admissions among those aged 0-4 and 15-29. For alder pollen, the strongest evidence of increased risk was among 5-14 year-olds.

We identified an exposure-response relationship characterised by an initial increase in risk, followed by attenuation, and in some cases reduction, of risk at high levels. This finding has relevance for preventative measures and warning systems, suggesting that these efforts should be triggered at relatively low exposure levels. For all ages, the relative increase in risk associated with medium pollen exposure corresponds to roughly three additional asthma-related admissions per day, given a baseline of approximately 120 admissions in England. Similar results of higher risk associated with lower (but still elevated) exposures have been observed in the context of air pollution, specifically for SO_2 and allergic rhinitis (Teng et al., 2017) and $PM_{2.5}$ and respiratory mortality (Yan et al., 2019). Additionally, we find linear models are not suitable for characterising the association, and seem to underestimate risks at low pollen levels. The log-transformed exposure model is more appropriate, imposing an initial increase in risk at elevated levels of exposure with little additional risk as the exposure continues to increase. This characterisation of risk is suitable for exposures that exhibit a saturation in the biological response or susceptible population, or where behavioural adaptations occur at high levels.

This study reports consistent evidence of increased risk of admission for asthma associated with alder pollen for the 5–14 age group. In contrast, the only existing time-series study that examined the relationship between alder pollen concentrations and asthma hospitalisations reported only a 0.2% change in asthma admissions per interquartile range increase in pollen count (95% CI: -2.2, 2.7), with weak evidence of associations observed across age groups (Guilbert et al., 2018). This interesting age-specific finding from our study could be attributed to several factors. Alder pollen season begins earlier in the year (January) than birch (March). Temporal overlap between the alder pollen season and the circulation of respiratory viruses, both of which are established triggers of asthma exacerbations (Katz et al., 2024), may increase susceptibility in school-aged children (5–14 years). Similarly, as cross-allergenicity between alder and birch pollen is well established (Weber, 2003), alder may act as an early-season sensitiser, triggering allergic responses before preventive measures are consistently implemented. Additionally, established pollen warning systems during the birch season may enhance preparedness and mitigate health impacts, which may explain the reduced risk associated with high and very high birch pollen concentrations.

A number of previous studies support the relevance of birch pollen on asthma exacerbations, particularly in children and adolescents. A London-based time-series study reported a 0.78% (95% CI: 0.15, 1.42) increase in daily asthma-related emergency department admissions in the total population per 10-unit rise in birch pollen counts (Anderson et al., 1998). Age-stratified analysis identified significant associations in the 0–14 year (0.90%; 95% CI: 0.14, 1.67) and 15–64 year (1.11%; 95% CI: 0.11, 2.12) age groups, while no significant association was found for the 65 and older age group. Another time-series study conducted in London did not identify a clear association between birch pollen concentrations and asthma-related hospital admissions (Osborne et al., 2017). However, the analysis was restricted to the working-age population (16–64 years). Evidence from other geographical regions suggests that younger individuals may be more susceptible to pollen-related asthma exacerbations. A Belgium-based study reported a 3.2% (95%

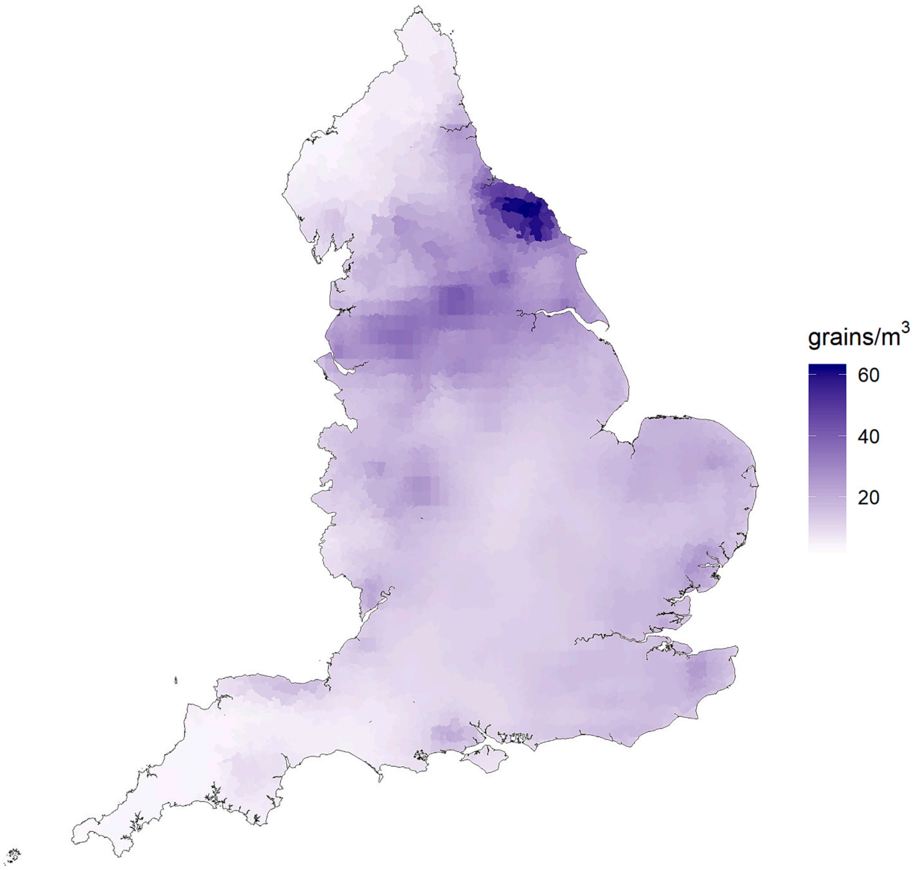

Fig. 1. (*continued*).

CI: 1.1, 5.3) increase in asthma hospitalisations associated with an interquartile range increase in birch pollen concentrations (Guilbert et al., 2018). Age-stratified analyses showed statistically significant associations for all age groups, with a progressive decrease in effect estimates with increasing age: 3.3% (95% CI: 1.1, 5.5) in the 0–14 year group, 3.3% (95% CI: 1.1, 5.6) in the 15–59 year group, and 2.8% (95% CI: 0.6, 5.1) in the 60+ year group. Consistently with these results, a time-series analysis conducted in Atlanta (Lappe et al., 2023) reported an overall RR of 1.038 (95% CI: 1.025, 1.050) for primary asthma- and wheeze-related emergency department visits associated with a standard deviation rise in birch pollen concentrations, again age-stratified analyses found lower RRs as age increased: 1.037 (95% CI: 1.012, 1.063) for individuals aged 5–17 years, 1.033 (95% CI: 1.014, 1.053) for those aged 18–65, and 0.969 (95% CI: 0.916, 1.026) for those over 65.

The results of the age-stratified analysis support those observed in earlier studies. A recent systematic review (Annesi-Maesano et al., 2023) examined the association between exposure to various pollen types and the risk of moderate and severe asthma exacerbations, concluding that airborne pollen exposure may worsen asthma symptoms, particularly among children and adolescents. The impact of aeroallergens on asthma exacerbations is especially pronounced in children, as it is estimated that more than half of paediatric patients with asthma have an allergic phenotype (De Roos et al., 2024; Kuruvilla et al., 2019). This heightened susceptibility is partly due to their immature immune system, which may trigger exaggerated allergic responses to pollen and other environmental allergens (Holgate, 2012). Additionally, their smaller airway calibre and inherent bronchial hyperresponsiveness further increase their susceptibility to inflammation, bronchoconstriction and intermittent airway obstruction, which in turn increases the risk of asthma symptom exacerbation, such as wheeze (Hallas et al., 2019). Other contributing factors could be linked to improved management of the condition in adults and differences in the clinical pathways through which exacerbations are dealt with. Older adults may also be less likely to have asthma as a primary cause of hospital admission due to the presence of co-morbidities. Asthma can play a role in triggering or exacerbating other coexisting respiratory conditions in adults, such as chronic obstructive pulmonary disease (COPD) (Postma & Rabe, 2015).

It is important to note that establishing a definitive asthma diagnosis in children under five is clinically challenging because objective tests are difficult to perform and reliable reference standards are limited (NICE, 2024). Although recurrent wheezing is common in children under five, it is not a reliable indicator of asthma onset. In this age group, wheezing is a heterogeneous clinical presentation with multiple potential etiologies, frequently associated with upper respiratory tract infections, and should not be interpreted as asthma without further clinical evidence (GINA, 2024). Consequently, some misclassification of the outcome is likely in this age group and is expected to be non-differential with respect to pollen exposure, increasing uncertainty and attenuating estimates towards the null. This diagnostic uncertainty contributes to delayed diagnosis of asthma, which affects approximately 65% of children with recurrent symptoms and is associated with a reported median delay of 3.3 years. Affected children are frequently undertreated, resulting in an increased risk of exacerbations (Wi et al., 2025). This suggests the true absolute risk of asthma-related admission among children could be greater.

A strength of our study was the allocation of pollen exposure at high spatial resolution, whilst maintaining a nationally representative dataset, facilitated by the case time series design. The study utilised newly available, high-resolution tree pollen data for Europe, representing a significant improvement in exposure allocation and spatial coverage compared to previous studies. Using a strata parameterisation to characterise the exposure-response relationship allowed us to assess non-linearity in a flexible way. However, some limitations must be acknowledged. First, this study is limited in its characterisation of

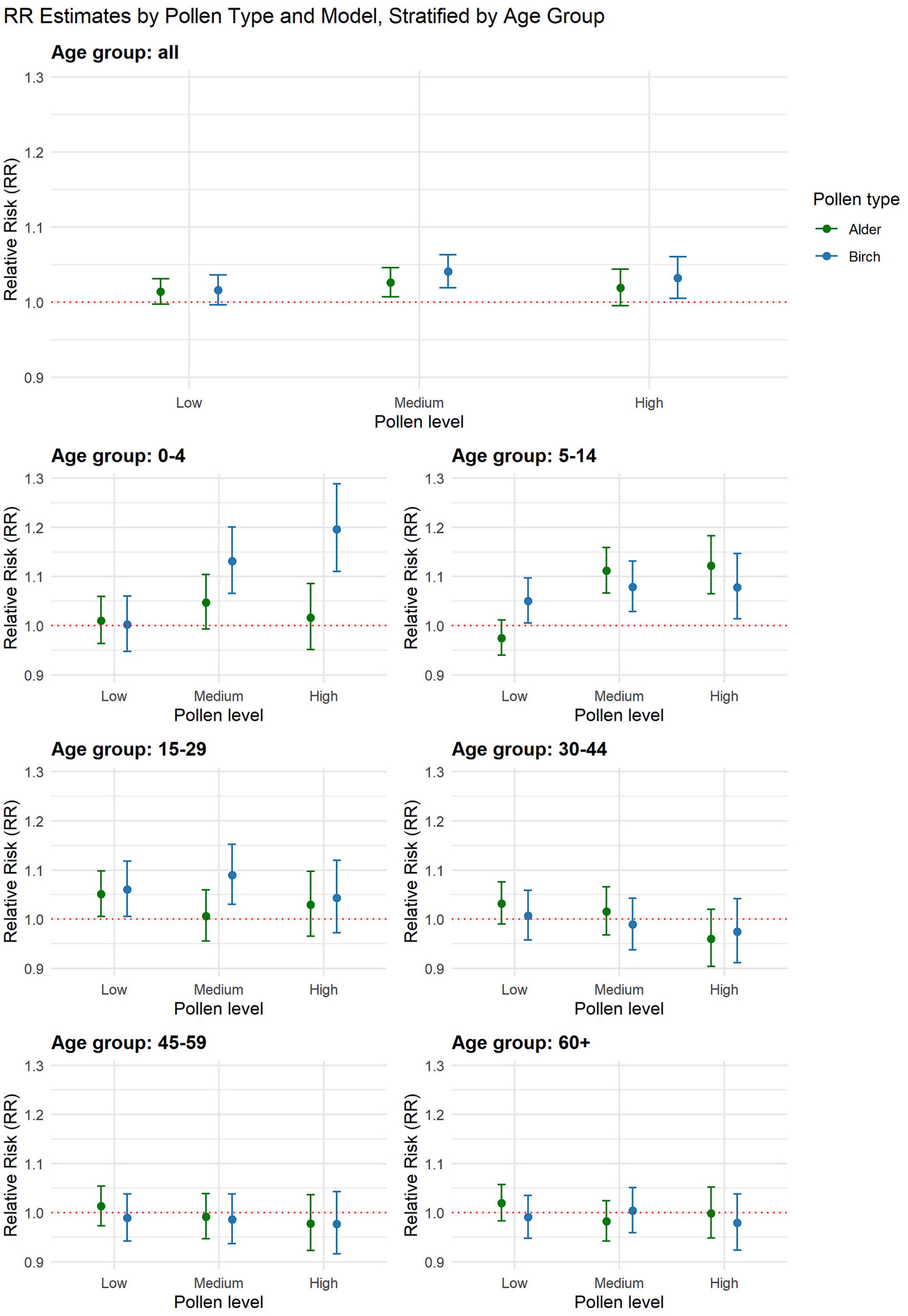

Fig. 2. Plots of the relative risk (RR) for each pollen type and exposure level from the full model and each of the age-stratified analyses. Exposure levels for each pollen type are low (alder: 1-5; birch: 5-50), medium (alder: 5-20; birch: 50-200), and high (alder: 20+; birch: 200+). See Supplementary tables E1 and E2 for the exact figures.

pollen, focusing on two species, while other types can impact asthma-related outcomes. Related to this, the effects of residual confounding by additional aeroallogens (e.g. grass and weeds) and viral circulation is not accounted for explicitly. However, this is captured, atleast in part, by strong control for seasonality. Despite the use of relatively high resolution exposure data, exposure misclassification and non-differential exposure error are still present in this study due to the use of residential addresses without mobility information and 10km resolution exposure data aggregated to LSOA for the exposure allocation. Health data are also limited in that they do not include asthma exacerbations that do not result in hospitalisation or are dealt with via alternative pathways (e.g. GP visits, outpatient care, emergency department attendances). Therefore, the full impact could be greater than predicted here. Finally, whilst our model adjusts for confounding by environmental factors, and so our results represent the direct effect of pollen on hospitalisation risk, we do not include potential synergistic effects of pollen via these environmental factors.

5. Conclusions

This study assessed the effect of alder and birch pollen concentrations on asthma-related hospital admissions at small-area level across England. Children and young adults exhibit greater susceptibility to pollen-related asthma exacerbations. Birch pollen was more consistently associated with increased asthma-related hospitalisation risk. The findings of this study have implications for public health alerts related to pollen concentrations. The results suggest that warning strategies should target susceptible age groups and be triggered at moderate exposure levels.

Further work would extend the model presented here to include other pollen types, healthcare settings and potential socio-economic risk modifiers. There is evidence of disparities in childhood asthma prevalence for the UK, and so including socio-economic information would assess whether these disparities are present in asthma-related hospital admissions associated with elevated pollen concentrations.

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CRediT authorship contribution statement

Rebecca Cole: Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Leire Luque García:** Writing – review & editing, Writing – original draft, Conceptualization. **Gillian Flower:** Writing – review & editing, Data curation. **Arturo de la Cruz Libardi:** Data curation, Writing – review & editing. **Mikhail Sofiev:** Writing – review & editing, Data curation. **Pierre Masselot:** Writing – review & editing, Supervision. **Antonio Gasparrini:** Writing – review & editing, Supervision, Methodology, Funding acquisition.

Ethics approval and consent to participate

This study was approved by the NHS Research Ethics Committee (Reference: 21/LO/0377) and the London School of Hygiene and Tropical Medicine Ethics Committee (Reference: 27353). Data are annonymised and no individual level data is presented. Results are presented at national level.

Data sharing

The pollen data were derived from the SILAM model, developed by the FMI and can be reproduced using open access code (https://github.com/fmidev/silam-model/tree/silam_v5_9pub). Temperature data from the UK Met Office can be downloaded from the CEDA archive (https://catalogue.ceda.ac.uk/uuid/4dc8450d889a491ebb20e724debe2dfb/).

PM2.5 and NO2 data were produced by the Environment & Health Modelling (EHM) Lab at the London School of Hygiene & Tropical Medicine (de la Cruz Libardi et al., 2024), and they will be released soon in a public repository. Requests for additional information or early access can be sent to the corresponding or senior authors.

Access to the hospital admissions data is restricted and access can be requested here (https://digital.nhs.uk/services/hospital-episode-statistics).

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2026.110130.

Data availability

The specific details for each dataset used are included in the data sharing section at the end of the manuscript.

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