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Pollen and asthma morbidity in Atlanta: A 26-year time-series study

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ABSTRACT

Background: Compared to many environmental risk factors, the relationship between pollen and asthma is understudied, including how associations may differ by pollen type and between subgroups, and how associations may be changing over time.
Objectives: We evaluated the association between ambient pollen concentrations and emergency department (ED) visits for asthma and wheeze in Atlanta, Georgia during 1993–2018. We estimated overall associations for 13 individual pollen taxa, as well as associations by decade, race, age (5–17, 18–64, 65+), and insurance status (Medicaid vs non-Medicaid).
Methods: Speciated pollen data were acquired from Atlanta Allergy & Asthma, a nationally certified pollen counting station. ED visit data were obtained from individual hospitals and from the Georgia Hospital Association. We performed time-series analyses using quasi-Poisson distributed lag models, with primary analyses assessing 3-day (lag 0–2 days) pollen levels. Models controlled for day of week, holidays, air temperature, month, year, and month-by-year interactions.
Results: From 1993 to 2018, there were 686,259 ED visits for asthma and wheeze in the dataset, and the number of ED visits increased over time. We observed positive associations of asthma and wheeze ED visits with nine of the 13 pollen taxa: trees (maple, birch, pine, oak, willow, sycamore, and mulberry), two weeds (nettle and pigweed), and grasses. Rate ratios indicated 1–8% increases in asthma and wheeze ED visits per standard deviation increases in pollen. In general, we observed stronger associations in the earliest period (1993–2000), in younger people, and in Black patients; however, results varied by pollen taxa.
Conclusions: Some, but not all, types of pollen are associated with increased ED visits for asthma/wheeze. Associations are generally higher in Black and younger patients and appear to have decreased over time.

1. Introduction

In the United States, approximately 8% of the population, or 25 million people, have physician-diagnosed asthma (Centers for Disease Control and Prevention). Asthma is associated with considerable morbidity – including an estimated 1.8 million emergency department (ED) visits in 2019 – as well as direct economic costs of over $80 billion per year (Pate et al., 2021; Nurmagambetov et al., 2018). The burden of asthma is not distributed evenly across population subgroups, differing based on individual risk factors, environmental exposures, and access to healthcare; higher-prevalence populations include people from low-income families and people from racial and ethnic minority groups (Centers for Disease Control and Prevention; Pate et al., 2021).

As the U.S economic burden of asthma has increased over the past several decades (Nunes et al., 2017; Yaghoubi et al., 2019; Moorman et al., 2012; Akinbami et al., 2016), the importance of understanding the contribution of environmental exposures has also grown, including the role of pollen. An estimated 19.2 million Americans reported seasonal allergies in the past 12 months (National Center for Health Statistics, 2022), and concerns about pollen have heightened in the context of

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climate change, which can affect the duration, timing and intensity of the pollen season (Damialis et al., 2007; Anenberg et al., 2017; Schramm et al., 2021; Bach, 2002; Isolauri et al., 2004; Pearce et al., 2000). Vegetation fertilization from higher CO_2 concentrations is also likely to increase pollen emissions and may make pollen more allergenic (Zhang and Steiner, 2022; Cecchi et al., 2010).

Previous studies have examined the relationship of pollen with asthma ED visits and have found positive associations (Anenberg et al., 2017; Darrow et al., 2012; Ito et al., 2015; Neumann et al., 2019; Zhong et al., 2006). However, these studies have generally assessed relatively short study periods, focused on only a few pollen taxa or groups of taxa, or limited their study to the population as a whole without exploring impacts on sub-groups that may be disproportionately impacted (Neumann et al., 2019; Erbas et al., 2018). This type of refined information is needed to better target health interventions for those affected by allergic asthma.

In this study, we evaluate the association between short-term fluctuations in 13 pollen taxa and ED visits for asthma and wheeze over a 26-year period (1993–2018) in metropolitan Atlanta, GA. The metropolitan Atlanta area is home to over 6 million people and is a large and rapidly growing city known for its dense urban tree canopy (Profile of Metro Atlanta. Metro Atlanta Chamber; 2021; Giarrusso and Smith, 2014). Evidence indicates that pollen seasons in Atlanta are occurring earlier than in the past, are lengthening, and have higher pollen counts (Manangan et al., 2021). To our knowledge, this is the longest epidemiological study of its kind (Manangan et al., 2021) and provides an unparalleled opportunity to investigate the impacts of speciated pollen by population sub-groups in a large city with increasing pollen concerns.

2. Methods

We conducted a daily time-series study on the association of ambient pollen concentrations and ED visits for asthma and wheeze between 1993 and 2018.

3. Health data

Patient-level billing record data on ED visits to metropolitan Atlanta hospitals were obtained for the 1993–2018 study period. Hospitals were solicited individually for data acquisition during 1993–2004, and in subsequent years data for all hospitals were acquired from the Georgia Hospital Association. Records included both ED outpatients (patients seen in the ED and discharged) as well as ED inpatients (patients seen in the ED and then admitted). Key variables include admission date, International Classification of Diseases (ICD) version 9 (prior to October 2015) or version 10 (after October 2015) discharge diagnosis codes, and patient age, race, and insurance status for the visit. These data have been used in prior environmental epidemiologic studies with a focus on asthma, including publications based on the 1993–2004 data (Darrow et al., 2012; Strickland et al., 2010) and 1993–2013 data (Winquist et al., 2016; O'Lenick et al., 2017). The current application is the first to pull together all 26 years of data. As described previously (O'Lenick et al., 2017); visit capture increased over the study period: data were procured from 7 of 44 hospitals operating in 1993; by 2004, data were obtained from 38 of 41 hospitals (capturing over 90% of all ED visits); and from 2005 onward, over 95% of all ED visits in the study area were captured.

We aggregated the patient-level data across all hospitals to daily counts of ED visits for all patients aged 5 years and older with a primary ICD diagnosis code indicating asthma (ICD-9 code 493; ICD-10 code J45) or wheeze (ICD-9 code 786.07, ICD-10 code R06.2). For sub-group analyses, daily ED visit counts were aggregated separately by race (Black/White), age group (5–17 years, 18–65 years, >65 years), and insurance status (Medicaid, Non-Medicaid). Black and White were the only two race categories that were consistently and reliably collected throughout the 26-year time period; thus, race-stratified analyses focused on these two categories only.

4. Pollen data

Pollen concentrations were obtained from Atlanta Allergy & Asthma – the only pollen counting station in the city that is certified by the National Allergy Bureau – for the period January 1, 1993 to December 31, 2018. Atlanta Allergy & Asthma sample processing has been described previously in Darrow et al. (2012) and Manangan et al. (2021). Briefly, pollen concentrations are hand-counted and reported as pollen grains per cubic meter of air, and typically reported five days per week (Monday-Friday), excluding national holidays. In more recent years, pollen was counted seven days per week during periods of peak pollen production, but to ensure data consistency across the 26-year study period, pollen data in the analytic dataset was limited to the five weekdays. The pollen monitoring site was moved 3 times over the 26-year period (in 1998, 2010, and 2015) but remained within a 9-mile radius (Manangan et al., 2021); a previous analysis found that the changes to the station location did not impact the assessment of population-level exposure (Manangan et al., 2021).

We selected 13 pollen taxa for analysis based on (Centers for Disease Control and Prevention) putative allergenicity, (Pate et al., 2021) consistent sampling throughout the study period, and (Nurmagambetov et al., 2018) taxa that comprised the majority of pollen in Atlanta (over 88% of January to June pollen and over 76% of July to December pollen) (Manangan et al., 2021). Of the 13 pollen taxa, nine were trees [Birch (*Betula*), Juniper (*Juniperus*), Oak (*Quecerus*), Pine (*Pinus*), Maple (*Acer*), Mulberry (*Morus*), Sycamore (*Platanus*), Elm (*Ulnus*), Willow (*Salux*], three were weeds [Pigweed (*Amaranthus*), Nettle (*Urticaceae*), and Ragweed (*Ambrosia*)], and one represented grasses (*Poaceae*). Based on previous research (Manangan et al., 2021) and visual inspection of the data, analyses were limited to the relevant pollen seasons for each taxon, as months outside of these seasons generally had extremely low concentrations (Fig. 1).

4.1. Data analysis

We performed time-series analyses using log-linear quasi-Poisson regression models. Primary analyses assessed associations using 3-day (lag 0–2) distributed lag models, in which the cumulative effect of exposure on the current day (lag 0), the previous day (lag 1), and the day before that (lag 2) was estimated. Effects of single-day lagged exposures up to lag 2 were also evaluated. Our focus on short lags was largely based on prior studies (Darrow et al., 2012; Kitinoja et al., 2020); but also because of the lack of consistent weekend pollen counts; in this context, inclusion of additional lag terms beyond lag 2 substantially reduced the number of observations that could be analyzed.

To control for potential temporal confounding, including seasonality and long-term trends (such as changes in visit capture or population growth over the study period), we included indicator variables for day of week, federal holidays, month and year as well as month-by-year interaction terms; the latter variables ensured that effects were estimated within each month of each year and thus controlled for trends over time. We also included cubic functions for individual lags 0, 1, and 2 of daily mean temperature, obtained from the Atlanta Hartsfield International Airport weather station via the National Climatic Data Center.

In secondary analyses, we conducted models stratified by decade (1993–2000, 2001–2010, 2011–2018, patient age group (5–17, 18–65, >65 years), race (Black, White), and insurance status (Medicaid, non-Medicaid). We also incorporated several sensitivity analyses to confirm that observed patterns of effect were not driven by changes population characteristics over time, changes in ED capture over time, or confounding by air pollution, including (1) presentation of double-stratified models by decade and age, race, and insurance status, (2) an analysis restricted to the 23 hospitals with at least three years of data in

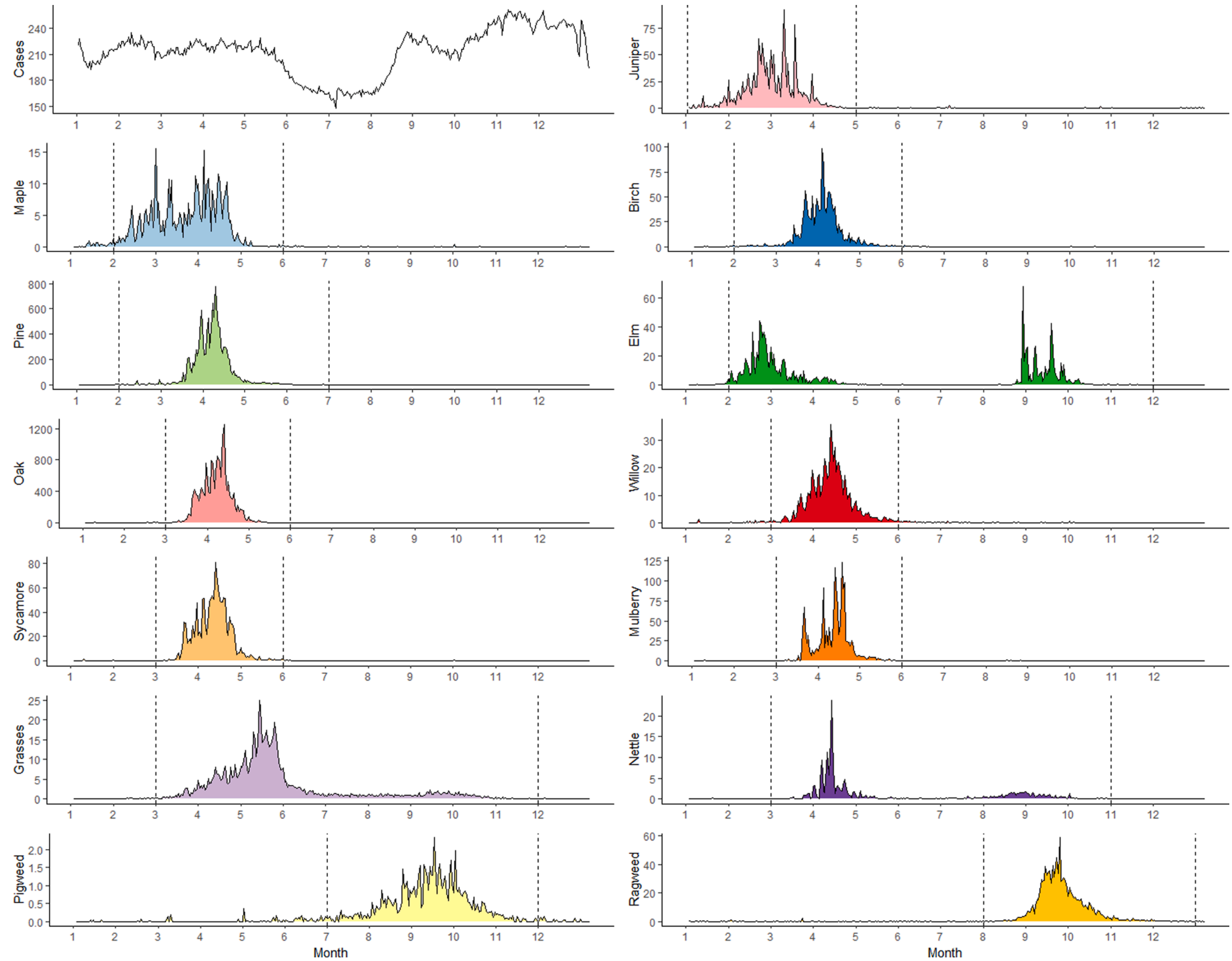

Fig. 1. Day-of-year mean asthma/wheeze ED visits and mean pollen concentration (grains/m^3) by taxa in Atlanta over the 26-year study period. Dashed lines indicate the seasonal period included for each taxa-specific analysis.

each decade, and (3) the addition of air pollution (ozone, NO_2, PM_{10}, and $PM_{2.5}$) as potential confounders.

All results are presented as rate ratios (RR) and 95% confidence intervals (CI) for taxa-specific standard deviation increases in pollen counts based on the full 1993–2018 study period.

This study was approved by Emory University's Institutional Review Board.

5. Results

The final dataset included a total of 686,259 ED visits for asthma or wheeze in metropolitan Atlanta from 1993 to 2018 (Table 1). The ED visits exhibited a strong seasonal pattern, with a peak late in November (late autumn) and a trough in July (mid-summer) (Fig. 1). The number of visits increased substantially over time (Table 1, Supplementary Fig. 1), which partly reflects population growth and an increase in asthma prevalence (Moorman et al., 2012; Akinbami et al., 2016; Serebrisky, 2019), but is also a function of the expanding number of hospitals included in the dataset. Patient data on race was available for 71.1% of asthma/wheeze patient visits over the whole study period, with Black patients making up about half of all visits compared to about a third for White patients (Table 1). The annual distribution of concentrations for each pollen taxa is reported in Fig. 1. Most taxa peaked between February and June, except for ragweed and pigweed which had highest concentrations in September. Peak pollen concentrations differed by orders of magnitude between taxa, with tree pollen, particularly Oak (*Quecerus*) and Pine (*Pinus*), being the most prolific (Table 2). The time-series of pollen concentrations, presented in Supplementary Fig. 2, indicate trends of increasing concentrations over time for several taxa, as has been reported elsewhere (Manangan et al., 2021). Descriptive statistics on pollen concentrations by decade are reported in Supplementary Table 1.

The highest correlations between taxa were between several of the trees, with a maximum correlation of 0.7 (Supplementary Figure 3). Pollen and air pollution were in general not strongly correlated (Supplementary Figure 3).

Effect estimates for 3-day cumulative lags of pollen and asthma ED visits are reported in Fig. 2. Over the whole study period, significant ($p < 0.05$) positive associations were evident for nine of the 13 taxa (Fig. 2, panel A). The strongest estimated effects were for willow (RR: 1.082, 95% CI: 1.066, 1.098 for each 15 grains/m^3 increase), sycamore (RR: 1.069, 95% CI: 1.055, 1.083 for each 40 grains/m^3 increase), and oak (RR: 1.061, 95% CI: 1.048, 1.073 for each 540 grains/m^3 increase) among the trees, and pigweed (RR: 1.028, 95% CI: 1.011, 1.046 for each 1 grains/m^3 increase) among the weeds; grasses were marginally associated (RR: 1.010, 95% CI: 0.998, 1.022 for each 7 grains/m^3 increase). Associations were consistent with the null for juniper, elm, and nettle, and consistently negative for ragweed.

Table 1
Primary asthma and wheeze emergency department visits in the Atlanta, GA metropolitan area included in the study during 1993–2018, overall and by decade, patient age, race, and insurance status. Parentheses show the percent of the column total.

	Asthma and Wheeze ED Visit Counts			
	All years (% of Total)	*1993–2000 (% of Total)*	*2001–2010 (% of Total)*	*2011–2018 (% of Total)*
Total	686,259	80,423 (11.7%)	292,578 (42.6%)	313,258 (45.6%)
Age				
5–17	151,633 (22.1%)	21,958 (27.3%)	57,615 (19.7%)	72,060 (23%)
18–65	201,943 (29.4%)	27,285 (33.9%)	76,167 (26%)	98,491 (31.4%)
>65	21,652 (3.2%)	2,761 (3.4%)	8,820 (3%)	10,071 (3.2%)
Race				
Black	332,332 (48.4%)	23,413 (29.2%)	138,588 (47.4%)	170,331 (54.3%)
White	155,603 (22.7%)	23,192 (28.9%)	74,944 (25.6%)	57,467 (18.3%)
Missing/ other	198,324 (28.9%)	33,818 (42.1%)	79,046 (27%)	85,460 (27.3%)
Insurance Status				
Medicaid	240,607 (35.1%)	18,032 (22.4%)	103,575 (35.4%)	119,000 (38%)
Non-Medicaid	422,304 (65.1%)	58,568 (72.8%)	170,108 (58.1%)	193,628 (61.8%)
Missing	23,348 (3.4%)	3,823 (4.8%)	18,895 (6.5%)	630 (<1%)

Table 2
Descriptive statistics of pollen concentrations (in grains/m^3), 1993–2018. Months reports the season analyzed for each pollen taxa. Number of days reports the total number of days over the 26-year study period that was included in the analysis. Number of days NA reports the number of days over the 26-year study period for which pollen was not available or excluded during each taxa's pollen season. The standard deviation for each taxa is the scaling factor used to report the relative risks.

Pollen Taxa	*Months*	*Number of Days (NA)*	*Mean (SD)*	*50th*	*75th*	*Max*
Trees						
Juniper (*Juniperus*)	Jan-Apr	3126 (1034)	14.7 (51.8)	1.8	10.1	1234.3
Maple (*Acer*)	Feb-Apr	2320 (700)	4.9 (15.0)	0.6	4.1	227.8
Birch (*Betula*)	Feb-May	3126 (956)	11.9 (44.1)	0.6	5.9	1149.7
Pine (*Pinus*)	Feb-Jun	3906 (1185)	82.9 281.1)	3.6	27.2	4160.5
Elm (*Ulnus*)	Feb-Nov	4680 (2490)	4.1 (27.0)	0.0	0.6	1223.4
Oak (*Quecerus*)	Mar-May	2392 (718)	210.2 (540.3)	10.8	138.8	5538.0
Willow (*Salix*)	Mar-May	2392 (718)	7.5 (15.6)	1.8	7.1	282.0
Sycamore (*Platanus*)	Mar-May	2392 (718)	16.5 (40.0)	1.2	11.2	468.6
Mulberry (*Morus*)	Mar-May	2392 (718)	17.4 (81.7)	1.2	6.5	1240.8
Grasses						
Grasses (*Poceae*)	Mar-Nov	3952 (2252)	2.8 (6.6)	0.6	2.4	112.4
Weeds						
Nettle (*Urticaceae*)	Mar-Oct	1586 (2252)	0.8 (8.8)	0.0	0.0	412.2
Pigweed (*Amaranthus*)	July-Nov	1586 (1305)	0.5 (1.0)	0.0	0.6	17.2
Ragweed (*Ambrosia*)	Aug-Dec	3172 (1397)	8.2 (18.3)	1.2	8.9	490.2

This pattern of association across pollen taxes was largely observed in analyses stratified by decade (Fig. 2, panel B). When considering observed effects across decades, 9 of the 13 taxa showed the highest rate ratios in the earliest decade (1993–2000). Among the nine taxa that showed an effect overall (Fig. 2, panel A), seven had higher effects in the earliest decade.

In analyses stratified by race (Fig. 2, panel C), 7 of the 13 taxa showed higher RRs in Black compared to White patients; for birch, pine, oak, willow, sycamore, and mulberry, effect estimates for Black patients were more than twice those for White patients. In the nine taxa that showed an effect overall (Fig. 2, panel A), seven had higher effects in Black patients.

In terms of age-specific results (Fig. 2, panel D), there was no evidence of an effect for any taxa in the oldest age group (>65). In the younger two age groups, significant effects were present for several taxa (birch, pine, oak, willow, sycamore), with differences between the two groups often small. The payment-specific results (Fig. 2, panel E) showed mostly similar or higher estimated effects in non-Medicaid vs Medicaid patients, with the exception of nettle.

Supplemental Figure 4 reports double-stratified results, by decade and by race, age, and insurance status; these results largely confirm the overall finding of higher effect estimates in the earliest time period – particularly for trees – regardless of race, age group, or payment method suggesting that any changes over time in these factors are not driving the overall pattern of decreasing risk ratios over time. Overall findings were also generally the same when including air pollutants in the models and when restricting the analysis to the 22 hospitals with at least three years of data in all decades (Supplementary Figure 5).

For most taxa, the cumulative 3-day distributed lag model yielded stronger associations than any of the single-day lags (Supplementary Table 3). Most of the single-day lags showed similar effects to each other, although some had higher effects on day 0 or 1 (grasses, ragweed, willow, mulberry) and others on day 2 (pigweed and birch).

6. Discussion

We analyzed the short-term association between 13 individual pollen taxa and ED visits for asthma and wheeze in metropolitan Atlanta, GA over a 26-year period. To our knowledge, this is the longest study of its kind, and one of the few to estimate effects by decade, race, age, and payment method. Overall, we found evidence of positive associations with ED visits for nine of the 13 pollen taxa, comprised of seven trees (maple, birch, oak, pine, willow, sycamore, and mulberry) and two weeds (nettle and pigweed); there was suggestive evidence of an association with grasses. Rate ratios for the entire study period indicated ~ 1–8% increases in asthma/wheeze ED visits per standard deviation increase in pollen concentrations, which is broadly consistent with previous research (Darrow et al., 2012; Ito et al., 2015; Erbas et al., 2018; Erbas et al., 2012). For many pollen taxa, we observed stronger effects in the earliest decade of the study period, amongst Black patients, and in younger people.

Prior studies have examined the relationship of pollen to asthma-related ED visits, although the presence and strength of the observed associations have varied by pollen type and between studies. Similar to other studies, we found associations with oak (Anenberg et al., 2017; Darrow et al., 2012; Ito et al., 2015; Zhong et al., 2006), maple (Ito et al., 2015; Zhong et al., 2006), birch (Ito et al., 2015), sycamore (Ito et al., 2015), and grasses (Darrow et al., 2012; Babin et al., 2007; Héguy et al., 2008). We also found evidence of an association with pine, which supports other work questioning the historical assumption that pine species are non-allergenic (Zhong et al., 2006). In contrast, we did not find an association with ragweed – commonly assumed to be allergenic – that also supports other relatively recent studies that have reported similar results (Darrow et al., 2012; Héguy et al., 2008; Gleason et al., 2014; De Roos et al., 2020), including when controlling for weekly rhinovirus counts (De Roos et al., 2020). We observed positive effects for willow

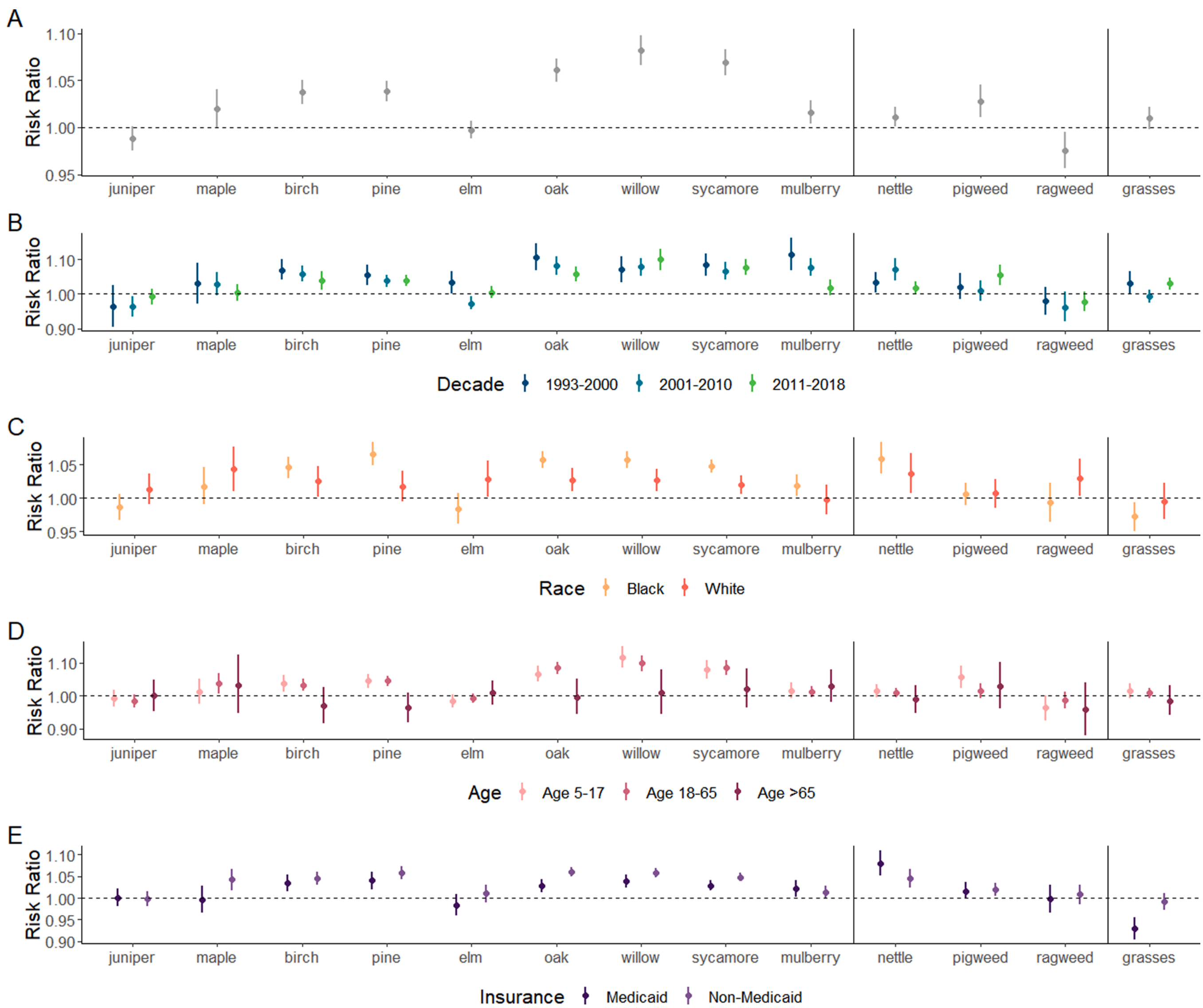

Fig. 2. Rate ratios and 95% CIs for primary asthma and wheeze ED visits per standard deviation increase in pollen taxa concentration: (a) overall, (b) by decade, (c) by patient race, (d) by patient age, and (e) by insurance status. Effect estimates are also reported numerically in Supplementary Table 2.

and pigweed, which are not commonly studied as individual taxa. We should note that in general, some differences across studies may be attributable to geography and local climate, which can affect the timing and amount of pollen releases, and the vegetation mix and its spatial distribution relative to residential areas.

A major contribution and expansion over prior research is our assessment of effect modification by decade, race, age, and payment type. We found evidence in most pollen taxa of stronger associations in the earliest period (1993–2000) compared to the two later periods (2001–2010 and 2011–2020), both for ED visits overall as well as in sensitivity analyses stratified by patient race and age. Our results indicate consistency in temporal trends of pollen-asthma associations across these selected population subgroups and suggest that the overall observed trend of decreasing rate ratios over time is unlikely due to temporal changes in these factors. There are however several possible other explanations for this finding, of which we highlight three. The first is that pollen may have become less allergenic over time. This reasoning is unlikely in the context of climate change (Cecchi et al., 2010; Beggs, 2004), but could be possible from other environmental changes. For example, certain gaseous air pollutants such as ozone are thought to make pollen more allergenic, and ozone has decreased over the study period (Sedghy et al., 2018); however, we did not find evidence that air pollution was responsible. The second possible explanation is that actual exposure may no longer be as tightly correlated to fluctuations in ambient concentrations because of changes in people's day-to-day lives, such as their housing, how they travel, where they work, or their access to indoor air conditioning. And third, population risk may have changed for other reasons. For example, asthma control may have improved during the study period from the more widespread use of efficacious medications and treatments that would reduce the likelihood that pollen exposure would lead to a hospital visit. In the last two decades, increased use of advanced asthma therapies (e.g. biologics) that specifically target allergic asthma pathways is likely to have reduced asthma exacerbations and emergency room visits in many patients (Inselman et al., 2020). These therapies were not widely available in the earliest time period assessed (1993–2000).

For most pollen species, effect estimates per unit of pollen were higher among Black patients compared to White patients. Similar findings have been reported in some, but not all, studies of other environmental risk factors, including particulate matter and ozone air pollution (Gleason et al., 2014; Hajat et al., 2015). There are several reasons why effects may be higher in the Black population. One is if the ambient pollen concentrations measured at the pollen counting station better represent personal exposure in Black compared to White patients, either because of the location of the counting station (unlikely in this context) or if the Black population is more impacted by pollen levels, for example due to less access to air conditioning or air filtration, more dependence of public transit (with higher outdoor exposures) or occupations that put them at higher exposure risk. A second explanation may be related to racial differences in access to care and asthma treatment adherence; large studies of Black patients in Atlanta that are at risk for asthma have shown that under-diagnosis and under-treatment is common (Harris et al., 2020; Harris et al., 2019). And third, there is evidence that marginalized populations may be disproportionately exposed to multiple environmental risks simultaneously (Lane et al., 2022), which could lead to worse outcomes either because of compounding stress on the body or interactions between exposures themselves, such as between air pollution and pollen, as the former may modify allergenic potential and/or enhance the expression of some allergens in pollen grains (Sedghy et al., 2018).

In the age-stratified analyses, children (5–17 years) were often, but not always, the sub-group with the highest rate ratios. Differences between children and older people were particularly pronounced for willow. Associations in the oldest age group (>65) were not significant for any taxa, which is consistent with prior studies (Darrow et al., 2012; Ito et al., 2015).

The results by insurance status (Medicaid vs non-Medicaid) are difficult to interpret. The binary variable means that the non-Medicaid group likely includes people at both the high end of the income distribution (i.e. those with private insurance) and those at the low end (i.e. those without any type of coverage). Our finding of effect sizes that were mostly similar or higher in patients not covered with Medicaid is perhaps counter to expectations, but similar results were reported in a much smaller study from New Jersey that based socioeconomic status on an area-level indicator of poverty (Gleason et al., 2014).

Concerns about the health effects of pollen are enhanced in the context of climate change. Climate change is expected to increase pollen exposure in many locations throughout the United States by changing season timing, length, and intensity, the amount of pollen produced, the allergic content of pollen, and the distribution of pollen species (Beggs, 2004; Fann et al., 2016; Albertine et al., 2014; Bielory et al., 2012; Cecchi et al., 2010; Anderegg et al., 2021). These changes in pollen exposure have implications for the timing of starting allergy treatments, which has yet to be studied in detail epidemiologically. It is beyond the scope of this paper to project future health burdens from climate change in Atlanta, but we note that a prior phenological study from Atlanta using the same pollen exposure data reported increased pollen concentrations and longer seasons for several taxa, including oak, which is the most prolific spring pollen source in Atlanta and one of the taxa we find to be most associated with asthma/wheeze (Manangan et al., 2021).

There are several important limitations to this analysis. There is only a single pollen counting station certified by the National Allergy Bureau in all metropolitan Atlanta, and this represents a limitation in exposure analysis. Previous research has demonstrated that the pollen monitoring station in Atlanta is representative of up to a distance of 25 miles (Pashley et al., 2009; Katelaris et al., 2004). Therefore, we included hospitals within 25 miles of pollen station. It is not unusual for cities to have only one station, but it could contribute to exposure misclassification, particularly for people living farther away from the station. There was also a lack of continuous exposure data because pollen was generally not counted on weekends and holidays, which limited the exploration of the lag structure of the effects. Data surrounding a range of clinical variables that are known to impact asthma outcomes (e.g. comorbidities, access to primary or specialty care, medication adherence) were not available. Additionally, data on specific asthma/wheeze phenotypes were not available, and therefore the analysis represents the association of pollen on unspecific asthma/wheeze. Specific asthma/wheeze outcomes, such as allergic asthma, may have stronger associations. Finally, we note that data completeness varied over the 26-year time period, and was generally sparser at the beginning of the study, when there were fewer hospitals providing data and when demographic variables were less complete.

This study highlights several areas for future research. The first is to explore the potential for a non-linear relationship between pollen and asthma. We assumed a linear association, which is consistent with other literature (Anderson et al., 1998; Salvaggio et al., 1971; Rossi et al., 1993; Garty et al., 1998; Rosas et al., 1998; Dales et al., 2000; Stieb et al., 2000), but given the expectation of increasing pollen levels with climate change, it is worth revisiting the possibility of non-linearities in the event that health effects may change at levels not commonly experienced previously. Second, an extension of this work would be to explore in more detail whether mixtures of different pollen types or exposure to multiple environmental risks simultaneously could produce synergist effects. Third, it is important to further investigate why we observed differences in risks across time, age group, and race. In addition to more studies from other locations, a key step would be to initiate a more expansive pollen monitoring network to improve exposure estimates across neighborhoods and as pollen exposures change through time as a result of urbanization, greening, and climate change. And finally, there is some evidence that pollen increases the risk of other diseases such as allergic rhinitis and cardiovascular diseases (Brunekreef et al., 2000; Weichenthal et al., 2016; Meng et al., 2016), which would also benefit from studies with long time series, multiple taxa, and sub-group analysis.

Author contributions: BL, SE and NS conceived of and designed the work. BL conducted the analyses with support from HC, SE, AS and NS. HC, RDS, SE, AM, CB, and SS contributed to data acquisition and/or data management. BL, SE and NS drafted the manuscript. All authors critically revised the work for important intellectual content and approved the submitted version.

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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.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2023.107998.

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