Published in final edited form as:
Ann Allergy Asthma Immunol. 2021 October ; 127(4): 471–480.e4. doi:10.1016/j.anai.2021.07.012.

Long-term pollen trends and associations between pollen phenology and seasonal climate in Atlanta, Georgia (1992–2018)

Arie Manangan, MA[*], **Claudia Brown, MDP**[*], **Shubhayu Saha, PhD**[*], **Jesse Bell, PhD**[†], **Jeremy Hess, MD, PhD**[‡], **Chris Uejio, PhD**[§], **Stanley Fineman, MD**[||,¶], **Paul Schramm, MPH**[*]

[*]Climate and Health Program, Division of Environmental Health Science and Practice, National Center for Environmental Health, Centers for Disease Control and Prevention, Atlanta, Georgia

[†]Department of Environmental, Agricultural, and Occupational Health, College of Public Health, University of Nebraska Medical Center, Omaha, Nebraska

[‡]Division of Emergency Medicine, Department of Medicine, University of Washington School of Medicine, Seattle, Washington

[§]Department of Geography, College of Social Sciences and Public Policy, Florida State University, Tallahassee, Florida

[||]Adjunct Associate Professor, Department of Pediatrics, Emory University School of Medicine, Atlanta, Georgia

[¶]Atlanta Allergy and Asthma Clinic, Marietta, Georgia

Abstract

Background: Previous research has revealed that airborne pollen concentrations and phenology in allergenic plants are changing. In addition, variations in seasonal climate are known to affect pollen phenology in trees, weeds, and grasses.

Objective: To investigate localized trends in pollen concentrations and pollen phenology over time and the effect of seasonal climate variations.

Methods: We used daily pollen count concentrations from a National Allergy Bureau pollen counting station located in metropolitan Atlanta, Georgia, for 13 allergenic taxa. To evaluate long-term trends over time, we developed linear regression models for 6 pollen measures. To evaluate the effect of seasonal climate on phenology, we developed regression models using seasonal climate measures as independent variables and pollen measures as dependent variables.

Results: For several tree pollen taxa, pollen concentrations increased over time, including oak and juniper pollen. In multiple species, pollen seasons trended toward an earlier release throughout the 27-year period. Variations in seasonal climate did have an effect on pollen counts and the

Reprints: Arie Manangan, MA, Climate and Health Program, Asthma and Community Health Branch, Division of Environmental Health Science and Practice, National Center for Environmental Health, Centers for Disease Control and Prevention, 4770 Buford Highway, CHAM S6-106, Chamblee, GA 30341; mqa2@cdc.gov., AManangan1@cdc.gov.

Disclosures: The authors have no conflicts of interest to report.

timing of pollen release but varied by taxa. Generally, warmer spring temperatures were associated with an earlier pollen release. In addition, increased precipitation from the preceding fall was associated with increased pollen concentration in the spring months.

Conclusion: Allergenic pollen concentrations for several types of pollen are increasing and trending toward an earlier pollen release in Atlanta, Georgia. Warmer temperatures preceding the pollen season were associated with the earlier pollen release.

Introduction

Airborne pollen and mold spores are the primary cause for seasonal allergic rhinitis,[1] often known as hay fever. In the United States, 19.8 million adults and 5.6 million children are reported to have allergic rhinitis.[2] Allergic rhinitis decreases work productivity, with an estimated 35.9% of people experiencing impaired work performance owing to allergic rhinitis.[3] In addition, in 2005, the overall annual treatment costs in the United States for allergic rhinitis were $11.2 billion, with direct costs estimated at $3.4 billion, which includes prescription medications and outpatient visits.[4] The prevalence of allergic disease is increasing in industrialized countries,[5] and more specifically, allergic rhinitis has increased in the United States.[6,7] The cause for the increase in allergic rhinitis and other allergic diseases is unknown, but it may be related to changes in pollen exposure or allergenicity.[8]

Studies have revealed an increasing trend in allergenic pollen production from trees, weeds, and grasses[9–13] in addition to earlier and longer allergenic pollen seasons in some regions.[13–15] A recent international meta-analysis found increasing allergenic pollen levels in 71% of study sites, whereas 65% of the sites had lengthening pollen seasons.[16] In the United States, further research is needed to evaluate the long-term trends in pollen production for multiple allergenic plant taxa because individuals with allergy are often hypersensitive to specific pollen types.[17,18]

Seasonal temperatures and precipitation affect both the production and timing of pollen for allergenic plants.[14,19,20] Nevertheless, climate associations vary according to plant type[9,10,20] and location,[12] which underscores the importance of conducting climate analyses with local pollen. Although there has been an abundance of research in Europe on the climatic drivers of allergic pollen,[12,15,16,21] there is a distinct gap in knowledge on how interannual climate variability affects pollen production throughout the various ecoregions of the United States and for the numerous allergenic plants present in North America.

For this study, we investigated the relationship between pollen production and seasonal climate variables in metropolitan Atlanta, Georgia, from 1992 to 2018, using airborne pollen data for 13 allergenic taxa. In addition, we conducted an analysis of pollen categories, including trees, weeds, and grasses. This is the first study to evaluate the long-term pollen trends as it relates to climate in the Southeastern United States and provides a methodology to conduct a climate and pollen analysis at other locations.

Methods

Pollen Data

We analyzed airborne pollen concentration data collected by the Atlanta Allergy & Asthma practice from 1992 to 2018. The pollen station was located in Marietta, Georgia, a northern suburb of metropolitan Atlanta. Airborne pollen grains were collected using a Rotorod sampler and pollen collection methods certified by the National Allergy Bureau, as described in detail in previous studies.[22–24] The National Allergy Bureau provides standardized criteria for collection of pollen data in the United States and Canada. Pollen concentrations were reported as grains per cubic meter (PPCM) of air and were typically collected 5 days a week (Sunday-Thursday), excluding national holidays. Starting in 2011, pollen concentrations were recorded every day (including weekends) during the periods of high pollen concentrations (eg, spring pollen season), typically in April.[25] A total of 13 pollen taxa were selected for analysis based on the following 2 criteria: (1) known allergenicity (ie, the ability to cause an allergic reaction in patients)[17,18] and (2) the percentage of total pollen concentration. On the basis of these criteria, we analyzed the following pollen taxa: *Acer* (maple), *Ambrosia* (ragweed), *Amaranthus* (pigweed), *Betula* (birch), *Juniperus* (juniper), *Morus* (mulberry), *Pinus* (pine), *Platanus* (sycamore), *Poaceae* (grasses), *Quercus* (oak), *Ulmus* (elm), *Salix* (willow), and *Urticaceae* (nettle) (Table 1). In the 27-year period, the pollen monitoring site has been in 4 different locations. It was moved in 1998, 2010, and 2015, with all locations within a 9-mile radius. Using a regression discontinuity design analysis, we found that shifts in pollen concentration data owing to station location change were not statistically significant ($\alpha = 0.05$).

Pollen Seasonality Measures

We calculated the following 6 pollen season characteristics: average daily pollen concentration, peak pollen concentration, season start date, season peak date, season end date, and season length. We calculated the season start and end date using a 3-day consecutive approach, similar to the methodology used in other studies.[15,19,26] The 3-day consecutive approach specifies the start date of the pollen season after 3 consecutive days of observed pollen above 1.0 PPCM for each pollen type and the end of the pollen season after 3 consecutive days of pollen less than 1.0 PPCM. We aggregated the pollen concentration data into 2 different pollen seasons, the spring pollen season (January-June) and the fall pollen season (July-December), to account for the bimodal distribution of the pollen data, which typically peaked in the spring months (eg, tree pollen) and fall months (eg, weed pollen). Compared with other methodologies used to define pollen season timing, such as the cumulative percentage method[12,19] and a 5-day consecutive method, the 3-day consecutive method seems to be more sensitive in capturing the entirety of the pollen season (ie, the 3-day method defines the season onset date earlier and the season end date later) as indicated in a comparison of methods in Figure 1. Furthermore, the 3-day consecutive method can be calculated near-real time, whereas the cumulative percentage method requires the entire pollen season to be observed before the onset date and end date can be calculated.

Climate Data

Temperature and precipitation indicators were derived from the National Oceanographic and Atmospheric Administration (NOAA) Climate at a Glance data set, which consists of county-level temperature and precipitation data that have been reanalyzed and adjusted to account for artificial effects introduced into the climate record, such as instrument errors or changes in monitoring locations.[27] The climate variables included in this analysis were daily average minimum temperatures, daily average temperatures, daily average maximum temperatures, and total precipitation, calculated for the following seasons: winter (December-February), spring (March-May), summer (June-August), and fall (September-November) (Fig 2). We found an increasing trend in spring and summer average temperatures during the 27-year period ($\alpha = 0.05$). (Fig 2).

Statistical Analysis

To evaluate the taxa-specific trends over time for the various pollen season indicators (eg, average daily pollen concentration, peak pollen concentration, season onset date, season peak date, season end date, season length), we developed a linear regression model to determine the line of best fit using the 27 years of data. A goodness-of-fit was calculated for each model (R^2) to report the compatibility of the observed and predicted values of the dependent variable (eg, average daily pollen concentration) based on this model. Percent change was calculated by log transforming the dependent variable (ie, pollen indicators) and interpreting the regression parameter as percent change over time.

To evaluate the effect that year-to-year seasonal climate variations have on pollen production, we developed simple linear regression models using seasonal climate measures from NOAA as the independent variable (average temperatures, total precipitation) with 6 measures of pollen production as the dependent variable (mean daily pollen concentration, peak pollen concentration, season onset date, season peak date, season end date, season length). To account for multiple, nonindependent comparisons (4 seasonal temperature averages), we report the Holm-Bonferroni−adjusted *P* values. For those pollen measures that had a statistically significant trend ($\alpha = 0.05$), a detrended pollen data set was used in the regression model to account for nonstationarity. In addition, a detrended data set was used in the regression models for those climate variables that had a statistically significant ($\alpha = 0.05$) trend (eg, average spring and summer temperatures).

Results

Descriptive Analysis

For the spring pollen season (January-June), oak (41.1%) was the predominant pollen type in Atlanta, which is considered highly allergenic[18] (Table 1). Pine pollen (28.1%) was the second most abundant pollen. Although not considered a substantial contributor to allergic rhinitis, pine pollen may act as a respiratory irritant[18,28] (Table 1). Juniper pollen, also a highly allergenic pollen type, was the third most prevalent pollen type during the spring pollen season, followed by sycamore and birch, each comprising 3.4% or less of average spring pollen (Table 1). Juniper pollen season also started the earliest (January 25) of all pollen types included in this analysis. Grouping the pollen analysis by trees, weeds, and grasses for the spring pollen season, tree pollen had the earliest season onset (January 16) with an average peak date of April 4 (Table 2). Tree pollen levels during the spring pollen season were magnitudes higher compared with the fall pollen season (Fig 3). The fall tree pollen season was dominated by elm. Grouped grass pollen had a relatively late pollen season onset (March 29) and peak (May 10), with an average season end date of June 25 (Table 2). Weed pollen was much more abundant during the fall pollen season compared with the spring and was dominated by ragweed pollen (48%) (Table 1), one of the most important causes of allergic rhinitis owing to its high allergenicity.[18]

Pollen Trend Analysis

We analyzed long-term pollen trends over the 27-year period and found statistically significant ($\alpha = 0.05$) trends in pollen concentration and the timing of pollen release. Specifically, during the spring pollen season, the peak pollen date occurred earlier for oak, mulberry, and juniper (Table 3). In addition, the season start date occurred earlier for mulberry and sycamore, whereas seasons lengthened for sycamore, maple, willow, and weeds. Pollen season length decreased for maple, which also had an earlier pollen season end date (Table 3). During the fall pollen season, all trees and elm pollen season lengthened.

Pollen from all trees combined in addition to 7 distinct tree pollens had a significant ($\alpha = 0.05$) increasing trend in airborne pollen concentrations in the 27-year period, and none had a significant decreasing trend (Fig 4). The average daily pollen concentration for oak pollen, the most abundant pollen type, increased annually by 5.2%, whereas juniper pollen concentration increased by 9.9%. Increasing trends in peak pollen concentration (ie, the maximum pollen concentration recorded each season) were also statistically significant ($\alpha = 0.05$) for oak (+4.9%), juniper (+5.8%), sycamore (+7.9%), birch (+6.7%), mulberry (+12.8%), and willow (+5.6%). Similarly, an increasing trend was found in grouped tree pollen concentrations during both the spring pollen season (+3.9%) and fall pollen season (+10.4%). Weeds during spring pollen season also had an increasing trend (+5.2%) in daily average pollen concentration. There were few increasing trends during the fall pollen season, except for pollen from all trees (+10.4%).

Climate and Pollen Phenology

Spring Pollen Season—From our results to determine the effect that year-to-year climate variations have on phenology, we found that seasonal spring temperatures were the most consistent factor in influencing the timing of pollen release. Specifically, warmer spring temperatures were associated with an earlier peak pollen date for several pollen types, including pollen from all trees. Spring temperatures did not influence average daily pollen concentrations or peak pollen concentrations. In addition, there were no associations between any pollen measure and spring precipitation.

Preceding winter temperatures also influenced pollen phenology, but associations varied by pollen type. Specifically, warmer temperatures were associated with earlier pollen season start dates for pine and elm (Table 4). In addition, warmer winter temperatures were associated with earlier peak pollen dates for pine. The preceding winter precipitation was found to be a significant factor in determining peak pollen concentrations in elm pollen (eTable 1).

Preceding fall temperatures did not play a significant role in the timing of spring pollen phenology. Nevertheless, preceding fall precipitation did have a significant effect on average daily pollen concentrations for pine and weed pollens. Specifically, as fall precipitation increased, pollen average daily pollen concentrations also increased. Fall precipitation also had a significant effect on the pollen season start date for pine pollen; increased precipitation delayed pollen season start date. Preceding summer temperatures and precipitation had no effect on spring pollen concentration and pollen phenology.

Fall Pollen Season—For the fall pollen season (July-December), there were no statistically significant ($\alpha = 0.05$) associations with seasonal temperatures (eTable 2). Nevertheless, fall precipitation did have an influence on both peak pollen concentration and pollen phenology for several plant types (eTable 3). Specifically, for fall pollen season, fall precipitation influenced pollen season start in all trees, in addition to pollen season end date for all weeds and ragweed. Precipitation from the previous summer and winter had no effect on the timing of pollen season.

Discussion

Increasing Pollen Concentration and Shifts in Pollen Season Timing

Airborne pollen concentrations (average daily pollen concentration) increased in the 27-year period, especially in trees during the spring pollen season. Specifically, 6 of the 9 trees included in this study exhibited a statistically significant ($\alpha = 0.05$) increasing trend in pollen concentration over time. Oak pollen, which was the most abundant pollen type in addition to being highly allergenic, increased by 5.2% (average daily pollen concentration) every year. Furthermore, even when outliers were removed from the data set, all existing increasing trends were still statistically significant except for willow, which had an exceedingly high average pollen concentration in 2018. For certain pollen types, pollen seasons occurred earlier or lengthened (eg, mulberry and sycamore), further increasing the likelihood of allergenic pollen exposure throughout the year. An increasing trend in pollen concentrations in conjunction with lengthening pollen seasons suggests that human exposure to allergenic pollen has increased in Atlanta in the last 27 years, potentially increasing the risk of negative health impacts related to pollen exposure, such as allergic rhinitis or asthma-related hospitalizations.[23] Our results are consistent with recent global studies that also found an increasing trend in pollen concentrations, in addition to lengthening pollen seasons in certain allergenic species, such as ragweed.[16,19,20]

Climate and Pollen Phenology

Recent variations in seasonal climate also played a significant role in pollen phenology, but the associations of seasonal climate varied by taxa. Even after considering the observed trend in warming temperatures during the spring (March-May) and summer (June-August) months by detrending the data before performing the regression analysis, we found that warmer temperatures hastened pollen phenology for several taxa, including oak, pine, mulberry, sycamore, and weeds. In addition, when we ignored existing linear trends in the climate and pollen variables by not detrending the data in a linear regression analysis, we found that climate variables still had a significant effect on pollen concentrations and pollen season timing for a wide breadth of taxa. We also found that associations between seasonal climate and pollen season timing differed according to taxa, which is consistent with previous research which also found that seasonal temperatures can affect pollen season timing and tree growth, but only for certain species.[12,14,16,20,34] According to our results, increased precipitation during the preceding fall months (September-November) had a positive effect on spring pollen concentrations (average daily pollen concentration) for pine and weeds. In summary, seasonal variations in seasonal climate did have an effect on pollen phenology, increasing the risk of pollen exposure, which suggests that the risk for aeroallergen-related illness also increases with a warming climate.

Although we found increasing trends in both average daily pollen concentrations and peak pollen concentrations, we found few associations with any seasonal temperature and precipitation variables. This suggests that other factors besides climate might have contributed to the increasing trend in average spring pollen concentrations in trees and weeds, such as land use changes or increased CO_2 in the atmosphere, neither of which were included in this analysis. We also found that seasonal variations in spring temperatures affected pollen season start date (eg, warmer spring temperatures hastened the start of pollen season); spring temperatures exhibited a long-term increasing trend and spring pollen seasons trended to earlier start dates. Recent research focused in North America has revealed that anthropogenic climate change has exacerbated pollen seasons, especially in terms of spring pollen season timing.[36]

Limitations and Discontinuity Analysis

Although our pollen concentration data set spanned a 27-year period from 1992 to 2018, one limitation to this study was the lack of a continuous daily pollen concentration data because pollen counting did not occur on weekends and holidays. Nevertheless, pollen concentrations were collected every day during the peak pollen season (typically in spring) in the latter years of the study period. The lack of a continuous pollen data set is not unique in the United States because many pollen monitoring stations are not automated; the current method for collecting pollen concentration, using an air sampling rod that is examined under microscopy to count individual pollen grains, is time and resource intensive.

In addition, although the station moved to 3 different locations throughout the period of record, all locations were within a 9-mile radius. To quantify the impact of station movement on pollen concentrations, we conducted a regression discontinuity analysis for the time periods (1992–2000, 2000–2010, 2010–2015, 2015–2018), and the models were not statistically significant ($\alpha = 0.05$), which suggests that our results are valid.

We only used a single pollen station for the analysis, but previous research has revealed that a pollen monitoring station is representative of up to a distance of 25 miles, and the distance from the pollen counting station to the weather station is within this range.[29] Although we have some limitations with the pollen concentration data, the data are a relatively robust long-term data set and within the auspices of the National Allergy Bureau, which sets stringent quality standards for pollen collection. Furthermore, the data set used for the study is one of the longest on record for the United States that contains speciated pollen data.

The Atlanta metropolitan area has undergone considerable land use change since 1992, transitioning from rural farmland to more urban and suburban development. In Cobb County, Georgia, where our pollen counting stations were located, developed areas (eg, highly developed areas and suburban areas) increased by 12.8% and impervious surfaces increased by 19.4%, from 2001 to 2016.[35] In addition, the percent increase in urban development is likely much larger when taking into account the entire period of our analysis from 1992 to 2018 owing to the large increase (+70%) in Cobb County's population from 1990 to 2020.[37] Land cover and land use changes could have increased surrounding surface temperatures at weather observation stations owing to the increased impervious surfaces absorbing radiant heat from the sun, in addition to other factors. To account for these changes and to reduce the potential for artificial effects in the climate record, we used a climate reanalysis data set from NOAA, which recalibrates the weather station data from multiple weather stations at a county level. An increase in developed land coincided with a 16.6% decrease in forested areas; however, our results found a significant increase in tree pollen throughout the entirety of the 27 years of record, which further underscores the validity of our results because there would be an expected decrease in tree pollen with a decrease in tree cover.

Changes in Pollen Exposure and the Public Health Burden

In the United States, asthma prevalence is 8% for adults[30] and 8.3% for children,[31] which suggests that a large population of sensitive individuals may be subject to increased pollen exposure, as allergenic pollen is a known trigger for asthma-related symptoms.[28] In addition, owing to the increased use of nonnative ornamental trees, such as Chinese elm, in landscaping, pollen exposure may be further extending into different periods of the year where previously pollen exposure was low, owing to the release of pollen during different times of the year than native plant species.[22] From our analysis, we found that elm pollen has recently become abundant in both the spring and fall pollen seasons, whereas previously elm pollen was only found during the spring pollen season.

Although an exact dose-response relationship between pollen concentrations and the onset of allergic rhinitis remains unclear, previous studies have revealed that high pollen concentrations were associated with increased allergic rhinitis cases,[32] allergy medication sales,[33] and asthma and wheeze-related emergency department visits.[23] Future research can incorporate pollen in addition to other air pollutants in asthma epidemiology studies. Nevertheless, this study provides quantitative evidence of an increased risk of pollen exposure in a long-term period and offers clinicians and their patients with more than anecdotal evidence on when to start allergy treatments. For example, the results of our analysis may provide information for clinicians on when to administer allergy treatments (eg, sublingual immunotherapy tablets need to be started 12 weeks before the onset of pollen season) and timing of measures to reduce pollen exposure for patients who have allergic rhinitis or other allergic illnesses. From a public health perspective, this research elucidates the relationship between specific pollen producing plants and seasonal variations in climate and provides the scientific basis for future health studies to develop pollen models and early warning systems. Other pollen measures can be explored (eg, satellite imagery, phenology, automated pollen monitoring) to provide a high resolution data set of continuous pollen exposure. Furthermore, the need for more localized pollen information is important because the presence of allergenic pollen types varies greatly across regions, and any effective health communications (eg, high pollen concentration alerts) would need to incorporate these variations in potential pollen exposures. This research emphasizes the need for increased access to fine-scale pollen information which could potentially be used to tailor health communications based on localized pollen levels.

In conclusion, we characterized pollen phenology for 13 allergenic taxa and 3 pollen groups (trees, weeds, and grasses) for both the spring and fall pollen seasons in Atlanta, Georgia, and found that many allergenic pollen exhibited an increasing trend in pollen concentration and that pollen phenology is shifting. We found that pollen concentration and phenology were also associated with year-to-year variations in seasonal climate, which could be useful in the future development of predictive pollen models. The results of our analysis suggest that changes in seasonal climate (eg, warming seasonal temperatures or increased precipitation) could hasten the timing of pollen seasons and increase pollen concentrations, increasing the risk of allergy-related disease, such as asthma.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Funding:

The authors have no funding sources to report.

References

1. Grammer L, Greenberger P. Patterson's Allergic Diseases. 8th ed. Chicago, IL: Wolter Kluwer; 2018.
2. Centers for Disease Control and Prevention. National health interview survey. Available at: https://www.cdc.gov/nchs/nhis/SHS/tables.htm. Accessed June 1, 2019.
3. Vandenplas O, Vinnikov D, Blanc PD, et al. Impact of rhinitis on work productivity: a systematic review. J Allergy Clin Immunol Pract. 2018;6(4):1274–1286. .e9. [PubMed: 29017832]
4. Meltzer EO, Bukstein DA. The economic impact of allergic rhinitis and current guidelines for treatment. Ann Allergy Asthma Immunol. 2011;106(suppl 2):S12–S16. [PubMed: 21277528]
5. Pawankar R, Canonica GW, ST Holgate ST, Lockey RF, Blaiss M, The WAO White Book on Allergy (Update. 2013). Available at: https://www.worldallergy.org/UserFiles/file/WhiteBook2-2013-v8.pdf. Accessed August 16, 2021.
6. Wallace DV, Dykewicz MS, Bernstein DI, et al. The diagnosis and management of rhinitis: an updated practice parameter. J Allergy Clin Immunol. 2008;122(suppl 2): S1–S84. [PubMed: 18662584]
7. Yoo B, Park Y, Park K, Kim HA. A 9-year trend in the prevalence of allergic disease based on National Health Insurance Data. J Prev Med Public Health. 2015;48(6):301–309. [PubMed: 26639744]
8. Sheffield PE, Weinberger KR, Kinney PL. Climate change, aeroallergens, and pediatric allergic disease. Mt Sinai J Med. 2011;78(1):78–84. [PubMed: 21259264]
9. Corden J, Millington W. A study of Quercus pollen in the Derby area, UK. Aerobiologia. 1999;15(1):29–37.

10. Frei T, Gassner E. Climate change and its impact on birch pollen quantities and the start of the pollen season an example from Switzerland for the period 1969–2006. Int J Biometeorol. 2008;52(7):667–674. [PubMed: 18481116]

11. Ziska LH, Beggs PJ. Anthropogenic climate change and allergen exposure: the role of plant biology. J Allergy Clin Immunol. 2012;129(1):27–32. [PubMed: 22104602]

12. Emberlin J, Detandt M, Gehrig R, Jaeger S, Nolard N, Rantio-Lehtimäki A. Responses in the start of Betula (birch) pollen seasons to recent changes in spring temperatures across Europe. Int J Biometeorol. 2002;46(4):159–170. [PubMed: 12242471]

13. Ziello C, Bock A, Estrella N, Ankerst D, Menzel A. First flowering of wind-pollinated species with the greatest phenological advances in Europe. Ecography. 2012;35(11):1017–1023.

14. Garcia-Mozo H, Galan C, Jato V, et al. Quercus pollen season dynamics in the Iberian Peninsula: response to meteorological parameters and possible consequences of climate change. Ann Agric Environ Med. 2006;13(2):209–224. [PubMed: 17195993]

15. Ariano R, Canonica GW, Passalacqua G. Possible role of climate changes in variations in pollen seasons and allergic sensitizations during 27 years. Ann Allergy Asthma Immunol. 2010;104(3):215–222. [PubMed: 20377111]

16. Ziska LH, Makra L, Harry SK, et al. Temperature-related changes in airborne allergenic pollen abundance and seasonality across the northern hemisphere: a retrospective data analysis. Lancet Planet Health. 2019;3(3):e124–e131. [PubMed: 30904111]

17. Lin RY, Clauss AE, Bennett ES. Hypersensitivity to common tree pollens in New York City patients. Allergy Asthma Proc. 2002;23(4):253–258. [PubMed: 12221895]

18. Lewis WH, Vinay P, Zenger VE. Airborne and Allergenic Pollen of North America. Baltimore, MD: Johns Hopkins University Press; 1983.

19. Ziska L, Knowlton K, Rogers C, et al. Recent warming by latitude associated with increased length of ragweed pollen season in central North America. Proc Natl Acad Sci U S A. 2011;108(10):4248–4251. [PubMed: 21368130]

20. Emberlin J, Smith M, Close R, Adams-Groom B. Changes in the pollen seasons of the early flowering trees Alnus spp. and Corylus spp. in Worcester, United Kingdom, 1996–2005. Int J Biometeorol. 2007;51(3):181–191. [PubMed: 17024396]

21. D'Amato G, Cecchi L, Bonini S, et al. Allergenic pollen and pollen allergy in Europe. Allergy. 2007;62(9):976–990. [PubMed: 17521313]

22. Shams M, Fineman S. High Chinese elm pollen counts in the fall in Atlanta, Georgia, 2009–2015. Ann Allergy Asthma Immunol. 2016;117(5):553–554. [PubMed: 27637427]

23. Darrow L, Hess J, Rogers CA, Tolbert PE, Klein M, Sarnat SE. Ambient pollen concentrations and emergency department visits for asthma and wheeze. J Allergy Clin Immunol. 2012;130(3):630–638.e4. [PubMed: 22840851]

24. Levetin E Methods for aeroallergen sampling. Curr Allergy Asthma Rep. 2004;4(5):376–383. [PubMed: 15283878]

25. Pennington AF, Sircar KD, Hsu J. Report on understanding the national allergy bureau as a public health surveillance system. J Allergy Clin Immunol. 2019;143(2):AB192.

26. Bastl K, Kmenta M, Berger UE. Defining pollen seasons: background and recommendations. Curr Allergy Asthma Rep. 2018;18(12):73. [PubMed: 30374908]

27. Climate at a Glance: Global Mapping [Internet]. Asheville (NC): NOAA (US), National Centers for Environmental Information. [2021] - [cited 2019 Jun 1]. Available at: https://www.ncdc.noaa.gov/cag/.

28. Grammer L, Greenberger P. Patterson's Allergic Diseases. 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2009.

29. Pashley CH, Fairs A, Edwards RE, Bailey JP, Corden JM, Wardlaw AJ. Reproducibility between counts of airborne allergenic pollen from two cities in the East Midlands, UK. Aerobiologia. 2009;25(4):249–263.

30. QuickStats: percentage of adults aged 18–64 years with current asthma,* by state—National Health Interview Survey,† 2014–2016. MMWR Morb Mortal Wkly Rep. 2018;67(20):590. [PubMed: 29795078]

31. Zahran H, Bailey CM, Damon SA, Garbe PL, Breysse PN. Vital Signs: asthma in children—United States, 2001–2016. MMWR Morb Mortal Wkly Rep. 2018;67(5):149–155. [PubMed: 29420459]
32. Breton M-C, Garneau M, Fortier I, Guay F, Louis J. Relationship between climate, pollen concentrations of Ambrosia and medical consultations for allergic rhinitis in Montreal, 1994–2002. Sci Total Environ. 2006;370(1):39–50. [PubMed: 16899280]
33. Sheffield P, Weinberger KR, Ito K, et al. The association of tree pollen concentration peaks and allergy medication sales in New York City: 2003–2008. ISRN Allergy. 2011;2011: 537194. [PubMed: 23724230]
34. Maurya JP, Bhalerao RP. Photoperiod- and temperature-mediated control of growth cessation and dormancy in trees: a molecular perspective. Ann Bot. 2017;120(3):351–360. [PubMed: 28605491]
35. Homer C, Dewitz J, Jin S, et al. Conterminous United States land cover change patterns 2001–2016 from the 2016 National Land Cover Database. ISPRS J Photogramm Remote Sens. 2020;162:184–199. [PubMed: 35746921]
36. Anderegg R, Abatzoglou JT, Anderegg LDL, Bielory L, Kinney PL, Ziska L. Anthropogenic climate change is worsening North American pollen seasons. Proc Natl Acad Sci U S A. 2021;118:(7) e2013284118.
37. United States Census Bureau. Quick facts for Cobb County, Georgia. 2021.. Available at: https://www.census.gov/quickfacts/cobbcountygeorgia. Accessed June 1, 2021.

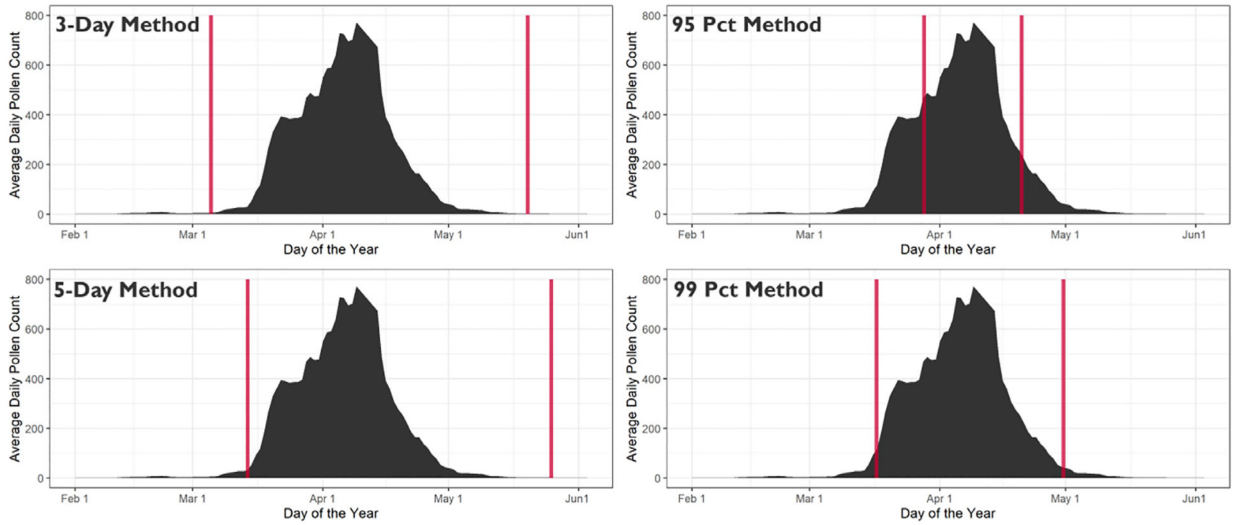

Figure 1.

Comparison of methodologies to define the calculated onset data and end data (red vertical lines) of pollen season compared with actual pollen concentrations (area in black), using oak pollen data from Atlanta, Georgia (1992–2018).

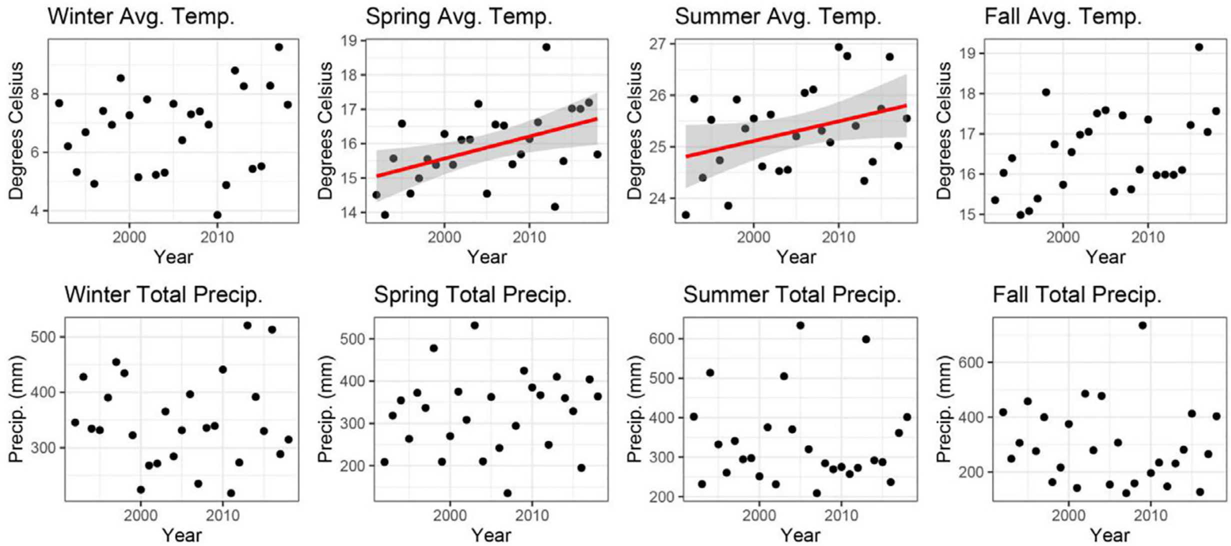

Figure 2.
A scatterplot of climate data (1992–2018) for average temperatures and total precipitation for the following seasons: summer (June-August), fall (September-November), winter (December-February), and spring (March-May). The increasing linear trend in spring and summer average temperatures are shown with a red line, with the confidence interval shown in gray.

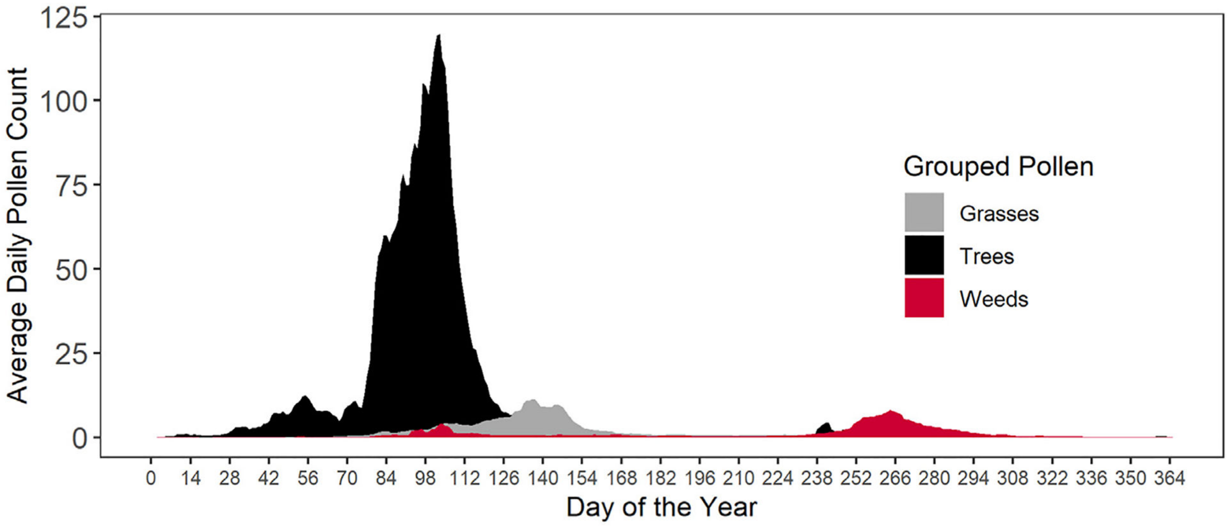

Figure 3.

Average daily pollen concentrations for grouped pollen according to trees, weeds, and grasses (1992–2018). The Y-axis represents the average daily pollen concentration (total annual pollen concentration/number of observation days). The X-axis represents the day of the year.

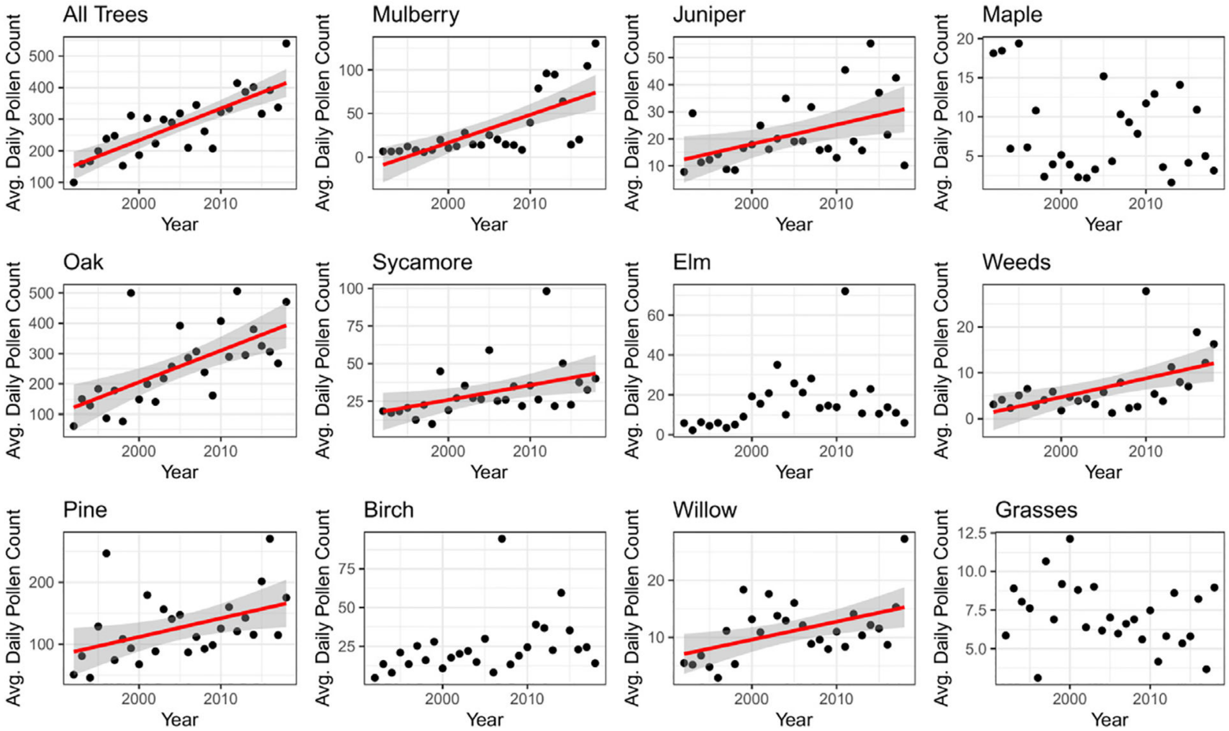

Figure 4.
Scatterplots of average daily pollen concentrations over time (1992–2018). The time series linear regression line is in red, and the confidence interval is in gray.

Table 1

Percentage of Total Pollen Count by Season

Spring pollen season (January-June)	Percentage of pollen (%)
Quercus (oak)	41.1
Pinus (pine)	28.1
Juniperus (juniper)	3.4
Platanus (sycamore)	3.4
Betula (birch)	3.1
Morus (mulberry)	2.8
Ulmus (elm)	1.6
Salix (willow)	1.5
Poaceae (grasses)	1.5
Acer (maple)	1.1
Fall pollen season (July-December)	
Ambrosia (ragweed)	48.3
Ulmus (elm)	17.5
Poaceae (grasses)	5.1
Amaranthus (pigweed)	3.0
Urticaceae (nettle)	2.7

NOTE. Regression models that were stastically signficant ($\alpha = 0.05$).

Table 2

Annually Averaged Pollen Metrics From 1992 to 2018, 95% Confidence Intervals in Parentheses

Pollen type (common name)	Average daily pollen concentration		Peak pollen concentration		Season start date		Season peak date		Season end date		Season length (d)		N
Spring season (January 1–June 30)		**(95% CI)**		**(95% CI)**		**(95% CI)**		**(95% CI)**		**(95% CI)**		**(95% CI)**	
All trees	283.7	(245.1–322.4)	4296.7	(3521.3–5072.1)	January 16	(January 11–January 21)	April 4	(April 2–April 7)	June 23	(June 20–June 26)	159.0	(151.7–166.3)	27
Quercus (oak)	257.9	(207.9–307.8)	2599.0	(2039.6–3158.4)	March 3	(February 27–March 8)	April 4	(April 1–April 8)	May 18	(May 14–May 22)	76.4	(69.2–83.7)	27
Pinus (pine)	127.0	(105.6–148.4)	1825.1	(1367.2–2282.9)	February 23	(February 15–March 2)	April 4	(April 1–April 7)	June 5	(May 27–June 13)	102.7	(90.8–114.6)	27
Morus (mulberry)	32.6	(18.3–46.9)	270.4	(117.3–423.5)	March 29	(March 25–April 3)	April 10	(April 6–April 13)	May 10	(May 6–May 14)	41.6	(36.2–47.1)	27
Platanus (sycamore)	30.8	(23.8–37.7)	174.3	(127.1–221.5)	March 24	(March 18–March 30)	April 8	(April 4–April 11)	May 6	(April 30–May 12)	43.3	(33.9–52.7)	27
Betula (birch)	24.4	(17.2–31.6)	195.4	(108.7–282.1)	March 5	(February 28–March 10)	April 4	(April 1–April 7)	April 28	(April 23–May 3)	54.6	(47.3–62)	27
Juniperus (juniper)	21.7	(16.8–26.5)	283.3	(182.3–384.3)	January 24	(January 18–January 30)	February 25	(February 20–March 2)	April 4	(March 29–April 10)	70.8	(62.8–78.8)	27
Ulmus (elm)	15.9	(10.3–21.4)	131.0	(86.3–175.8)	February 12	(February 8–February 17)	February 26	(February 21–March 2)	March 28	(March 22–April 4)	45.0	(36.7–53.3)	27
Salix (willow)	11.2	(9.2–13.2)	68.4	(47.1–89.7)	March 22	(March 16–March 28)	April 6	(April 1–April 12)	May 15	(May 6–May 23)	53.4	(45.3–61.4)	27
Acer (maple)	8.0	(5.8–10.2)	65.3	(41.3–89.4)	February 14	(February 7–February 21)	March 18	(March 7–March 28)	April 5	(March 27–April 13)	50.4	(41.6–59.1)	27
All weeds	6.8	(4.4–9.1)	82.7	(35.6–129.8)	March 11	(February 23–March 27)	April 19	(April 9–April 29)	May 21	(May 6–June 5)	71.3	(48.8–93.8)	27
Poaceae (grasses)	7.5	(6.6–8.4)	47.5	(37.8–57.2)	March 29	(March 24–April 3)	May 10	(May 4–May 16)	June 18	(June 14–June 23)	81.4	(75–87.9)	27
Fall season (July 1–December 31)													
All trees	6.9	(3.8–9.9)	136.2	(32.6–239.7)	July 29	(July 15–Augustl3)	September 6	(August 23–September 20)	September 26	(September 10–October 11)	58.5	(38.5–78.5)	27
Ulmus (elm)	19.9	(1.1–38.6)	117.7	(14.7–220.7)	August 20	(August 7–September 2)	August 23	(August 9–September 6)	September 1	(August 16–Septemebr 16)	11.7	(5.9–17.5)	27

All weeds	11.7	(10–13.4)	105.2	(67.5–142.9)	July 15	(July 8–July 22)	September 16	(September 13–September 20)	November 14	(November 7–November 21)	121.7	(112–131.5)	27
Ambrosia (ragweed)	14.4	(12.2–16.6)	89.3	(54.8–123.8)	August 21	(August 18–August 25)	September 17	(September 14–September 21)	November 8	(November 3–November 14)	79.0	(72.2–85.8)	27
Amaranthus (pigweed)	1.8	(1.5–2)	5.5	(4.3–6.6)	August 25	(August 18–September 1)	September 6	(August 29–September 14)	September 11	(September 3–September 20)	17.0	(10.3–23.6)	27
Urticaceae (nettle)	1.8	(1.5–2.1)	6.0	(4.5–7.5)	August 18	(August 9–August 28)	August 26	(August 17–September 4)	September 5	(August 27–September 14)	17.8	(11.2–24.3)	27
Poaceae (grasses)	1.7	(1.2–2.2)	7.0	(5.6–8.4)	July 21	(July 11–July 31)	September 4	(August 22–September 16)	September 16	(September 4–September 27)	56.4	(42.5–70.3)	27

NOTE. Pollen concentrations were measured in pollen grains per cubic meter. The pollen “spring season” was defined as January 1 to June 30, and “fall season” was defined as July 1 to December 31

Table 3

Annual Change in Pollen Count Concentration in Pollen Grains Per Cubic Meter and Change in Season Timing by Day

Pollen type (common name)	Pollen count change (average daily pollen concentration) (%)	Average daily pollen concentration		Peak pollen concentration		Start date (d)		Peak date (d)		End date (d)		Length (d)	
Spring season (January 1–June 30)		**β**	**(95% CI)**	**β**	**(95% CI)**	**β**	**(95% CI)**	**β**	**(95% CI)**	**β**	**(95% CI)**	**β**	**(95% CI)**
All trees	+3.9	**10.1**	**(7.1–13)** [a]	**139**	**(55–223.2)** [a]	**−0.63**	**(−1.3 to 0)** [b]	−0.3	(−0.3 to 0.04)	**0.47**	**(0.1–0.9)** [b]	**1.1**	**(0.3–1.9)** [b]
Quercus (oak)	+5.2	**10.4**	**(5.5–15.4)** [a]	**104**	**(43.9–163.3)** [a]	−0.18	(−0.9 to 0.5)	**−0.5**	**(−0.5 to −0.04)** [b]	−0.3	(−0.8 to 0.3)	−0.1	(−1 to 0.9)
Pinus (pine)	+2.9	**2.99**	**(0.5–5.5)** [b]	35.1	(−23.3 to 93.4)	−0.46	(−1.5 to 0.6)	−0.2	(−0.2 to 0.2)	−0.6	(−1.7 to 0.6)	−0.1	(−1.7 to 1.5)
Morus (mulberry)	+9.9	**3.19**	**(1.9–4.5)** [a]	**32**	**(16.9–47.2)** [a]	**−0.64**	**(−1.2 to −0.1)** [b]	**−0.5**	**(−0.5 to −0.1)** [b]	0.02	(−0.5 to 0.6)	0.66	(0–1.3)
Platanus (sycamore)	+3.3	**0.97**	**(0.2–1.8)** [b]	**9.55**	**(4.8–14.3)** [a]	**−1.09**	**(−1.8 to −0.4)** [a]	−0.2	(−0.2 to 0.3)	**0.98**	**(0.3–1.6)** [a]	**2.07**	**(1.2–3)** [a]
Betula (birch)		0.83	(0–1.7)	11.9	(1.7–22.2)	−0.48	(−1.2 to 0.3)	**−0.4**	**(−0.4 to −0.02)** [b]	−0.1	(−0.8 to 0.5)	0.35	(−0.6 to 1.3)
Juniperus (juniper)	+9.9	**3.19**	**(1.9–4.5)** [a]	**16.3**	**(4.9–27.8)** [a]	−0.66	(−1.3 to 0)	−0.3	(−0.3 to 0.4)	0.06	(−0.8 to 0.9)	0.73	(−0.3 to 1.7)
Ulmus (elm)		0.55	(−0.1 to 1.2)	3.75	(−1.9 to 9.4)	−0.08	(−0.6 to 0.5)	0.32	(0.3–1)	−0.1	(−0.9 to 0.8)	0.04	(−1 to 1.1)
Salix (willow)	+3.4	**0.31**	**(0.1–0.5)** [a]	**3.39**	**(1–5.8)** [a]	−0.65	(−1.4 to 0.1)	−0.1	(−0.1 to 0.6)	0.56	(−0.5 to 1.7)	**1.21**	**(0.3–2.1)** [b]
Acer (maple)		−0.2	(−0.5 to 0.1)	−2.3	(−5.3 to 0.7)	−0.06	(−1 to 0.9)	−1	(−1 to 0.3)	**−1.5**	**(−2.4 to −0.6)** [a]	**−1.4**	**(−2.4 to −0.5)** [a]
All weeds	+5.2	**0.41**	**(0.1–0.7)** [a]	**9.44**	**(4.6–14.2)** [a]	**−2.43**	**(−4.4 to −0.5)** [b]	−0.8	(−0.8 to 0.5)	0.62	(−1.4 to 2.6)	**3.05**	**(0.4–5.7)** [b]
Poaceae (grasses)		−0.1	(−0.2 to 0)	−0.9	(−2.1 to 0.4)	−0.28	(−1 to 0.4)	−0.2	(−0.2 to 0.6)	−0.4	(−1 to 0.1)	−0.1	(−1 to 0.7)
Fall season (July 1–December 31)													
All trees	+10.4	**0.6**	**(0.3–0.9)** [a]	**17**	**(5.3–28.6)** [a]	**−2.73**	**(−4.3 to−1.1)** [a]	−0.4	(−0.4 to 1.3)	1.79	(−0.1 to 3.7)	**4.51**	**(2.7–6.4)** [a]
Ulmus (elm)[c]	+19.9	**3.46**	**(−1.8 to 8.7)** [b]	**22.5**	**(−5.3 to 50.3)** [b]	**−1.39**	**(−2.6 to −0.2)** [a]	**−0.8**	**(−0.8 to 0.5)** [a]	**0.19**	**(−1.2 to 1.6)** [a]	**1.58**	**(0.4–2.8)** [a]
All weeds		−0	(−0.2 to 0.2)	1.59	(−3.3 to 6.5)	−0.82	(−1.6 to 0)	0.4	(0.4–0.8)	0.43	(−0.5 to 1.4)	**1.25**	**(0.1–2.4)** [b]

Ambrosia (ragweed)	0.13	(−0.2 to 0.4)	0.63	(−3.9 to 5.1)	−0.09	(−0.5 to 0.3)	0.3	(0.3–0.7)	0.02	(−0.7 to 0.7)	0.12	(−0.8 to 1)
Amaranthus (pigweed)	−0	(−0.04 to 0.03)	0.06	(−0.1 to 0.2)	0.09	(−0.8 to 1)	0.3	(0.3–1.3)	0.42	(−0.7 to 1.5)	0.33	(−0.5 to 1.2)
Urticaceae (nettle)	−0	(−0.05 to 0.02)	−0.1	(−0.3 to 0.1)	−0.2	(−1.5 to 1.1)	−0.1	(−0.1 to 1.1)	−0.3	(−1.5 to 0.9)	−0.1	(−1 to 0.8)
Poaceae (grasses)	−0	(−0.1 to 0.03)	−0.1	(−0.2 to 0.1)	**−1.42**	**(−2.6 to −0.2)** [b]	**−2.3**	**(−2.3 to −0.9)** [a]	**−1.8**	**(−3.2 to −0.4)** [b]	−0.4	(−2.2 to 1.5)

Abbreviation: CI, confidence interval.

NOTE. Confidence interval by 95% is indicated in parentheses.

Regression models that were stastically signficant (α = 0.05).

[a] 99% significance level.

[b] 95% significance level.

[c] 2001–2018.

Table 4

Results of the Linear Regression Model for the Spring Pollen Season (January-June) Using Seasonal Average Temperatures as Independent Variables and 6 Pollen Measures as Dependent Variables

	Spring temperature average				Previous winter temperature average				Previous fall temperature average				Previous summer temperature average			
	R	95% CI	R^2	SIG	R	95% CI	R^2	SIG	R	95% CI	R^2	SIG	R	95% CI	R^2	SIG
Average daily pollen count																
All trees	−6.6	(−30.6 to 17.3)	0.01	0.999	0.4	(−15.8 to 16.6)	0.00	0.999	−4.0	(−27.4 to 19.3)	0.01	0.999	6.5	(−23.2 to 36.1)	0.01	0.999
Quercus (oak)	9.7	(−30.8 to 50.2)	0.01	0.999	6.1	(−21.2 to 33.4)	0.01	0.999	18.6	(−20.2 to 57.3)	0.04	0.999	10.6	(−39.5 to 60.7)	0.01	0.999
Pirns (pine)	−2.3	(−23 to 18.5)	0.00	0.999	−10.1	(−23.5 to 3.2)	0.09	0.522	−7.8	(−27.7 to 12.1)	0.03	0.999	−2.5	(−28.2 to 23.1)	0.00	0.999
Morus mulberry)	−2.8	(−13.7 to 8.2)	0.01	0.999	*4.8*	*(−2.3 to 11.9)*	*0.07*	*0.712*	2.4	(−8.2 to 13)	0.01	0.999	5.8	(−7.5 to 19.2)	0.03	0.999
Platanus (sycamore)	4.9	(−1.5 to 11.3)	0.09	0.501	3.3	(−1 to 7.7)	0.09	0.501	1.5	(−5 to 8)	0.01	0.691	3.8	(−4.4 to 12)	0.04	0.691
Betula (birch)	1.9	(−5.8 to 9.6)	0.01	0.999	0.3	(−4.9 to 5.6)	0.00	0.999	−1.8	(−9.2 to 5.7)	0.01	0.999	1.9	(−7.6 to 11.4)	0.01	0.999
Juniperus (juniper)	1.2	(−3.4 to 5.8)	0.01	0.999	−2.4	(−5.4 to 0.6)	0.10	0.430	0.9	(−3.6 to 5.4)	0.01	0.999	−0.1	(−5.8 to 5.6)	0.00	0.999
Ulmus (elm)	2.4	(−3.5 to 8.3)	0.03	0.501	−2.2	(−6.1 to 1.7)	0.05	0.501	3.9	(−1.6 to 9.5)	0.08	0.472	*6.9*	*(0.1–13.7)*	*0.15*	*0.190*
Salix (willow)	0.0	(−1.9 to 1.9)	0.00	0.999	0.9	(−0.3 to 2.1)	0.08	0.453	1.7	(0−3.4)	0.14	0.210	−0.4	(−2.8 to 1.9)	0.01	0.999
Acer (maple)	−1.0	(−3.3 to 1.3)	0.03	0.999	−0.4	(−2 to 1.1)	0.01	0.999	−0.9	(−3.2 to 1.3)	0.03	0.999	−1.3	(−4.2 to 1.5)	0.04	0.999
All weeds	−1.1	(−3.2 to 1)	0.04	0.999	−0.7	(−2.1 to 0.7)	0.04	0.999	−0.5	(−2.6 to 1.6)	0.01	0.999	−1.0	(−3.7 to 1.6)	0.03	0.999
Poaceae (grasses)	−0.4	(−1.4 to 0.6)	0.03	0.999	0.1	(−0.6 to 0.8)	0.00	0.999	−0.3	(−1.3 to 0.6)	0.02	0.999	−0.4	(−1.6 to 0.8)	0.02	0.999
Peak pollen count																
All trees	133.9	(−555.6 to 823.5)	0.01	0.999	−71.4	(−536 to 393.2)	0.00	0.999	−364.3	(−1018.4 to 289.9)	0.05	0.999	329.5	(−514.2 to 1173.3)	0.03	0.999
Quercus (oak)	8.6	(−482.7 to 499.9)	0.00	0.999	−2.4	(−333.1 to 328.2)	0.00	0.999	−39.4	(−515.8 to 437)	0.00	0.999	−62.7	(−669.1 to 543.7)	0.00	0.999
Pinus (pine)	33.7	(−460.5 to 527.8)	0.00	0.999	−166.0	(−491.5 to 159.6)	0.04	0.931	−276.7	(−742.5 to 189.2)	0.06	0.931	75.6	(−534.3 to 685.5)	0.00	0.999
Morus (mulberry)	−19.5	(−143.8 to 104.9)	0.00	0.999	*87.2*	*(11.5–163)*	*0.18*	*0.103*	5.0	(−115.9 to 125.8)	0.00	0.999	75.3	(−75.5 to 226)	0.04	0.940
Platanus (sycamore)	7.1	(−32.1 to 46.4)	0.01	0.711	21.1	(−3.9 to 46.1)	0.11	0.380	17.8	(−19.7 to 55.2)	0.04	0.676	29.1	(−18 to 76.2)	0.06	0.644

	Spring temperature average				Previous winter temperature average				Previous fall temperature average				Previous summer temperature average			
	R	95% CI	R^2	SIG	R	95% CI	R^2	SIG	R	95% CI	R^2	SIG	R	95% CI	R^2	SIG
Betula (birch)	−17.0	(−101.2 to 67.1)	0.01	0.999	−28.0	(−83.6 to 27.6)	0.04	0.999	−23.3	(−113.6 to 67)	0.01	0.999	−53.0	(−166.5 to 60.5)	0.04	0.999
Juniperus (juniper)	19.1	(−74.5 to 112.7)	0.01	0.999	−39.5	(−100.6 to 21.6)	0.07	0.781	−2.1	(−93.2 to 89.1)	0.00	0.999	−58.9	(−172.4 to 54.6)	0.04	0.887
Ulmus (elm)	26.0	(−21.2 to 73.1)	0.05	0.802	−10.0	(−42.3 to 22.2)	0.02	0.999	7.0	(−39.8 to 53.8)	0.00	0.999	*59.7*	*(5.3–114.1)*	*0.17*	*0.131*
Salix (willow)	−7.0	(−26.7 to 12.7)	0.02	0.941	10.8	(−1.9 to 23.4)	0.11	0.369	9.6	(−9.3 to 28.5)	0.04	0.917	−7.7	(−32.1 to 16.6)	0.02	0.941
Acer (maple)	−1.3	(−27.2 to 24.7)	0.00	0.999	−3.6	(−21 to 13.8)	0.01	0.999	−19.7	(−43.6 to 4.1)	0.10	0.401	−11.9	(−43.6 to 19.8)	0.02	0.999
All weeds	9.4	(−30 to 48.7)	0.01	0.647	17.9	(−7.7 to 43.5)	0.08	0.647	25.8	(−11 to 62.7)	0.08	0.647	27.4	(−20.1 to 74.9)	0.05	0.647
Poaceae (grasses)	−1.2	(−11.7 to 9.2)	0.00	0.999	−0.9	(−7.9 to 6.1)	0.00	0.999	−1.7	(−11.8 to 8.5)	0.00	0.999	−8.4	(−20.9 to 4)	0.07	0.702
Pollen season onset date																
All trees	0.1	(−5.1 to 5.2)	0.00	0.983	*−3.2*	*(−6.4 to 0)*	*0.14*	*0.211*	1.7	(−3.2 to 6.7)	0.02	0.950	3.3	(−2.9 to 9.5)	0.05	0.862
Quercus (oak)	−0.7	(−6.4 to 5)	0.00	0.999	−2.9	(−6.5 to 0.8)	0.10	0.468	1.9	(−3.5 to 7.4)	0.02	0.999	−1.8	(−8.9 to 5.2)	0.01	0.999
Pinus (pine)	3.5	(−4.9 to 11.9)	0.03	0.831	***−9.3***	***(−13.6 to −5)***	***0.44***	***<0.001***	−1.9	(−10.2 to 6.3)	0.01	0.831	−5.5	(−15.8 to 4.7)	0.05	0.831
Morus (mulberry)	***−5.6***	***(−9.6 to −1.7)***	***0.26***	***0.028***	−2.6	(−5.5 to 0.3)	0.12	0.236	−2.9	(−7.1 to 1.4)	0.07	0.340	−3.7	(−9.2 to 1.7)	0.07	0.340
Platanus (sycamore)	1.2	(−4.3 to 6.7)	0.01	0.999	−2.6	(−6.1 to 1)	0.08	0.579	0.5	(−4.8 to 5.9)	0.00	0.999	−2.0	(−8.7 to 4.7)	0.01	0.999
Betula (birch)	−1.7	(−7.9 to 4.5)	0.01	0.999	−3.0	(−7 to 1.1)	0.08	0.577	−2.8	(−8.8 to 3.1)	0.04	0.999	−1.7	(−9.4 to 6)	0.01	0.999
Juniperus (juniper)	1.3	(−4.7 to 7.3)	0.01	0.999	−3.6	(−7.4 to 0.2)	0.13	0.241	−2.3	(−8.1 to 3.5)	0.03	0.999	−0.4	(−7.8 to 7.1)	0.00	0.999
Ulmus (elm)	1.9	(−2.6 to 6.4)	0.03	0.999	***−3.6***	***(−6.3 to−0.9)***	***0.23***	***0.042***	0.7	(−3.7 to 5.2)	0.00	0.999	−0.2	(−5.9 to 5.4)	0.00	0.999
Salix (willow)	−6.1	*(−11.8 to −0.3)*	*0.16*	*0.154*	−2.2	(−6.3 to 1.9)	0.05	0.818	−3.0	(−8.9 to 3)	0.04	0.818	−2.1	(−9.8 to 5.6)	0.01	0.818
Acer (maple)	−2.6	(−10.2 to 5)	0.02	0.999	−1.7	(−6.8 to 3.4)	0.02	0.999	5.7	(−1.4 to 12.7)	0.10	0.438	−3.4	(−12.8 to 6)	0.02	0.999
All weeds	***−21.6***	***(−34.7 to −8.5)***	***0.32***	***0.009***	0.3	(−10.4 to 10.9)	0.00	0.957	*−16.2*	*(−30.1 to −2.4)*	*0.19*	*0.062*	*−21.0*	*(−38.6 to −3.5)*	*0.20*	*0.062*
Poaceae (grasses)	−4.3	(−9.6 to 1.1)	0.10	0.456	−0.5	(−4.3 to 3.3)	0.00	0.999	0.6	(−4.8 to 6.1)	0.00	0.999	−4.1	(−10.9 to 2.6)	0.06	0.656
Pollen season peak date																
All trees	***−5.5***	***(−7.6 to −3.3)***	***0.52***	***<0.001***	−0.5	(−2.6 to 1.6)	0.01	0.691	−1.4	(−4.4 to 1.6)	0.04	0.691	−3.0	(−6.6 to 0.7)	0.10	0.318

	Spring temperature average				Previous winter temperature average				Previous fall temperature average				Previous summer temperature average			
	R	95% CI	R^2	SIG	R	95% CI	R^2	SIG	R	95% CI	R^2	SIG	R	95% CI	R^2	SIG
Quercus (oak)	***−6.3***	***(−8.7 to −3.8)***	***0.53***	***<0.001***	−0.3	(−2.7 to 2.1)	0.00	0.999	−0.7	(−4.1 to 2.8)	0.01	0.999	−2.8	(−7 to 1.5)	0.07	0.570
Pinus (pine)	***−4.2***	***(−6.6 to −1.7)***	***0.33***	***0.007***	***−2.6***	***(−4.3 to −0.9)***	***0.29***	***0.012***	−1.7	(−4.5 to 1.1)	0.06	0.228	−2.9	(−6.4 to 0.6)	0.10	0.210
Morus (mulberry)	*−4.0*	*(−7 to −0.9)*	*0.22*	*0.053*	−1.1	(−3.4 to 1.2)	0.04	0.674	0.2	(−3.2 to 3.5)	0.00	0.918	−3.7	(−7.7 to 0.3)	0.13	0.196
Platanus (sycamore)	***−4.5***	***(−8 to −1.1)***	***0.23***	***0.045***	*−2.8*	*(−5.2 to −0.5)*	*0.20*	*0.060*	0.5	(−3.2 to 4.3)	0.00	0.777	−2.1	(−6.8 to 2.7)	0.03	0.758
Betula (birch)	−3.3	(−6.3 to −0.4)	0.18	0.114	−0.5	(−2.6 to 1.7)	0.01	0.951	1.1	(−2 to 4.2)	0.02	0.951	−2.0	(−5.9 to 2)	0.04	0.938
Juniperus (juniper)	1.7	(−4.3 to 7.7)	0.01	0.999	*−4.2*	*(−7.8 to −0.5)*	*0.18*	*0.111*	−1.2	(−7 to 4.6)	0.01	0.999	−3.0	(−10.3 to 4.3)	0.03	0.999
Ulmus (elm)	2.5	(−3 to 8)	0.03	0.999	−0.9	(−4.7 to 2.8)	0.01	0.999	0.9	(−4.4 to 6.3)	0.01	0.999	−5.3	(−11.9 to 1.2)	0.10	0.415
Salix (willow)	*−6.1*	*(−11.3 to −0.9)*	*0.19*	*0.091*	−1.3	(−5.2 to 2.5)	0.02	0.976	−0.9	(−6.5 to 4.7)	0.00	0.976	−6.4	(−13 to 0.2)	0.14	0.176
Acer (maple)	−6.3	(−17.3 to 4.6)	0.05	0.981	−4.1	(−11.5 to 3.3)	0.05	0.981	−1.4	(−12.3 to 9.5)	0.00	0.999	1.8	(−12.1 to 15.7)	0.00	0.999
All weeds	−3.5	(−14to 7.1)	0.02	0.999	3.6	(−3.4 to 10.6)	0.04	0.999	1.1	(−9.3 to 11.5)	0.00	0.999	−5.0	(−18 to 8)	0.02	0.999
Poaceae (grasses)	*−6.3*	*(−12.1 to −0.5)*	*0.17*	*0.104*	−2.7	(−6.9 to 1.4)	0.07	0.369	−2.5	(−8.6 to 3.6)	0.03	0.409	***−10.3***	***(−16.9 to −3.6)***	***0.29***	***0.015***
Peak season end date																
All trees	0.2	(−2.9 to 3.3)	0.00	0.999	*2.0*	*(0.1–3.9)*	*0.16*	*0.162*	1.1	(−1.9 to 4.1)	0.02	0.999	0.3	(−3.6 to 4.1)	0.00	0.999
Quercus (oak)	−3.3	(−7.3 to 0.7)	0.10	0.450	0.5	(−2.3 to 3.4)	0.01	0.850	−2.1	(−6.3 to 2)	0.04	0.723	−3.0	(−8.3 to 2.2)	0.05	0.723
Pinus (pine)	−1.8	(−11.3 to 7.8)	0.01	0.705	−3.2	(−9.5 to 3.1)	0.04	0.615	−8.0	(−16.7 to 0.6)	0.13	0.258	−10.4	(−21.4 to 0.7)	0.13	0.258
Morus (mulberry)	***−6.8***	***(−10.3 to −3.3)***	***0.39***	***0.002***	0.3	(−2.8 to 3.3)	0.00	0.864	*−4.0*	*(−8 to 0)*	*0.15*	*0.146*	−4.0	(−9.3 to 1.3)	0.09	0.262
Platanus (sycamore)	−1.6	(−7 to 3.8)	0.01	0.999	−2.5	(−6 to 1)	0.08	0.626	0.4	(−4.9 to 5.7)	0.00	0.999	1.2	(−5.6 to 7.9)	0.01	0.999
Betula (birch)	−3.6	(−8.8 to 1.6)	0.08	0.648	−1.1	(−4.7 to 2.5)	0.02	0.999	3.0	(−2.1 to 8.1)	0.06	0.708	0.8	(−5.8 to 7.5)	0.00	0.999
Juniperus (juniper)	−1.3	(−8.1 to 5.5)	0.01	0.999	−0.8	(−5.4 to 3.7)	0.01	0.999	0.2	(−6.4to 6.8)	0.00	0.999	−5.0	(−13.1 to 3.1)	0.06	0.869
Ulmus (elm)	0.2	(−7.1 to 7.4)	0.00	0.999	−0.3	(−5.2 to 4.5)	0.00	0.999	−2.6	(−9.6 to 4.3)	0.02	0.999	−1.8	(−10.8 to 7.1)	0.01	0.999
Salix (willow)	−5.7	(−14.7 to 3.2)	0.06	0.800	2.7	(−3.4 to 8.8)	0.03	0.999	−1.3	(−10.3 to 7.6)	0.00	0.999	−4.3	(−15.6 to 7)	0.02	0.999
Acer (maple)	−5.4	(−12.5 to 1.7)	0.09	0.517	−1.0	(−6 to 3.9)	0.01	0.999	−0.6	(−7.8 to 6.6)	0.00	0.999	−0.9	(−10 to 8.3)	0.00	0.999
All weeds	−6.6	(−22.7 to 9.5)	0.03	0.999	2.9	(−8 to 13.8)	0.01	0.999	4.4	(−11.3 to 20.2)	0.01	0.999	−12.5	(−32 to 7)	0.06	0.799
Poaceae (grasses)	0.0	(−4.8 to 4.9)	0.00	0.999	−1.5	(−4.7 to 1.7)	0.03	0.999	−1.0	(−5.7 to 3.7)	0.01	0.999	2.6	(−3.3 to 8.5)	0.03	0.999

	Spring temperature average				Previous winter temperature average				Previous fall temperature average				Previous summer temperature average			
	R	95% CI	R^2	SIG	R	95% CI	R^2	SIG	R	95% CI	R^2	SIG	R	95% CI	R^2	SIG
Pollen season length																
All trees	0.2	(−6.8 to 7.2)	0.00	0.999	*5.2*	*(1–9.4)*	*0.21*	*0.070*	−0.6	(−7.4 to 6.2)	0.00	0.999	−3.0	(−11.6 to 5.5)	0.02	0.999
Quercus (oak)	−2.6	(−10.4 to 5.2)	0.02	0.993	3.2	(−1.9 to 8.3)	0.06	0.866	−4.1	(−11.5 to 3.4)	0.05	0.866	−1.2	(−10.9 to 8.5)	0.00	0.993
Pinus (pine)	−5.2	(−17.9 to 7.4)	0.03	0.936	6.1	(−2.2 to 14.4)	0.08	0.566	−6.1	(−18.3 to 6.1)	0.04	0.936	−4.8	(−20.5 to 10.9)	0.02	0.936
Morus (mulberry)	−1.1	(−7 to 4.7)	0.01	0.999	3.5	(−0.2 to 7.2)	0.13	0.240	1.0	(−4.7 to 6.6)	0.00	0.999	−0.3	(−7.5 to 7)	0.00	0.999
Platanus (sycamore)	−2.8	(−10.1 to 4.5)	0.02	0.999	0.1	(−4.9 to 5)	0.00	0.999	−0.2	(−7.3 to 7)	0.00	0.999	3.2	(−5.8 to 12.2)	0.02	0.999
Betula (birch)	−1.9	(−9.8 to 5.9)	0.01	0.999	1.8	(−3.5 to 7.1)	0.02	0.999	5.9	(−1.5 to 13.2)	0.10	0.447	2.5	(−7.2 to 12.3)	0.01	0.999
Juniperus (juniper)	−2.6	(−11.2 to 6)	0.02	0.999	2.8	(−2.9 to 8.5)	0.04	0.999	2.5	(−5.9 to 10.8)	0.01	0.999	−4.6	(−15.2 to 5.9)	0.03	0.999
Ulmus (elm)	−1.7	(−10.6 to 7.2)	0.01	0.999	3.3	(−2.6 to 9.2)	0.05	0.999	−3.3	(−11.9 to 5.2)	0.02	0.999	−1.6	(−12.7 to 9.4)	0.00	0.999
Salix (willow)	0.4	(−7.3 to 8)	0.00	0.999	3.6	(−1.3 to 8.6)	0.08	0.562	−2.4	(−9.7 to 5)	0.02	0.999	−2.2	(−11.6 to 7.2)	0.01	0.999
Acer (maple)	−2.8	(−10.8 to 5.3)	0.02	0.999	0.6	(−4.9 to 6)	0.00	0.999	−6.5	(−13.9 to 1)	0.11	0.339	2.5	(−7.4 to 12.5)	0.01	0.999
All weeds	15.0	(−6.1 to 36.1)	0.08	0.469	2.0	(−12.8 to 16.8)	0.00	0.999	18.6	(−1.3 to 38.6)	0.13	0.265	8.6	(−18.4 to 35.5)	0.02	0.999
Poaceae (grasses)	4.3	(−2.4 to 11)	0.06	0.600	−1.0	(−5.6 to 3.7)	0.01	0.999	−1.7	(−8.4 to 5)	0.01	0.999	6.8	(−1.3 to 14.9)	0.11	0.389

Abbreviations: CI, confidence interval; SIG, significance probability.

NOTE. Preceding temperatures had a significant effect on the timing of the start of the spring pollen season and peak date. The table reports the Holm-Bonferroni−adjusted *P* values.

Regression models that were stastically signficant (α = 0.05).