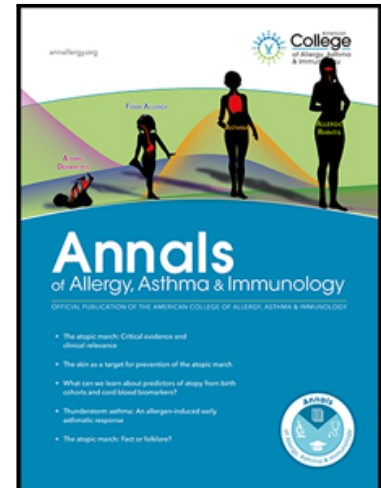


Journal Pre-proof

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

PII: S1081-1206(21)00503-2
DOI: <https://doi.org/10.1016/j.anai.2021.07.012>
Reference: ANAI 3660



To appear in: *Annals of Allergy, Asthma Immunology*

Received date: 8 April 2021
Revised date: 8 June 2021
Accepted date: 14 July 2021

Please cite this article as: 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 , Long-term pollen trends and associations between pollen phenology and
seasonal climate in Atlanta, Georgia (1992-2018), *Annals of Allergy, Asthma Immunology* (2021), doi:
<https://doi.org/10.1016/j.anai.2021.07.012>

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2021 American College of Allergy, Asthma & Immunology. Published by Elsevier Inc.

Title: “Long-term pollen trends and associations between pollen phenology and seasonal climate in Atlanta, Georgia (1992-2018)”

Authors:

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

Arie Manangan was the lead scientist and formulated the conception and design of this study, conducted the analysis, and drafted the manuscript. He gives final approval for the manuscript to be published and agrees to be accountable for all aspect of this original work.

Claudia Brown contributed significantly to the methodology, formulation of results, and discussion. She drafted elements of the manuscript and provided critical review of scientific content. She gives final approval for the manuscript to be published and agrees to be accountable for all aspect of this original work.

Shubhayu Saha made substantial contributions to the design of the study and interpretation of results, reviewed the article, and significantly contributed to the analysis of the manuscript. He gives final approval for the manuscript to be published and agrees to be accountable for all aspect of this original work.

Jesse Bell was integral in acquiring climate data, interpreting the correlation results, and providing a climatological perspective to the design of the methodology. He gives final approval for the manuscript to be published and agrees to be accountable for all aspect of this original work.

Jeremy Hess provided substantial contribution to the study design, drafting, and review of the manuscript, providing both a public health and clinician’s perspective. He gives final approval for the manuscript to be published and agrees to be accountable for all aspect of this original work.

Chris Uejio made significant contributions to the study design and statistical analysis for both the pollen trend analysis and the climatic analysis. He drafted the manuscript and critically reviewed for content and gives final approval for the manuscript to be published and agrees to be accountable for all aspect of this original work.

Stanley Fineman was integral in acquiring pollen data, interpreting the results, drafting the pollen collection methodology, and detailing the implications of our results for allergists and patients. He gives final approval for the manuscript to be published and agrees to be accountable for all aspect of this original work.

Paul Schramm made substantial contributions to the study design and formulation of results, providing critical review of the content through a public health lens. He gives final approval for the manuscript to be published and agrees to be accountable for all aspect of this original work.

Conflicts of Interest: none

Funding: none

Clinical Trial Registration: NA

Keywords: Pollen, Phenology, Pollinosis, Climate, Allergic Rhinitis, Meteorology, Allergy, Ragweed, Oak, Climate Change

Abbreviations: none

Word Count: 3,207

Figures: 4

Tables: 4

“This information is distributed solely for the purpose of pre-dissemination peer review under applicable information quality guidelines. It has not been formally disseminated by [the Centers for Disease Control and Prevention/the Agency for Toxic Substances and Disease Registry]. It does not represent and should not be construed to represent any agency determination or policy.”

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

Objective: We investigated 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 (NAB) pollen counting station located in metropolitan Atlanta, Georgia, U.S. for 13 allergenic taxa. To examine long-term trends over time, we developed linear regression models for six pollen measures. To examine 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 timing of pollen release but varied by taxa. Generally, warmer spring temperatures were associated with an earlier pollen release. Additionally, precipitation from the preceding fall and winter were 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, GA. 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, commonly 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 due to allergic rhinitis ³. Additionally, in 2005 the overall annual treatment costs in the United States for allergic rhinitis were \$11.2 billion, with direct costs estimated as \$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 disease is unknown, but may be related to changes in pollen exposure or allergenicity ⁸.

Studies have shown 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, while 65% of sites had lengthening pollen seasons ¹⁶. In the United States, further research is

needed to examine the long-term trends in pollen production for multiple allergenic plant taxa because allergy sufferers 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}. However, climate associations vary according to plant type^{9,10,20} and location¹², 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^{12,16,21,22}, there is a distinct gap in knowledge on how inter-annual climate variability affects pollen production throughout the various eco-regions 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, United States, from 1992 to 2018, using airborne pollen data for thirteen allergenic taxa. Additionally, we conducted an analysis of pollen categories, including trees, weeds, and grasses. This is the first study to examine 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, GA, 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 (NAB), as described in detail in previous studies²³⁻²⁵. The NAB provides standardized criteria for collection of pollen data in the U.S. and Canada. Pollen concentrations were reported as grains per cubic meter

(PPCM) of air and were typically collected five 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 (e.g. spring pollen season), typically in April²⁶. Thirteen pollen taxa were selected for analysis based on two criteria: 1) known allergenicity (i.e. the ability to cause an allergic reaction in patients)^{17,18}, and 2) the percentage of total pollen concentration. Based on 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). Over the 27-year period, the pollen monitoring site has been in four different locations. It was moved in 1998, 2010, and 2015, with all locations within a nine-mile radius. Utilizing a regression discontinuity design analysis, we found that shifts in pollen concentration data due to station location change were not statistically significant ($\alpha = 0.05$).

Pollen Seasonality Measures. We calculated six 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^{15,19,27}. The 3-day consecutive approach specifies the start date of the pollen season after three consecutive days of observed pollen above 1.0 PPCM for each pollen type, and the end of the pollen season after three consecutive days of pollen less than 1.0 PPCM. We aggregated the pollen concentration data into two different pollen seasons, the spring pollen season (January – June) and the fall pollen season (July-December), in order to account for the bi-modal distribution of the pollen data, which typically peaked in the spring months (e.g. tree pollen) and fall months (e.g. weed) pollen. As

compared to 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 appears to be more sensitive in capturing the entirety of the pollen season (i.e. 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, while 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 dataset, 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 ²⁸. The climate variables included in this analysis were daily average minimum temperature, 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) (Figure 2). We found an increasing trend in spring and summer average temperatures during the 27-year period at the 95% significance level (Figure 2).

Statistical Analysis. To determine the taxa specific trends over time for the various pollen season indicators (e.g. 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 (e.g., average daily pollen concentration) based on this model. Percent change was

calculated by log transforming the dependent variable (i.e., pollen indicators) and interpreting the regression parameter as percent change over time.

To determine 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 six 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, non-independent, comparisons (four seasonal temperature averages), we report the Holm–Bonferroni adjusted p-values. For those pollen measures that exhibited a statistically significant trend, a detrended pollen data set was used in the regression model to account for non-stationarity. Additionally, a detrended dataset was used in the regression models for those climate variables that exhibited a statistically significant trend (e.g., 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 allergenic¹⁸ (Table 1). Pine pollen (28.1%) was the second most abundant pollen. Although not considered a significant contributor to allergic rhinitis, pine pollen may act as a respiratory irritant^{18,29} (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) out 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 to the fall pollen season (Figure 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 as compared to the spring, and was dominated by ragweed pollen (48%) (Table 1), one of the most important causes of allergic rhinitis due to its high allergenicity¹⁸.

Pollen Trends Analysis. We analyzed long-term pollen trends over the 27-year period and found statistically significant 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). Additionally, the season start date occurred earlier for mulberry and sycamore, while 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 seven distinct tree pollens exhibited a significant increasing trend in airborne pollen concentrations over the 27-year period, and none exhibited a significant decreasing trend (Figure 4). The average daily pollen concentration for oak pollen, the most abundant pollen type, increased annually by 5.2% while juniper pollen concentration increased by 9.9%. Increasing trends in peak pollen concentration (i.e., the maximum pollen concentration recorded each season) were also statistically significant 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 exhibited 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 determining 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 nor peak pollen concentrations. Additionally, 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). Additionally, 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.

Preceding fall temperatures did not play a significant role in the timing of spring pollen phenology. However, preceding fall precipitation did have a significant effect on average daily pollen concentrations for *pine* and *weed* pollen. 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.

Climate and Pollen Phenology - Fall Pollen Season. For the fall pollen season (July – Dec.), there were no statistically significant associations with seasonal temperatures. However, fall precipitation did have an influence on both peak pollen concentration and pollen phenology for several plant types. 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 over the 27-year period, especially in trees during the spring pollen season. Specifically, six of the nine trees included in this study exhibited a statistically significant 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% increase (average daily pollen concentration) every year. Furthermore, even when outliers were removed from the dataset, 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 (e.g., 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 over the last 27 years, potentially increasing the risk of negative health impacts related to pollen exposure such as allergic rhinitis or asthma-related hospitalizations²⁴. 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 (Mar. - May) and summer months (Jun. – Aug.) 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. Additionally, 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 associations between seasonal climate and pollen season timing differed according to taxa, which is consistent with previous research that also found that seasonal temperatures can affect pollen season timing and tree growth, but only for certain species^{12, 14, 16, 20, 35}. According to our results, increased precipitation during the preceding fall months (Sep. – Nov.) had a positive effect on pollen concentrations (average daily pollen concentration) months later for *pine* and *all weeds* in the spring. In summary, seasonal variations in seasonal climate did have an effect on pollen phenology, increasing the risk of pollen exposure, which suggests 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 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 CO₂ in the atmosphere, neither of which were not included in this analysis. We also found that seasonal variations in spring temperatures affected pollen season start date (e.g.,

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 shown that anthropogenic climate change has exacerbated pollen seasons, especially in terms of spring pollen season timing [Add source Anderegg 2021] .

Limitations and Discontinuity Analysis. Although our pollen concentration dataset 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. However, 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 dataset is not unique in the United States because a large majority of pollen monitoring stations are not automated; the current method for collecting pollen concentration, utilizing an air sampling rod that is examined under microscopy to count individual pollen grains, is time and resource intensive.

Additionally, although the station moved to three different locations throughout the period of record, all locations were within a nine-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, which suggests that our results are valid.

We only used a single pollen station for the analysis, but previous research has shown 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 range³⁰. Although we have some

limitations with the pollen concentration data, the data is relatively robust long-term dataset and within the auspices of the National Allergy Bureau, which sets stringent quality standards for pollen collection. Furthermore, the data set used for 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 (e.g., highly developed areas and suburban areas) increased by 12.8% and impervious surfaces increased by 19.4%, from 2001 to 2016. Additionally, the percent increase in urban development is likely much larger when taking into account the entire period of our analysis from 1992 to 2018 due to the large increase (+70%) in Cobb County's population from 1990 to 2020. Land cover and land use changes could have increased surrounding surface temperatures at weather observation stations due 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 dataset 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 ³¹ and 8.3% for children ³², 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 symptoms²⁹. Additionally, due to the increased use of non-native 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, due to the release of pollen during different times of the year than native plant species²³. From our analysis, we found that elm pollen has recently become abundant in both the spring and fall pollen seasons, while previously elm pollen was only found during the spring pollen season.

While an exact dose-response relationship between pollen concentrations and the onset of allergic rhinitis remains unclear, previous studies have shown that high pollen concentrations were associated with increased allergic rhinitis cases³³, allergy medication sales³⁴, and asthma and wheeze-related emergency department visits²⁴. 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 over 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 (e.g., sublingual immunotherapy tablets need to be started 12 weeks prior to the onset of pollen season) and timing of measures to reduce pollen exposure for patients who suffer from allergic rhinitis or other allergic illness. 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 (e.g., satellite imagery, phenology, automated pollen monitoring) to provide a high resolution and dataset 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 (e.g., 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 three pollen groups (trees, weeds, grasses) for both the spring and fall pollen season in Atlanta, GA, and found that a large majority of 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 (e.g. 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.

REFERENCE LIST

- 1 Grammer, L. & Greenberger, P. 713 (Wolters Kluwer, New York, 2009).
- 2 Centers for Disease Control and Prevention, N. C. f. H. S. *National Health Interview Survey 2017* on <https://www.cdc.gov/nchs/nhis/SHS/tables.htm>, released 2019. , <<https://www.cdc.gov/nchs/nhis/SHS/tables.htm>> (2017).
- 3 Vandenplas, O. et al. Impact of Rhinitis on Work Productivity: A Systematic Review. *Journal of Allergy and Clinical Immunology. In Practice* **6**, 1274-1286.e1279, doi:<http://dx.doi.org/10.1016/j.jaip.2017.09.002> (2018).
- 4 Meltzer, E. O. & Bukstein, D. A. The economic impact of allergic rhinitis and current guidelines for treatment. *Ann Allergy Asthma Immunol* **106**, S12-16, doi:10.1016/j.anai.2010.10.014 (2011).
- 5 Pawankar, R., Canonica, G., ST Holgate, S., Lockey, R. & Blaiss, M. (ed World Allergy Organization) (2013).
- 6 Wallace, D. V. et al. The diagnosis and management of rhinitis: An updated practice parameter. *Journal of Allergy and Clinical Immunology* **122**, S1-S84, doi:<http://dx.doi.org/10.1016/j.jaci.2008.06.003> (2008).
- 7 Yoo, B., Park, Y., Park, K. & Kim, H. A 9-year Trend in the Prevalence of Allergic Disease Based on National Health Insurance Data. *J Prev Med Public Health* **48**, 301-309, doi:10.3961/jpmph.15.011 (2015).

- 8 Sheffield, P. E., Weinberger, K. R. & Kinney, P. L. Climate Change, Aeroallergens, and Pediatric Allergic Disease. *Mount Sinai Journal of Medicine* **78**, 78-84, doi:10.1002/msj.20232 (2011).
- 9 Corden, J. & Millington, W. A study of Quercus pollen in the Derby area, UK. *Aerobiologia* **15** (1999).
- 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. *International Journal of Biometeorology* **52**, 667-674, doi:10.1007/s00484-008-0159-2 (2008).
- 11 Ziska, L. & Beggs, P. Anthropogenic climate change and allergen exposure: The role of plant biology. *Journal of Allergy and Clinical Immunology* **129**, 27-32, doi:10.1016/j.jaci.2011.10.032 (2012).
- 12 Emberlin, J. *et al.* Responses in the start of Betula (birch) pollen seasons to recent changes in spring temperatures across Europe. *International Journal of Biometeorology* **46**, 159-170, doi:10.1007/s00484-002-0139-x (2002).
- 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* **35**, 1017-1023, doi:10.1111/j.1600-0587.2012.07607.x (2012).
- 14 Garcia-Mozo, H. *et al.* Quercus pollen season dynamics in the Iberian Peninsula: Response to meteorological parameters and possible consequences of climate change. *Annals of Agricultural and Environmental Medicine* **13**, 209-224 (2006).
- 15 Ariano, R., Canonica, G. W. & Passalacqua, G. Possible role of climate changes in variations in pollen seasons and allergic sensitizations during 27 years. *Annals of Allergy Asthma & Immunology* **104**, 215-222, doi:10.1016/j.anai.2009.12.005 (2010).
- 16 Ziska, L. H. *et al.* Temperature-related changes in airborne allergenic pollen abundance and seasonality across the northern hemisphere: a retrospective data analysis. *The Lancet Planetary Health* **3**, e124-e131, doi:10.1016/S2542-5196(19)30015-4 (2019).
- 17 Lin, R. Y., Clauss, A. E. & Bennett, E. S. Hypersensitivity to common tree pollens in New York City patients. *Allergy and Asthma Proceedings* **23**, 253-258 (2002).
- 18 Lewis, W., Vinay, P. & Zenger, V. *Airborne and Allergenic Pollen of North America*, (1983).
- 19 Ziska, L. *et al.* Recent warming by latitude associated with increased length of ragweed pollen season in central North America. *Proceedings of the National Academy of Sciences of the United States of America* **108**, 4248-4251, doi:10.1073/pnas.1014107108 (2011).
- 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. *International Journal of Biometeorology* **51**, 181-191, doi:10.1007/s00484-006-0059-2 (2007).
- 21 Ariano, R., Canonica, G. W. & Passalacqua, G. Possible role of climate changes in variations in pollen seasons and allergic sensitizations during 27 years. *Annals of Allergy, Asthma & Immunology* **104**, 215-222, doi:<http://dx.doi.org/10.1016/j.anai.2009.12.005> (2010).
- 22 D'Amato, G. *et al.* Allergenic pollen and pollen allergy in Europe. *Allergy* **62**, 976-990, doi:10.1111/j.1398-9995.2007.01393.x (2007).
- 23 Shams, M. & Fineman, S. High Chinese elm pollen counts in the fall in Atlanta, Georgia, 2009–2015. *Annals of Allergy, Asthma & Immunology* **117**, 553-554, doi:10.1016/j.anai.2016.08.011 (2016).
- 24 Darrow, L. *et al.* Ambient pollen concentrations and emergency department visits for asthma and wheeze. *Journal of Allergy and Clinical Immunology* **130**, 630-638 (2011).
- 25 Levetin, E. J. C. A. & Reports, A. Methods for aeroallergen sampling. **4**, 376-383, doi:10.1007/s11882-004-0088-z (2004).

- 26 Pennington, A. F., Sircar, K. D. & Hsu, J. Report on Understanding the National Allergy Bureau as a Public Health Surveillance System. *Journal of Allergy and Clinical Immunology* **143**, AB192, doi:10.1016/j.jaci.2018.12.589 (2019).
- 27 Bastl, K., Kmenta, M. & Berger, U. E. Defining Pollen Seasons: Background and Recommendations. *Curr Allergy Asthma Rep* **18**, 73-73, doi:10.1007/s11882-018-0829-z (2018).
- 28 Information, N. N. C. f. E. (2019).
- 29 Grammer, L. & Greenberger, P. *Patterson's Allergic Diseases*. 7th edn, (Lippincott Williams & Wilkins, 2009).
- 30 Pashley, C. H. *et al.* Reproducibility between counts of airborne allergenic pollen from two cities in the East Midlands, UK. *Aerobiologia* **25**, 249-263, doi:10.1007/s10453-009-9130-x (2009).
- 31 CDC. QuickStats: Percentage of Adults Aged 18–64 Years with Current Asthma, by State — National Health Interview Survey, 2014–2016. (CDC, 2018).
- 32 Zahran, H., Bailey, C., Damon, S., Garbe, P. & Breysse, P. Vital Signs: Asthma in Children — United States, 2001–2016. 149-155 (CDC, 2018).
- 33 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. *Science of the Total Environment* **370**, 39-50, doi:10.1016/j.scitotenv.2006.05.022 (2006).
- 34 Sheffield, P. *et al.* The Association of Tree Pollen Concentration Peaks and Allergy Medication Sales in New York City: 2003–2008 *Allergy* **2011** (2011).
- 35 Maurya J. & Bhalerao, R. Photoperiod- and temperature-mediated control of growth cessation and dormancy in trees: a molecular perspective, *Annals of Botany* **120**, 351–360 (2017)
- 36 Homer, C. *et al.* Conterminous United States land cover change patterns 2001–2016 from the 2016 National Land Cover Database. *ISPRS Journal of Photogrammetry and Remote Sensing* **162**, 184-199 doi.org/10.1016/j.isprsjprs.2020.02.019 (2020)
- 37 Anderegg, R *et al.* Anthropogenic climate change is worsening North American pollen seasons. *Proceedings of the National Academy of Sciences* (118) 7. DOI: 10.1073/pnas.2013284118
- 38 Quick Facts for Cobb County Georgia [Internet]. Suitland (MD): The US Census Bureau. c2021 - [cited 2021 May 26]. Available from: <https://www.census.gov/quickfacts/cobbcountygeorgia>

ALL TABLES

Table 1. Percentage of Total Pollen Count by Season

Spring Pollen Season (JAN - JUN)	Percent Pollen
<i>Quercus</i> (Oak)	41.1%
<i>Pinus</i> (Pine)	28.1%
<i>Juniperus</i> (Juniper)	3.4%
<i>Platanus</i> (Sycamore)	3.4%
<i>Betula</i> (Birch)	3.1%
<i>Morus</i> (Mulberry)	2.8%
<i>Ulmus</i> (Elm)	1.6%

<i>Salix</i> (Willow)	1.5%
<i>Poaceae</i> (Grasses)	1.5%
<i>Acer</i> (Maple)	1.1%
Fall Pollen Season (JAN - JUN)	
<i>Ambrosia</i> (Ragweed)	48.3%
<i>Ulmus</i> (Elm)	17.5%
<i>Poaceae</i> (Grasses)	5.1%
<i>Amaranthus</i> (Pigweed)	3.0%
<i>Urticaceae</i> (Nettle)	2.7%

Table 2. Annually averaged pollen metrics from 1992 to 2018, 95% confidence intervals in parentheses. Pollen concentrations were measured in pollen grains per cubic meter (PPCM). The pollen “Spring Season” was defined as January 1 - June 30, and “Fall Season” was defined as July 1 – December 31.

Pollen Type (Common Name)	Avg. Daily Pollen Conc.	Peak Pollen Concentration	Season Start Date	Season Peak Date	Season End Date	Season Length (Days)	N
Spring Season (JAN 1 - JUN 30)							
All Trees	283.7 (245.1 to 322.4)	4,296.7 (3521.3 to 5072.1)	Jan. 16 (Jan 11 to Jan 21)	Apr. 4 (Apr 2 to Apr 7)	Jun. 23 (Jun 20 to Jun 26)	159.0 (151.7 to 166.3)	27
Quercus(Oak)	257.9 (207.9 to 307.8)	2,599.0 (2039.6 to 3158.4)	Mar. 3 (Feb 27 to Mar 8)	Apr. 4 (Apr 1 to Apr 8)	May. 18 (May 14 to May 22)	76.4 (69.2 to 83.7)	27
Pinus (Pine)	127.0 (105.6 to 148.4)	1,825.1 (1367.2 to 2282.9)	Feb. 23 (Feb 15 to Mar 2)	Apr. 4 (Apr 1 to Apr 7)	Jun. 5 (May 27 to Jun 13)	102.7 (90.8 to 114.6)	27
Morus(Mulberry)	32.6 (18.3 to 46.9)	270.4 (117.3 to 423.5)	Mar. 29 (Mar 25 to Apr 3)	Apr. 10 (Apr 6 to Apr 13)	May. 10 (May 6 to May 14)	41.6 (36.2 to 47.1)	27
Platanus Sycamore)	30.8 (23.8 to 37.7)	174.3 (127.1 to 221.5)	Mar. 24 (Mar 18 to Mar 30)	Apr. 8 (Apr 4 to Apr 11)	May. 6 (Apr 30 to May 12)	43.3 (33.9 to 52.7)	27
Betula(Birch)	24.4 (17.2 to 31.6)	195.4 (108.7 to 282.1)	Mar. 5 (Feb 28 to Mar 10)	Apr. 4 (Apr 1 to Apr 7)	Apr. 28 (Apr 23 to May 3)	54.6 (47.3 to 62)	27
Juniperus(Juniper)	21.7 (16.8 to 26.5)	283.3 (182.3 to 384.3)	Jan. 24 (Jan 18 to Jan 30)	Feb. 25 (Feb 20 to Mar 2)	Apr. 4 (Mar 29 to Apr 10)	70.8 (62.8 to 78.8)	27
Ulmus(Elm)	15.9 (10.3 to 21.4)	131.0 (86.3 to 175.8)	Feb. 12 (Feb 8 to Feb 17)	Feb. 26 (Feb 21 to Mar 2)	Mar. 28 (Mar 22 to Apr 4)	45.0 (36.7 to 53.3)	27
Salix(Willow)	11.2 (9.2 to 13.2)	68.4 (47.1 to 89.7)	Mar. 22 (Mar 16 to Mar 28)	Apr. 6 (Apr 1 to Apr 12)	May. 15 (May 6 to May 23)	53.4 (45.3 to 61.4)	27
Acer(Maple)	8.0 (5.8 to 10.2)	65.3 (41.3 to 89.4)	Feb. 14 (Feb 7 to Feb 21)	Mar. 18 (Mar 7 to Mar 28)	Apr. 5 (Mar 27 to Apr 13)	50.4 (41.6 to 59.1)	27
All Weeds	6.8 (4.4 to 9.1)	82.7 (35.6 to 129.8)	Mar. 11 (Feb 23 to Mar 27)	Apr. 19 (Apr 9 to Apr 29)	May. 21 (May 6 to Jun 5)	71.3 (48.8 to 93.8)	27
Poaceae (Grasses)	7.5 (6.6 to 8.4)	47.5 (37.8 to 57.2)	Mar. 29 (Mar 24 to Apr 3)	May. 10 (May 4 to May 16)	Jun. 18 (Jun 14 to Jun 23)	81.4 (75 to 87.9)	27
Fall Season (JUL 1 - DEC 31)							
All Trees	6.9 (3.8 to 9.9)	136.2 (32.6 to 239.7)	Jul. 29 (Jul 15 to Aug 13)	Sep. 6 (Aug 23 to Sep 20)	Sep. 26 (Sep 10 to Oct 11)	58.5 (38.5 to 78.5)	27
Ulmus (Elm)	19.9 (1.1 to 38.6)	117.7 (14.7 to 220.7)	Aug. 20 (Aug 7 to Sep 2)	Aug. 23 (Aug 9 to Sep 6)	Sep. 1 (Aug 16 to Sep 16)	11.7 (5.9 to 17.5)	27

All Weeds	11.7	(10 to 13.4)	105.2	(67.5 to 142.9)	Jul. 15	(Jul 8 to Jul 22)	Sep. 16	(Sep 13 to Sep 20)	Nov. 14	(Nov 7 to Nov 21)	121.7	(112 to 131.5)	27
Ambrosia (Ragweed)	14.4	(12.2 to 16.6)	89.3	(54.8 to 123.8)	Aug. 21	(Aug 18 to Aug 25)	Sep. 17	(Sep 14 to Sep 21)	Nov. 8	(Nov 3 to Nov 14)	79.0	(72.2 to 85.8)	27
Amaranthus (Pigweed)	1.8	(1.5 to 2)	5.5	(4.3 to 6.6)	Aug. 25	(Aug 18 to Sep 1)	Sep. 6	(Aug 29 to Sep 14)	Sep. 11	(Sep 3 to Sep 20)	17.0	(10.3 to 23.6)	27
Urticaceae (Nettle)	1.8	(1.5 to 2.1)	6.0	(4.5 to 7.5)	Aug. 18	(Aug 9 to Aug 28)	Aug. 26	(Aug 17 to Sep 4)	Sep. 5	(Aug 27 to Sep 14)	17.8	(11.2 to 24.3)	27
Poaceae (Grasses)	1.7	(1.2 to 2.2)	7.0	(5.6 to 8.4)	Jul. 21	(Jul 11 to Jul 31)	Sep. 4	(Aug 22 to Sep 16)	Sep. 16	(Sep 4 to Sep 27)	56.4	(42.5 to 70.3)	27

Table 3. Annual change in pollen concentration in Pollen Grains Per Cubic Meter (PPCM) and change in season timing by day. Confidence Interval by 95% is indicated in parentheses.

Pollen Type (Common Name)	Pct. Change (Avg. Daily Pollen Conc.)	Average Daily Pollen Conc.	Peak Pollen Concentration	Start Date (Days)	Peak Date (Days)	End Date (Days)	Length (Days)
Spring Season (JAN 1 - JUN 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)**	139 (55,223.2)**	-0.63 (-1.3,0)*	-0.3 (-0.3,0.04)	0.47 (0.1,0.9)*	1.1 (0.3,1.9)*
Quercus (Oak)	+5.2%	10.4 (5.5,15.4)**	104 (43.9,163.3)**	0.18 (-0.9,0.5)	-0.5 (-0.5,-0.04)*	-0.3 (-0.8,0.3)	-0.1 (-1.0,9)
Pinus (Pine)	+2.9%	2.9 (0.5,5.5)*	35.1 (-23.3,93.4)	0.46 (-1.5,0.6)	-0.2 (-0.2,0.2)	-0.6 (-1.7,0.6)	-0.1 (-1.7,1.5)
Morus (Mulberry)	+9.9%	3.1 (1.9,4.5)**	32 (16.9,47.2)**	0.64 (-1.2,-0.1)*	-0.5 (-0.5,-0.1)*	0.02 (-0.5,0.6)	0.66 (0.1,3)
Platanus (Sycamore)	+3.3%	0.9 (0.2,1.8)*	9.55 (4.8,14.3)**	1.09 (-1.8,-0.4)**	-0.2 (-0.2,0.3)	0.98 (0.3,1.6)**	2.07 (1.2,3)**
Betula (Birch)		0.8 (0.1,7)	11.9 (1.7,22.2)	0.48 (-1.2,0.3)	-0.4 (-0.4,-0.02)*	-0.1 (-0.8,0.5)	0.35 (-0.6,1.3)
Juniperus (Juniper)	+9.9%	3.1 (1.9,4.5)**	16.3 (4.9,27.8)**	0.66 (-1.3,0)	-0.3 (-0.3,0.4)	0.06 (-0.8,0.9)	0.73 (-0.3,1.7)
Ulmus (Elm)		0.5 (-0.1,1.2)	3.75 (-1.9,9.4)	0.08 (-0.6,0.5)	0.32 (0.3,1)	-0.1 (-0.9,0.8)	0.04 (-1.1,1)
Salix (Willow)	+3.4%	0.3 (0.1,0.5)**	3.39 (1.5,8)**	0.65 (-1.4,0.1)	-0.1 (-0.1,0.6)	0.56 (-0.5,1.7)	1.21 (0.3,2.1)*
Acer (Maple)		-0.2 (-0.5,0.1)	-2.3 (-5.3,0.7)	0.06 (-1.0,9)	-1 (-1.0,3)	-1.5 (-2.4,-0.6)**	-1.4 (-2.4,-0.5)**
All Weeds	+5.2%	0.4 (0.1,0.7)**	9.44 (4.6,14.2)**	2.43 (-4.4,-0.5)*	-0.8 (-0.8,0.5)	0.62 (-1.4,2.6)	3.05 (0.4,5.7)*
Poaceae (Grasses)		-0.1 (-0.2,0)	-0.9 (-2.1,0.4)	0.28 (-1.0,4)	-0.2 (-0.2,0.6)	-0.4 (-1.0,1)	-0.1 (-1.0,7)

Fall Season (JUL 1 - DEC 31)

All Trees	+10.4%	0.6	(0.3,0.9)**	17	(5.3,28.6)**	-	(-4.3,-1.1)**	-0.4	(-0.4,1.3)	1.79	(-0.1,3.7)	4.51	(2.7,6.4)**
<i>Ulmus</i> (Elm)++	+19.9%	3.4	(-1.8,8.7)*	22.5	(-5.3,50.3)*	-	(-2.6,-0.2)**	-0.8	(-0.8,0.5)**	0.19	(-1.2,1.6)**	1.58	(0.4,2.8)**
All Weeds		-0	(-0.2,0.2)	1.59	(-3.3,6.5)	-	(-1.6,0)	0.4	(0.4,0.8)	0.43	(-0.5,1.4)	1.25	(0.1,2.4)*
<i>Ambrosia</i> (Ragweed)		0.1	(-0.2,0.4)	0.63	(-3.9,5.1)	-	(-0.5,0.3)	0.3	(0.3,0.7)	0.02	(-0.7,0.7)	0.12	(-0.8,1)
<i>Amaranthus</i> (Pigweed)		-0	(-0.04,0.03)	0.06	(-0.1,0.2)	0.09	(-0.8,1)	0.3	(0.3,1.3)	0.42	(-0.7,1.5)	0.33	(-0.5,1.2)
<i>Urticaceae</i> (Nettle)		-0	(-0.05,0.02)	-0.1	(-0.3,0.1)	-0.2	(-1.5,1.1)	-0.1	(-0.1,1.1)	-0.3	(-1.5,0.9)	-0.1	(-1.0,8)
<i>Poaceae</i> (Grasses)		-0	(-0.1,0.03)	-0.1	(-0.2,0.1)	-	(-2.6,-0.2)*	-2.3	(-2.3,-0.9)**	-1.8	(-3.2,-0.4)*	-0.4	(-2.2,1.5)

*95% significance level

**99% significance level

++2001-2018

Table 4. Results of the linear regression model for the spring pollen season (Jan. – Jun.), using seasonal average temperatures as independent variables and six pollen measures as dependent variables. 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.

	Spring Temperature Average				Previous Winter Temp Average				Previous Fall Temp Average				Previous Summer Temp Average			
	R	95% CI	R2	SIG	R	95% CI	R2	SIG	R	95% CI	R2	SIG	R	95% CI	R2	SIG
Avg. Daily Pollen Count																
All Trees	-6.6	(-30.6,17.3)	0.0	0.999	0.4	(-15.8,16.6)	0	0.999	-4.0	(-27.4,19.3)	0.0	0.99	6.5	(-23.2,36.1)	0.0	0.99
<i>Quercus</i> (oak)	9.7	(-30.8,50.2)	0.0	0.999	6.1	(-21.2,33.4)	0.0	0.999	18.6	(-20.2,57.3)	0.0	0.99	10.6	(-39.5,60.7)	0.0	0.99
<i>Pinus</i> (pine)	-2.3	(-23,18.5)	0.0	0.999	-10.1	(-23.5,3.2)	0.0	0.522	-7.8	(-27.7,12.1)	0.0	0.99	-2.5	(-28.2,23.1)	0.0	0.99
<i>Morus</i> (mulberry)	-2.8	(-13.7,8.2)	0.0	0.999	4.8	(-2.3,11.9)	0.0	0.712	2.4	(-8.2,13)	0.0	0.99	5.8	(-7.5,19.2)	0.0	0.99
<i>Platanus</i> (sycamore)	4.9	(-1.5,11.3)	0.0	0.501	3.3	(-1.7,7)	0.0	0.501	1.5	(-5,8)	0.0	0.99	3.8	(-4.4,12)	0.0	0.99
<i>Betula</i> (birch)	1.9	(-5.8,9.6)	0.0	0.999	0.3	(-4.9,5.6)	0.0	0.999	-1.8	(-9.2,5.7)	0.0	0.99	1.9	(-7.6,11.4)	0.0	0.99
<i>Juniperus</i> (juniper)	1.2	(-3.4,5.8)	0.0	0.999	-2.4	(-5.4,0.6)	0.0	0.430	0.9	(-3.6,5.4)	0.0	0.47	-0.1	(-5.8,5.6)	0.0	0.9
<i>Ulmus</i> (elm)	2.4	(-3.5,8.3)	0.0	0.501	-2.2	(-6.1,1.7)	0.0	0.501	3.9	(-1.6,9.5)	0.0	0.47	6.9	(0.1,13.7)	0.0	0.19

<i>Betula</i> (birch)	-1.7	(-7.9,4.5)	0.0	1	0.999	-3.0	(-7,1.1)	8	0.577	-2.8	(-8.8,3.1)	0.0	9	0.99	-1.7	(-9.4,6)	0.0	9	0.99
<i>Juniperus</i> (juniper)	1.3	(-4.7,7.3)	0.0	1	0.999	-3.6	(-7.4,0.2)	3	0.241	-2.3	(-8.1,3.5)	0.0	9	0.99	-0.4	(-7.8,7.1)	0.0	9	0.99
<i>Ulmus</i> (elm)	1.9	(-2.6,6.4)	0.1	3	0.999	-3.6	(-6.3,-0.9)	3	0.042	0.7	(-3.7,5.2)	0.0	9	0.99	-0.2	(-5.9,5.4)	0.0	9	0.99
<i>Salix</i> (willow)	-6.1	(-11.8,-0.3)	0.0	6	0.154	-2.2	(-6.3,1.9)	5	0.818	-3.0	(-8.9,3)	0.0	8	0.81	-2.1	(-9.8,5.6)	0.0	8	0.81
<i>Acer</i> (maple)	-2.6	(-10.2,5)	0.0	2	0.999	-1.7	(-6.8,3.4)	2	0.999	5.7	(-1.4,12.7)	0.1	8	0.43	-3.4	(-12.8,6)	0.0	9	0.99
All Weeds	21.6	(-34.7,-8.5)	0.1	2	0.009	0.3	(-10.4,10.9)	0	0.957	-16.2	(-30.1,-2.4)	0.1	2	0.06	-21.0	(-38.6,-3.5)	0.2	2	0.06
<i>Poaceae</i> (grasses)	-4.3	(-9.6,1.1)	0.0	0	0.456	-0.5	(-4.3,3.3)	0	0.999	0.6	(-4.8,6.1)	0.0	9	0.99	-4.1	(-10.9,2.6)	0.0	6	0.65
Pollen Season Peak Date																			
All Trees	-5.5	(-7.6,-3.3)	0.5	2	<0.00	-0.5	(-2.6,1.6)	1	0.691	-1.4	(-4.4,1.6)	0.0	1	0.69	-3.0	(-6.6,0.7)	0.1	8	0.31
<i>Quercus</i> (oak)	-6.3	(-8.7,-3.8)	0.5	3	<0.00	-0.3	(-2.7,2.1)	0	0.999	-0.7	(-4.1,2.8)	0.0	9	0.99	-2.8	(-7.1,5)	0.0	8	0.57
<i>Pinus</i> (pine)	-4.2	(-6.6,-1.7)	0.3	3	0.007	-2.6	(-4.3,-0.9)	9	0.012	-1.7	(-4.5,1.1)	0.0	8	0.22	-2.9	(-6.4,0.6)	0.1	0	0.21
<i>Morus</i> (mulberry)	-4.0	(-7,-0.9)	0.2	2	0.053	-1.1	(-3.4,1.2)	4	0.674	0.2	(-3.2,3.5)	0.0	8	0.91	-3.7	(-7.7,0.3)	0.0	6	0.19
<i>Platanus</i> (sycamore)	-4.5	(-8,-1.1)	0.2	3	0.045	-2.8	(-5.2,-0.5)	0	0.060	0.5	(-3.2,4.3)	0.0	7	0.77	-2.1	(-6.8,2.7)	0.0	8	0.75
<i>Betula</i> (birch)	-3.3	(-6.3,-0.4)	0.1	8	0.114	-0.5	(-2.6,1.7)	1	0.951	1.1	(-2,4.2)	0.0	1	0.95	-2.0	(-5.9,2)	0.0	8	0.93
<i>Juniperus</i> (juniper)	1.7	(-4.3,7.7)	0.0	1	0.999	4.2	(-7.8,-0.5)	8	0.111	-1.2	(-7,4.6)	0.0	9	0.99	-3.0	(-10.3,4.3)	0.0	9	0.99
<i>Ulmus</i> (elm)	2.5	(-3,8)	0.0	3	0.999	-0.9	(-4.7,2.8)	1	0.999	0.9	(-4.4,6.3)	0.0	9	0.99	-5.3	(-11.9,1.2)	0.1	5	0.41
<i>Salix</i> (willow)	-6.1	(-11.3,-0.9)	0.1	9	0.091	-1.3	(-5.2,2.5)	2	0.976	-0.9	(-6.5,4.7)	0.0	6	0.97	-6.4	(-13,0.2)	0.0	6	0.17
<i>Acer</i> (maple)	-6.3	(-17.3,4.6)	0.0	5	0.981	-4.1	(-11.5,3.3)	5	0.981	-1.4	(-12.3,9.5)	0.0	9	0.99	1.8	(-12.1,15.7)	0.0	9	0.99
All Weeds	-3.5	(-14,7.1)	0.0	2	0.999	3.6	(-3.4,10.6)	4	0.999	1.1	(-9.3,11.5)	0.0	9	0.99	-5.0	(-18,8)	0.0	9	0.99
<i>Poaceae</i> (grasses)	-6.3	(-12.1,-0.5)	0.1	7	0.104	-2.7	(-6.9,1.4)	7	0.369	-2.5	(-8.6,3.6)	0.0	9	0.40	-		0.2	9	0.01
Peak Season End Date																			
All Trees	0.2	(-2.9,3.3)	0.0	0	0.999	2.0	(0.1,3.9)	6	0.162	1.1	(-1.9,4.1)	0.0	9	0.99	0.3	(-3.6,4.1)	0.0	9	0.99
<i>Quercus</i> (oak)	-3.3	(-7.3,0.7)	0.1	0	0.450	0.5	(-2.3,3.4)	1	0.850	-2.1	(-6.3,2)	0.0	3	0.72	-3.0	(-8.3,2.2)	0.0	3	0.72
<i>Pinus</i> (pine)	-1.8	(-11.3,7.8)	0.0	1	0.705	-3.2	(-9.5,3.1)	4	0.615	-8.0	(-16.7,0.6)	0.1	8	0.25	-10.4	(-21.4,0.7)	0.1	8	0.25
<i>Morus</i> (mulberry)	-6.8	(-10.3,-3.3)	0.0	0	0.002	0.3	(-2.8,3.3)	0.0	0.864	-4.0	(-8,0)	0.1	0	0.14	-4.0	(-9.3,1.3)	0.0	0	0.26

	9				0			5				6		9				2	
<i>Platanus</i> (sycamore)	-1.6	(-7,3.8)	0.0 1 0.0	0.999	-2.5	(-6,1)	0.0 8 0.0	0.626	0.4	(-4.9,5.7)	0.0 0 0.0	0.99 9 0.70	1.2	(-5.6,7.9)	0.0 1 0.0	0.99 9 0.99			
<i>Betula</i> (birch)	-3.6	(-8.8,1.6)	8 0.0	0.648	-1.1	(-4.7,2.5)	2 0.0	0.999	3.0	(-2.1,8.1)	6 0.0	8 0.99	0.8	(-5.8,7.5)	0 0.0	9 0.86			
<i>Juniperus</i> (juniper)	-1.3	(-8.1,5.5)	1 0.0	0.999	-0.8	(-5.4,3.7)	1 0.0	0.999	0.2	(-6.4,6.8)	0 0.0	9 0.99	-5.0	(-13.1,3.1)	6 0.0	9 0.99			
<i>Ulmus</i> (elm)	0.2	(-7.1,7.4)	0 0.0	0.999	-0.3	(-5.2,4.5)	0 0.0	0.999	-2.6	(-9.6,4.3)	2 0.0	9 0.99	-1.8	(-10.8,7.1)	1 0.0	9 0.99			
<i>Salix</i> (willow)	-5.7	(-14.7,3.2)	6 0.0	0.800	2.7	(-3.4,8.8)	3 0.0	0.999	-1.3	(-10.3,7.6)	0 0.0	9 0.99	-4.3	(-15.6,7)	2 0.0	9 0.99			
<i>Acer</i> (maple)	-5.4	(-12.5,1.7)	9 0.0	0.517	-1.0	(-6,3.9)	1 0.0	0.999	-0.6	(-7.8,6.6)	0 0.0	9 0.99	-0.9	(-10.8,3)	0 0.0	9 0.79			
All Weeds	-6.6	(-22.7,9.5)	3 0.0	0.999	2.9	(-8,13.8)	1 0.0	0.999	4.4	(-11.3,20.2)	1 0.0	9 0.99	-12.5	(-32,7)	6 0.0	9 0.99			
<i>Poaceae</i> (grasses)	0.0	(-4.8,4.9)	0 0.0	0.999	-1.5	(-4.7,1.7)	3 0.0	0.999	-1.0	(-5.7,3.7)	1 0.0	9 0.99	2.6	(-3.3,8.5)	3 0.0	9 0.99			
Pollen Season Length																			
All Trees	0.2	(-6.8,7.2)	0 0.0	0.999	5.2	(1.9,4)	1 0.0	0.070	-0.6	(-7.4,6.2)	0 0.0	9 0.86	-3.0	(-11.6,5.5)	2 0.0	9 0.99			
<i>Quercus</i> (oak)	-2.6	(-10.4,5.2)	2 0.0	0.993	3.2	(-1.9,8.3)	6 0.0	0.866	-4.1	(-11.5,3.4)	5 0.0	6 0.93	-1.2	(-10.9,8.5)	0 0.0	3 0.93			
<i>Pinus</i> (pine)	-5.2	(-17.9,7.4)	3 0.0	0.936	6.1	(-2.2,14.4)	8 0.1	0.566	-6.1	(-18.3,6.1)	4 0.0	6 0.99	-4.8	(-20.5,10.9)	2 0.0	6 0.99			
<i>Morus</i> (mulberry)	-1.1	(-7,4.7)	1 0.0	0.999	3.5	(-0.2,7.2)	3 0.0	0.240	1.0	(-4.7,6.6)	0 0.0	9 0.99	-0.3	(-7.5,7)	0 0.0	9 0.99			
<i>Platanus</i> (sycamore)	-2.8	(-10.1,4.5)	2 0.0	0.999	0.1	(-4.9,5)	0 0.0	0.999	-0.2	(-7.3,7)	0 0.1	9 0.44	3.2	(-5.8,12.2)	2 0.0	9 0.99			
<i>Betula</i> (birch)	-1.9	(-9.8,5.9)	1 0.0	0.999	1.8	(-3.5,7.1)	2 0.0	0.999	5.9	(-1.5,13.2)	0 0.0	7 0.99	2.5	(-7.2,12.3)	1 0.0	9 0.99			
<i>Juniperus</i> (juniper)	-2.6	(-11.2,6)	2 0.0	0.999	2.8	(-2.9,8.5)	4 0.0	0.999	2.5	(-5.9,10.8)	1 0.0	9 0.99	-4.6	(-15.2,5.9)	3 0.0	9 0.99			
<i>Ulmus</i> (elm)	-1.7	(-10.6,7.2)	1 0.0	0.999	3.3	(-2.6,9.2)	5 0.0	0.999	-3.3	(-11.9,5.2)	2 0.0	9 0.99	-1.6	(-12.7,9.4)	0 0.0	9 0.99			
<i>Salix</i> (willow)	0.4	(-7.3,8)	0 0.0	0.999	3.6	(-1.3,8.6)	8 0.0	0.562	-2.4	(-9.7,5)	2 0.1	9 0.33	-2.2	(-11.6,7.2)	1 0.0	9 0.99			
<i>Acer</i> (maple)	-2.8	(-10.8,5.3)	2 0.0	0.999	0.6	(-4.9,6)	0 0.0	0.999	-6.5	(-13.9,1)	1 0.1	9 0.26	2.5	(-7.4,12.5)	1 0.0	9 0.99			
All Weeds	15.0	(-6.1,36.1)	8 0.0	0.469	2.0	(-12.8,16.8)	0 0.0	0.999	18.6	(-1.3,38.6)	3 0.0	5 0.99	8.6	(-18.4,35.5)	2 0.1	9 0.38			
<i>Poaceae</i> (grasses)	4.3	(-2.4,11)	6 0.0	0.600	-1.0	(-5.6,3.7)	1 0.0	0.999	-1.7	(-8.4,5)	1 0.0	9 0.99	6.8	(-1.3,14.9)	1 0.0	9 0.99			

FIGURE LEGEND

Figure 1. Comparison of methodologies to define the onset data and end data (red vertical lines) of pollen season as compared to actual pollen concentrations (area in black), using oak pollen data from Atlanta, GA (1992-2018).

Figure 2. A scatter-plot 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).

Figure 3. Average daily pollen concentrations for grouped pollen according to trees, weeds, and grasses (1992-2018). The Y-axis represents the average daily average pollen concentration (total annual pollen concentration/number of observation days). The X-axis represents the day of the year.

Figure 4. Scatter plots of average daily pollen concentrations over time (1992-2018). The time series linear regression line is colored in red, the confidence interval is colored in gray.

ALL FIGURES

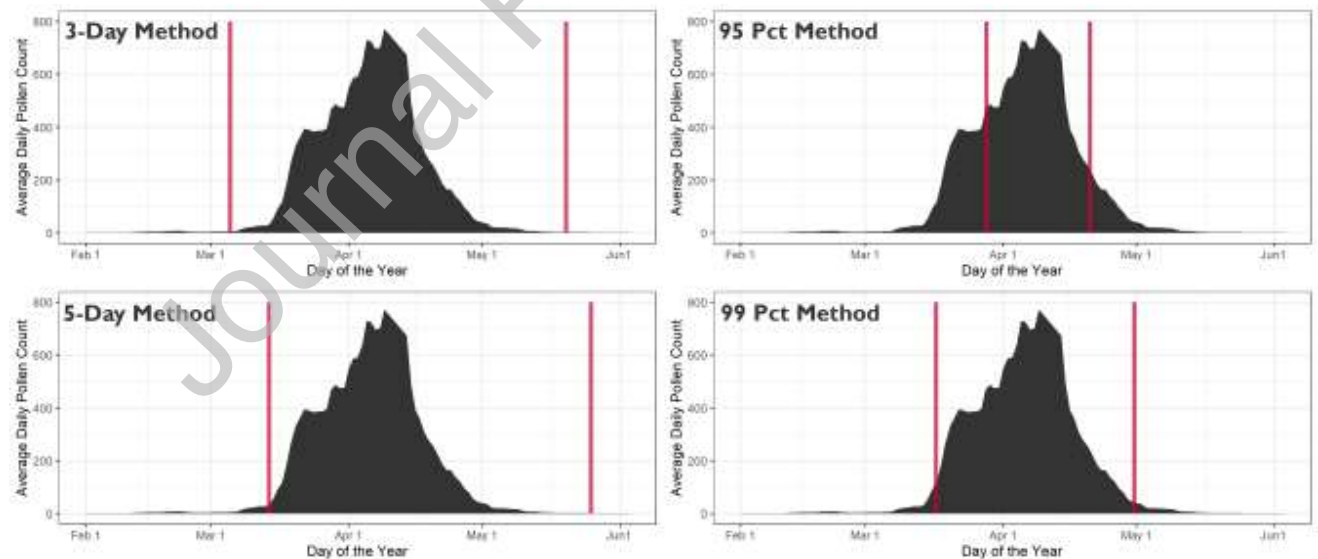


Figure 1.

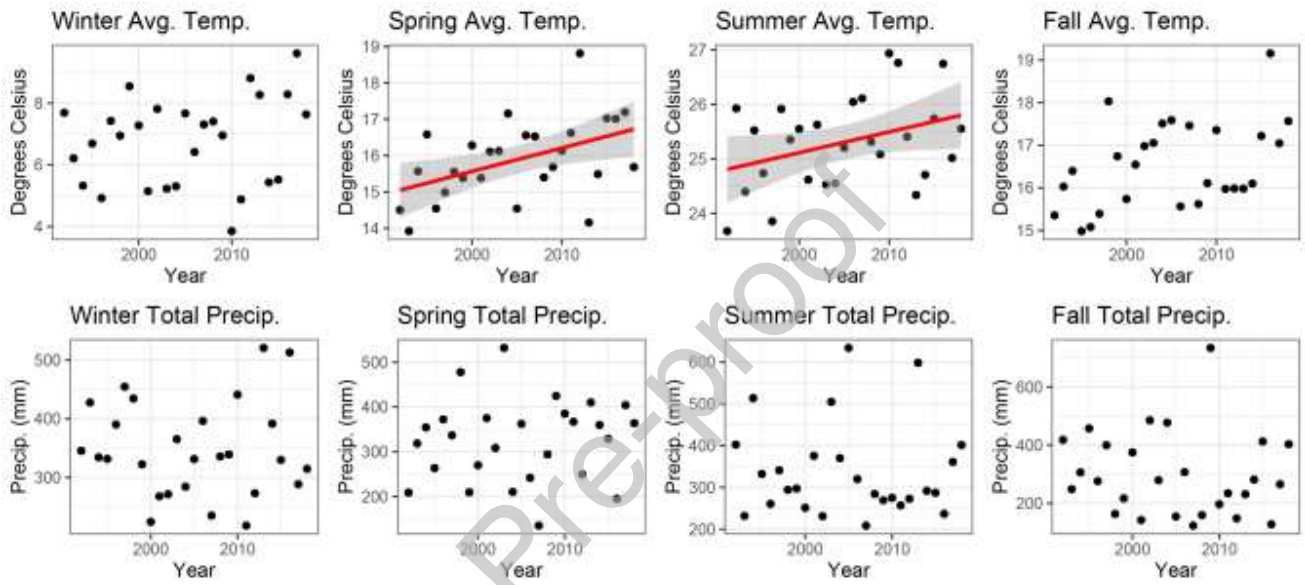


Figure 2.

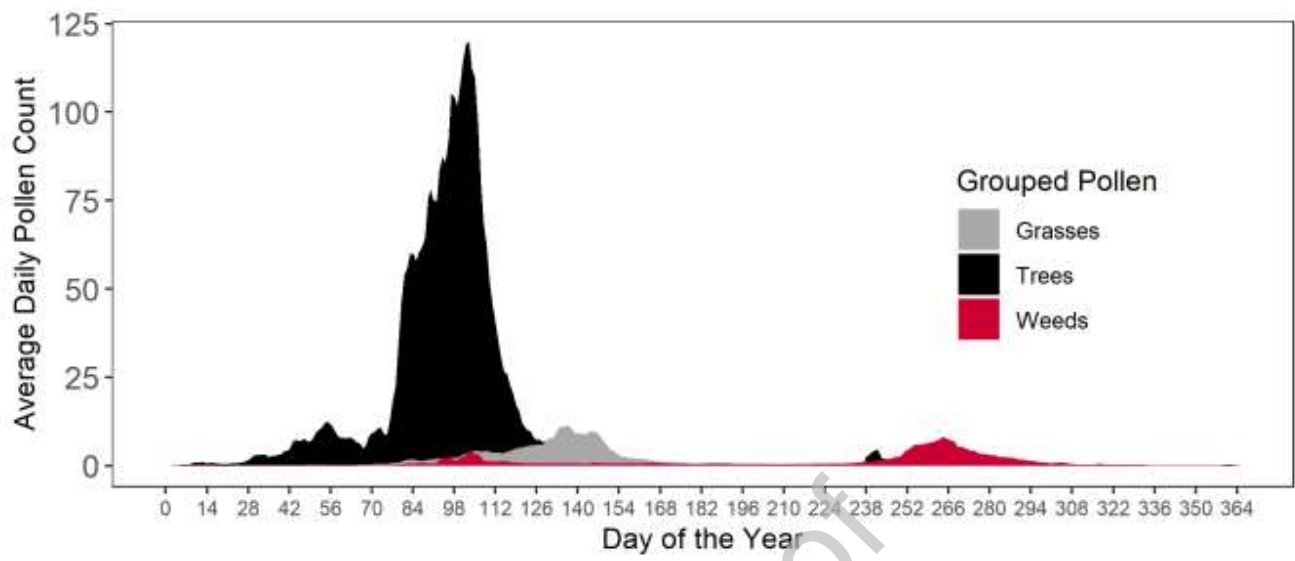


Figure 3.

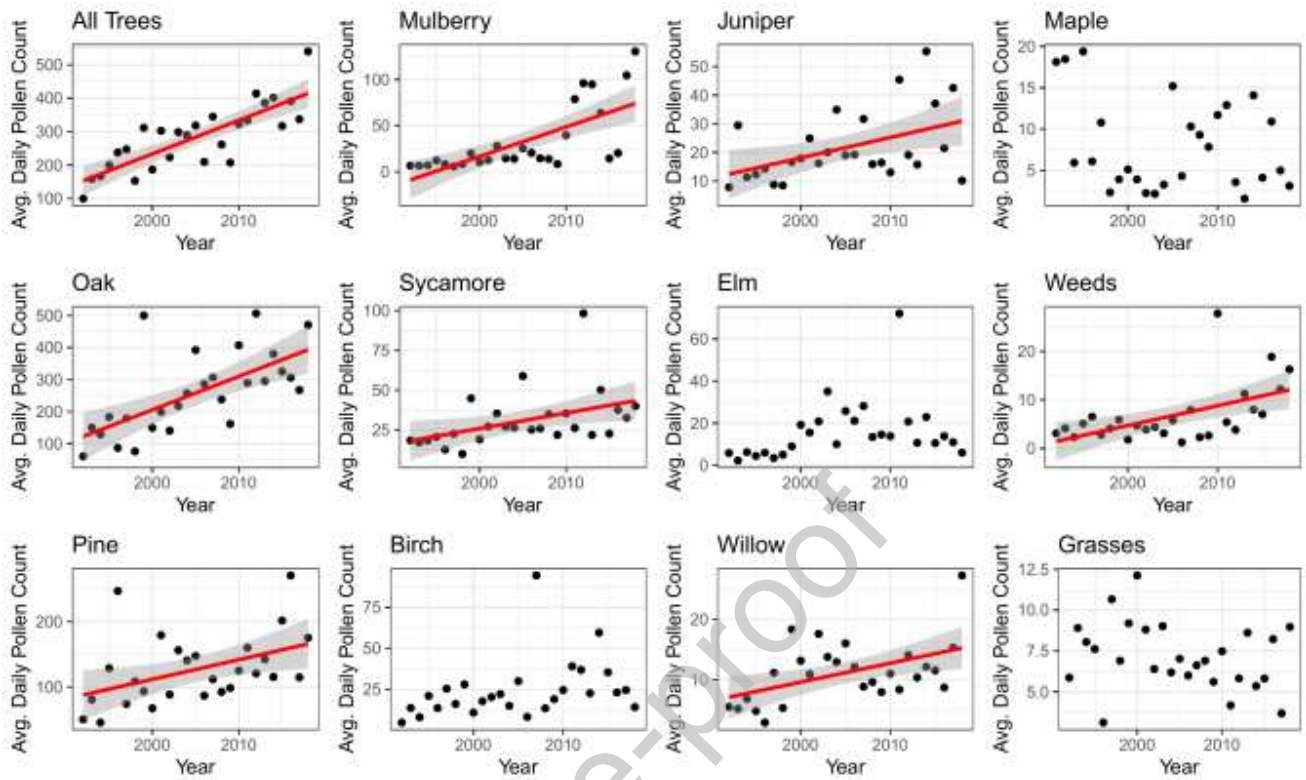


Figure 4.