



The impact of weather and climate on pollen concentrations in Denver, Colorado, 2010–2018



Lara Gross, MD ^{*,†,‡}; Richard Weber, MD ^{†,‡}; Molly Wolf, BS [†];
James L. Crooks, PhD, MS ^{‡,§}

^{*} Dallas Allergy & Asthma Center, Dallas, Texas

[†] National Jewish Health, Denver, Colorado

[‡] University of Colorado School of Medicine, Aurora, Colorado

[§] Colorado School of Public Health, Aurora, Colorado

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ABSTRACT

Background: Increasing evidence indicates that climate change is affecting the timing of pollen season and concentrations of allergenic pollens. To date, pollen trends and their associations with meteorological variables have not been studied in most of the United States.

Objective: The purpose of this study was to investigate the effects of weather and climate on pollen concentrations and pollen season timing in Denver, Colorado.

Methods: We retrospectively analyzed tree, grass, and weed pollen counts and meteorological variables from 2010–2018 using linear and Poisson regression models.

Results: Pollen season timing did not demonstrate uniform trends from 2010 to 2018. Certain species demonstrated earlier season start dates (linden, oak) or end dates (birch, maple), and others had later end dates (oak, grass). Only a few species demonstrated changes in season duration (linden, oak, maple, birch) and peak date (maple, birch). Pollen concentrations either remained stable or increased over the years. Temperature and carbon dioxide levels increased over the study period, with the exception of decreased temperature in August. Wind speed remained stable or decreased over the study period.

Conclusion: This study illustrates the complex interactions between pollens and meteorology. Meteorological variables associated with climate change do appear to affect allergenic pollens, though the relationship is variable both amongst pollens and from year to year.

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Introduction

The effects of climate change are diverse and include a multitude of detrimental effects on human health. A growing body of evidence examines changes in pollination patterns attributable to climate change.^{1,2} Increased pollen concentrations and longer pollen seasons have been observed; these climate change–related trends have been linked to an increase in the development of and exacerbations of allergic disease.^{1,3–6}

Increasing concentrations of greenhouse gases, particularly carbon dioxide, caused by industrialization and urbanization, are the main drivers of climate change. The warming associated with increased greenhouse gases is responsible for temperature and

precipitation changes, as well as extreme weather events, such as heat waves, floods, and droughts.⁷

Warmer temperatures associated with climate change lead to earlier pollination of many plants and longer duration of pollination. Several species have been shown to produce more pollen with warmer temperatures. Increases in carbon dioxide also correlate with these pollen trends. Ziska and colleagues^{8,9} examined increased carbon dioxide concentrations and higher temperatures associated with urbanization and their effects on ragweed. In a 2-year period comparing urban and rural sites, they found urbanization, which they considered a surrogate for climate change, correlated with larger ragweed plant size, earlier presence of pollen, and increased pollen concentrations. Hess and colleagues^{6,10} investigated pollen trends and their associations with temperature and morbidity using data from 51 pollen monitoring stations around the United States, though their work has not yet been published in full.

Climate change has been posited to worsen allergic disease by several mechanisms. Longer pollen seasons increase duration of

Reprints: James L. Crooks, PhD, 1400 Jackson St, Denver, CO 80206; E-mail: CrooksJ@NJHealth.org.

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exposure, potentially resulting in more sensitization. Longer pollen seasons also lead to longer symptomatic periods in those with allergic disease, and higher pollen concentrations may lead to more severe symptoms.^{2,11,12} Additionally, climate change is thought to increase the quantity of allergenic protein that individual pollen grains contain.⁷

Although some studies focus on climate change and pollen from the United States, most of the published literature comes from Europe. In Europe, pollen sampling is performed by national weather agencies, and the pollen databases are more accessible.^{13,14} In the United States, sampling is performed by various agencies and allergy clinics, and each individual sampling station must give consent for the National Allergy Bureau to release its data for research purposes.¹⁴

Many of the US studies have found that temperature and precipitation changes are correlated with latitude. Indeed, the first frost is delayed more as latitude increases.² Zhang and colleagues¹⁵ examined pollen counts and meteorological variables across the United States from 1994 to 2010 and found that, with increasing latitude, temperature and precipitation increased, which correlated with longer pollen season durations.¹⁵ Ziska and colleagues² demonstrated a lengthening of pollen seasons ranging from 13 to 27 days in cities ranging from Texas to Canada, with larger differences in length correlating with more northern locations.² This study looked at one of the longest time intervals of pollen collection in the United States, with data ranging from 15 to 27 years, depending on the pollen collection site. Ariano and colleagues¹⁶ examined allergenic pollens over a prolonged period of 27 years, but this study looked at pollen counts and meteorological variables in Italy only. Although some European studies have observed pollen counts over an extended duration in relation to climate change, scant information exists on pollen and climate change in any single United States locale. Having geographic-specific information on pollen trends may enable better treatment of patients locally, because treatment can be tailored more specifically, and flares of allergic asthma and other allergic disease may be more predictable and, thus, preventable. To our knowledge, the effects of climate change on pollen counts in Denver, Colorado, have not been previously examined. Furthermore, few studies in the United States look at pollen trends over multiple decades and none spanning more than 30 years. This study aims to characterize shifts in pollen concentrations and duration of pollen season over a 9-year span in relation to climate change—associated meteorological variables.

Methods

Records of pollen counts from 2010 to 2018 were collected at National Jewish Health (NJH), a respiratory research hospital in Denver, Colorado. The second author of the current work was involved in the management of the sampling station as part of a rigorous monitoring program. Pollen data before 2010 were not retained. Atmospheric sampling at NJH was performed with a Burkard sampler, with continuous sampling over the course of 1 day. Pollen counts were assessed at least 3 times weekly. The start and end date of pollen counting was variable but typically started in March and ended in October. The pollen species routinely counted and included in our analysis were: ash, birch, cedar/juniper, elm, linden, maple, oak, pine, *Populus*, walnut, chenopod-amaranth, ragweed, sage, and total grass. Also measured were miscellaneous trees and weeds, defined as any species of tree or weed pollen not included in the above list. Time series of pollen concentrations are plotted in eFigure 1, and boxplots showing the distribution of pollen concentrations by month are year displayed in eFigure 2.

The meteorological data were obtained from the National Oceanic and Atmospheric Administration (NOAA); the weather station at Buckley Air Force Base in Aurora, Colorado (16.2 km east

of NJH) was used for all meteorological variables because of its proximity to the pollen monitor site and its continuous data series over the full period. Meteorological variables assessed were daily mean temperature, minimum and maximum temperature, dew point temperature, precipitation, relative humidity, sea-level equivalent atmospheric pressure, wind speed, maximum sustained wind speed, and maximum wind gust. Time series of these meteorological variables are plotted in eFigure 3.

For most of these meteorological variables, the observations at Buckley Air Force Base are representative of observations that would be made at NJH, given the short distance between the 2 locations and the flatness of the topography on the eastern side of the city. This is highlighted in eTable 1, which shows site-to-site correlations between the Buckley Air Force Base monitor and 2 other meteorological stations in the area, at Denver International Airport and Centennial Airport, both of which are farther from NJH. Between-station correlations in daily temperature, dew point temperature, relative humidity, and sea-level pressure are above 0.98. Other meteorological variables are less spatially homogeneous: correlations in precipitation are 0.62, and correlations in the wind speed variables, while high for daily averages (0.880–0.890), are lower for maximum sustained wind speed (0.707–0.723) and maximum gust (0.602–0.625). The correlation between Buckley Air Force Base and NJH should be higher than these values, given the shorter distance. However, lack of co-located meteorology and pollen monitoring is a limitation of our study, particular for precipitation and wind speed variables.

Carbon dioxide levels were obtained from a NOAA-affiliated station in Niwot Ridge, Colorado (68 km west of NJH).¹⁷ Because there are local gradients in CO₂ concentrations¹⁸ driven by, for example, plant uptake, we acknowledge that the CO₂ data we use in the current work are representative of the global background concentration rather than the local concentration in the immediate vicinity of NJH Merged, complete data for this study are available at <https://osf.io/fd92u/>.

Statistical Analyses

We performed 7 analyses. Four analyses investigated changes in pollen season timing (start date, end date, peak date, and overall season length) over the 9-year study period. The fifth and sixth analyses tested trends in pollen concentrations and weather observations over the study period, broken down by calendar month. The seventh analysis estimated associations between individual pollen species' concentrations and individual weather variables. All analyses were performed in the R language version 3.4.3.¹⁹ Except where otherwise specified, a *P* value of less than .05 or a 95% confidence interval excluding the null value was considered statistically significant.

Trends in Pollen Season Timing

Changes in pollen season start date, end date, peak date, and duration between 2010 and 2018 were estimated using the *survreg* function from the survival package^{20,21} (version 2.41-3) in R with Gaussian-distributed times and day-of-year treated as a continuous variable. Because pollen collection in each year did not necessarily start on the day the earliest pollinating species first released pollen grains, species with non-zero counts on the first collection day of the year were treated as having a left-censored start date. Left censoring means that the true start date fell no later than the date of the first observation but could have fallen earlier. The *survreg* function accounted for this censoring uncertainty when estimating the trend in start dates over our study period. Similarly, species with non-zero counts on the last day of sampling were treated as having a right-censored end date. The difference between the estimated start and end dates, estimated via the *glht* function in the *multcomp* package²² (version 1.4-8), was used to calculate the season length. The peak date of a given species was considered to

be the day of the year with the highest pollen concentration. If multiple dates had measured concentrations equal to the peak concentration for the given species in the given year, then the median of these dates was treated as the peak date.

The timing of pollen season for miscellaneous weeds and trees was not analyzed because these categories are mixtures of potentially many different species, making interpretation difficult. Likewise, the timing of pollen season for walnut was not analyzed because it is only sparsely recorded in our pollen record.

Trends in Meteorology and Pollen Concentrations

Month-specific (March–October) associations between daily meteorological observations and year (treated as a continuous linear variable) were estimated using standard linear regression. Month-specific associations between daily pollen concentrations and year were estimated using Bayesian Poisson regression with the log link and accounting for overdispersion. These Poisson models were fitted using the *bayesglm* function in the *arm* package²³ (version 1.10-1) with default prior distributions. The *bayesglm* function was used instead of the standard *glm* function to eliminate the numerical instabilities found in the un-regularized Poisson regression results. An offset was incorporated in the Poisson models as a conversion factor to account for the ratio of observed counts to ambient concentration specific to the hardware platform. The statistical models for both pollen and meteorology included parameters for the month-specific mean observation and for the month-specific linear annual trend over the study period. Having separate mean parameters for each calendar month allowed control for confounding by time of year.

Having fitted these models for each meteorological variable and pollen species, a likelihood ratio test was then used to test whether accounting for the linear annual trends improved model fit. These tests compared the models described above with simpler models including only separate parameters for calendar month.

Associations between Meteorology and Pollen Concentrations

Models estimating associations between species-specific pollen counts (treated as the dependent variable) and individual meteorological variables (treated as the independent variable) also used the Bayesian Poisson regression approach as described above and included separate parameters for each calendar month and month-specific linear annual trend in addition to a linear term for the meteorological variable.

Results

Trends in Pollen Season Timing

Pollen season start dates were largely unchanged over the study period, with the exception of linden, which started an average of 5.1 days earlier per year (95% confidence interval [CI]: 2.2, 7.9) over the study period (Fig 1). Oak also displayed a trend toward earlier start dates, but this trend was not significant under a Bonferroni correction.

Likewise, birch and maple yielded trends toward earlier end dates (7.8 [95% CI: 3.7, 12.0] and 32.3 [95% CI: 25.5, 39.1] days per year earlier, respectively), whereas oak tended toward a later end date (8.0 [95% CI: 5.2, 10.7] days per year later) (Fig 2). The end date for grass pollen also shifted later, though this trend was not significant under a Bonferroni correction.

Only maple yielded a statistically significant change in peak date (17.4 [95% CI: 10.6, 24.2] days per year earlier), though birch trended earlier as well (Fig 3).

Overall season length for linden increased by an average of 7.5 days per year (95% CI: 3.4, 11.5), oak increased by 11.8 days per year (95% CI: 7.8, 15.8), and maple decreased by 27.7 days per year

(95% CI: 17.2, 38.2) (Fig 4). Birch pollen season length decreased by 6.2 days per year (95% CI: 0.3, 12.1), although this trend was not significant under Bonferroni correction.

Trends in Meteorology and Pollen Concentrations

Month-specific trends in meteorological variables over our study period are shown in Figure 5. Dew point temperature, relative humidity, and sea-level pressure were stable or positive. Dew point temperature increased in March and May, relatively humidity increased in March, May, and August, and sea-level pressure increased in April, May, July, and August. Mean temperature trends were stable across all months except August, which featured a negative trend, meaning the mean temperature in August was cooler toward the end of our study period than it was earlier in our study period. Trends for the wind speed variables were stable or negative as well, with the negative trends occurring in the spring months. As expected from other global measurements, month-specific CO₂ levels increased over time.

Month-specific trends in pollen concentrations are shown in Figure 6. Many pollen species had increasing trends. Ash, cedar/juniper, linden, maple, oak, pine, ragweed, sage, and total weeds yielded flat or increasing month-specific trends over our study period, although they differ in which calendar month the increasing trends fell. Linden concentrations, for example, increased in June and July, by 46.1% (95% CI: 32.4, 61.2) and 26.8% (95% CI: 15.8, 38.8) per year, respectively. The June result is, at least in part, driven by the pollen season start day shifting to earlier in that month. Populus, by contrast, yielded flat or negative month-specific trends, with the negative trends falling in the spring months. However, other species, such as birch, walnut, total trees, grass, and chenopod-amaranth, displayed an increasing trend in some months offset by a decreasing trend in other months, suggesting an overall shift in the season.

Associations between Meteorology and Pollen Concentrations

Analyses of associations between individual meteorological variables and individual pollen species' concentrations controlling for calendar month are shown in Figure 7. Mean daily temperature was positively associated with pollen concentrations for grass, total tree pollen, and most tree species, but not with weeds. Humidity and sea-level pressure were negatively associated with grasses, total tree pollen, pine, and cedar/juniper. Relative humidity was also negatively associated with Populus and elm, whereas sea-level pressure was negatively associated with pine. The wind speed variables were positively associated with cedar/juniper and miscellaneous tree pollen, and, in addition, mean wind speed was positively associated with total tree pollen and Populus.

Discussion

We did not find evidence for a trend in the start, end, or peak dates of pollen season for most species from 2010 to 2018. The major exception was linden, whose start season moved an average of 5.1 (95% CI: 2.2, 7.9) days earlier per year, and whose season length consequently increased by 7.5 (95% CI: 3.4, 11.5) days per year. The peak and end dates for maple also shifted earlier in the year by 32.3 (95% CI: 25.5, 39.1) and 17.4 (95% CI: 10.6, 24.2) days per year, respectively, though only over the years for which maple was consistently measured, 2014 to 2018. Conversely, oak pollen season ended 8.0 days later per year (95% CI: 5.2, 10.7), and its overall season length increased by 11.8 days per year (95% CI: 7.8, 15.8). However, oak and maple are not common pollens in our data set and were unobserved for 3 and 4 years, respectively, of the 9 years in our study period. This suggests that the results for these

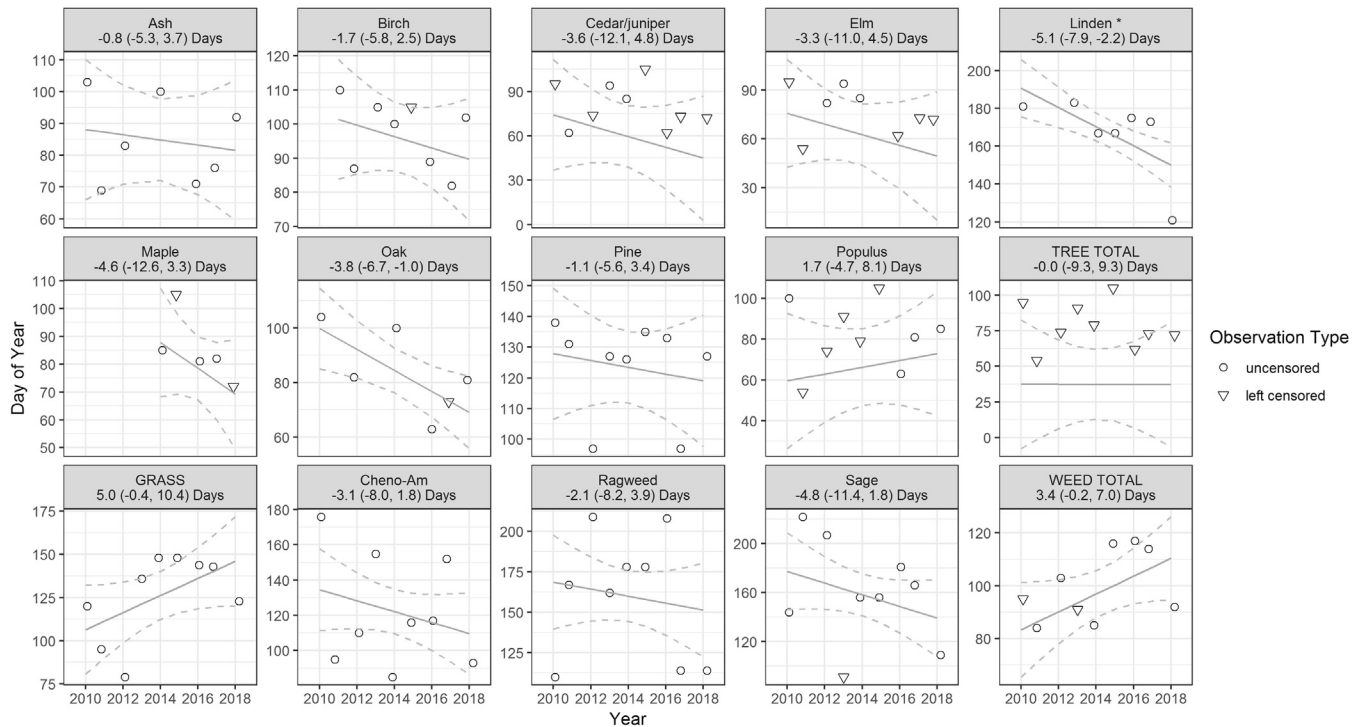


Figure 1. Pollen season start date trends by species. Numbers in the panel labels indicate the point estimates and 95% confidence intervals for the change in start date. An asterisk (*) next to the species name indicates a Bonferroni-corrected statistically significant difference between decades ($P < .05/13 = .0038$, where 13 is the number of tests in the figure). Fitted trends and 95% prediction intervals are shown by a solid line and dashed lines, respectively.

species should be interpreted with caution. Furthermore, although the trends for birch were not significant after Bonferroni correction, its end and peak dates shifted earlier by approximately 6.1 (95% CI:

1.9, 10.3) days per year, and the overall season length decreased by 6.2 (95% CI: 0.03, 12.1) days per year.

The month-specific temperature trends observed in Denver from 2010 to 2018 were not consistent with the warming trend reported

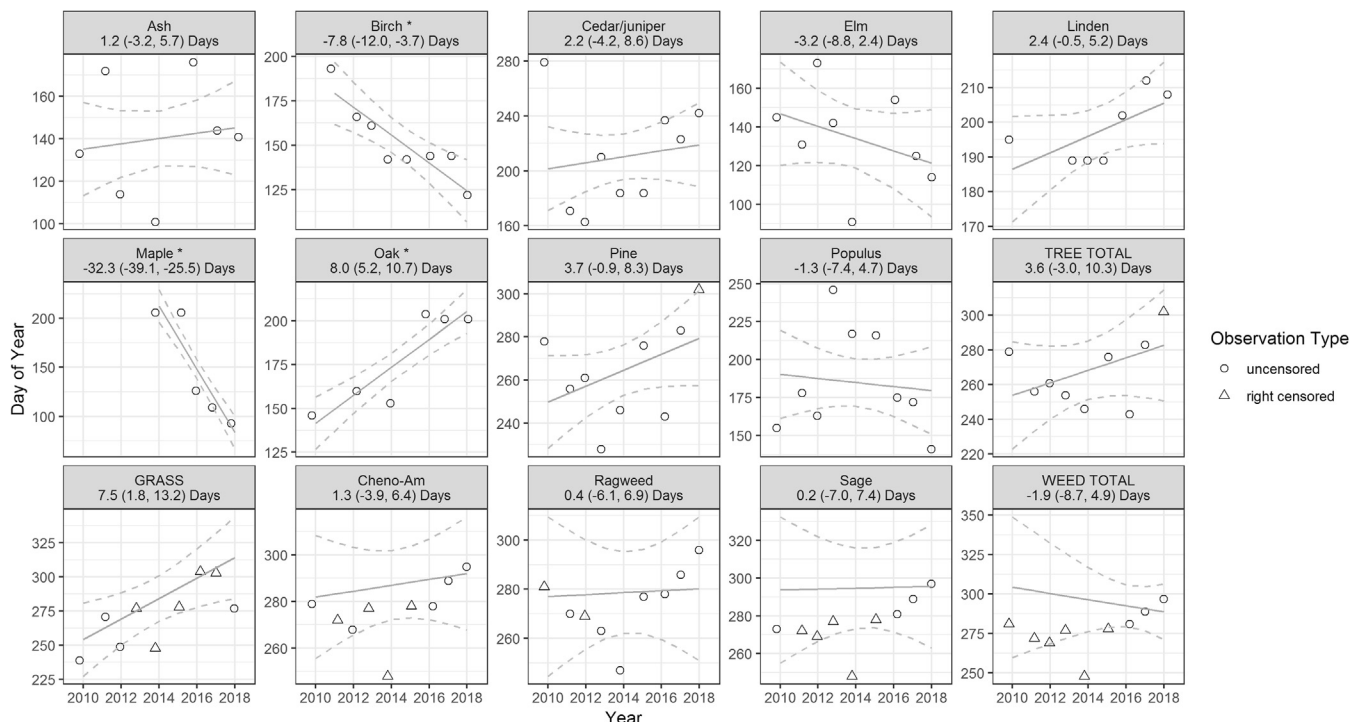


Figure 2. Pollen season end date trends by species. Numbers in the panel labels indicate the point estimates and 95% confidence intervals for the change in end date. An asterisk (*) next to the species name indicates a Bonferroni-corrected statistically significant difference between decades ($P < .05/13 = .0038$, where 13 is the number of tests in the figure). Fitted trends and 95% prediction intervals are shown by a solid line and dashed lines, respectively.

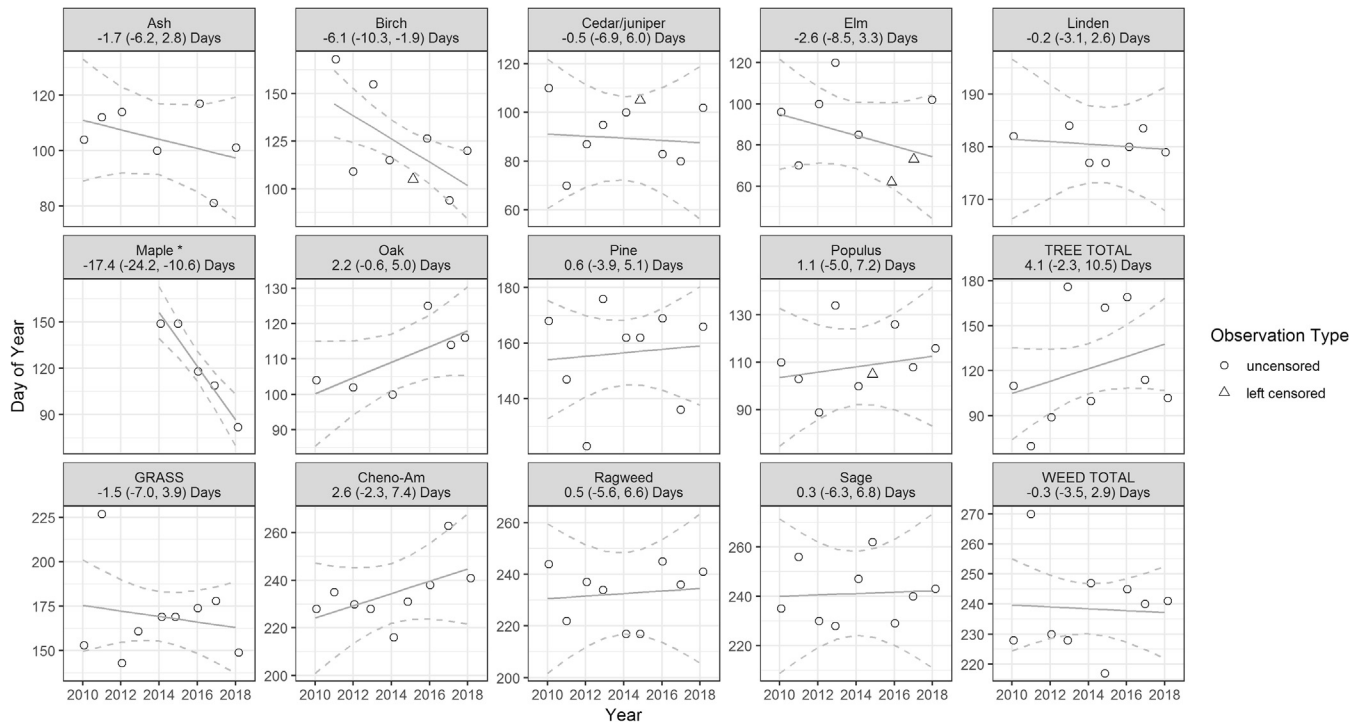


Figure 3. Pollen peak date trends by species. Numbers in the panel labels indicate the point estimates and 95% confidence intervals for the change in peak date. Asterisk (*) next to the species name indicates a Bonferroni-corrected statistically significant difference between decades ($P < .05/13 = .0038$, where 13 is the number of tests in the figure). Fitted trends and 95% prediction intervals are shown by a solid line and dashed lines, respectively.

globally, though viewing the Denver temperature data over a longer time span does show warming at the Buckley Air Force Base monitor (eFig 4) in most months. Average global temperatures increased 0.85°C (1.53°F) from 1880 to 2012.²⁴ In Colorado, annual average

temperatures increased by 2°F over a 30-year span (1971–2000), the same as the North American average temperature increase of 2°F.²⁵

No long-term trends in precipitation were observed in Colorado, which is consistent with prior literature.²⁶ However, relative

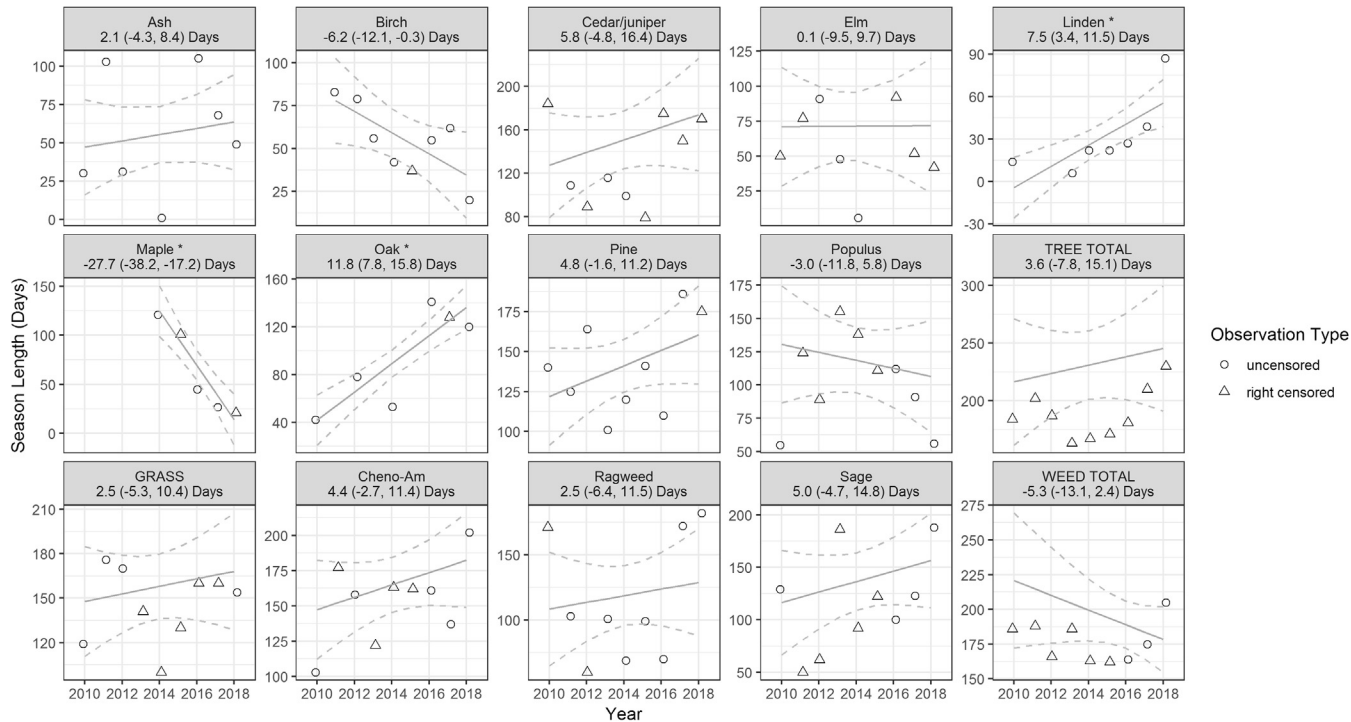


Figure 4. Pollen season length trends by species. Numbers in the panel labels indicate the point estimates and 95% confidence intervals for the change in season length. Asterisk (*) next to the species name indicates a Bonferroni-corrected statistically significant difference between decades ($P < .05/13 = .0038$, where 13 is the number of tests in the figure). Fitted trends and 95% prediction intervals are shown by a solid line and dashed lines, respectively.

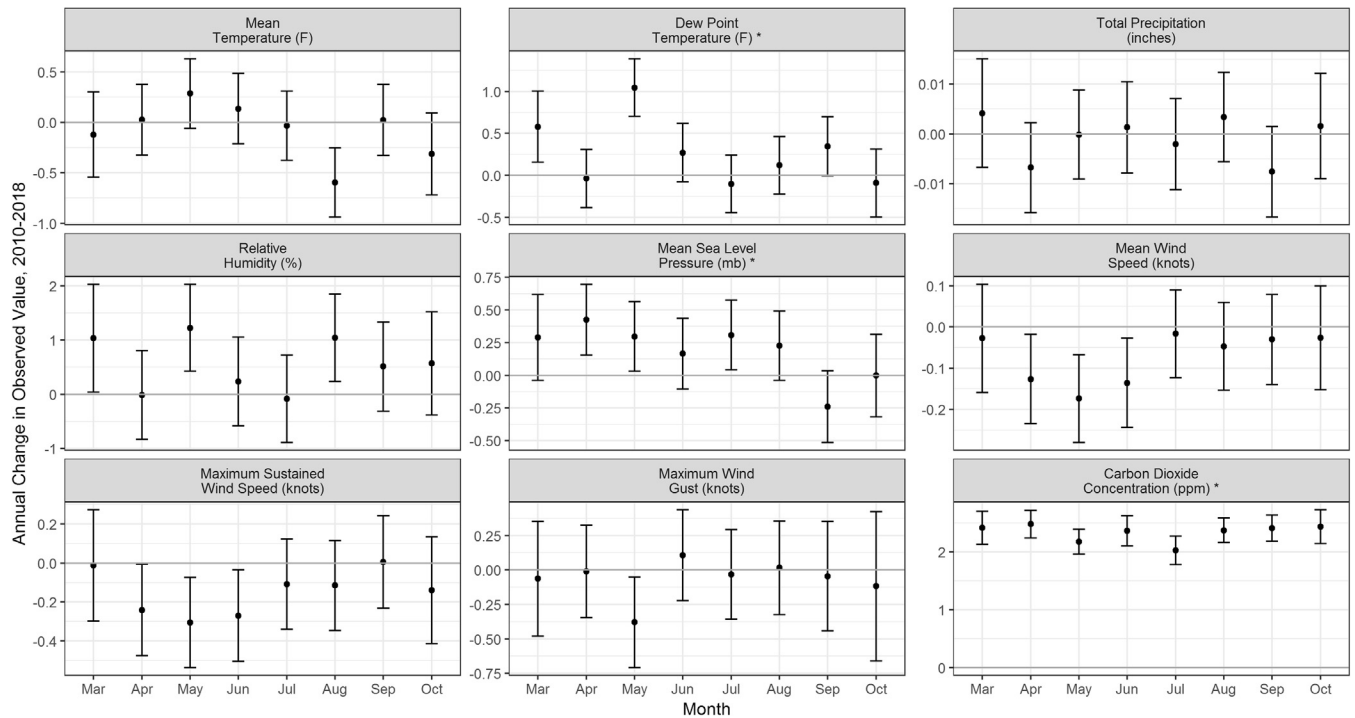


Figure 5. Absolute changes in daily meteorological observations by calendar month. Point estimates and 95% confidence intervals represent the estimated annual mean change. An asterisk (*) next to the variable name indicates a Bonferroni-corrected statistically significant improvement in model fit when accounting for month-specific linear annual trends for the given variable ($P < .05/12 = .0042$, where 12 is the number of global tests in the figure).

humidity and dew point temperature displayed increasing trends in March and May. Furthermore, during spring months, atmospheric pressure increased and wind speeds decreased over our study period. Together these results potentially suggest a trend

toward sunnier days, leading to more evaporation from melting snow.

Although climate model predictions of precipitation levels are less certain than predictions of temperature at the same spatial and

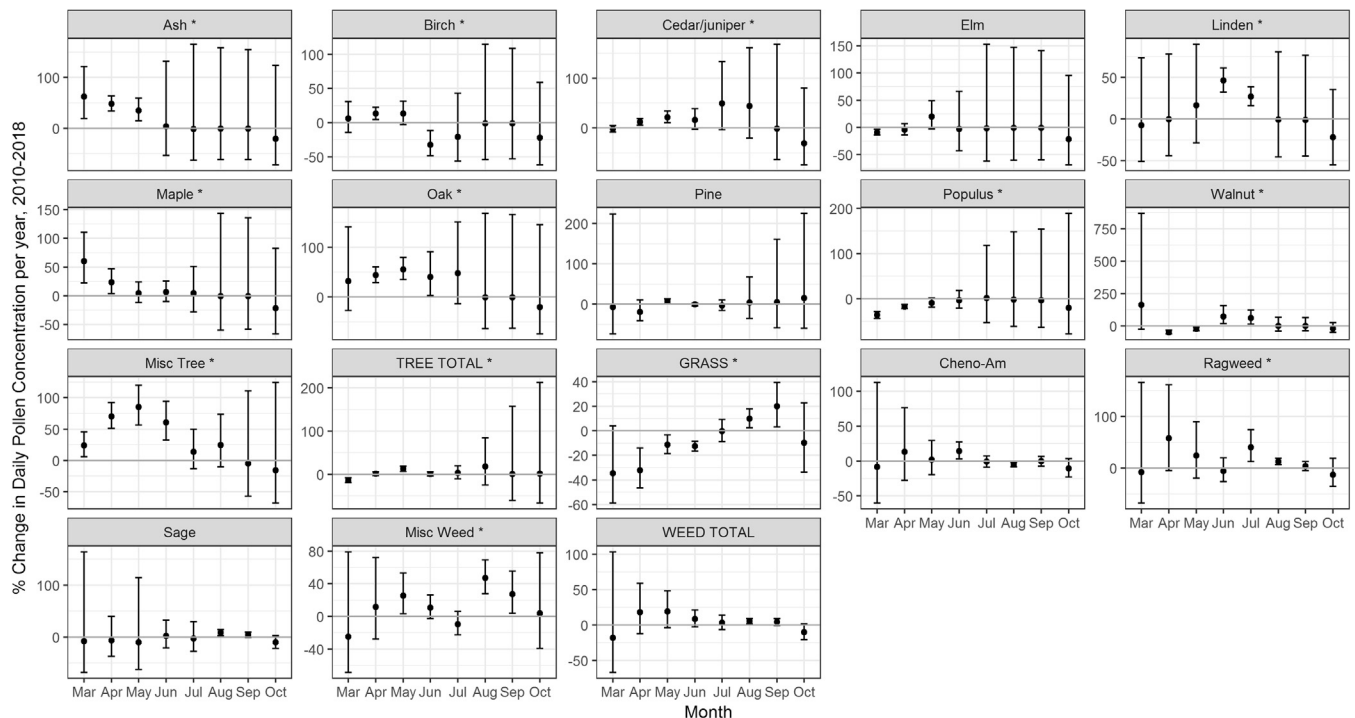


Figure 6. Percent changes in daily pollen concentration by calendar month. Point estimates and 95% confidence intervals represent the estimated annual % change. An asterisk (*) next to the species name indicates a Bonferroni-corrected statistically significant improvement in model fit when accounting for month-specific linear annual trends for the given species ($P < .05/13 = .0038$, where 13 is the number of global tests in the figure).

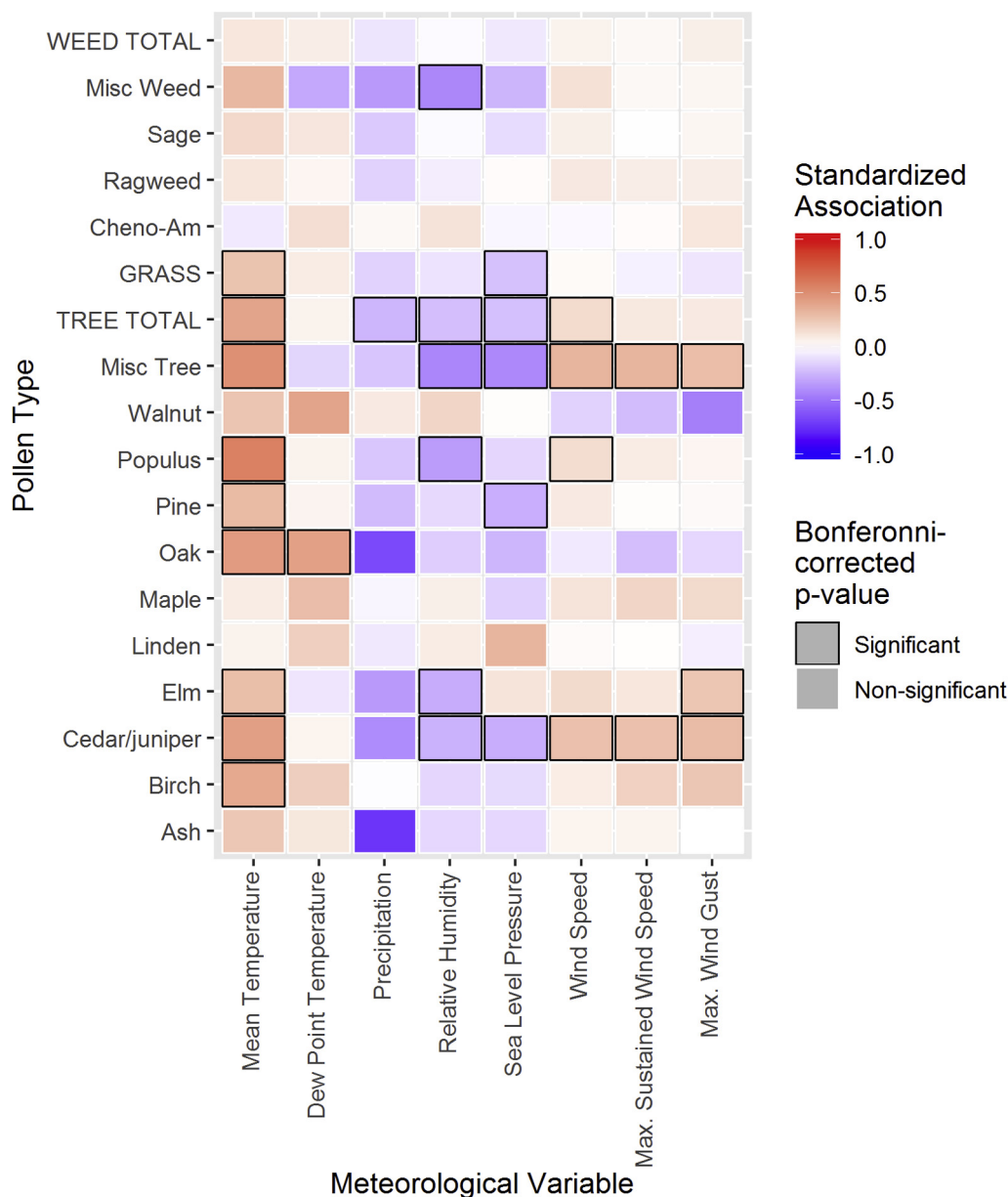


Figure 7. Standardized pairwise associations between pollen species and weather variables accounting for calendar month and month-specific annual trend. Meteorological values were standardized within calendar month. Associations are presented on the log-risk scale. Outlined boxes indicate a Bonferonni-corrected statistically significant association after accounting for year and calendar month ($P < .05/144 = .00035$, where 144 is the number of tests in the figure).

temporal scale,^{25,27} in general the expectation is that distribution of precipitation will shift to yield a higher proportion of heavy precipitation days, a higher proportion of precipitation-free days, and fewer days in the middle, with substantial variation by region.^{25,26} In certain regions of the United States, increased heavy precipitation events have been observed, but this has not held true in the Southwest.²⁵ In Colorado, there have not been significant trends in heavy precipitation events.²⁵ However, downscaled predictions for the Denver metro region have found that winter precipitation will increase, although there is not a consensus about whether annual precipitation totals will increase or decrease.^{25,27}

Our finding of a decreasing wind speed trend over our study period is not consistent with other studies of climate change.²⁸ However, over a longer time span, the Buckley Air Force Base monitor does observe a marked increase in wind speed (eFig 4). Still, because wind speed affects pollen transport, how this aberrant trend affected the pollen counts during the study period is unclear.

Month-specific trends in pollen concentration do not display a consistent pattern across species, with some species showing increasing trends, 1 species showing a decreasing trend, and others showing a mix of increase and decrease, depending on the month. For the aggregate categories, total trees, grass, and total weeds, the first 2 display a decreasing trend early in their respective growing seasons (March for trees, April and May for grass), followed by an increasing trend later in the seasons (May for trees, August and September for grass). Total tree pollen concentrations are dominated by the contributions from pine and Populus, and to a lesser extent, oak (eFigs 1 and 2). Weeds, by contrast, do not show a decreasing trend in any month but do show an increasing trend in both August and September.

Higher mean daily temperature was, after controlling for calendar month and month-specific annual trend, positively associated with pollen concentrations from grass and from nearly all tree species. The exceptions tended to be low-concentration species

such as maple, linden, and walnut. Prior studies have shown that higher temperatures can accelerate pollen germination and pollen tube growth for some species but have a detrimental effect on others,¹³ although we find no evidence for a detrimental effect on any species.^{25,27,29}

Precipitation was associated with only 1 type of pollen (total tree pollen, in the negative direction). Increased precipitation and humidity have been associated in the literature with suppression of anthesis, resulting in lower pollen concentrations. Furthermore, as described by Ziska in the context of ragweed, precipitation also washes pollen from the air.⁸ We did not explore the impact of extreme rainfall events or rainfall variability, which could have affected pollen counts.

We found that sea-level pressure was negatively associated with total tree pollen as well as with miscellaneous trees and cedar/juniper, whereas the wind speed variables were positively associated with these same species. However, the trend of increasing cedar/juniper and miscellaneous weed pollen concentrations observed over our study period in April, May, and June falls during the same months that the wind speed variables show a decreasing trend. This apparent contradiction may be explained by the fact that the associations between pollen concentration and meteorological variables (Fig 7) are sensitive to day-to-day co-variation in the 2, whereas the estimated month-specific trends in meteorology (Fig 5) and pollen concentration (Fig 6) are more sensitive to monthly averages.

Wind speed and wind direction can affect the spread of pollen as well as the concentrations in the air through processes such as entrainment.^{13,30,31} Cedar/juniper in particular has been found to travel long distances.³² Wind direction was not included in this study, because a prior study of Denver pollen counts found that wind direction did not affect Denver pollen counts.³³

Other factors can affect the relationships we observed between meteorology and pollen counts, both now and in the future. Our meteorological variables do not include measures of visibility, solar irradiance, or cloudiness, which can affect the rate of plant growth, and we do not attempt to relate pollen or meteorology to air pollution levels. Both cloud cover and wildfire smoke attenuate solar irradiance at ground level and are influenced by climate change.^{25,34} Anthropogenic air pollution can be influenced by weather conditions, through both weather-dependent emissions behavior and chemical reactions in the atmosphere, and these air pollutants can then affect the morphology^{30,35} and allergenicity^{36,37} of pollen grains. Although anthropogenic and total particulate air pollution concentrations have fallen in Denver since the 1980s,³⁸ climate change may reverse these gains.

Carbon dioxide is a primary driver of climate change. Though considered detrimental to humans, carbon dioxide facilitates plant growth and development by enhancing photosynthesis and reproductive effects.^{7,39} Plants grown in artificially high carbon dioxide environments typically grow faster and are larger at maturity.⁴⁰ Our findings are generally consistent with the expectation that increased carbon dioxide will correlate positively with increased pollen concentrations, although there are notable exceptions for particular species in certain calendar months. This inconsistency may be attributable to the fact that our study did not measure local CO₂ concentrations at the pollen monitor itself but relied on a CO₂ monitor used to study global trends.

Closely tied to CO₂ production is urbanization, for which our study could not directly account. Urbanization results in vegetation changes and, thus, affects plant species and pollination. Ornamental planting also can affect types and quantities of pollen in the air.

This study has several strengths. First, our study reports pollen counts from a large number of monitored species, including 10 tree

species and 3 weed species. Second, pollen monitoring was overseen by the same highly experienced investigator throughout the study period, assuring consistency. Third, this study uses more advanced statistical methods than much of the previous work on pollen season timing. In particular, it uses methods for calculating start and end dates that account for the uncertainty caused by censoring of these dates by the lack of data collection in cooler months.

There were a number of limitations to this study. First, because pollen counts were not obtained throughout the year, the study may have missed not only the start of tree season but the true peak of tree pollination for the earliest pollinating species. Second, some pollens could have been systematically misidentified. Though the pollen counting was done by trained individuals under the supervision of the same senior investigator throughout the study period (second author of the present work), the pollen counts used in the study were not all counted by the same person. Third, because this study focused only on a single city, our results may not generalize to other locations. Fourth, we did not attempt to characterize extreme weather events, such as droughts, heat waves, and wildfires, which could have impacted pollen production and dispersal. Fifth, the meteorological and carbon dioxide monitors used in the study were not co-located with the pollen monitor, which could confound the results of our pollen/meteorology regressions, particularly those involving precipitation, wind speed, and CO₂ concentration. Finally, we cannot rule out the possibility that the decade-scale changes in tree and grass pollen counts we found were attributable at least in part to shifts in ornamental planting patterns (because of either changing consumer preference or growing population) rather than weather or climate. However, because weeds are not planted intentionally and because with increased urbanization there is less available land for growth, we have greater confidence that the observed increases in total weed concentrations (Fig 6) are attributable to climate-influenced weather changes.

This study is a unique addition to a growing body of data supporting the impact of climate change on pollen and allergic disease. Further research at local levels, in addition to nationwide and global levels, is imperative. We are seeing more evidence of accelerating climate change, and such data are helpful both to prepare for the health impacts and to compel change to slow the effects of climate change.

Supplementary Data

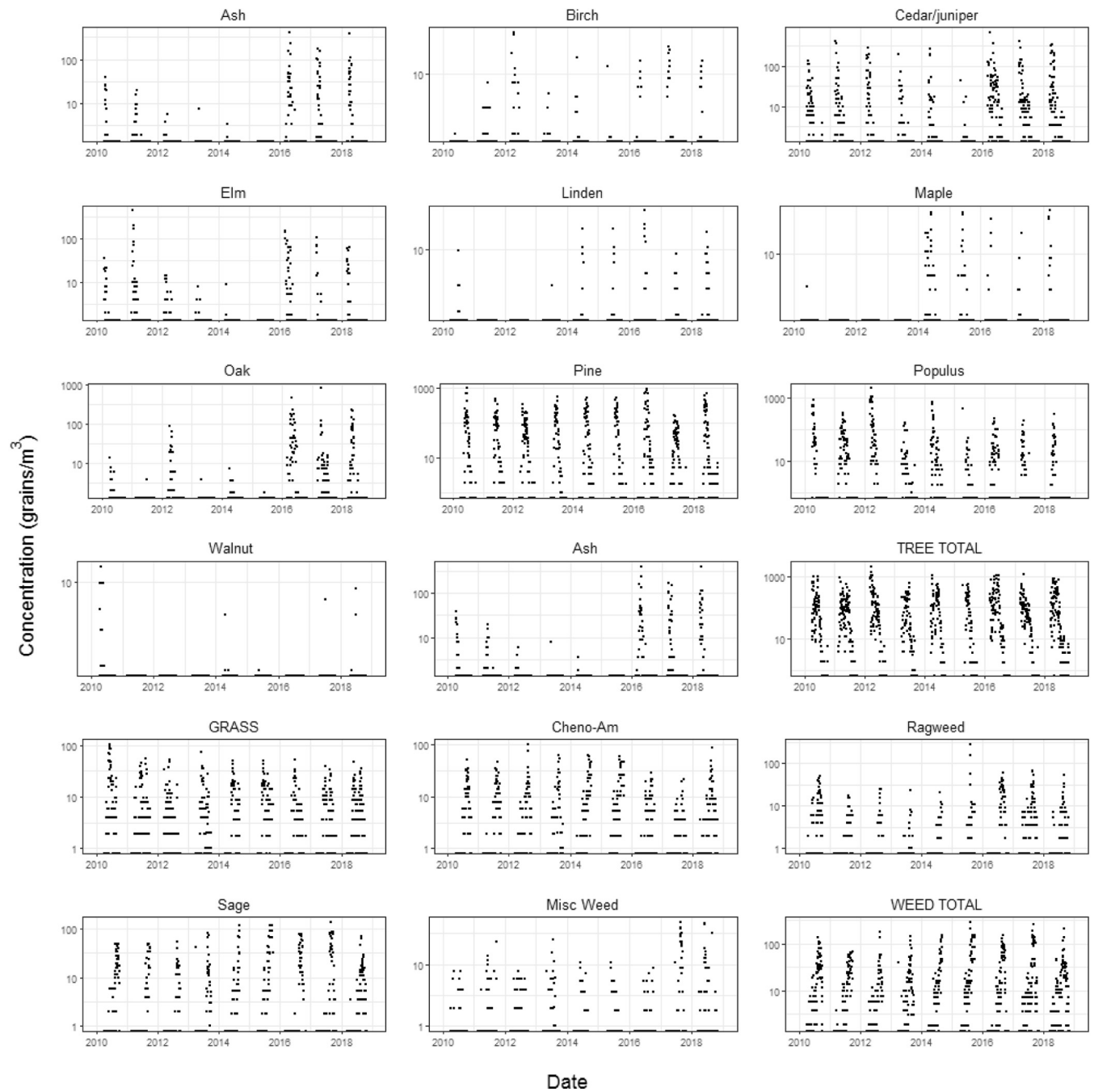
Supplementary data related to this article can be found online at <https://doi.org/10.1016/j.anai.2019.08.002>.

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Supplementary Data



eFigure 1. Time series of daily pollen counts by species. Counts are shown on the log-10 scale.

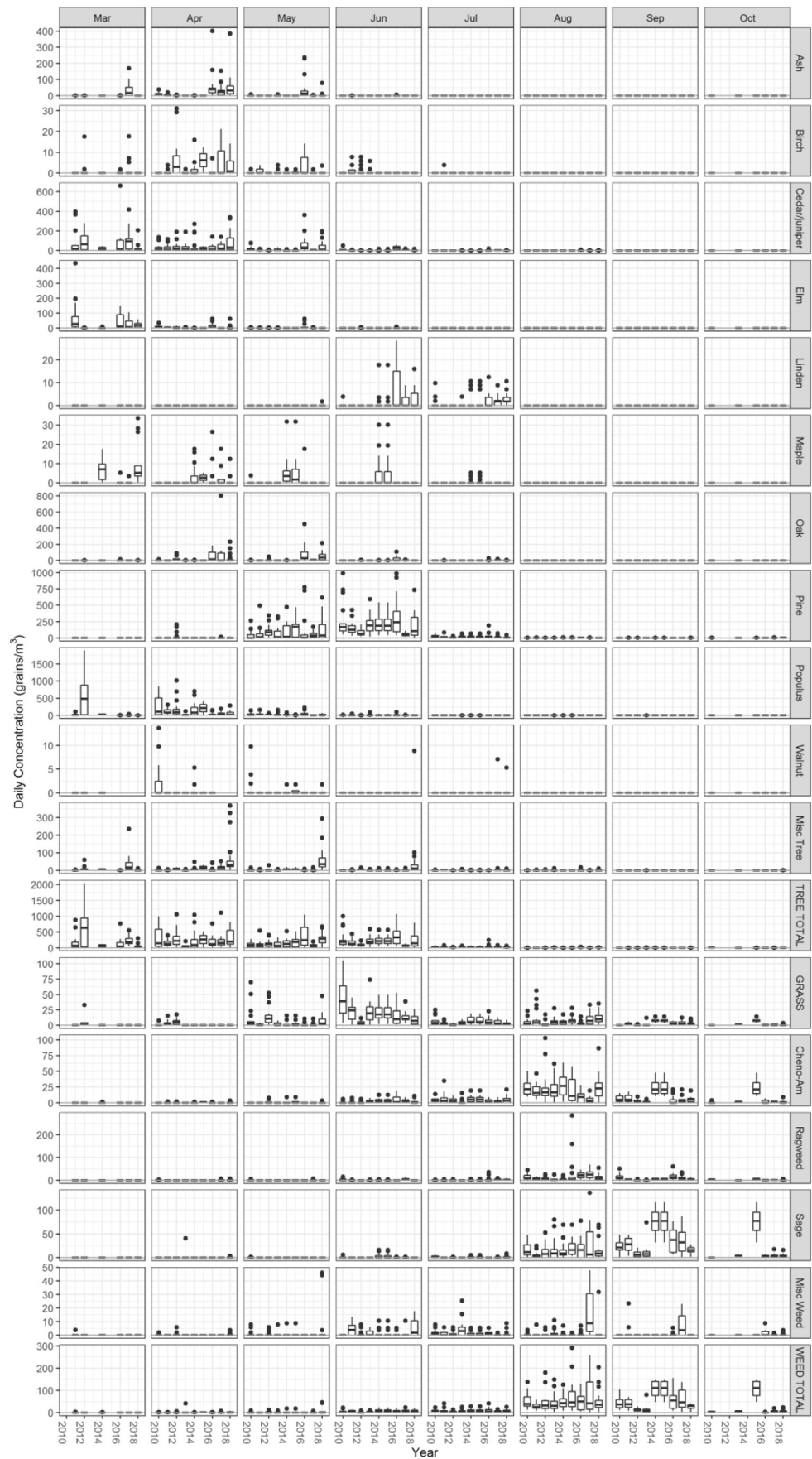


Figure 2. Bar-and-whisker plots of pollen counts by year, broken out by calendar month.

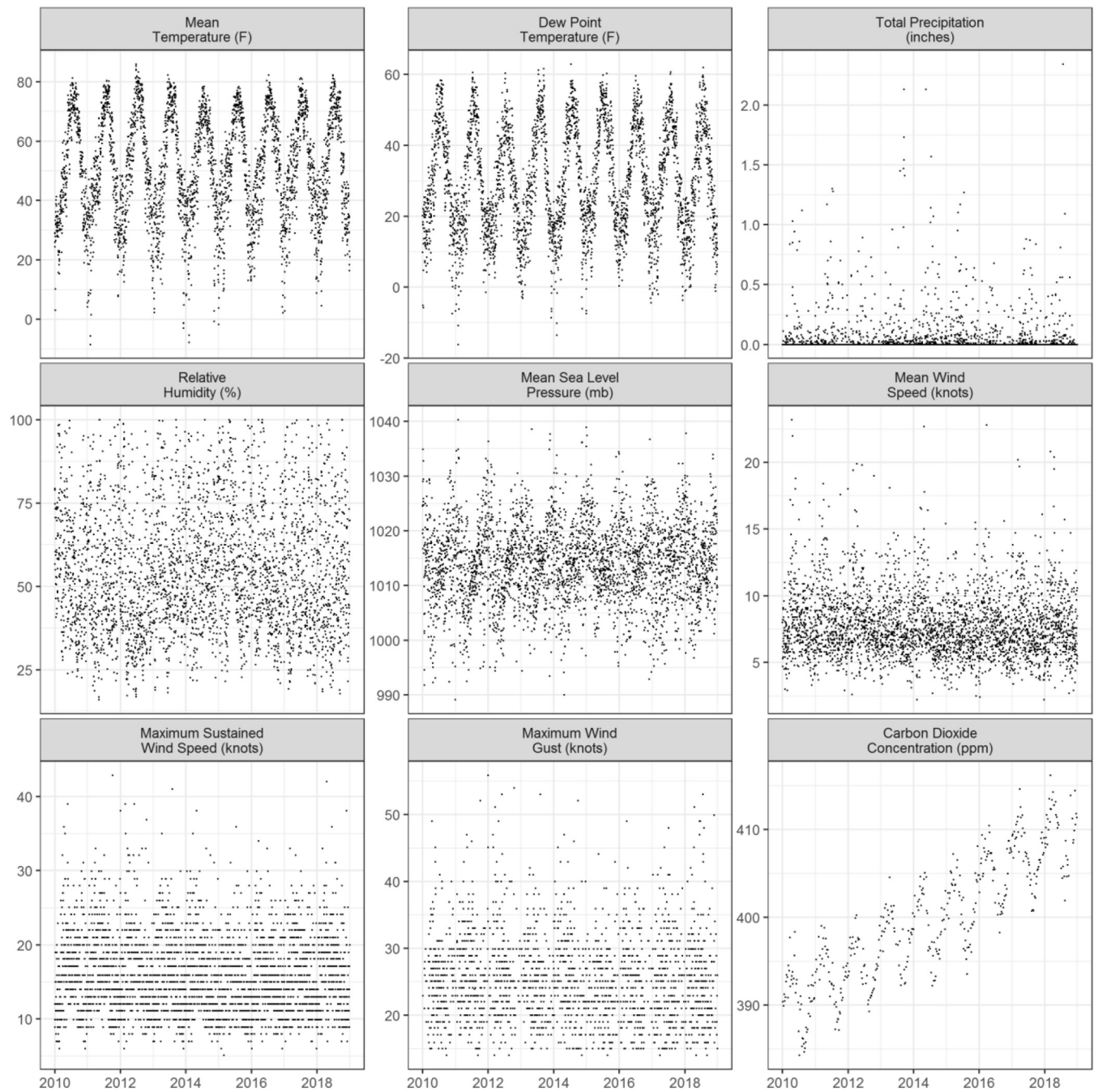
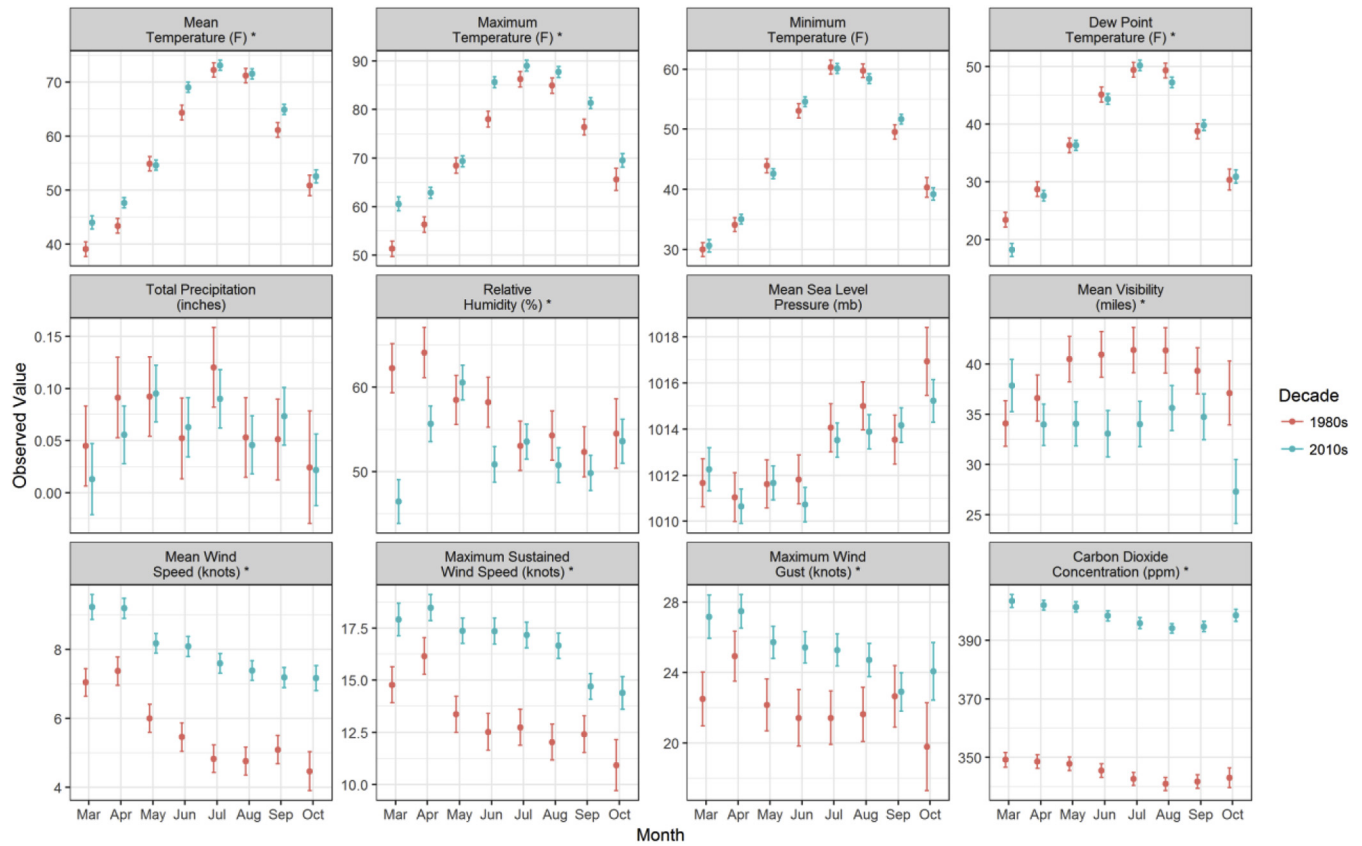


Figure 3. Daily monitor observations for meteorological observations and carbon dioxide.



eFigure 4. Comparison of mean monthly meteorological observations by calendar month, showing comparisons between 1983 and 1986 (“1980s”) and 2010 and 2018 (“2010s”).

eTable 1
Pearson correlations in meteorological observations between the Buckley Air Force base monitor (used in the present work) and two other weather stations in the metropolitan Denver region

Meteorological variable	Correlations	
		Buckley Air Force Base
Mean temperature	Buckley Air Force Base	1.000
	Centennial Airport	0.998
	Denver International Airport	0.996
Dew point temperature	Buckley Air Force Base	1.000
	Centennial Airport	0.993
	Denver International Airport	0.992
Precipitation	Buckley Air Force Base	1.000
	Centennial Airport	0.620
	Denver International Airport	0.618
Relative humidity	Buckley Air Force Base	1.000
	Centennial Airport	0.986
	Denver International Airport	0.981
Sea level pressure	Buckley Air Force Base	1.000
	Centennial Airport	0.997
	Denver International Airport	0.994
Wind speed	Buckley Air Force Base	1.000
	Centennial Airport	0.890
	Denver International Airport	0.880
Max. sustained wind speed	Buckley Air Force Base	1.000
	Centennial Airport	0.723
	Denver International Airport	0.707
Max. wind gust	Buckley Air Force Base	1.000
	Centennial Airport	0.602
	Denver International Airport	0.625