Temporal Analysis of the Relationship between Meteorological Factors and Pollen Abundance in Raleigh, North Carolina

By

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Abstract

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Climate change affects both meteorological factors and plant processes. In order to observe climate and pollen relationships, pollen counts are plotted against temperature, humidity (in the form of dew point temperature), and precipitation in Raleigh, North Carolina from February 2, 1999 to September 4, 2018. Linear regression tools in Microsoft Excel were used to analyze annual and seasonal data that had been aggregated by month. The annual data revealed the strongest correlation between the increased temperature in the area and pollen count, particularly in tree pollen species. Conversely, the seasonal data for spring showed a stronger correlation between average precipitation and pollen count. The IPCC has predicted that temperature and precipitation will both continue to rise and, based on historical data, it is likely that the relationship between pollen and temperature, as supported by annual tree pollen data, as well as the relationship between pollen and precipitation, as supported by weed and grass seasonal pollen analysis, will increase the pollen counts in Raleigh. While a direct correlation cannot be concluded definitively, the results indicate that temperature is related to tree pollen count and precipitation is related to grass and weed pollen count.

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Introduction

As the leading international body for the assessment of climate change, the Intergovernmental Panel on Climate Change (IPCC) has long since confirmed that climate change is occurring (IPCC 2014). Further, the IPCC says that the increase in air pollution, largely stemming from the industrial and economic growth in the last century, cannot be explained without attribution to humans. Specifically, although the patterns of Earth's ambient temperatures and atmospheric processes are cyclical, the current concentrations of air contaminants are far higher than have ever been recorded in the last 800,000 years, which is as far back as scientists are currently able to measure, using air bubbles trapped in ice (IPCC 2014). A major driver of this anthropogenic climate change is the atmospheric carbon dioxide concentration, which is projected to rise from current levels around 400 ppm to 730-1020 ppm by 2100 (Albertine et al. 2014). The increase of greenhouse gas concentrations has a strict correlation to the rising global temperatures and the other indicators of climate change (IPCC 2014).

Pollen concentration and distribution already may be changing due to a positive correlation with climate change. Studies have shown a correlation between carbon dioxide, temperature, and pollen production, where CO_2 concentrations, ambient temperature, and allergenic production are all positively related (Hoflich et al. 2016). Climate can affect the biological and chemical components of pollen by altering the shape, density, size, or vitality of pollen particles in the environment (Makra et al. 2014), potentially leading to greater susceptibility in humans. Furthermore, climate change is likely inducing longer and more severe pollen seasons, on top of other heightened air pollution episodes, because the warmer climates are more suitable to pollen production. Spring and Summer have started 2.5 days earlier per decade since 1971, whereas pollen season has started 10 days earlier on the same timeline but does not end any earlier (Makra et al. 2014).

With climate change, it is possible that the abundance of pollen will change, along with altered weather conditions (Zhang et al. 2014). In fact, there are changes that have already been observed in pollen activity (Zhang et al. 1994), and adaptation measures could actually have a negative impact. If the species richness of allergenic plants changes, the various pollen allergens could then impact populations more severely. As the maximum pollen count a human is exposed to increases, the intensification in total allergenic inhalation could heighten severity of respiratory symptoms (Hoflich at al. 2016). Cumulatively, future climate change and air pollution may act in a positive feedback loop, changing the timing, amount, and allergenicity of pollen, increasing both the number of people affected and symptom severity (Albertine et al. 2014).

Coincident with climate change, industrialized nations are facing increased frequency of respiratory allergy and asthma, as the advancement of urbanization merges with poorer air quality, exacerbating pollen acting as a trigger for respiratory diseases (Makra et al. 2014). Pollen affects approximately 20% of the U.S. population, causing allergies or aggravating asthma, with more than 2/3 of the continental U.S being adversely affected (Tagaris et al. 2009). This percentage is higher than in industrialized rather than developing countries, because of the interaction between air pollution and pollen (D'Amato et al. 2014). Globally, more than 1.5 billion people suffer from pollen allergies, with children being disproportionately affected, because they inhale a higher volume of air (meaning a higher volume of pollen) per body weight than adults (Gleason et al. 2014).

Along with chemical pollutants, biogenic particulates, such as pollen, can cause adverse health effects. Pollen particles, though larger than particulate matter with a diameter of less than 2.5 micrometers ($PM_{2.5}$), can work in combination with the other air pollutants, potentially creating multiple health problems for people with allergies and those predisposed to asthma. Sensitization to pollen is increased with co-stressors like exposure to the criteria air pollutants (Zhang et al. 2014). Multiple studies confirmed that exposure to bioaerosol allergens like pollen, mixed with outdoor air pollutants, exacerbate allergenic airway disease (AAD), becoming a major public health issue for those predisposed, vulnerable populations (Zhang et al. 2014; Zhang et al. 1994).

There are three primary types of pollen: weed, tree, and grass (NAB 2018). A single weed plant, for example, can produce up to 10^9 grains of pollen annually (Katz et al. 2014). Only 10 grains/m^3 cubed are necessary to irritate those with allergies or cause respiratory rhinitis. Peaks in pollen count have been linked to higher rates of hospital visits. As earth's average climate conditions warm, Katz et al. are predicting that ragweed will produce even more allergenic pollen in areas where it already exists, like Raleigh, North Carolina, becoming a serious human health issue.

Raleigh, North Carolina is home to many different pollen species, over the course of multiple pollen seasons (first: tree, second: grass, third: ragweed). Therefore, this study will focus on the broad palynological taxa, as opposed to a specific species, in order to identify patterns relevant to the study area. Phenological characteristics, like the duration of pollen season, and other quantitative data, such as total species count, of different pollen taxa are likely correlated to the meteorological variables (D'Amato 2014). While other abiotic factors, like soil biology, topography, and nutrient availability influence the dispersal activity of pollen, air pollution, temperature, precipitation, and other meteorological factors are more relevant to this research.

Objective Statement

This project will combine meteorological data with data for pollen abundance to identify relationships between pollen counts and meteorological variables and related trends in Raleigh, North Carolina. Specifically, this project will evaluate how rising temperatures, precipitation, and humidity, in the form of dew point measurements, are associated with increased pollen counts in Raleigh. It is hypothesized that the increase in temperature and precipitation, thought to be caused by climate change, are correlated to an increase in pollen counts throughout the Raleigh area.

Methods

Location and Data Sources

Raleigh (35.88° N, 78.79° W (Weather Underground 2018)) is the capital and second-largest city in North Carolina, located in the Piedmont region, 315 ft above sea level and expanding over 142.9 square miles (Census 2018). According to the most recent census in 2010, the population of Raleigh was 403,892, but was estimated to be 464,758, as of July 2017 (Census 2018). It is known as the "City of Oaks," blending an urban and forest environment. Specifically, the jurisdiction of Raleigh is 13.6% parks, greenways, and open spaces; 19.6% vacant land; and 61.4% developed land, combining residential, industrial, and institutional land uses (City of Raleigh 2017). Like most of the southeastern United States, Raleigh has a humid, subtropical climate with four distinct seasons. The average temperature is 60.8°F, with an average annual precipitation of 46.58 inches (U.S. Climate Data 2018). Raleigh is susceptible to periods of drought, as well as hurricanes.

Observed daily temperature, precipitation, and dew point data from February 1999 to September 2018 were collected from the Raleigh-Durham International Airport weather station by the National Oceanic and Atmospheric Administration (NOAA) through their Climate Data Online portal (https://www.ncdc.noaa.gov/cdo-web/). Daily temperature data from 2005 to 2014 were missing from the NOAA's dataset and were manually filled in from historical data collected from the same weather station by Weather Underground (https://www.wunderground.com/forecasts/RDU.html).

Observed daily pollen count data from February 1999 to September 2018 were collected from the Raleigh-Durham International Airport weather station via the North Carolina Department of Environmental Quality's (NCDEQ) Ambient Monitoring Data Request Form. While these data are considered "daily," data were only available for 3,559 days out of the total 7,155 days during the study period, providing data for only 49.74% of total study period. 16.46% of days with missing data occurred during December and January, with the rest of the missing data distributed evenly from February through November, about 4 days of data per week on average.

Pollen Types

There are three basic types of pollen collected by the NCDEQ: tree, grass, and weed (NCDEQ 2018). The pollen count for each of these types is the number of grains recorded at the sample site per day.

In Raleigh, there are many different species of tree, grass, and weed pollen, which vary by season. The counts of different species for each category are shown in Table 1. Specific pollen species are listed for tree, grass, and weed types in Appendix Tables A1, A2, and A3, respectively.

Table 1. Count of types of species by season (Pollen Library 2018).

	Spring	Summer	Autumn	Winter	Totals
Tree Pollen	124	63	18	37	126[a]
Grass Pollen	39	53	34	12	54[a]
Weed Pollen	48	54	43	15	57[a]

Totals	211	170	95	64	**237**[a]

[a] – Some pollen species bloom through multiple seasons, so pollen type totals are represented with duplicates removed. It is for this reason the totals are lower than the sum of all seasons for each pollen type.

Statistical Modeling

All three meteorological factors (temperature, precipitation, and humidity via dew point) and the pollen count data were aggregated by month and year. While temperature and dew point were averaged, precipitation data were both averaged and summed. For the time period studied (February 1, 1999 to September 4, 2018), each factor had 236 data points. Each pollen type was plotted using a scatterplot against each meteorological factor by subsequent year and month. Each meteorological factor was plotted against the others as well in order to identify any climatological patterns or anomalies that may have occurred throughout the study period. The goal of the scatterplots was to identify trends and relationships among the pollen data and meteorological data. Specifically, each plot was designed to determine a relationship between each climate variable and pollen counts to potentially isolate one meteorological variable that has a more substantial correlation to pollen count.

The scatterplots were then analyzed using linear regression in Microsoft Excel. With a trendline added to the plots, the slope, intercept, and R^2 were identified. The slope for each plot showed the change in pollen counts with increase in one meteorological factor to test if there is a relationship between pollen count and the meteorological factor. R^2 identifies how strong the trend is. The closer the R^2 value is to 1.00, the stronger the correlation; the closer the R^2 value is to 0.00, the weaker the relationship between the two factors.

Data were then aggregated by season and year. The seasons were defined in this research as spring (March, April, May), summer (June, July, August), autumn (September, October, November), and winter (December, January, February). Similar to the monthly data, each pollen type was plotted using a scatterplot against each meteorological factor's seasonal averages, as well as the seasonal sums of precipitation. Each meteorological factor was then plotted against the others. Since pollen is frequently defined by season, it was important for this research to also define both the meteorological factors and pollen count data by season, because the monthly-aggregated data were sometimes skewed by a singular peak or inactive month.

Both the pollen data and meteorological data were refined by season in order to alter the scatter patterns and reanalyze the trendlines found from the monthly data using linear regression in Microsoft Excel. With a trendline added to the plots, the slope, intercept, and R^2 were identified. Winter was omitted from this part of the analysis because the pollen data during the winter season were scarce; only 19.7% of daily data from February were available and none for December or January.

Results

From 1999-2018, the average temperature in Raleigh, North Carolina increased slightly, with a slope of 0.06 and an R^2 value of 0.08 (Figure 1). The data fluctuated but ended with the warmest year in the past two decades. Similarly, the average amount of annual precipitation also increased (Figure 2). Even though the precipitation trend had more high-low oscillations than average temperature, it had a stronger positive increase, with a slope of 0.48 and an R^2 value of 0.16.

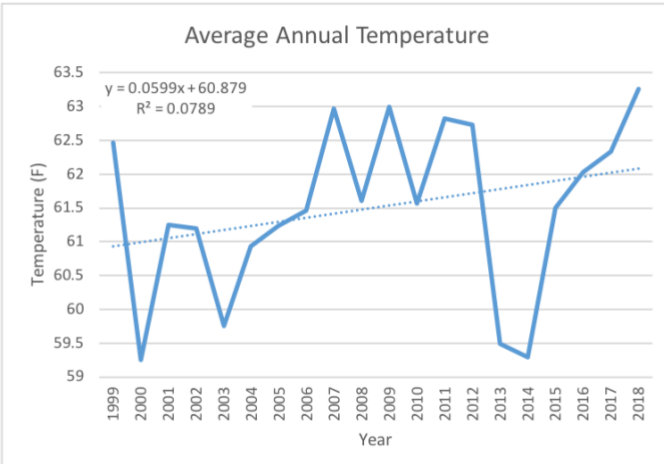

Figure 1. Average Annual Temperature, Averaged by Month, in Raleigh, North Carolina from 1999 - 2018

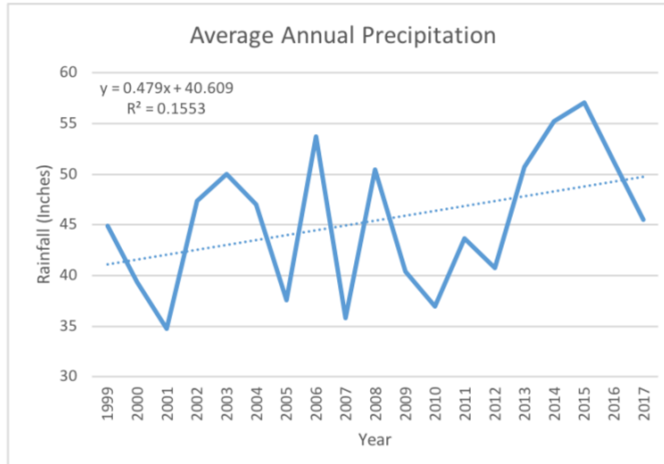

Figure 2. Average Annual Precipitation, Averaged by Month, in Raleigh, North Carolina from 1999 - 2017

The temporal analysis of grass, weed, and tree pollen showed that tree pollen counts were roughly ten times higher than grass and weed pollen counts (Figure 3). While 2016 and 2017 had the highest grass and weed pollen counts observed in the last two decades, both pollen types had low fit to the regression line (Table 1). Conversely, tree pollen, though it also fluctuated, more steadily increased with a higher R^2 value to the regression line.

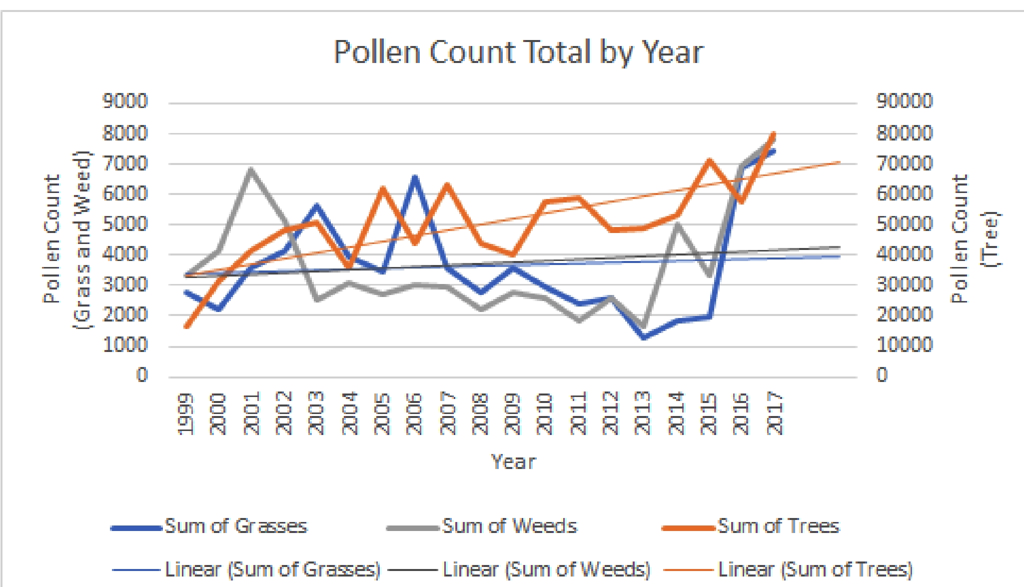

Figure 3. Grass, Weed, and Tree Pollen Count Sum by Year from 1999-2017.

Table 1. Slope and R^2 Values of Grass, Weed, and Tree Pollen Based on the Graph from 1999-2017.

Pollen Type	Slope	R^2 Value
Grass	29.00	0.01
Weed	49.81	0.02
Tree	1849.40	0.52

The annual data, which were aggregated monthly over the 20-year period, showed significantly more scatter than the seasonal data. Pollen was observed during the years 1999-2018 for the months where the average temperature was between 35°F and 85°F, a 50° range. Grass pollen had the lowest total pollen count with a maximum average of 167.82 grains in one month. Weed pollen had a maximum average of 234 grains, while tree pollen had the largest count of pollen, with 2419.82 grains reported in just one month. Each type of pollen had a vertical scatter at a different average temperature (Figure 4). Tree pollen, which had the highest count of pollen annually, had the most scatter around 60°F and the peak pollen count at 57°F. However, about half of the pollen counts dropped to 0 as the temperature increased, diverging from the steady rise at about 47°F. Because the annual tree pollen data were observed to follow two lines, one dropping to zero and staying constant as temperature increased, and the other rising steadily up to about 65°F, the regression lines were not reported for annual tree pollen data. The scatter between grass and weed pollen was more similar to one another, though grass pollen had a more condensed cluster between 65°F and 85°F, with the highest counts of pollen in this range. The scatter pattern for weed pollen was similar, but more spread out, and both grass and weed pollen had a visible peak at 70°F.

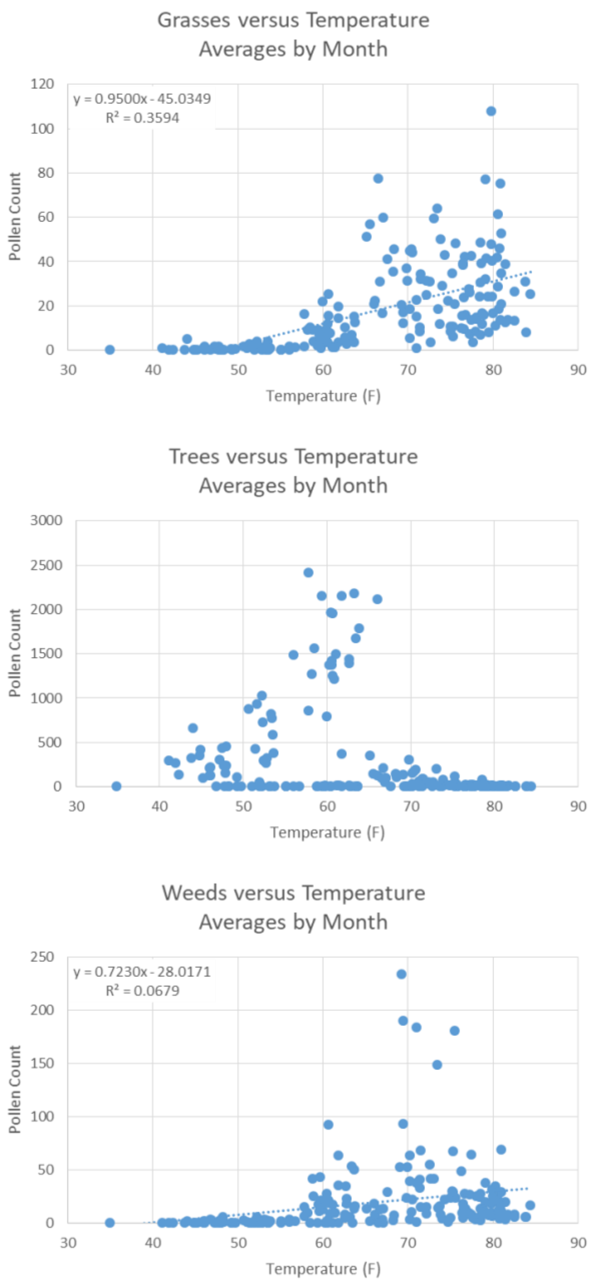

Figure 4. Annual Pollen Count for Grass, Weed, and Tree Pollen from 1999 – 2018, Averaged Monthly, versus the Average Annual Temperature in Fahrenheit, Averaged by Month.

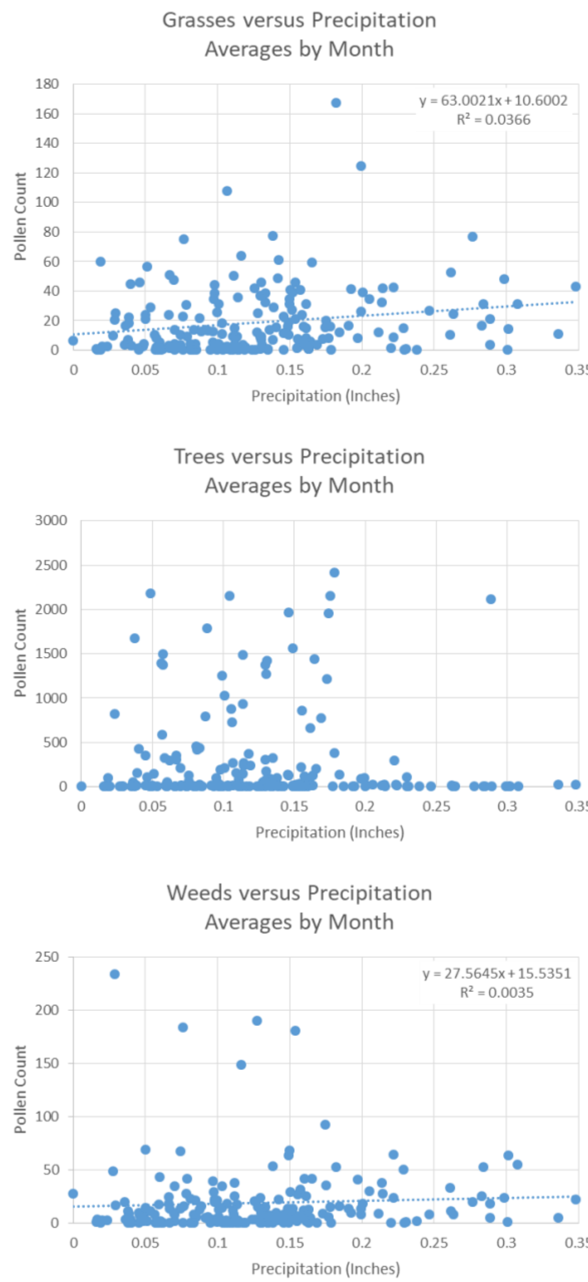

Figure 5. Annual Pollen Count for Grass, Weed, and Tree Pollen from 1999 – 2018, Averaged Monthly, versus the Average Precipitation Rate in Inches, Averaged by Month.

The annual data showed more scatter for pollen count versus the average precipitation each month throughout the 20-year period (Figure 5) compared with the plots of pollen count versus temperature. As was the case for annual temperature data, the pollen count slopes were positive for grass and weed pollen and were excluded for tree pollen because of a diverging pattern (Table 2). The data for tree pollen count and average annual precipitation followed the fork pattern, though the non-zero prong was less linear than was the case for average annual temperature, with a 10-degree horizontal spread as the pollen count grew from 0 to 2,419. However, all three pollen types skewed towards higher pollen counts during less than 0.2 inches of average monthly rainfall, with all three pollen type maxima (Grass: 167.32, Tree: 2419.82, Weed: 234) occurring under 0.20 inches of average precipitation. For grass and weed pollen, the scatter was more condensed to only 25% of the maximum pollen count for each type, while the scatter for tree pollen, though mostly consolidated to 20% of the maximum pollen, has substantial spread through the maximum 2419 pollen count.

Table 2. Slope and R^2 Values of Grass, Weed, and Tree Pollen for Average Annual Meteorological Data.

Pollen Type	Meteorological Factor	Slope	R^2 Value
Grass	Temperature	0.95	0.36[a]
	Precipitation	63.00	0.04[a,b]
Weed	Temperature	0.72	0.07
	Precipitation	27.56	0.00[b]
Tree	Temperature	n/a	n/a
	Precipitation	n/a	n/a

[a] – Outliers that affected the grass pollen versus all meteorological factor R^2 values were removed from May 2016 grass pollen average and May 2017 grass pollen average

[b] – Outlier that affected all annual pollen versus precipitation R^2 values were removed from September 2000

Over 20 years, seasonal relationships of pollen with temperature, precipitation, and dew point averages behaved differently. For temperature and dew point averages, each season had all pollen data points within an 8°F range from the low end to high end of temperature (spring: 57°F - 65°F, summer: 75°F - 83°F, autumn: 59°F - 67°F) (Figure 6, Appendix C1). The scatter within the temperature range varies by season, with the most scatter occurring with tree pollen in the spring, fluctuating from 550 to 1096 pollen count, whereas, in the summer and autumn, the range of observed pollen is only 5-35 grains and 0-39 grains, respectively. In the spring for grass and weed pollen, the quantity of pollen is lower, but the regression line is similar to that of spring's tree pollen: grass, weed, and tree pollen have relatively low R^2 values (Table 3). In the spring, grass pollen count had two data points much higher than the rest of the data, both at about 62°F. Furthermore, 9 of the 20 data points for grass pollen versus temperature in the spring are within a 1°F standard deviation of 62°F, with the second highest count of pollen in this range and the highest count just outside at 62.4°F. Similarly, tree pollen data for spring by temperature also had 9 of 20 data points within the 1°F standard deviation of 62°F, with the highest tree pollen count at 61°F. Weed pollen had 9 of 19 data points within the same range from 61°F to 63°F and, like grass pollen, had the highest weed pollen count just outside the range at 62.4°F, with one of the other highest counts at 61°F.

Table 3. Slope and R^2 Values of Grass, Weed, and Tree Pollen for Seasonal Meteorological Data for spring.

Pollen Type	Meteorological Factor	Slope	R^2 Value
Grass	Temperature	1.58	0.04
	Precipitation	255.26	0.32

Weed	Temperature	1.32	0.10[a]
	Precipitation	165.04	0.48[a]
Tree	Temperature	5.98	0.03
	Precipitation	1772.85	0.10[b]

[a] – Outlier that affected weed pollen count seasonal averages was removed from spring 2014

[b] – Outlier that affected tree pollen count for precipitation and dew point seasonal averages were removed from spring 1999

The fluctuation of average precipitation per season was smallest in the spring, with the highest average at only 0.19 inches, whereas the highest average for summer and autumn went up to 0.24 inches and 0.28 inches, respectively (Figure 7, Appendix C4, Appendix C8). While the largest concentration of pollen count data points was within the 0.13 to 0.15 inch range, grass and weed pollen's highest concentration occurred at the highest end of spring's average precipitation range, which was 0.19 inches. For tree pollen at 0.19 inches, there was also one of the highest concentrations of pollen with a count of 1061, but there were actually two data points with higher counts of pollen, 1087 and 1096, near the peak range of 0.13 inches. Furthermore, the regression line for weed pollen was positive in spring but, in summer and autumn, had a negative slope (Table 3). In spring for grass pollen, the average precipitation data had a similar relationship as weed pollen and followed a similar line. The scope of pollen count for tree pollen is larger than that of the other two types, so it had a larger slope, but also a lower R^2 value.

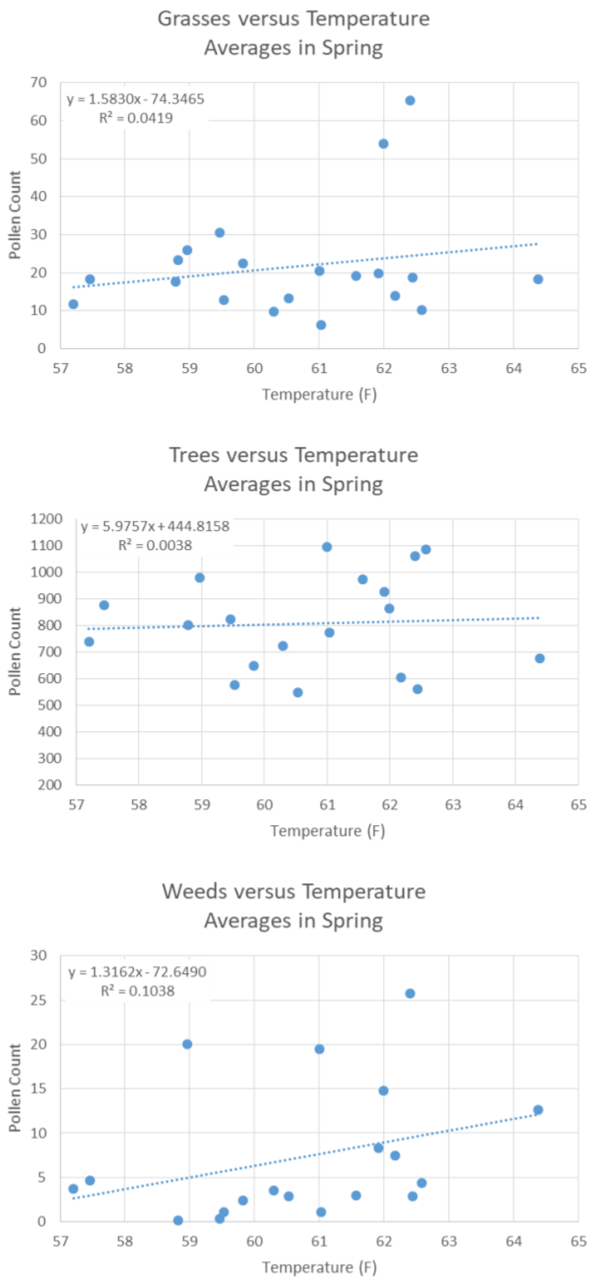

Figure 6. Seasonal Pollen Count for Grass, Weed, and Tree Pollen during the Spring (March – May) from 1999 – 2018 versus the Average Temperature in Fahrenheit.

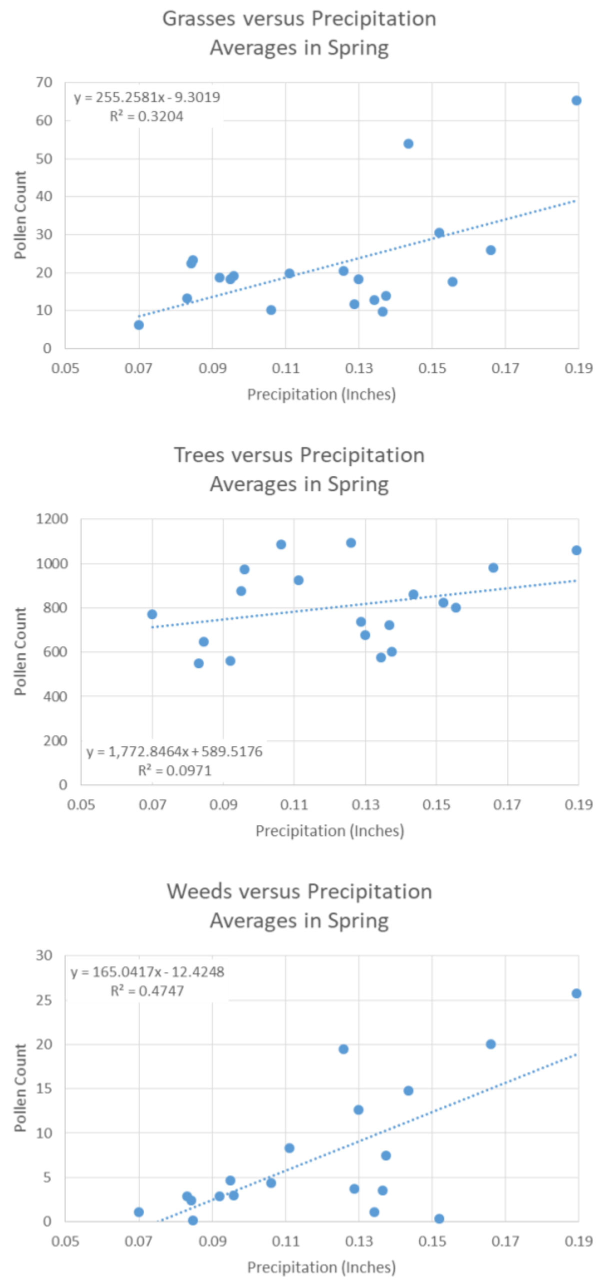

Figure 7. Seasonal Pollen Count for Grass, Weed, and Tree Pollen during the Spring (March – May) from 1999 – 2018 versus the Average Precipitation Rate in Inches.

Overall, the seasonal versus annual data actually displayed different scatter for each of the three pollen types, with the seasonal temperature data having lower R^2 values than the annual temperature data for grass, weed, and tree pollen. Conversely, the seasonal precipitation data had R^2 values that were, on average, higher than those for annual precipitation data for the three pollen types.

Discussion

Annual Data

From February 1999 through September 2018, pollen count in Raleigh, North Carolina fluctuated annually, by season, and by species. Ultimately, there was no discernible pattern between weed or grass pollen count and temperature. Because annual temperature oscillates, as shown in Figure 1, Katz et al. have shown that ragweed seed germination is not very sensitive to changes in temperature, meaning that the relationship between pollen count and temperature is convoluted, if it exists, and is not necessarily linear (Katz et al. 2014).

Tree pollen, with its R^2 of 0.52, displays an increasing trend. The National Allergy Bureau confirms that tree pollen has a much earlier peak season than the other two pollen types do, peaking in April, as opposed to September for weed pollen and June or July for grass pollen (NAB 2018). According to the Intergovernmental Panel on Climate Change, the anticipated weather patterns that correspond with each season are shifting, with "spring" attributes occurring earlier in the year, meaning the temperature is warmer earlier (IPCC 2014). However, based on the data from the last twenty years, there is inconclusive evidence that because spring begins earlier, the increase in tree pollen count could be attributed to the rise in temperature.

While Raleigh has an average low temperature of 50°F and an average high temperature of 71.3°F, the largest peaks for all three pollen types was at the high end of this range (U.S. Climate Data 2018). While tree pollen count peaked at 65°F, both weed and grass pollen peaked at 70°F, which is about the average annual high temperature. As the average annual temperature continues to increase with climate change (IPCC 2014), it is likely that the peak pollen counts for weeds and grasses will increase, therefore producing more pollen for a longer amount of time annually because the daily minimum temperatures will increase more rapidly than the daily maximum temperatures (Meehl et al. 2007). As daily minimum temperatures likely limit pollination productivity, the expansion of the window of subtropical conditions will increase plant productivity in Raleigh, North Carolina. However, climate change will eventually bring extreme weather and temperatures to regions that are usually more temperate (IPCC 2014), so while warmer temperatures can increase the rate of plant development, this relationship does not continue linearly (Hatfield and Prueger 2015). Exposure to temperatures above 86°F start to damage cell division in plants, reducing pollination and, ultimately, yield, which is why plants in tropical biomes, for example, produce less pollen than those in a more temperate climate.

When plotted against annual data for temperature, dew point, and precipitation, tree pollen data diverged, with about half of the pollen count data rising up linearly and the other half dropping down to counts of zero tree pollen. Because there are 242 season-specific types of tree pollen in the study area, it is likely that, since the data were aggregated monthly, some of those trees are deciduous plants, meaning they lose their pollinating flowers and therefore do not evenly contribute to the pollen count throughout the year (Pollen Library 2018). In fact, deciduous tree pollen output is more reliant on past meteorological elements than current data, likely because of the annual cycle these trees undergo, meaning the factors like temperature, dew point, and previous years' precipitation affect the pollen production in the future (Makra et al. 2014). The trees that are evergreen and bloom year-round are the likely contributors to the increase in pollen count with temperature. It should be noted, though, that evergreen trees also have peak seasons, and do not pollinate equally year-round. The data for tree pollen count and average annual precipitation also followed the fork pattern, though the non-zero prong showed more scatter than was the case for average annual temperature.

The weed and grass pollen data similarly had the majority of pollen count from 0.00 to 0.20 inches of average annual precipitation. Because all three pollen counts showed much higher concentrations under 0.20 inches of rain, it is possible that pollen data are skewed by run-off, a physical module that is often parameterized in pollen models by using emission fluxes (Zhang et al. 2014a). Wet conditions, according to the National Allergy Bureau, limit the amount of airborne pollen, but only temporarily (NAB 2018). With an annual precipitation average of more than 0.20 inches of rain, the larger quantity of water could dissipate the concentration of pollen, so it is not properly analyzed in the spore trap at the weather station. Conversely, at least some rain is necessary for pollen to occur, likely because the flora in the sample area is accustomed to a subtropical climate, as it is part of the Piedmont region, meaning the plants in the area are accustomed to humid and moist conditions, requiring rain to grow and flower (CEC 2011).

There were several outliers that were removed from the annual meteorological data averages. For temperature, precipitation, and dew point, May 2016 and May 2017 grass pollen counts were removed because they deviated from the regression line to an extreme, with average counts of 125 and 167 grains of pollen, respectively, whereas all other pollen data was measured at or below 100 grains. They were uncharacteristically high when compared to the historical data, but current pollen counts are being affected by climate change, so it is possible that they are being acted upon by more extreme meteorological factors. Similarly, the grass, weed, and tree pollen data were removed for September 2000, because it was outside the rest of the scatterplot pattern and uncharacteristically high.

Seasonal Data

North Carolina is one of the areas in the United States that is known for experiencing all four seasons. Therefore, the meteorological and pollen data were aggregated by season and analyzed. While plants in North Carolina pollinate year-round, the highest pollen counts are in the spring (March – May). This is likely due to the fact that tree pollen is the largest contributor to total pollen in North Carolina (NAB 2018). Spring is tree pollen’s peak season, having a maximum concentration of 30 times any other season’s maximum, as shown in Figures 4 and 5. Grass and weed pollens’ seasons are both longer than tree pollen’s, with grass pollen’s peak season also beginning in spring. Therefore, spring plots, containing the largest counts, was the focus of the seasonal analysis.

A study by Zhang et al. in 2014 also focused on spring when looking at a pollen emission framework, using five representative tree pollen types (Zhang et al. 2014a). Zhang also observed the highest quantity of pollen in May, with another peak in March, marking the boundaries of spring as defined in this study. Further supporting the selection of spring as the main season to observe pollen counts, they used one representative grass pollen type for comparison. In this research, and similar to Zhang et al.’s findings, the regression lines of grass and weed pollen for temperature and precipitation look similar to tree pollen in the spring, even though the quantities are lower.

Precipitation averages for spring, when compared against the pollen count data for the same time period, had a much stronger, positive correlation than the temperature or dew point data. In spring, the maximum amount of rain for the season was 0.20 inches, which is the same where the largest cluster of annual precipitation data was plotted, as well. This is also where the maximum concentration of each type of pollen is plotted, showing that the more precipitation that occurs, the higher the amount of pollen, which contradicts the annual data that showed more of a bell curve. It is possible that the positive correlation exists only for spring conditions, and then falls back down to a skewed distribution for the other seasons. The increase of precipitation and temperature suggests that the start date of pollen production has changed, with a correlation between lengthened spring pollen season and increased abundance (Zhang et al. 2014b).

The seasonal pollen data had high variation for the 8-degree spread (57°F - 65°F) of spring's average temperature, yet all three pollen types had an increasing relationship with temperature. Though seasonal parameters vary by ecological zone, in southern areas of the United States, like Raleigh, spring temperatures are highly correlated with season onset, supporting an association between increasing pollen counts and increasing temperature for a longer period of time (Hess et al. 2018). All three pollen types clustered between a 2-degree spread (61°F - 63°F), though, with almost half of the data points falling in between those boundaries for grass, weed, and tree pollen. This cluster indicates a favorable temperature for pollen, which is further displayed in the temperature average plots for autumn as well (Appendix C6), since that 2-degree range corresponds to peak pollen counts for the autumn months. Including lingering frost days and early summer heat waves, or the opposite for autumn (lingering heat waves and early frost days), the average temperature for these two prominent pollen seasons is about 62°F, the midpoint of the 2-degree range. In a laboratory under synthetic conditions, researchers found that the optimal temperature for pollen is about 60°F, though larger pollen grains flourished under slightly higher temperatures (Ejsmond et al. 2011). This controlled laboratory study reinforces patterns that are observed with historical data by exposing pollen grains to various conditions found in nature. By counting how many survive, germinate, and increase in size, it emphasizes that specific pollen species have preferred temperatures for flourishing.

According to Makra et al. (2014), precipitation in the spring contributes to pollen production (Makra et al. 2014). The springtime correlation between precipitation and pollen count is stronger than that of temperature or dew point in this study. Because spring is defined by some of the rainiest months of the year in Raleigh, NC, precipitation plays a larger role than it would in dryer seasons (U.S. Climate Data 2018). The higher frequency of precipitation events also means that rain water can soak into the soil, continuing to provide water to plants, which they need to pollinate, even during drought or longer periods without rain (USGS 2016).

Several outliers that were removed from the Spring data. For temperature, dew point, and precipitation, the 2014 weed pollen datum was removed, as it was almost twice as high as the second highest data point. The 1999 tree pollen datum was removed from the dew point and precipitation plots for being only 1/3 of the next lowest data point. This is likely because it was the first year when data were collected and tracked in North Carolina. Because tree pollen peaks earliest, the concentrations from months at the beginning are imperative to build up pollen count, and without those data, the tree pollen count for spring of 1999 was skewed lower than was expected.

Limitations

This study is limited by data availability and scope. Pollen data for the Piedmont region in North Carolina was only available from one data collection site, the Raleigh-Durham Airport Weather Station, so a spatial analysis was not possible. The pollen data were limited by availability throughout the year, with only February – November data reporting, which included only about 5 days of data on a typical 7-day week. Winter (December – February) was excluded because data availability was limited; little pollen data were available for February. As to not skew the entire season's plots by a singular month of data, the entire season was not included. Furthermore, for pollen data, it was not broken down in the NC DEQ database by specific pollen species but only by type: tree, grass, and weed. This limits the ability to discriminate tree pollen between deciduous and evergreen varieties that could have helped distinguish patterns in the forked plots of tree pollen count versus the meteorological parameters.

Only three meteorological factors were assessed, although there are many other considerations that could have a correlation to pollen count data. The meteorological data were taken from the same weather station, but also had gaps and was filled in manually. The NC DEQ data report and the Weather Underground historical data were not always identical on a daily basis, leading to discrepancies in meteorological data. Furthermore, all of the data from the NC DEQ, including pollen and meteorological data, were only available for 20 years back to February 1999, limiting the analysis of historical data.

Other scientific research has used historical data to assess the relationship between meteorological factors. Use of predictive models and scenarios enables incorporation of historical data with current data and projected meteorological outcomes to quantify the future of pollen counts. Currently, there are not enough pollen data for an accurate prediction based on climate change scenarios in this study, because the scope is too narrow.

Conclusion

The IPCC (2014) has predicted that temperature will continue to rise. Based on the data from the annual plots, there might be a correlation between temperature and tree pollen count. Since the peak pollen count occurred at 70°F, this means that, as temperature increases, it is possible that pollen count will increase with it. This relationship is not definitive though, and an increase in temperature could produce a different pattern of pollen release throughout the year.

The rising temperatures will also likely produce increased evaporation, which, in turn, results in more precipitation (NASA 2018). There was an observed correlation between seasonal precipitation and pollen counts, particularly during the rainy season. As more of the year becomes rainy because of climate change (NASA 2018), it is probable that pollen counts could increase as well.

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Appendix

Appendix A. – Pollen Species by Season

Spring	Summer	Autumn	Winter
Annual Blue Grass (Poa annua)	Annual Blue Grass (Poa annua)	Annual Blue Grass (Poa annua)	Annual Blue Grass (Poa annua)
Bald Brome (Bromus racemosus)	Bald Brome (Bromus racemosus)	Bermuda Grass (Cynodon dactylon)	Broad-Leaf Cat-Tail (Typha latifolia)
Bermuda Grass (Cynodon dactylon)	Bermuda Grass (Cynodon dactylon)	Big Bluestem (Andropogon gerardii)	Broom-Sedge (Andropogon virginicus)
Broad-Leaf Cat-Tail (Typha latifolia)	Big Bluestem (Andropogon gerardii)	Broad-Leaf Cat-Tail (Typha latifolia)	Eastern Mock Grama (Tripsacum dactyloides)
Cheat Grass (Bromus tectorum)	Black Bent (Agrostis gigantea)	Broom-Corn (Sorghum bicolor)	Elliott's Bent (Agrostis elliottiana)
Clustered Fescue (Festuca paradoxa)	Broad-Leaf Cat-Tail (Typha latifolia)	Broom-Sedge (Andropogon virginicus)	Johnson Grass (Sorghum halepense)
Common Timothy (Phleum pratense)	Broom-Corn (Sorghum bicolor)	Cheat Grass (Bromus tectorum)	Large Barnyard Grass (Echinochloa crus-galli)
Eastern Mock Grama (Tripsacum dactyloides)	Broom-Sedge (Andropogon virginicus)	Common Timothy (Phleum pratense)	Little Barley (Hordeum pusillum)
Eight-Flower Six-Weeks Grass (Vulpia octoflora)	Cheat Grass (Bromus tectorum)	Corn (Zea mays)	Smut Grass (Sporobolus indicus)
Elliott's Bent (Agrostis elliottiana)	Clustered Fescue (Festuca paradoxa)	Eastern Mock Grama (Tripsacum dactyloides)	Tufted Meadow-Foxtail (Alopecurus
Fall Panic Grass (Panicum dichotomiflorum)	Common Timothy (Phleum pratense)	Fall Panic Grass (Panicum dichotomiflorum)	Winter Bent (Agrostis hyemalis)
Fox-Tail Barley (Hordeum jubatum)	Corn (Zea mays)	Golden Crown Grass (Paspalum dilatatum)	Yellow Flat Sedge (Cyperus flavescens)
Fringed Sedge (Carex crinita)	Eastern Bottle-Brush Grass (Elymus hystrix)	Green Bristle Grass (Setaria viridis)	
Golden Crown Grass (Paspalum dilatatum)	Eastern Mock Grama (Tripsacum dactyloides)	Hairy Crab Grass (Digitaria sanguinalis)	
Green Bristle Grass (Setaria viridis)	Eight-Flower Six-Weeks Grass (Vulpia octoflora)	Indian Wood-Oats (Chasmanthium latifolium)	
Hairy Crab Grass (Digitaria sanguinalis)	Elliott's Bent (Agrostis elliottiana)	Johnson Grass (Sorghum halepense)	
Hairy Wild Rye (Elymus villosus)	Fall Panic Grass (Panicum dichotomiflorum)	Kentucky Blue Grass (Poa pratensis)	
Hairy Wood-Rush (Luzula acuminata)	Fox-Tail Barley (Hordeum jubatum)	Large Barnyard Grass (Echinochloa crus-galli)	
Johnson Grass (Sorghum halepense)	Fringed Sedge (Carex crinita)	Little False Bluestem (Schizachyrium	
Kentucky Blue Grass (Poa pratensis)	Golden Crown Grass (Paspalum dilatatum)	Orchard Grass (Dactylis glomerata)	
Large Barnyard Grass (Echinochloa crus-galli)	Green Bristle Grass (Setaria viridis)	Red-Top Panic Grass (Panicum rigidulum)	
Large Sweet Vernal Grass (Anthoxanthum	Hairy Crab Grass (Digitaria sanguinalis)	Slender Fimbry (Fimbristylis autumnalis)	
Lesser Quaking Grass (Briza minor)	Hairy Wild Rye (Elymus villosus)	Smooth Crab Grass (Digitaria ischaemum)	
Little Barley (Hordeum pusillum)	Indian Wood-Oats (Chasmanthium latifolium)	Smut Grass (Sporobolus indicus)	
Nodding Fescue (Festuca subverticillata)	Johnson Grass (Sorghum halepense)	Spreading Bent (Agrostis stolonifera)	
Oat (Avena sativa)	Kentucky Blue Grass (Poa pratensis)	Stink Grass (Eragrostis cilianensis)	
Orchard Grass (Dactylis glomerata)	Large Barnyard Grass (Echinochloa crus-galli)	Sweet Wood-Reed (Cinna arundinacea)	
Oval-Leaf Sedge (Carex cephalophora)	Large Sweet Vernal Grass (Anthoxanthum	Tall Redtop (Tridens flavus)	
Rough-Stalk Blue Grass (Poa trivialis)	Lesser Quaking Grass (Briza minor)	Upland Bent (Agrostis perennans)	
Slender Fimbry (Fimbristylis autumnalis)	Little Barley (Hordeum pusillum)	Vasey's Grass (Paspalum urvillei)	
Smut Grass (Sporobolus indicus)	Little False Bluestem (Schizachyrium scoparium)	Virginia Wild Rye (Elymus virginicus)	
Spreading Bent (Agrostis stolonifera)	Nodding Fescue (Festuca subverticillata)	Wand Panic Grass (Panicum virgatum)	
Stink Grass (Eragrostis cilianensis)	Oat (Avena sativa)	Yellow Flat Sedge (Cyperus flavescens)	
Tufted Meadow-Foxtail (Alopecurus carolinianus)	Orchard Grass (Dactylis glomerata)	Yellow Indian Grass (Sorghastrum nutans)	
Uptight Sedge (Carex stricta)	Oval-Leaf Sedge (Carex cephalophora)		
Vasey's Grass (Paspalum urvillei)	Red-Top Panic Grass (Panicum rigidulum)		
Virginia Wild Rye (Elymus virginicus)	Rough-Stalk Blue Grass (Poa trivialis)		
Wand Panic Grass (Panicum virgatum)	Slender Fimbry (Fimbristylis autumnalis)		
Winter Bent (Agrostis hyemalis)	Smooth Crab Grass (Digitaria ischaemum)		
	Smut Grass (Sporobolus indicus)		
	Spreading Bent (Agrostis stolonifera)		
	Stink Grass (Eragrostis cilianensis)		
	Sweet Wood-Reed (Cinna arundinacea)		
	Tall Redtop (Tridens flavus)		
	Tufted Meadow-Foxtail (Alopecurus carolinianus)		
	Upland Bent (Agrostis perennans)		
	Uptight Sedge (Carex stricta)		
	Vasey's Grass (Paspalum urvillei)		
	Virginia Wild Rye (Elymus virginicus)		
	Wand Panic Grass (Panicum virgatum)		
	Winter Bent (Agrostis hyemalis)		
	Yellow Flat Sedge (Cyperus flavescens)		
	Yellow Indian Grass (Sorghastrum nutans)		

Appendix A1. Grass Pollen Species by Season (Pollen Library 2018).

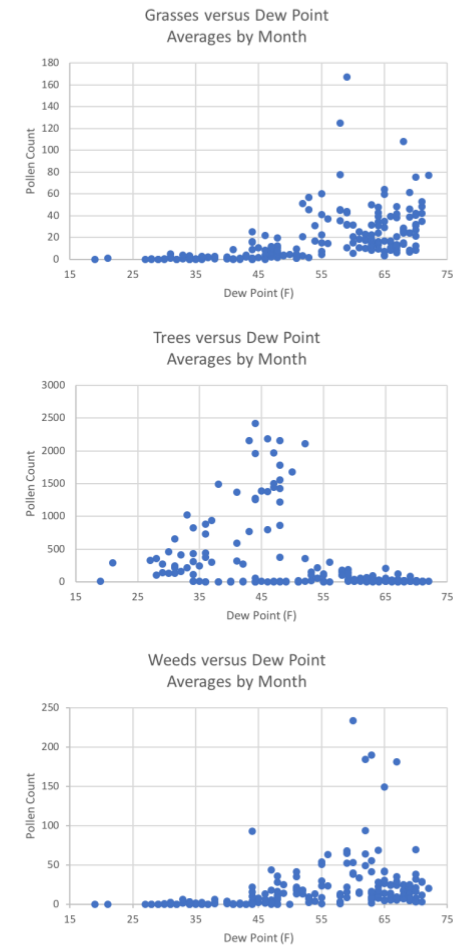
Spring		Summer	Autumn	Winter
Allegheny-Chinkapin (Castanea pumila)	Northern Spicebush (Lindera benzoin)	Allegheny-Chinkapin (Castanea pumila)	Alternate-Leaf Dogwood (Cornus	Allegheny-Chinkapin (Castanea pumila)
Alternate-Leaf Dogwood (Cornus alternifolia)	Northern White Oak (Quercus alba)	Alternate-Leaf Dogwood (Cornus alternifolia)	American Witch-Hazel (Hamamelis	American Beech (Fagus grandifolia)
American Basswood (Tilia americana)	Osage-Orange (Maclura pomifera)	American Basswood (Tilia americana)	Autumn-Olive (Elaeagnus umbellata)	American Elm (Ulmus americana)
American Beech (Fagus grandifolia)	Overcup Oak (Quercus lyrata)	American Holly (Ilex opaca)	Black Elder (Sambucus nigra)	American Hornbeam (Carpinus
American Elm (Ulmus americana)	Painted Buckeye (Aesculus sylvatica)	American Hornbeam (Carpinus caroliniana)	Cock-Spur Hawthorn (Crataegus crus-galli)	American Sycamore (Platanus
American Hazelnut (Corylus americana)	Paper-Mulberry (Broussonetia papyrifera)	American Plum (Prunus americana)	Common Hackberry (Celtis occidentalis)	American Witch-Hazel (Hamamelis
American Holly (Ilex opaca)	Peach (Prunus persica)	American Sycamore (Platanus occidentalis)	Dwarf Hackberry (Celtis tenuifolia)	Black Elder (Sambucus nigra)
American Hornbeam (Carpinus caroliniana)	Pecan (Carya illinoinensis)	American Witch-Hazel (Hamamelis	Evergreen Bayberry (Morella caroliniensis)	Box Elder, Ash-Leaf Maple (Acer negundo)
American Plum (Prunus americana)	Pignut Hickory (Carya glabra)	Atlantic Poison-Oak (Toxicodendron	Groundseltree (Baccharis halimifolia)	Brookside Alder (Alnus serrulata)
American Sycamore (Platanus occidentalis)	Pin Oak (Quercus palustris)	Autumn-Olive (Elaeagnus umbellata)	Japanese Honeysuckle (Lonicera japonica)	Carolina Ash (Fraxinus caroliniana)
American Witch-Hazel (Hamamelis	Pond Pine (Pinus serotina)	Big-Leaf Magnolia (Magnolia macrophylla)	New Jersey-Tea (Ceanothus americanus)	Carolina Holly (Ilex ambigua)
Atlantic Poison-Oak (Toxicodendron	Post Oak (Quercus stellata)	Black Cherry (Prunus serotina)	Silktree (Albizia julibrissin)	Deciduous Holly (Ilex decidua)
Atlantic White-Cedar (Chamaecyparis	Pumpkin Ash (Fraxinus profunda)	Black Elder (Sambucus nigra)	Sourwood (Oxydendrum arboreum)	Downy Service-Berry (Amelanchier
Autumn-Olive (Elaeagnus umbellata)	Red Buckeye (Aesculus pavia)	Black Locust (Robinia pseudoacacia)	Southern Bayberry (Morella cerifera)	Eastern Hop-Hornbeam (Ostrya virginiana)
Beaked Hazelnut (Corylus cornuta)	Red Maple (Acer rubrum)	Black Tupelo (Nyssa sylvatica)	Sugar-Berry (Celtis laevigata)	Evergreen Bayberry (Morella caroliniensis)
Big-Leaf Magnolia (Magnolia macrophylla)	Red Mulberry (Morus rubra)	Black Walnut (Juglans nigra)	Sweet-Bay (Magnolia virginiana)	Flowering Dogwood (Cornus florida)
Bitter-Nut Hickory (Carya cordiformis)	Redbud (Cercis canadensis)	Black Willow (Salix nigra)	Trumpet Honeysuckle (Lonicera	Green Ash (Fraxinus pennsylvanica)
Black Cherry (Prunus serotina)	River Birch (Betula nigra)	Canadian Service-Berry (Amelanchier	Winged Sumac (Rhus copallinum)	Inkberry (Ilex glabra)
Black Elder (Sambucus nigra)	Rusty Blackhaw (Viburnum rufidulum)	Carolina Willow (Salix caroliniana)		Japanese Honeysuckle (Lonicera japonica)
Black Locust (Robinia pseudoacacia)	Sand Hickory (Carya pallida)	Catawba Rosebay (Rhododendron		Northern Spicebush (Lindera benzoin)
Black Oak (Quercus velutina)	Sassafras (Sassafras albidum)	Cock-Spur Hawthorn (Crataegus crus-galli)		Red Buckeye (Aesculus pavia)
Black Tupelo (Nyssa sylvatica)	Scarlet Oak (Quercus coccinea)	Common Hoptree (Ptelea trifoliata)		Red Maple (Acer rubrum)
Black Walnut (Juglans nigra)	Shag-Bark Hickory (Carya ovata)	Common Winterberry (Ilex verticillata)		Red Mulberry (Morus rubra)
Black Willow (Salix nigra)	Short-Leaf Pine (Pinus echinata)	Downy Service-Berry (Amelanchier arborea)		Redbud (Cercis canadensis)
Blackjack Oak (Quercus marilandica)	Shumard's Oak (Quercus shumardii)	Eastern Hop-Hornbeam (Ostrya virginiana)		River Birch (Betula nigra)
Box Elder, Ash-Leaf Maple (Acer negundo)	Silktree (Albizia julibrissin)	Eastern Poison-Ivy (Toxicodendron radicans)		Rusty Blackhaw (Viburnum rufidulum)
Brookside Alder (Alnus serrulata)	Silky Willow (Salix sericea)	Evergreen Bayberry (Morella caroliniensis)		Sassafras (Sassafras albidum)
Canadian Service-Berry (Amelanchier	Silver Maple (Acer saccharinum)	Flowering Dogwood (Cornus florida)		Silver Maple (Acer saccharinum)
Carolina Ash (Fraxinus caroliniana)	Slippery Elm (Ulmus rubra)	Great-Laurel (Rhododendron maximum)		Southern Bayberry (Morella cerifera)
Carolina Holly (Ilex ambigua)	Smooth Sumac (Rhus glabra)	Groundseltree (Baccharis halimifolia)		Southern Catalpa (Catalpa bignonioides)
Carolina Willow (Salix caroliniana)	Smooth Winterberry (Ilex laevigata)	Highbush Blueberry (Vaccinium		Sweet-Gum (Liquidambar styraciflua)
Catawba Rosebay (Rhododendron	Sourwood (Oxydendrum arboreum)	Inkberry (Ilex glabra)		Trumpet Honeysuckle (Lonicera
Chestnut Oak (Quercus prinus)	Southern Bald-Cypress (Taxodium	Japanese Honeysuckle (Lonicera japonica)		White Ash (Fraxinus americana)
Chickasaw Plum (Prunus angustifolia)	Southern Bayberry (Morella cerifera)	Mountain-Laurel (Kalmia latifolia)		White Fringetree (Chionanthus virginicus)
Chinese Privet (Ligustrum sinense)	Southern Catalpa (Catalpa bignonioides)	New Jersey-Tea (Ceanothus americanus)		White Mulberry (Morus alba)
Chinese Tallowtree (Triadica sebifera)	Southern Crabapple (Malus angustifolia)	Osage-Orange (Maclura pomifera)		White Poplar (Populus alba)
Coastal Service-Berry (Amelanchier obovalis)	Southern Red Oak (Quercus falcata)	Paper-Mulberry (Broussonetia papyrifera)		Winged Elm (Ulmus alata)
Cock-Spur Hawthorn (Crataegus crus-galli)	Stiff Dogwood (Cornus foemina)	Red Buckeye (Aesculus pavia)		
Common Hackberry (Celtis occidentalis)	Sugar-Berry (Celtis laevigata)	Red Mulberry (Morus rubra)		
Common Hoptree (Ptelea trifoliata)	Swamp Chestnut Oak (Quercus michauxii)	River Birch (Betula nigra)		
Common Pear (Pyrus communis)	Swamp Cottonwood (Populus	Rusty Blackhaw (Viburnum rufidulum)		
Common Winterberry (Ilex verticillata)	Swamp White Oak (Quercus bicolor)	Sassafras (Sassafras albidum)		
Cultivated Apple (Malus pumila)	Sweet-Bay (Magnolia virginiana)	Silktree (Albizia julibrissin)		
Deciduous Holly (Ilex decidua)	Sweet-Fern (Comptonia peregrina)	Silver Maple (Acer saccharinum)		
Downy Service-Berry (Amelanchier arborea)	Sweet-Gum (Liquidambar styraciflua)	Smooth Sumac (Rhus glabra)		
Dwarf Hackberry (Celtis tenuifolia)	Tree-of-Heaven (Ailanthus altissima)	Smooth Winterberry (Ilex laevigata)		
Eastern Hemlock (Tsuga canadensis)	Trumpet Honeysuckle (Lonicera	Sourwood (Oxydendrum arboreum)		
Eastern Hop-Hornbeam (Ostrya virginiana)	Tuliptree (Liriodendron tulipifera)	Southern Bayberry (Morella cerifera)		
Eastern Poison-Ivy (Toxicodendron radicans)	Turkey Oak (Quercus laevis)	Southern Catalpa (Catalpa bignonioides)		
Eastern Red-Cedar (Juniperus virginiana)	Umbrella Magnolia (Magnolia tripetala)	Southern Crabapple (Malus angustifolia)		
Evergreen Bayberry (Morella caroliniensis)	Virginia Pine (Pinus virginiana)	Stiff Dogwood (Cornus foemina)		
Flowering Dogwood (Cornus florida)	Water Oak (Quercus nigra)	Sugar-Berry (Celtis laevigata)		
Green Ash (Fraxinus pennsylvanica)	White Ash (Fraxinus americana)	Sweet-Bay (Magnolia virginiana)		
Highbush Blueberry (Vaccinium	White Fringetree (Chionanthus virginicus)	Sweet-Fern (Comptonia peregrina)		
Inkberry (Ilex glabra)	White Mulberry (Morus alba)	Sweet-Gum (Liquidambar styraciflua)		
Japanese Honeysuckle (Lonicera japonica)	White Poplar (Populus alba)	Tree-of-Heaven (Ailanthus altissima)		
Loblolly Pine (Pinus taeda)	White Willow (Salix alba)	Trumpet Honeysuckle (Lonicera		
Long-Leaf Pine (Pinus palustris)	Wild Hydrangea (Hydrangea arborescens)	Tuliptree (Liriodendron tulipifera)		
Mockernut Hickory (Carya alba)	Willow Oak (Quercus phellos)	White Fringetree (Chionanthus virginicus)		
Mountain-Laurel (Kalmia latifolia)	Winged Elm (Ulmus alata)	White Mulberry (Morus alba)		
New Jersey-Tea (Ceanothus americanus)	Winged Sumac (Rhus copallinum)	Wild Hydrangea (Hydrangea arborescens)		
Northern Red Oak (Quercus rubra)	Yellow Buckeye (Aesculus flava)	Winged Sumac (Rhus copallinum)		
		Yellow Buckeye (Aesculus flava)		

Appendix A2. Tree Pollen Species by Season (Pollen Library 2018).

Spring	Summer	Autumn	Winter
Alfalfa (Medicago sativa)	Alfalfa (Medicago sativa)	Alfalfa (Medicago sativa)	Annual Ragweed (Ambrosia artemisiifolia)
Annual Ragweed (Ambrosia artemisiifolia)	Annual Ragweed (Ambrosia artemisiifolia)	Annual Ragweed (Ambrosia artemisiifolia)	Black Medick (Medicago lupulina)
Bitter Dock (Rumex obtusifolius)	Bitter Dock (Rumex obtusifolius)	Bitter Dock (Rumex obtusifolius)	Chicory (Cichorium intybus)
Black Medick (Medicago lupulina)	Black Medick (Medicago lupulina)	Black Medick (Medicago lupulina)	Common Dandelion (Taraxacum officinale)
Black-Seed Plantain (Plantago rugelii)	Black-Seed Plantain (Plantago rugelii)	Black-Seed Plantain (Plantago rugelii)	Common Sheep Sorrel (Rumex acetosella)
Canadian Clearweed (Pilea pumila)	Canadian Clearweed (Pilea pumila)	Canadian Clearweed (Pilea pumila)	Curly Dock (Rumex crispus)
Canadian Wood-Nettle (Laportea canadensis)	Canadian Wood-Nettle (Laportea canadensis)	Canadian Wood-Nettle (Laportea canadensis)	Great Plantain (Plantago major)
Chicory (Cichorium intybus)	Chicory (Cichorium intybus)	Chicory (Cichorium intybus)	Japanese Honeysuckle (Lonicera japonica)
Common Daffodil (Narcissus pseudonarcissus)	Common Dandelion (Taraxacum officinale)	Common Dandelion (Taraxacum officinale)	Pale-Seed Plantain (Plantago virginica)
Common Dandelion (Taraxacum officinale)	Common Hop (Humulus lupulus)	Common Hop (Humulus lupulus)	Sleepingplant (Chamaecrista fasciculata)
Common Sheep Sorrel (Rumex acetosella)	Common Sheep Sorrel (Rumex acetosella)	Common Sheep Sorrel (Rumex acetosella)	Spiny Amaranth (Amaranthus spinosus)
Common St. John's-Wort (Hypericum perforatum)	Common St. John's-Wort (Hypericum perforatum)	Common St. John's-Wort (Hypericum perforatum)	Trumpet Honeysuckle (Lonicera sempervirens)
Crimson Clover (Trifolium incarnatum)	Common Three-Seed-Mercury (Acalypha rhomboidea)	Common Three-Seed-Mercury (Acalypha rhomboidea)	Virginia-Creeper (Parthenocissus quinquefolia)
Curly Dock (Rumex crispus)	Common Wormwood (Artemisia vulgaris)	Common Wormwood (Artemisia vulgaris)	White Clover (Trifolium repens)
English Plantain (Plantago lanceolata)	Crimson Clover (Trifolium incarnatum)	Curly Dock (Rumex crispus)	Yellow Flat Sedge (Cyperus flavescens)
Field Horsetail (Equisetum arvense)	Curly Dock (Rumex crispus)	Dog-Fennel (Eupatorium capillifolium)	
Fragrant Sumac (Rhus aromatica)	Dog-Fennel (Eupatorium capillifolium)	English Plantain (Plantago lanceolata)	
Garden Buckwheat (Fagopyrum esculentum)	English Plantain (Plantago lanceolata)	Garden Buckwheat (Fagopyrum esculentum)	
Garden Vetch (Vicia sativa)	Fragrant Sumac (Rhus aromatica)	Garden Vetch (Vicia sativa)	
Great Plantain (Plantago major)	Garden Buckwheat (Fagopyrum esculentum)	Great Plantain (Plantago major)	
Great Ragweed (Ambrosia trifida)	Garden Vetch (Vicia sativa)	Great Ragweed (Ambrosia trifida)	
Heart-Wing Sorrel (Rumex hastatulus)	Great Plantain (Plantago major)	Japanese Honeysuckle (Lonicera japonica)	
Japanese Honeysuckle (Lonicera japonica)	Great Ragweed (Ambrosia trifida)	Japanese Hop (Humulus japonicus)	
King-of-the-Meadow (Thalictrum pubescens)	Heart-Wing Sorrel (Rumex hastatulus)	King-of-the-Meadow (Thalictrum pubescens)	
Lamb's-Quarters (Chenopodium album)	Japanese Honeysuckle (Lonicera japonica)	Lamb's-Quarters (Chenopodium album)	
Muscadine (Vitis rotundifolia)	Japanese Hop (Humulus japonicus)	Ox-Eye Daisy (Leucanthemum vulgare)	
Northern Bracken Fern (Pteridium aquilinum)	King-of-the-Meadow (Thalictrum pubescens)	Rabbit-Foot Clover (Trifolium arvense)	
Ox-Eye Daisy (Leucanthemum vulgare)	Lamb's-Quarters (Chenopodium album)	Red Clover (Trifolium pratense)	
Pale Dock (Rumex altissimus)	Muscadine (Vitis rotundifolia)	Rough Cockleburr (Xanthium strumarium)	
Pale-Seed Plantain (Plantago virginica)	Ox-Eye Daisy (Leucanthemum vulgare)	Sleepingplant (Chamaecrista fasciculata)	
Patience Dock (Rumex patientia)	Pale Dock (Rumex altissimus)	Slender Three-Seed-Mercury (Acalypha gracilens)	
Queen Anne's-Lace (Daucus carota)	Pale-Seed Plantain (Plantago virginica)	Small-Spike False Nettle (Boehmeria cylindrica)	
Rabbit-Foot Clover (Trifolium arvense)	Patience Dock (Rumex patientia)	Smooth Amaranth (Amaranthus hybridus)	
Red Clover (Trifolium pratense)	Queen Anne's-Lace (Daucus carota)	Spiny Amaranth (Amaranthus spinosus)	
Rough Cockleburr (Xanthium strumarium)	Rabbit-Foot Clover (Trifolium arvense)	Trumpet Honeysuckle (Lonicera sempervirens)	
Sleepingplant (Chamaecrista fasciculata)	Red Clover (Trifolium pratense)	Virginia Three-Seed-Mercury (Acalypha virginica)	
Slender Plantain (Plantago heterophylla)	Rough Cockleburr (Xanthium strumarium)	Virginia-Creeper (Parthenocissus quinquefolia)	
Small-Spike False Nettle (Boehmeria cylindrica)	Sleepingplant (Chamaecrista fasciculata)	White Clover (Trifolium repens)	
Smooth Amaranth (Amaranthus hybridus)	Slender Plantain (Plantago heterophylla)	White Snakeroot (Ageratina altissima)	
Smooth Sumac (Rhus glabra)	Slender Three-Seed-Mercury (Acalypha gracilens)	Wild Quinine (Parthenium integrifolium)	
Spiny Amaranth (Amaranthus spinosus)	Small-Spike False Nettle (Boehmeria cylindrica)	Winged Sumac (Rhus copallinum)	
Trumpet Honeysuckle (Lonicera sempervirens)	Smooth Amaranth (Amaranthus hybridus)	Yellow Flat Sedge (Cyperus flavescens)	
Turnip (Brassica napus)	Smooth Sumac (Rhus glabra)	Yellow Sweet-Clover (Melilotus officinalis)	
Virginia-Creeper (Parthenocissus quinquefolia)	Spiny Amaranth (Amaranthus spinosus)		
White Clover (Trifolium repens)	Trumpet Honeysuckle (Lonicera sempervirens)		
Wild Quinine (Parthenium integrifolium)	Turnip (Brassica napus)		
Winged Sumac (Rhus copallinum)	Virginia Three-Seed-Mercury (Acalypha virginica)		
Yellow Sweet-Clover (Melilotus officinalis)	Virginia-Creeper (Parthenocissus quinquefolia)		
	White Clover (Trifolium repens)		
	White Snakeroot (Ageratina altissima)		
	Wild Quinine (Parthenium integrifolium)		
	Winged Sumac (Rhus copallinum)		
	Yellow Flat Sedge (Cyperus flavescens)		
	Yellow Sweet-Clover (Melilotus officinalis)		

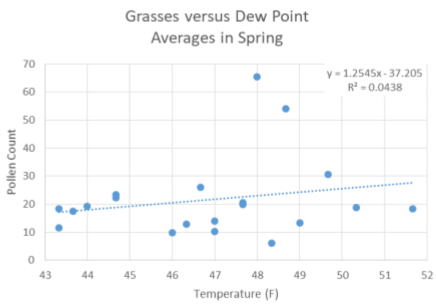
Appendix A3. Weed Pollen Species by Season (Pollen Library 2018).

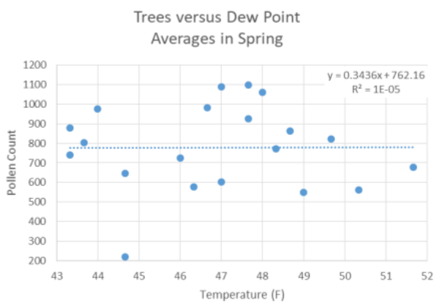
Appendix B. – Additional Annual Plots

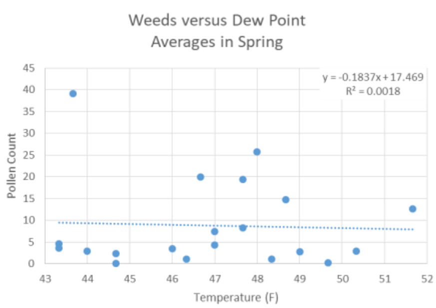


Appendix B1. Annual Pollen Count for Grass, Weed, and Tree Pollen from 1999 – 2018, Averaged Monthly, versus the Average Annual Dew Point Temperature in Fahrenheit, Averaged by Month.

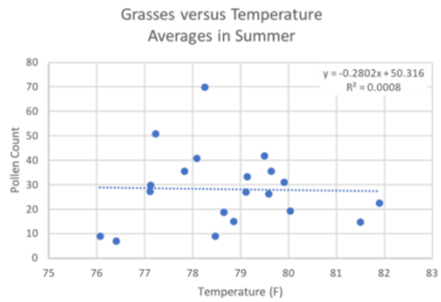
Appendix C. – Additional Seasonal Plots

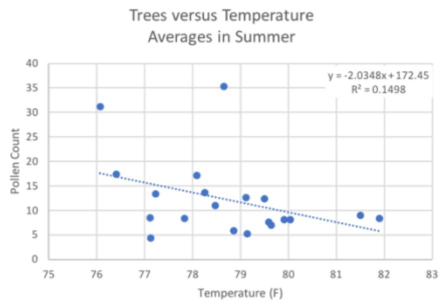


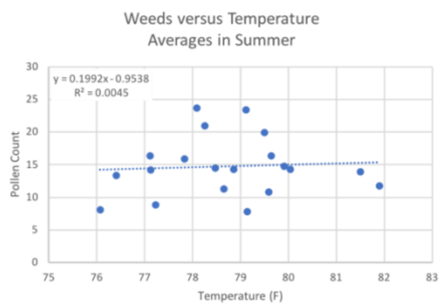




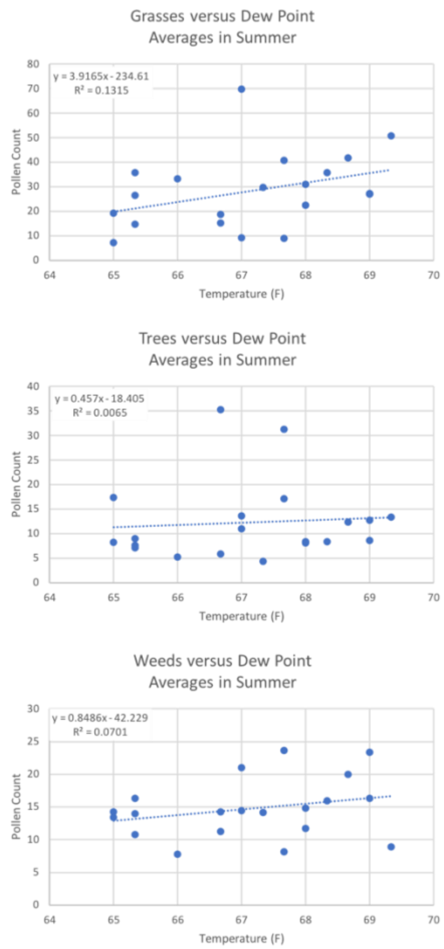
Appendix C1. Seasonal Pollen Count for Grass, Weed, and Tree Pollen during the Spring (March – May) from 1999 – 2018 versus the Average Dew Point Temperature in Fahrenheit.



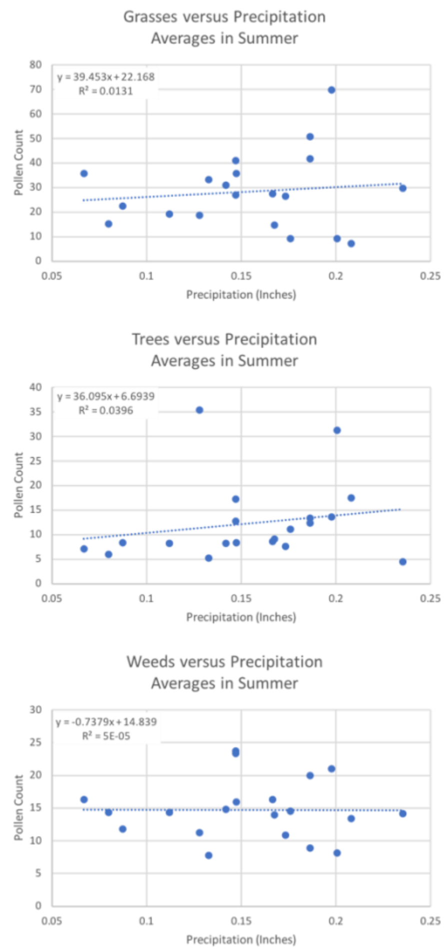




Appendix C2. Seasonal Pollen Count for Grass, Weed, and Tree Pollen during the Summer (June – August) from 1999 – 2018 versus the Average Temperature in Fahrenheit.



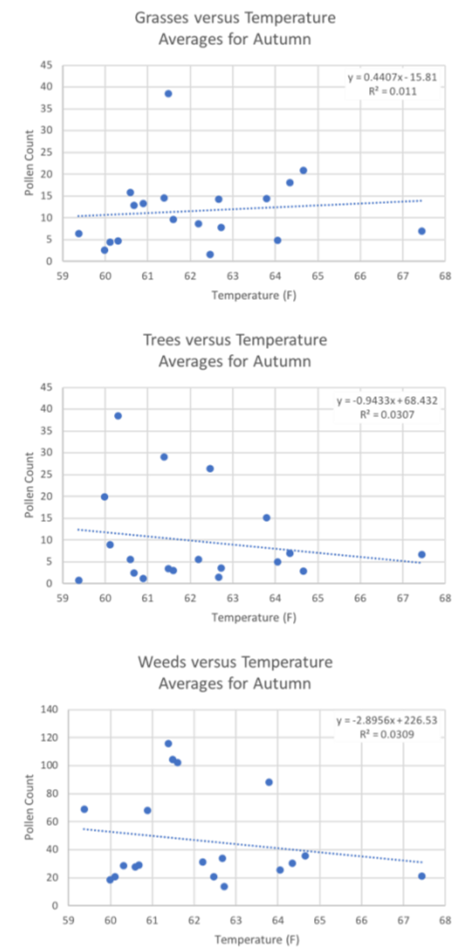
Appendix C3. Seasonal Pollen Count for Grass, Weed, and Tree Pollen during the Summer (June – August) from 1999 – 2018 versus the Average Dew Point Temperature in Fahrenheit.



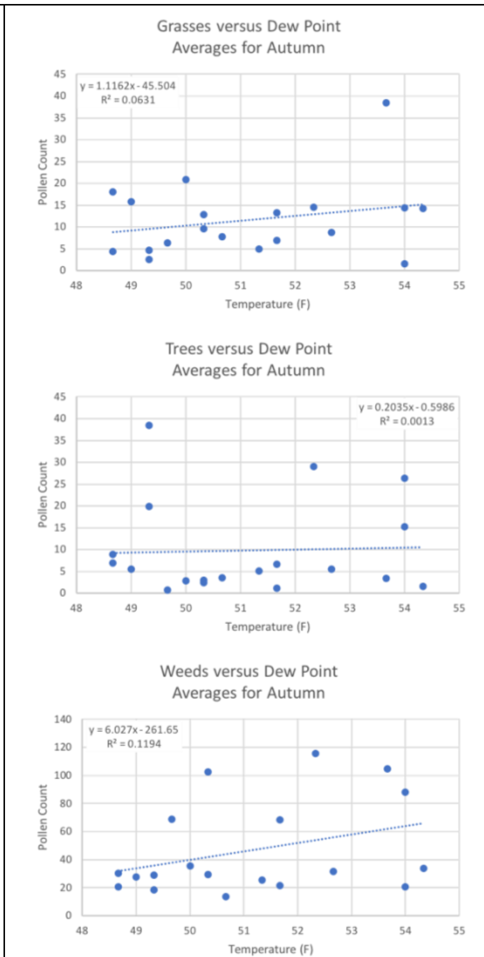
Appendix C4. Seasonal Pollen Count for Grass, Weed, and Tree Pollen during the Summer (June – August) from 1999 – 2018 versus the Average Precipitation Rate in Inches.

Appendix C5. Slope and R^2 Values of Grass, Weed, and Tree Pollen for Seasonal Meteorological Data for Summer.

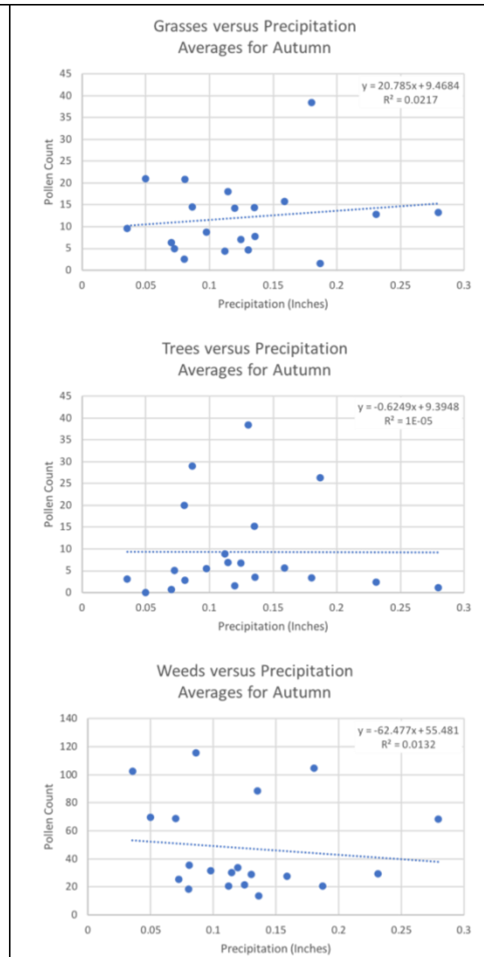
Pollen Type	Meteorological Factor	Slope	R^2 Value
Grass	Temperature	-0.28	0.00
	Dew Point	3.92	0.13
	Precipitation	39.45	0.01
Weed	Temperature	0.20	0.00
	Dew Point	0.85	0.07
	Precipitation	-0.74	0.00
Tree	Temperature	-2.03	0.15
	Dew Point	0.48	0.01
	Precipitation	36.10	0.04



Appendix C6. Seasonal Pollen Count for Grass, Weed, and Tree Pollen during Autumn (September – November) from 1999 – 2018 versus the Average Temperature in Fahrenheit.



Appendix C7. Seasonal Pollen Count for Grass, Weed, and Tree Pollen during Autumn (September – November) from 1999 – 2018 versus the Average Dew Point Temperature in Fahrenheit.



Appendix C8. Seasonal Pollen Count for Grass, Weed, and Tree Pollen during Autumn (September – November) from 1999 – 2018 versus the Average Precipitation Rate in Inches.

Appendix C9. Slope and R^2 Values of Grass, Weed, and Tree Pollen for Seasonal Meteorological Data for Autumn.

Pollen Type	Meteorological Factor	Slope	R^2 Value
Grass	Temperature	0.44	0.01
	Dew Point	1.12	0.06
	Precipitation	20.79	0.02
Weed	Temperature	-2.90	0.03
	Dew Point	6.03	0.12
	Precipitation	-62.48	0.01
Tree	Temperature	-0.94	0.03
	Dew Point	0.20	0.00
	Precipitation	-0.63	0.00