

# Airborne pollen characteristics and the influence of temperature and precipitation in Raleigh, North Carolina, USA (1999–2012)

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Received: 18 November 2015 / Accepted: 6 May 2016  
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**Abstract** The incidence of allergic diseases has been increasing in recent decades, in part due to increased exposure to aeroallergens, particularly pollen. Allergic diseases have a major burden on the health care system, with annual costs in the USA alone exceeding \$30 billion. There is evidence that the production of aeroallergens, including pollen, is increasing in response to environmental and climatic change, which has important implications for the treatment of allergy sufferers. In this study, pollen data from a Rotorod sampler in Raleigh, North Carolina, was used to characterize and examine trends in the atmospheric pollen seasons for trees, grasses, and weeds over the period 1999–2012. The influence of mean monthly antecedent and concurrent temperature and precipitation on the timing, duration, and severity of the pollen seasons was assessed using Pearson's product-moment correlation coefficients and multiple linear regression models. An increasing trend was noted in

seasonal tree pollen concentrations, while seasonal and peak weed pollen concentrations declined over time. The atmospheric pollen seasons for grasses and weeds trended toward earlier start dates and longer durations, while the tree pollen season trended toward an earlier end date. Peak daily tree pollen concentrations were strongly associated with antecedent temperature and precipitation, while peak daily grass pollen concentrations were strongly associated with concurrent precipitation. The strongest relationships between climate and weed pollen were associated with the timing and duration of the pollen season, with drier antecedent and warmer concurrent conditions tied to longer weed pollen seasons.

**Keywords** Pollen · Phenology · Temperature · Precipitation · Climate change

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## 1 Introduction

Over the past several decades, the incidence of respiratory diseases has increased worldwide (Portier et al. 2010). Respiratory allergic diseases, in particular, affect a large part of the global population. Allergic rhinitis, for instance, is believed to affect between 10 and 30 % of individuals across the globe (Albertine et al. 2014). One of the most common forms of allergic rhinitis is seasonal rhinitis, which is triggered primarily by biological and plant-based aeroallergens such as

mold and pollen (Wallace et al. 2008). In the USA, nearly 60 million people are affected by seasonal rhinitis, asthma, and hay fever, resulting in over \$30 billion annually in direct and indirect health care costs combined (Reid and Gamble 2009).

The incidence of respiratory diseases may be due in part to changes in plant phenology. For example, longer pollen seasons may increase the likelihood of exposure, thereby increasing the duration of allergic symptoms, while greater production of pollen grains may lead to increased sensitivity and severity of symptoms (Reid and Gamble 2009; Ziska et al. 2011; Bielory et al. 2012; Darrow et al. 2012). There is considerable evidence that the observed changes in plant phenology (i.e., earlier flowering, greater pollen production) are the result of changing land use patterns and climatic conditions (Ziska et al. 2011). Indeed, plant phenology is a key biological indicator of environmental change, and longer and more intense pollen seasons have been suggested under increased atmospheric carbon dioxide and global warming scenarios (Ziska et al. 2011; Bielory et al. 2012; Albertine et al. 2014).

The annual production and distribution of pollen is closely tied to meteorological conditions both before and during the flowering stage of plants (Dahl et al. 2013). For instance, most woody plants that flower early in the season require a sufficiently long and cold period of winter chilling to initiate reproductive growth (Luedeling et al. 2013). During the subsequent flowering period, additional factors such as the amount of sunshine, precipitation, and humidity, as well as temperature, influence the opening of anthers and the release of pollen grains (Weber 2003). Local to hemispheric circulation patterns (e.g., El Nino-Southern Oscillation, North Atlantic Oscillation) have an important effect on temperature and precipitation and can therefore influence the production, distribution, and transport of pollen grains. Such relationships have been found across parts of North America and Europe (Freye et al. 2001; Stach et al. 2008; Kizilpinar et al. 2010; Dahl et al. 2013). In general, annual variations in meteorological conditions during the different phenophases can affect the timing and severity of the pollen season and the incidence of allergic disease. Predictive models that incorporate relationships between atmospheric variables and plant phenology may help track and estimate the likelihood of pollen episodes that result in negative health outcomes.

**Fig. 1** **a** Map of the study area with county boundaries; **b** major land cover types and locations of the DAQ pollen sampler during the study period (*star*) and from August 2012 to present (*circle*). The location of the cooperative observer station at RDU is represented by the *triangle*

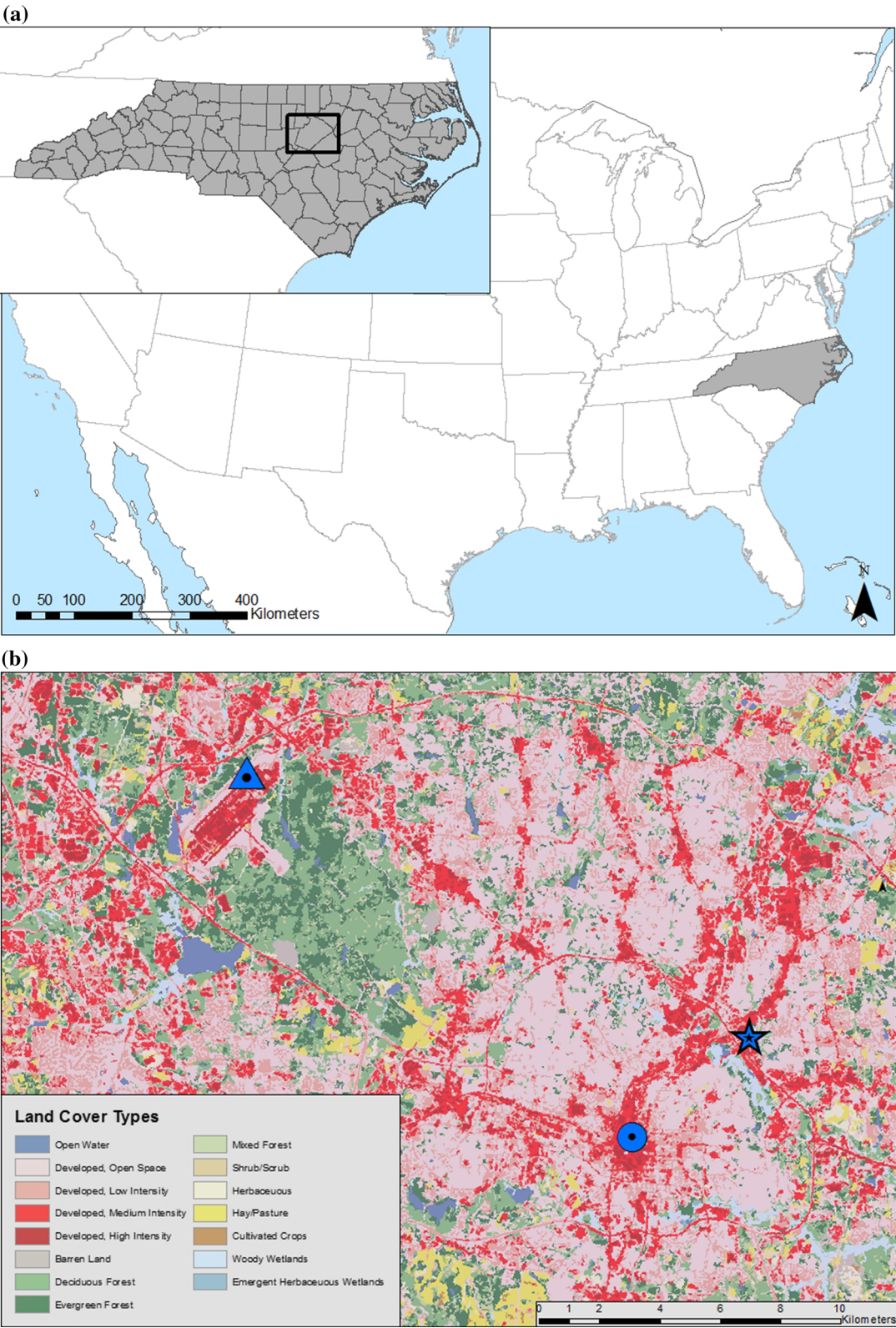
Estimates of pollen concentrations from these models are now available at the individual level through the use of smart phone applications (Kmenta et al. 2014). Currently, these applications are only available in parts of Europe and may not be representative of pollen–environment–health relationships elsewhere. Therefore, a need exists for more detailed spatial information on pollen production and its temporal variations, particularly as they relate to prevailing atmospheric conditions (Galán et al. 1995).

Much of the research on the relationships between plant phenology and meteorological conditions has been conducted in Europe, specifically in areas characterized by temperate continental, western maritime, or Mediterranean climates (Emberlin et al. 2002; Van Vliet et al. 2002; Gioulekas et al. 2004; Kizilpinar et al. 2010; Rodriguez-Rajo et al. 2011; Gonzalez-Parrado et al. 2013; Bogawski et al. 2014; Cariñanos et al. 2014). Far fewer studies have been conducted in North America, particularly in humid subtropical climates such as the Southeast USA (Levetin and Avery 2008; Kosisky et al. 2010; Ziska et al. 2011; Park and Schwartz 2014). This study aims to help fill this gap by examining annual variations and trends in the timing, duration, and severity of the atmospheric pollen season (APS) for trees, grasses, and weeds in Raleigh, North Carolina, over the period 1999–2012, and examining their associations with temperature and precipitation patterns prior to and during the APS. By identifying the characteristics and trends in the APS of different pollen sources, as well as the predominant meteorological factors that influence them, predictive models can be developed to estimate the public health burden of the upcoming APS.

## 2 Materials and methods

### 2.1 Study area

The city of Raleigh (35.78°N, 78.63°W) is located in the Piedmont region of North Carolina (Fig. 1a), which is characterized by gently rolling terrain and a



mix of rapidly growing urban corridors with dense conifer and deciduous forests (Fig. 1b). Cropland and pasture are also prevalent across the region. Raleigh is one of the fastest growing metropolitan areas in the USA, with a population of over 1.2 million according to 2014 census estimates (Carlyle 2015). Due to its location in the Southeast USA, Raleigh experiences a humid subtropical climate characterized by hot, humid summers, and mild-to-cool winters with no distinct dry season (Fig. 2).

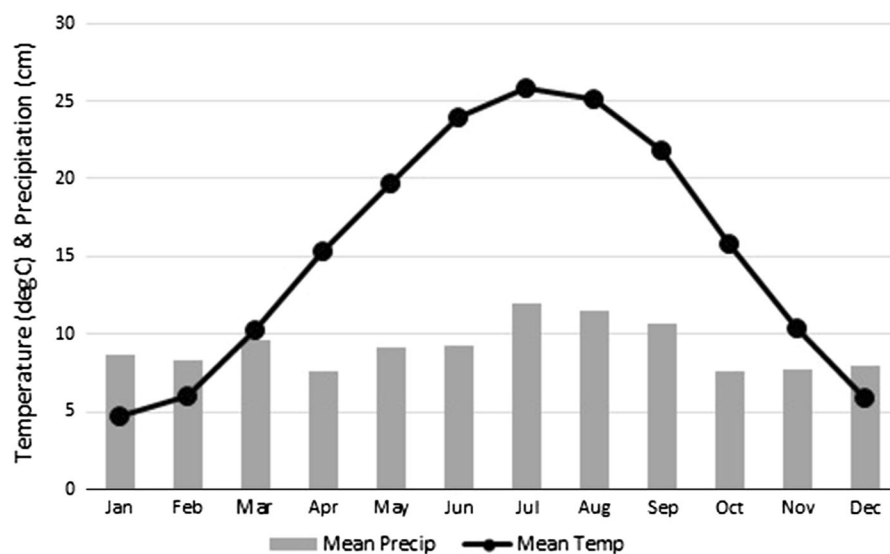
## 2.2 Pollen data

Airborne pollen data from 1999–2012 were obtained from the Division of Air Quality (DAQ) at the North Carolina Department of Environment and Natural Resources. The DAQ operates and maintains a Rotorod Model-40 volumetric sampler (Multidata Sampling Technologies) according to guidelines established by the National Allergy Bureau. The sampler contains a retracting head with two plastic collection rods coated with silicon grease. Every 10 min, the retracting head spins and the collection rods drop down to sample the air for 1 min. This process is repeated for 24 h. At the end of the analysis period (09 LST), the rods are removed and taken to a DAQ laboratory where they are stained with Calberla's solution and the grains are counted and categorized (tree, grass, or weed) under a microscope at 400 $\times$  magnification. Each pollen count is then converted to a concentration (grains m<sup>-3</sup>). Information

on the species of each pollen type was not available in the DAQ dataset, though previous aerobiological surveys in the eastern USA have identified several allergenic families, including Betulaceae (*Betula* spp.), Cupressaceae (*Juniperus* spp.), Fagaceae (*Quercus* spp.), Juglandaceae (*Carya* spp.), Oleaceae (*Fraxinus* spp.), Pinaceae (*Pinus* spp.), Ulmaceae (*Ulmus* spp.), Poaceae (grasses), and Asteraceae (ragweed) (Miller and Miller 1999; Lin et al. 2002; Kosisky et al. 2010). Among the dominant tree species in central North Carolina, hardwoods such as birch, oak, hickory, and elm, comprise approximately 75 % of the forest cover, with softwoods such as cedar and loblolly pine comprising the rest (Bobyarchick and Diemer 2000).

The DAQ pollen sampling period runs from 1 March to 31 October. Pollen samples are collected Monday through Friday, except on state holidays (e.g., Independence Day, Labor Day), and each daily count represents the concentration of airborne pollen over the preceding 24 h (i.e., 09 LST on the previous day to 09 LST on the collection day). To create a continuous, daily time series over the sampling period, pollen concentrations on days with missing values were estimated using linear interpolation. As in Darrow et al. (2012), a model validation exercise was conducted whereby imputations for Tuesday and Wednesday were correlated with their corresponding measured values. Spearman's correlation coefficients for these days were statistically significant ( $p < 0.001$ ) for tree ( $r_s = 0.89$ ), grass ( $r_s = 0.72$ ), and

**Fig. 2** Climograph illustrating mean monthly temperature and mean total precipitation using data from the cooperative observer station at RDU for the period 1944–2012



weed ( $r_s = 0.81$ ) pollen, thus validating the use of the linear interpolation model. From February 1999 to July 2012, the pollen sampler was located in an open field behind DAQ headquarters, approximately 5 km northeast of downtown Raleigh in an area of major urban development (Fig. 1b). On August 1, 2012, DAQ headquarters relocated to downtown Raleigh and the pollen sampler was moved to the rooftop of the nearby Nature Research Center (Fig. 1b). However, results from a one-way ANOVA test revealed that the relocation of the sampler had no significant effect ( $p = 0.647$ ) on the mean pollen concentrations during the final 3 months of the study period (August–October 2012).

### 2.3 Meteorological data

Monthly mean temperature and precipitation data from the Raleigh-Durham International Airport (RDU) were obtained through the Applied Climate Information System, a web-based data management system maintained by NOAA's Regional Climate Center Program (<http://www.rcc-acis.org/index.html>). The cooperative observer station at RDU (317069) is located in an open field approximately 20 km to the northwest of downtown Raleigh (Fig. 1b).

## 2.4 Methods

### 2.4.1 Defining the APS

The duration of the APS for each pollen type (trees, grasses, and weeds) was defined as the period where 95 % of the seasonal (March–October) pollen concentration was recorded. Therefore, the start date (end date) of the APS was the day on which the accumulated concentration reached 2.5 % (97.5 %) of the seasonal total. Using an accumulated percentage instead of a specific concentration level helps account for annual variations in pollen production, thereby allowing for comparisons in phenophases across multiple years. As in Andersen (1991) and Jato et al. (2009), we tested the use of different accumulated percentages (90, 95, and 98 %) and found that using 95 % yielded the lowest standard deviation in both duration and seasonal sum over the 14-year period of record. The severity of the APS for each pollen type was assessed using both the seasonal sum and the peak daily concentration.

### 2.4.2 Statistical analyses

The International Association for Aerobiology established the use of a 10-day running average of pollen concentrations when constructing a daily pollen calendar or time series (Gioulekas et al. 2004). Therefore, we employed a 10-day Gaussian smoother to illustrate the general trends and patterns in the APS for each pollen type. The equation used was adopted from Brooks et al. (2003) and implicitly assumes that the data recorded on a particular day (e.g., pollen concentration on 1 April) is influenced most strongly by the data recorded on nearby days (e.g., pollen concentration on 2 April) and less strongly on days further away in time (e.g., pollen concentration on 6 April).

Linear regression models were developed to detect possible trends in APS characteristics for each pollen type over the period of record. Characteristics of the APS included the start and end dates, duration, peak daily concentration, date of the peak daily concentration, and total seasonal sum. Pearson's product-moment correlation coefficients were used to determine the associations between characteristics of the APS and mean monthly temperature and precipitation totals both prior to and during the APS for each pollen type over the period of record. The specific time periods within which these associations were analyzed for each pollen type are provided in the "Appendix." Only the associations with the highest correlation coefficients are described. As in Emberlin et al. (2007), we developed standard multiple linear regression models using the most statistically significant associations from the correlation analysis to assess how well monthly temperature and precipitation values predict various characteristics of the APS. Levels of significance for all statistical tests were assessed at 5 and 10 %.

## 3 Results

### 3.1 Characteristics of the APS

General characteristics of the APS for each pollen type are illustrated in Fig. 3, while descriptive statistics are summarized in Table 1. The tree pollen season is the earliest and shortest of the three pollen seasons. It typically begins in early March, reaches a peak in early

to mid-April, and ends during the latter half of May. Despite the short duration, seasonal tree pollen concentrations are more than 12 times higher than seasonal grass or weed pollen concentrations, while peak concentrations are nearly 25 times higher.

The grass pollen season typically begins in late April following the peak in tree pollen. Unlike the other two pollen types, there exists a bimodal peak in the grass pollen production, which was present in eight of the 14 years analyzed in this study. The first (and often larger) peak typically occurs in mid- to late May and is followed by a decrease in grass pollen during the month of June. The second peak occurs between the middle of July and the beginning of September, after which pollen concentrations drop steadily until the season ends around the beginning of October (Fig. 3). The other 6 years exhibited a single peak in grass pollen. In three of these years, the peak occurred in May, while in the other 3 years the peak occurred in July or August.

The weed pollen season typically begins within a few weeks of the grass pollen season, but does not reach a peak until early to mid-September. In contrast to the shorter tree pollen season, grass and weed pollen seasons exhibit much longer durations (5–6 months) and greater inter-annual variability in duration (2–4 weeks).

### 3.2 Trends in APS characteristics

Results of the linear regression analysis (Table 2) revealed significant trends toward earlier APS start dates for both grasses and weeds, which resulted in significantly longer APS durations. While trees exhibited a significant trend toward an earlier APS end date, the overall duration of the APS did not significantly change. In addition, no significant trends were found in the date of peak concentration for any of the pollen types. In terms of the peak daily concentration, only weeds exhibited a significantly increasing trend. Both weeds and trees exhibited significantly higher seasonal sums over the 14-year period of record, while no significant trends were noted in either daily peak or seasonal grass pollen amounts.

### 3.3 Associations with temperature and precipitation

Results of the correlation analysis are presented in Table 3. In general, pollen characteristics were more strongly associated with temperature than with precipitation, while the strength of the associations relative to the APS (prior to or during) varied by pollen type. In terms of the amount of airborne pollen recorded for each type, associations with temperature

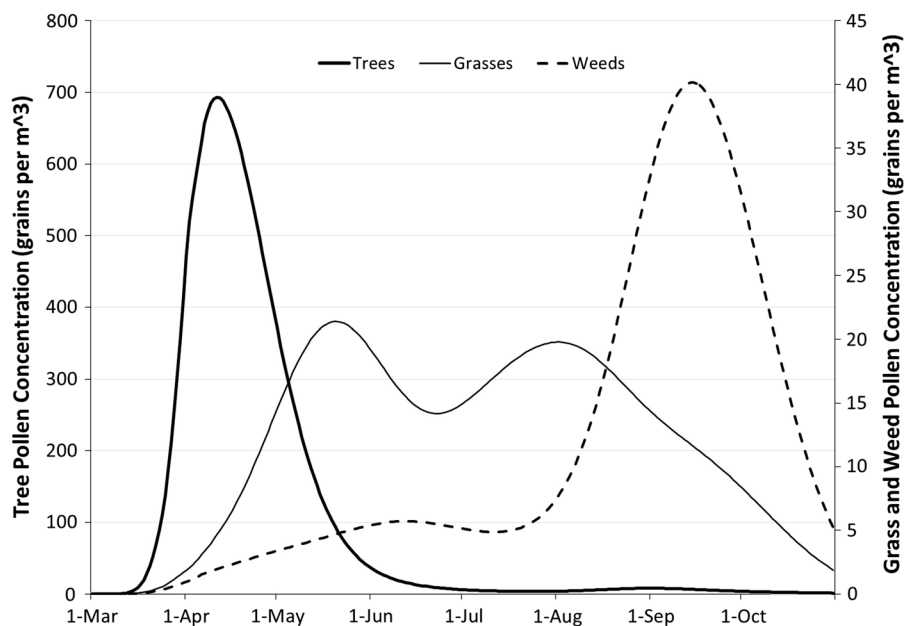


**Fig. 3** Mean daily concentrations of tree, grass, and weed pollen calculated from March through October, 1999–2012, using a 10-day Gaussian smoother

**Table 1** Descriptive statistics of the pollen season in Raleigh, 1999–2012

|                | Start date         | End date           | Duration (days) | Peak date                            | Peak daily concentration (grains/m <sup>3</sup> ) | Seasonal sum (grains/m <sup>3</sup> ) |
|----------------|--------------------|--------------------|-----------------|--------------------------------------|---------------------------------------------------|---------------------------------------|
| <b>Trees</b>   |                    |                    |                 |                                      |                                                   |                                       |
| Mean           | 7 Mar              | 19 May             | 74              | 7 Apr                                | 1692                                              | 20,884                                |
| SD             | ±5 (2–12 Mar)      | ±8 (11–27 May)     | ±9.2            | ±7 (1–14 Apr)                        | ±794                                              | ±5518                                 |
| Min (years)    | 1 Mar (2006)       | 9 May (2002)       | 52 (2002)       | 27 Mar (2007)                        | 533 (2000)                                        | 10744 (1999)                          |
| Max (years)    | 19 Mar (2002)      | 5 Jun (1999)       | 91 (2006)       | 16 Apr (2006)                        | 3524 (2010)                                       | 28823 (2007)                          |
| <b>Grasses</b> |                    |                    |                 |                                      |                                                   |                                       |
| Mean           | 22 Apr             | 4 Oct              | 167             | 19 May, 10 Aug                       | 63                                                | 1688                                  |
| SD             | ±14 (8 Apr–4 May)  | ±9 (27 Sep–13 Oct) | ±15.0           | ±6 (13–25 May)<br>±21 (17 Jul–3 Sep) | ±21                                               | ±505                                  |
| Min (years)    | 14 Mar (2012)      | 22 Sep (2012)      | 147 (2005)      | 10 May (2011)                        | 42 (2000)                                         | 1127 (2011)                           |
| Max (years)    | 7 May (2001)       | 24 Oct (2007)      | 196 (2011)      | 8 Oct (2007)                         | 117 (2003)                                        | 3038 (2006)                           |
| <b>Weeds</b>   |                    |                    |                 |                                      |                                                   |                                       |
| Mean           | 12 May             | 16 Oct             | 157             | 19 Sep                               | 76                                                | 1605                                  |
| SD             | ±26 (13 Apr–6 Jun) | ±4 (12–20 Oct)     | ±30.4           | ±14 (5 Sep–2 Oct)                    | ±56                                               | ±651                                  |
| Min (years)    | 27 Mar (2012)      | 9 Oct (2002)       | 87 (1999)       | 28 Aug (2011)                        | 34 (2011)                                         | 952 (2011)                            |
| Max (years)    | 20 Jul (1999)      | 23 Oct (2010)      | 206 (2012)      | 9 Oct (2006)                         | 219 (2001)                                        | 3132 (2001)                           |

SD standard deviation

**Table 2** Summary of linear regression models used to determine trends in tree, grass, and weed pollen characteristics in Raleigh from 1999 to 2012

|                | Start date | End date | Duration | Peak date | Peak daily concentration | Seasonal sum |
|----------------|------------|----------|----------|-----------|--------------------------|--------------|
| Trees          |            |          |          |           |                          |              |
| Slope          | −0.541     | −1.270   | −0.729   | −0.679    | 92.21                    | 899.93       |
| Adjusted $R^2$ | 0.161      | 0.408*   | 0.102    | 0.163     | 0.220                    | 0.432**      |
| Grasses        |            |          |          |           |                          |              |
| Slope          | −2.532     | −0.321   | 2.210    | 0.991     | −1.166                   | −30.33       |
| Adjusted $R^2$ | 0.546**    | 0.023    | 0.352*   | 0.008     | 0.052                    | 0.058        |
| Weeds          |            |          |          |           |                          |              |
| Slope          | −5.824     | 0.290    | 6.114    | −0.163    | −9.397                   | −115.23      |
| Adjusted $R^2$ | 0.637**    | 0.072    | 0.657**  | 0.002     | 0.454**                  | 0.508**      |

\*  $p < 0.10$ ; \*\*  $p < 0.05$

and precipitation were generally stronger among peak concentrations compared to seasonal sums.

A significant negative relationship was found between peak daily tree pollen concentrations and mean temperatures during the month of February. Significant negative relationships were also found between the end dates of the tree pollen season and temperatures during the APS, particularly from March to May. Antecedent precipitation from November to February exhibited a significantly positive relationship with peak daily tree pollen concentrations, while precipitation during the APS, specifically from March to April, was negatively correlated with the peak date.

With regards to grass pollen, a significant negative relationship was found between peak daily concentrations and temperatures during the APS. The strongest relationship was seen with mean temperatures from April to July and peak concentrations during the latter half of the APS. Antecedent temperatures during the month of March were significantly positively correlated with both the duration and peak date of the APS. Temperatures during the APS were also positively associated with the duration of the grass pollen season, but were not statistically significant. The strongest association with precipitation was found between the peak daily grass pollen concentration during the latter half of the APS (i.e., second peak in Fig. 3) and precipitation from April to July.

A significant positive relationship was found between the duration of the weed pollen season and mean monthly temperatures both before and during the APS. The strongest of these relationships was seen with mean antecedent temperatures during the months of March and April, as well as mean temperatures

during the first half of the APS from May to July. Antecedent temperatures were also significantly negatively correlated with the start date of the APS, particularly from March to April. Mean temperatures both before and during the APS were negatively associated with peak daily concentrations and seasonal sums, but were not statistically significant. Antecedent precipitation from January to April was significantly positively correlated with the start date of the APS and negatively correlated with the duration of the APS. Peak daily concentrations and seasonal sums were generally positively associated with antecedent precipitation, but negatively associated with precipitation during the APS.

The strongest relationships identified from the correlation analysis were subsequently used to construct standard multiple regression models (Table 4). February temperatures and antecedent precipitation from November to February had a statistically significant effect on the peak daily tree pollen concentration, with an explained variance of approximately 50 %. Antecedent temperatures and precipitation also had a significant effect on the timing and duration of the weed pollen season. In contrast, the combined effect of temperature and precipitation during the APS did not significantly influence the peak daily concentration of grass pollen.

## 4 Discussion

The seasonal distribution of airborne pollen in Raleigh follows the general distribution observed across much of North America, namely peaks in tree

**Table 3** Pearson's product-moment correlation coefficients (CC) between tree, grass, and weed pollen characteristics and mean temperatures and precipitation prior to (antecedent) and during (season) the APS

|                | Start date | End date | Duration | Peak date | Peak daily concentration | Seasonal sum |
|----------------|------------|----------|----------|-----------|--------------------------|--------------|
| <b>Trees</b>   |            |          |          |           |                          |              |
| Temperature    |            |          |          |           |                          |              |
| Antecedent     | Dec–Feb    | Jan–Feb  | Nov–Feb  | Dec–Feb   | Feb                      | Feb          |
| CC             | 0.235      | 0.297    | −0.131   | −0.226    | −0.710**                 | −0.364       |
| Season         | –          | Mar–May  | Mar–May  | Mar       | Mar–Apr                  | Mar–Apr      |
| CC             | –          | −0.690** | 0.248    | −0.450    | 0.174                    | 0.232        |
| Precipitation  |            |          |          |           |                          |              |
| Antecedent     | Jan–Feb    | Dec–Feb  | Nov–Feb  | Nov–Feb   | Nov–Feb                  | Jan–Feb      |
| CC             | 0.405      | 0.280    | 0.190    | −0.338    | 0.588**                  | −0.405       |
| Season         | –          | Mar–Apr  | Mar–Apr  | Mar–Apr   | Mar–Apr                  | Mar–May      |
| CC             | –          | 0.361    | 0.276    | −0.561**  | −0.238                   | 0.315        |
| <b>Grasses</b> |            |          |          |           |                          |              |
| Temperature    |            |          |          |           |                          |              |
| Antecedent     | Mar        | Feb–Mar  | Mar      | Mar       | Dec–Mar                  | Feb–Mar      |
| CC             | −0.419     | 0.095    | 0.515*   | 0.523*    | −0.121                   | −0.383       |
| Season         | –          | Apr–May  | Apr–Jul  | Apr–May   | Apr–Jul                  | Apr–Jul      |
| CC             | –          | −0.115   | 0.438    | 0.076     | −0.686**                 | −0.456       |
| Precipitation  |            |          |          |           |                          |              |
| Antecedent     | Mar        | Feb–Mar  | Dec–Mar  | Mar       | Dec–Mar                  | Mar          |
| CC             | −0.168     | −0.198   | −0.178   | 0.365     | 0.153                    | −0.298       |
| Season         | –          | Apr–May  | Apr–May  | Apr–Jun   | Apr–Jul                  | Apr–Jun      |
| CC             | –          | −0.227   | 0.252    | 0.253     | 0.459*                   | 0.196        |
| <b>Weeds</b>   |            |          |          |           |                          |              |
| Temperature    |            |          |          |           |                          |              |
| Antecedent     | Mar–Apr    | Jan–Apr  | Mar–Apr  | Mar–Apr   | Mar–Apr                  | Mar–Apr      |
| CC             | −0.639**   | −0.241   | 0.551**  | 0.428     | −0.337                   | −0.307       |
| Season         | –          | May–Aug  | May–Jul  | May–Aug   | May–Aug                  | May–Sep      |
| CC             | –          | 0.257    | 0.548*   | −0.259    | −0.393                   | −0.482*      |
| Precipitation  |            |          |          |           |                          |              |
| Antecedent     | Jan–Apr    | Apr      | Jan–Apr  | Feb–Apr   | Jan–Apr                  | Jan–Apr      |
| CC             | 0.556**    | 0.245    | −0.530*  | −0.365    | 0.336                    | 0.243        |
| Season         | –          | May–Jul  | May–Jun  | May–Aug   | May                      | May          |
| CC             | –          | −0.260   | 0.432    | −0.174    | −0.316                   | −0.415       |

\*  $p < 0.10$ ; \*\*  $p < 0.05$ 

pollen in spring, grass pollen in summer, and weed pollen in late summer and early fall (Ziska et al. 2011). The bimodal peak in the mean grass pollen season has also been noted across the Northeast USA and parts of Europe and is believed to reflect the different flowering times of specific Poaceae species, though weather and climate conditions may also be contributing factors (Jato et al. 2009; Bielory et al. 2012). While the weed pollen season begins within

just a few weeks of the grass pollen season, daily weed pollen concentrations do not typically reach allergenic levels (i.e., 10 grains  $\text{m}^{-3}$ ) until mid-August (Darrow et al. 2012). The greater inter-annual variability in the duration of the grass and weed pollen seasons should be explored further, as variations in seasonal exposure to these aeroallergens have a large impact on the overall burden of allergic disease (Darrow et al. 2012).

**Table 4** Summary of the multiple linear regression models (with standardized coefficients) used to predict characteristics of the APS for trees, grasses, and weeds in Raleigh

| APS characteristic                    | Regression equation                                                                               | Adjusted $R^2$ | $p$ value |
|---------------------------------------|---------------------------------------------------------------------------------------------------|----------------|-----------|
| Trees                                 |                                                                                                   |                |           |
| Peak daily concentration              | $y = 0 - (0.705 \times \text{Feb temperature}) + (0.007 \times \text{Nov–Feb precipitation})$     | 0.505          | 0.021     |
| Grasses                               |                                                                                                   |                |           |
| Peak daily concentration<br>(Jul–Aug) | $y = 0 - (0.279 \times \text{Apr–Jul temperature}) + (0.398 \times \text{Apr–Jul precipitation})$ | 0.206          | 0.112     |
| Weeds                                 |                                                                                                   |                |           |
| Start Date                            | $y = 0 - (0.509 \times \text{Mar–Apr temperature}) + (0.384 \times \text{Jan–Apr precipitation})$ | 0.356          | 0.088     |
| Duration                              | $y = 0 + (0.533 \times \text{Mar–Apr temperature}) - (0.351 \times \text{Jan–Apr precipitation})$ | 0.348          | 0.068     |

Results of the correlation analysis revealed several significant associations between temperature, precipitation, and characteristics of the APS. The strongest relationship indicated that lower February temperatures result in higher peak daily tree pollen concentrations. This is supported by previous research which showed an important link between the accumulation of winter chill and the flowering of early-season plants (Emberlin et al. 2002; Stach et al. 2008; Rodriguez-Rajo et al. 2011; Luedeling et al. 2013). Mean temperatures during the APS were not statistically associated with tree pollen concentrations, suggesting that overall production of airborne tree pollen in Raleigh is more sensitive to winter chill than seasonal heat accumulation. A recent study of plant phenology across South Carolina also suggested that temperatures near the onset of the growing season are the primary determinant for reproduction among spring flowering species (Park and Schwartz 2014). However, we did find that mean temperature and precipitation during the APS were strongly correlated with the timing and duration of the tree pollen season. Specifically, higher temperatures and increased precipitation during this period resulted in earlier peak and end dates. Similar results have been noted for various tree species across Europe (Emberlin et al. 2007; Stach et al. 2008; Newnham et al. 2013; Khwarahm et al. 2014). Warmer spring temperatures may accelerate the production of tree pollen, while increased precipitation (particularly of light to moderate intensity) may cleanse the air of pollen grains, both of which would contribute to a shorter APS (Weber 2003). In addition to mean February temperatures, increased antecedent precipitation during the months of November to February was associated with

higher peak daily tree pollen concentrations. This confirms the results of previous studies that found significant positive associations between antecedent precipitation, soil moisture storage, and tree pollen counts (Weber 2003).

Peak daily grass pollen concentrations were negatively associated with mean temperatures during the APS, suggesting that lower (higher) temperatures during the APS result in higher (lower) peak concentrations. Lower temperatures may be tied to lower rates of evaporation and a resultant increase in surface moisture and grass growth. A strong positive association was also found between peak daily grass pollen and precipitation during the APS. The strongest and most significant associations were found with the second seasonal peak in grass pollen that typically occurs in July or August. These results run counter to many previous studies, which show that increases in temperature and decreases in precipitation during the APS result in greater airborne grass pollen production (Gioulekas et al. 2004; Green et al. 2004; Kizilpinar et al. 2010; Kosisky et al. 2010; Khwarahm et al. 2014). However, if temperatures are too warm and too dry, particularly during the summer months, then pollen production and release may be reduced or prohibited (Galán et al. 1995). It is unclear if specific temperature or precipitation thresholds exist for the pollen types examined in this study. It is also possible that *daily* temperature and precipitation are more strongly associated with grass pollen production than monthly variables. We intend to investigate these relationships in a follow-up study.

Unlike tree pollen, and to a lesser extent grass pollen, the strongest associations between temperature, precipitation, and weed pollen were in the timing

and duration of the APS. Specifically, higher temperatures both before and during the APS, as well as decreased precipitation during the APS, resulted in a longer duration of the weed pollen season. Higher temperatures and lower precipitation in the months leading up to the APS were also associated with an earlier start date, while higher antecedent temperatures resulted in a later peak date. We did find weak associations between mean temperatures, precipitation, and weed pollen production, whereby decreased temperatures and lower precipitation both before and during the APS resulted in greater daily peak and seasonal weed pollen concentrations. While a link between lower antecedent temperatures and greater weed pollen production has been reported in previous studies, they also point to greater antecedent precipitation as contributing to increased pollen production (Levetin and Avery 2008; Gonzalez-Parrado et al. 2013; Bogawski et al. 2014; Cariñanos et al. 2014).

Overall, we found that associations between the APS and temperature are stronger than they are with precipitation, and that correlations between these two variables and the APS are stronger among trees than among grasses or weeds. These results are supported by previous studies (Reid and Gamble 2009; Bielory et al. 2012; Park and Schwartz 2014). We also found that the role of antecedent temperature and precipitation varied by pollen type and phenophase. Specifically, the link between antecedent conditions and pollen concentrations was strongest among trees, while the link between antecedent conditions and the timing and duration of the APS was strongest among grasses and weeds.

Several important trends were noted in the APS for each pollen type over the 14-year period of record. Seasonal airborne tree pollen concentrations in Raleigh have been increasing, while both seasonal and peak airborne weed pollen concentrations have been decreasing. Decreases in weed pollen have also been noted across the central USA from 1987 to 2006 (e.g., Tulsa, Oklahoma; Levetin and Avery 2008) and may be related to increasing urbanization. There is also evidence that the APS for grasses and weeds are beginning earlier and lasting longer, while the APS for trees is ending earlier. These trends stand in contrast to previous studies, which indicated shorter ragweed seasons across North America from

1995 to 2009 (Ziska et al. 2011) and later start dates among summer-flowering plant species across parts of the southern USA from 1951 to 2009 (Park and Schwartz 2014). Moreover, while some studies have indicated trends toward earlier start dates among various tree species (e.g., northwest Spain from 1995 to 2009; Rodriguez-Rajo et al. 2011), we did not find a significant change in the timing of the tree pollen season in Raleigh.

Changes in plant phenology in different parts of the world have been linked to changes in climate conditions. In a subsequent analysis, we examined changes in the monthly temperature and precipitation variables that exhibited the strongest correlations with the APS characteristics and found statistically insignificant trends over the 14-year period of record (all adjusted  $R^2$  values  $<0.2$ ,  $p > 0.05$ ), suggesting that other factors may play an equal if not more important role in airborne pollen production. Results of the multiple linear regression analysis support this assertion, as the most significant model, which included antecedent temperatures and precipitation, explained only about 50 % of the variance in peak daily tree pollen concentrations. Models of the timing and duration of the grass and weed pollen seasons were even weaker, as only about 20–35 % of the variance was explained by mean monthly temperatures and precipitation alone. At least some of the additional, unexplained variance may be due to the fact that individual plant species in our sample will respond differently to changes in atmospheric conditions.

It is important to discuss some limitations to our study. Because the DAQ operates a Rotorod sampler, we were limited to daily pollen information. Burkard samplers, which are more commonly used, can provide hourly pollen information, allowing for examination of the diurnal characteristics of the APS and the effects of boundary layer processes on pollen transport and deposition (Ziska et al. 2011). Moreover, because the collection methods vary between Rotorod and Burkard samplers, quantitative comparisons between them cannot be made unless a correction factor is applied (Peel et al. 2014). We were also hampered by the lack of information on pollen species, and were therefore unable to create a detailed pollen calendar for Raleigh or assess how specific species, particularly the most allergenic, related to temperature and precipitation.

For example, while increased precipitation during the APS was found to reduce the length of the tree pollen season, it is possible that individual species may respond differently due to variations in the timing and duration of their flowering period.

In this study, we focused on monthly temperature and precipitation values. As mentioned earlier, other variables such as humidity, wind speed, and cloud cover have been correlated with characteristics of the APS at daily time scales, and we intend to explore these associations in a follow-up study. Additional variables such as air mass type and the occurrence of thunderstorms may also be useful in predicting airborne pollen concentrations. For example, the incidence of asthma has been found to increase significantly following thunderstorms due to the rupture of large pollen grains into respirable airborne particles (Grundstein and Sarnat 2009).

It is important to note that the results presented in this study were based on 14 years of data, and a longer time series is necessary to better assess the significance and attribution of the trends and relationships identified. Indeed, one of the key limiting factors of most phenological studies is the lack of long-term pollen data. The vast majority of studies referenced in this paper examined <20 years, and in some cases <10 years, of pollen data. Future studies will also have to consider what effect the movement of the DAQ sampler may have on airborne pollen concentrations. For example, when the sampler was moved to its current location in downtown Raleigh in August 2012, it was placed in close proximity to several Chinese elm trees (*Ulmus parvifolia*), which exhibit a secondary flowering period in mid-summer (Corey Mocka, personal communication, 2013). For this reason, we did not include data from 2013 to 2015 in our analyses. Additionally, it is assumed that the meteorological conditions recorded at RDU are representative of the conditions in the vicinity of the pollen sampler, which is located approximately 20 km away.

A significant confounder in the association between atmospheric variables and pollen characteristics is land use and vegetation patterns both around and upwind of the sampler (Dahl et al. 2013). For example, it may be that increasing trends in pollen

concentrations in places like Raleigh, particularly over time scales of a few decades, are tied more to patterns of reforestation than climate variability and change, though increases in reproductive maturity of trees and vegetation over time are certainly related to meteorological variables (Reid and Gamble 2009).

Transport of pollen grains from distant sources may also be contributing to seasonal as well as long-term patterns in pollen concentrations in Raleigh. We obtained a daily pollen dataset for a Rotorod sampler located in Winston-Salem, North Carolina, approximately 150 km west of Raleigh and situated within the same physiographic region of the state. The sampler is operated and maintained by the Office of Environmental Assistance and Protection which, like the DAQ, is a unit within the North Carolina Department of Environment and Natural Resources and follows the same pollen collection and counting procedures. Spearman's correlation coefficients for peak daily pollen concentrations between Winston-Salem and Raleigh from 1999 to 2012 were statistically significant ( $p < 0.05$ ) for tree pollen ( $r_s = 0.83$ ), insignificant for weed pollen ( $r_s = 0.33$ ), and negligible for grass pollen ( $r_s = -0.06$ ). This further supports the assertion that tree pollen is more strongly influenced by mean monthly temperature and precipitation and exhibits a more homogenous regional signal, while grass and weed pollen is more strongly influenced by vegetation and land use characteristics near the sampler (Bielory et al. 2012).

**Acknowledgments** We thank the following individuals from the North Carolina Department of Environment and Natural Resources: Mary Clark (retired), Wayne Cornelius, and Corey Mocka of the Division of Air Quality for providing the Raleigh pollen data, and Robert Russ of the Office of Environmental Assistance and Protection for providing the Winston-Salem pollen data. We also thank Amy Sun from the Department of Epidemiology at the University of North Carolina at Chapel Hill for developing the code to conduct the data imputation. Lastly, we thank the two anonymous reviewers, whose comments helped improve the quality of the manuscript.

## Appendix

See Table 5.

**Table 5** List of monthly periods associated with antecedent and seasonal temperature and precipitation values for each pollen type

| Antecedent |         |         | Season  |         |         |
|------------|---------|---------|---------|---------|---------|
| Trees      | Grasses | Weeds   | Trees   | Grasses | Weeds   |
| Nov–Feb    | Dec–Mar | Jan–Apr | Mar     | Apr     | May     |
| Dec–Feb    | Jan–Mar | Feb–Apr | Mar–Apr | Apr–May | May–Jun |
| Jan–Feb    | Feb–Mar | Mar–Apr | Mar–May | Apr–Jun | May–Aug |
| Feb        | Mar     | Apr     |         | Apr–Jul | May–Sep |
|            |         |         |         | Apr–Aug | May–Oct |
|            |         |         |         | Apr–Sep |         |

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