Heterogeneity in ragweed pollen exposure is determined by plant composition at small spatial scales

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HIGHLIGHTS
• Ragweed pollen concentrations are highly variable within the urban environment.
• Plant populations within 10 m and 1 km determine ragweed pollen concentrations.
• Ragweed plant abundance is highest in vacant lots.
• Low income neighborhoods may be disproportionately impacted by allergenic pollen.

GRAPHICAL ABSTRACT

ABSTRACT
Pollinosis are one of the most common health problems in the United States and over 20% of Americans are sensitized to the pollen produced by common ragweed (Ambrosia artemisiifolia L.). Despite the importance of allergenic pollen to public health, no research has linked land use and plant populations to spatial heterogeneity in airborne pollen concentrations. In order to quantify these relationships and elucidate the processes which lead to pollen exposure, we surveyed ragweed stem density in Detroit (Michigan, USA) as a function of land use. We then deployed 34 pollen collectors throughout the city and recorded ragweed cover in the immediate vicinity of each pollen collector. We found that ragweed populations were highest in vacant lots, a common land cover type in Detroit. Because ragweed population density was so strongly correlated to vacant lots, for which spatially explicit data were available, we were able to investigate whether observed ragweed pollen concentrations were a function of land use at the spatial scales of 10 m and 1 km. Both relationships were significant, and the combination of these two variables predicts a large portion of airborne ragweed pollen concentrations (R² = 0.48). These results emphasize the important role of pollen production within the urban environment and show that management of allergenic pollen producing plants must be considered at multiple spatial scales. Our findings also demonstrate that there is too much spatial heterogeneity for a pollen collector at any given site to portray the allergenic pollen load experienced by different individuals within the same city. Finally, we discuss how spatial correlations between socio-economic status, vacant lots, and ragweed could help to explain the disproportionate amount of allergies and ragweed sensitization experienced by low income and minority populations in Detroit.

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1. Introduction

It is estimated that over 35 million Americans suffer from pollen allergies (Nathan et al., 1997). Although pollen is not a malignant substance, inhalation by sensitized individuals leads to the production of IgE antibodies, resulting in extreme inflammatory responses. The effects of these allergies go far beyond the nuisance of physical discomfort; each year, allergies cause 3.5 million lost workdays, 2 million lost school days, and more than 11.2 billion dollars in treatment costs (Nathan, 2007). Furthermore, pollen exposure increases the risk of developing asthma and can trigger fatal asthma attacks (Boulet et al., 1983; Huynh et al., 2010; Zeldin et al., 2006). Pollens have been found in about 40% of asthmatic 1 to 3 year old children (Ogershok et al., 2007), 80–90% of asthmatic children in general, and 40–50% of adult onset asthmatics (Taylor et al., 2007). Approximately 20 million Americans have asthma, which causes an average of 5500 deaths per year, and accounts for 16 million outpatient and hospital visits annually (CDC, 1998). Thus, exposure to allergenic pollen has a serious impact on public health. Although the negative effects of allergenic pollen exposure are well documented, far less is understood about the ecological processes which ultimately determine human exposure to pollen.

The two processes which determine airborne allergenic pollen concentrations (and therefore exposure) are pollen production and dispersal. Allergenic pollen is produced by various wind pollinated plants. One of the most important producers of allergenic pollen is common ragweed (Ambrosia artemisiifolia L.; hereafter referred to as ragweed), an early successional annual plant in the Asteracea family which thrives in disturbed areas. Ragweed is native to North America, but has been repeatedly introduced to Europe (Gladioux et al., 2011) and is now invasive there and becoming an increasingly important allergen (D’Amato et al., 2007). Ragweed is a prolific producer of pollen, and individual plants often produce between 10⁸ and 10⁹ grains of pollen (e.g., Fumanal et al., 2007; Rogers et al., 2006; Simard and Benoit, 2011). In areas where ragweed plants are common, such as vacant lots or road sides, they can reach average densities of up to 16 plants per m² (Simard and Benoit, 2010). Ragweed has long been considered one of the most important causes of allergic rhinitis (Bassett and Crompton, 1975); over 20% of people in the United States are sensitized to ragweed pollen and this percentage is rising (Quest Diagnostics Health Trends, 2011). High ragweed pollen levels have even been linked to increases in hospital visits (Breton et al., 2006).

Although plant populations determine pollen supply, little is known of how local plant communities impact airborne pollen concentrations on smaller spatial scales (e.g., tens of meters to kilometers), and very few observational studies trace the link between ragweed populations and pollen on a larger spatial scale (1 km). For correlations between ragweed populations and pollen on a larger spatial scale (1 km) the effects of local vegetation on pollen collectors (Durham, 1946); however this also means that the air is not representative of what people breathe (Myszkowska et al., 2007). While this approach may allow for a comparison of phenology or species composition between cities, and does minimize small scale stochastic variation on the scale of meters (which can be considerable; see Hall, 1992), it does not address spatial heterogeneity within a city, information that could be used to develop specific management plans. Moreover, the few studies that used multiple pollen collectors within the same city found important differences between pollen collectors for certain plant taxa (e.g., Arobba et al., 2000; Katelaris et al., 2004). Although early work recognized the potential importance of spatial correlations between plant populations and pollen concentrations (Koessler and Durham, 1926), these links still remain largely unquantified.

However, both experimental and theoretical works show that local production is the most important determinant of local pollen concentrations. For example, in an experiment on dispersal of ragweed pollen Raynor et al. (1970) found that fewer than 10% of released pollen traveled farther than 100 m, and the authors calculated that about 1% of released pollen remained airborne at a distance of 1 km (also see re-analysis and review by Frenz, 2000). Thus, although long distance transport is possible and can be a significant source of allergenic pollen at great distances (D’Amato et al., 2007; Zink et al., 2012), short distance dispersal and therefore local production is often more important.

Local sources of pollen could be especially noteworthy in urban environments, where allergy rates are also especially high (Eggelston, 2007). There are many potential sources of allergenic pollen in cities, such as vacant lots. Vacant lots tend to be kept in early successional stages, and thus tend to have high ragweed populations (e.g., Falck, 2010; Vincent and Bergeron, 1985). Moreover, urban areas have higher carbon dioxide concentrations and temperatures and various studies have shown that these conditions lead to increased pollen production in allergenic plants such as ragweed and birch (Singer et al., 2005; Wayne et al., 2002; Yli-Panula et al., 2009; Ziska and Caulfield, 2000; Ziska et al., 2003) or increased quantities of allergenic protein within pollen grains (Singer et al., 2005; Tashpulatov et al., 2004; see Ziska et al., 2003). Indeed, in urban areas, each individual plant tends to produce substantially more biomass and pollen (Ziska et al., 2003; see review by Ziska and Beggs, 2012). Furthermore, the pollen season starts earlier in urban areas than in nearby rural areas (Rodriguez-Rajo et al., 2010).

In order to determine the links between ragweed pollen production, dispersal, and airborne density, we conducted a series of observational studies in Detroit, Michigan. First, we used pollen collectors and tested whether local (~10 m) plant density impacted airborne pollen density. Next, we determined that a particular land use type, vacant lots, were the main habitat for ragweed in Detroit. This finding allowed us to use land use as a proxy for ragweed populations, which enabled us to look for correlations between ragweed populations and pollen on a larger spatial scale (1 km).

2. Materials and methods

2.1. Study area

We conducted our study in Detroit, Michigan, USA (42°19′N, 83°02′W), which has a humid continental climate, an average temperature of 10.6 °C, ranging from in −3.2 °C in January to 23.6 °C in July, and its average precipitation is 940 mm/yr. Detroit’s land use composition, and its large number of vacant lots, is strongly tied to its demographic and economic history. In the 1950s Detroit’s population was 1.8 million inhabitants, but by the 2010 census, it was down to 713,777 (US Census Bureau, 2010). In fact, Detroit’s population has decreased by about 25% from 2000 to 2010 (US Census Bureau, 2010). The city of Detroit covers an area of 370 km²; population density is 1985 people/km². As population has declined over the decades so has per capita income, and the city has experienced profound social and demographic shifts (Binelli, 2012). This combination of circumstances has led to the widespread abandonment of buildings, and Detroit has one of the highest proportions of vacant lots within the United States. In fact, in many neighborhoods over 50% of lots are considered vacant (Detroit Residential Parcel Survey; Fig. 1). According to the 2010 census, of 349,170 housing units in Detroit only 269,445 were occupied (US Census Bureau, 2010). This makes Detroit an especially good study system in which to investigate
the impacts of allergenic pollen production in vacant lots on local airborne pollen concentrations and therefore on public health.

2.2. Vegetation surveys

In order to determine whether ragweed populations were associated with particular land use types, we conducted a vegetation survey. To do so, we established four transects, each of which spanned three types of land uses: vacant lots, occupied residences, and parks. These transects were conducted in the same neighborhoods as pollen collection sites and, as such, all transects passed through areas which had varying percentages of vacant lots. Within each transect we established 5 m × 2 m plots every 40 m. These plots were arranged 1 m away from the sidewalk to minimize edge effects. We conducted visual surveys from the sidewalks; the maximum possible distance from the observer to a ragweed stem was 3 m. We then used a laser range finder to determine which stems of ragweed were inside the plot. In addition to land use, we also noted maintenance regime (i.e., approximate time since it was mowed).

2.3. Pollen collection and identification

Pollen grains were collected using Durham pollen collectors (Durham, 1946, 1951), which we constructed using plastic plates as rain shields. A microscope slide was suspended between them, and covered with an adhesive (petroleum jelly) to trap pollen grains. Although Durham pollen collectors are slightly biased towards larger pollen grains which settle out of the air faster, this methodology does allow for the measurement of relative concentrations of ragweed pollen across sites; studies which have used both Durham’s samplers and volumetric samplers have found similar patterns in results between methodologies (Bricchi et al., 2000; Piotrowska and Weryszko-Chmielewska, 2003; Teranishi et al., 2006). Another benefit of this type of pollen collector is that they are simple to assemble and inexpensive; they are also well suited for general use.

Pollen collectors were placed in several neighborhoods across Detroit (Fig. 1); they were deployed on August 23, 2012 and collected on August 28th. This corresponded with peak ragweed season in the Detroit metropolitan area in 2012 (personal communication Lakeshore Ear, Nose, and Throat Pollen Counting Station). Each collector was installed 1.5 m from the ground and all were at least 10 m from the nearest building. We also assessed the percent cover of ragweed within 10 m of each pollen collector using the following cover classes: 0%, 0–1%, 2–5%, 5–10%, 11–25%, and >25%. Analysis was conducted using the average of each cover class. However, because there were few pollen collectors with high ragweed cover, we also analyzed this variable categorically (<1% and >1% cover); both analyses provide consistent results (data not shown). Weather data for the study period were downloaded from the Detroit NOAA weather station (National Climate Data Center, 2013).

Fig. 1. Vacant lots, ragweed plant cover, and ragweed pollen concentrations in Detroit. Each pollen collector is represented by either a triangle or a circle, which correspond respectively to <1% and >1% ragweed cover within 10 m of the pollen collector. Size of the symbol is proportional to the sampled density of ragweed pollen grains. The proportion of lots within a census block that are vacant is shown by shading. Black circles depict the 1 km buffer surrounding each pollen collector.
located at regularly spaced intervals (2.5 mm apart) to prevent counting pollen grains twice. Conducting multiple sweeps per slide gave us estimates of pollen variability within each slide, but our unit of analysis was the actual slide.

2.4. Geographic and statistical analysis

In 2009 the Detroit Residential Parcel Survey quantified land use in Detroit, including vacant lots (Detroit Residential Parcel Survey, 2009). We digitized these maps using ArcGIS (ESRI, 2013) and determined the percentage of lots which were vacant around each pollen collector at three spatial scales: 500 m, 1000 m, and 1500 m (Fig. 1). Some census blocks were not reported on Data Driven Detroit’s maps; we did not include these blocks in our analysis. We then created generalized linear models using each variable (ragweed within 10 m and vacant lots at each spatial scale) and each possible combination of these variables. We fit these models using the generalized linear model (glm) function in R, version 2.15 (R Development Core Team, 2013). To select the best model, we used Akaike Information Criterion (AIC), which takes into account both the fit of the model and the number of parameters in it; the model with the smallest AIC value provides the best explanation for the data (Akaike, 1974). Other statistical techniques used included the Mann–Whitney U test and linear regression.

3. Results

3.1. Vegetation surveys

We surveyed a total of 98 plots, of which 41 were on residential parcels (both occupied and unoccupied), 44 were in vacant lots, and 13 were in parks. Of these land uses, vacant lots had significantly higher densities of ragweed plants (1.2 plants/m²; p < 0.05). Occupied residential lots had significantly lower ragweed densities (0.2 plants/m²), and no stems were observed in parks (0.0 plants/m²). For those plots which were in vacant lots, we did not see a significant effect of management regime but our sample sizes were too small to be conclusive (9 plots were mowed regularly, 32 were mowed once a year or less, and three were in advanced stages of secondary succession).

3.2. Pollen density and vacant lots

In total, we deployed 34 pollen collectors across Detroit, 31 of which we were able to recover and analyze (Fig. 1). Average ragweed pollen density was 0.12 grains/mm² across slides and ranged from 0 to 0.53 grains/mm² (i.e., the total number of pollen grains counted per slide ranged from 0 to 63). There was also considerable variation within individual slides; the mean standard deviation within each slide was 0.12 and the median standard deviation was 0.07; this is based on six sweeps per slide. The pollen density on each slide and the variation within each slide are shown in Fig. 2. There was a significant relationship between pollen density and the number of vacant lots; the strongest relationship occurred on a scale of 1 km (p < 0.05; Fig. 2), although it was also significant at the spatial scales of 500 m and 1500 m (Table 1). There was also a significant correlation between pollen density and ragweed cover within 10 m (R² = 0.27, p < 0.003); the combination of vacant lots within 1 km and ragweed cover within 10 m in a generalized linear model explained almost half of the variation in pollen concentrations between collectors (R² = 0.48, p < 0.0001; Table 1). There was not a significant correlation between ragweed cover within 10 m and the percentage of vacant lots within 1 km (R² = 0.02, p = 0.48) or within 0.5 km (R² < 0.01, p = 0.71) or within 1.5 km (R² < 0.01, p = 0.63).

Based on weather station measurements in Detroit (National Climate Data Center, 2013), temperature during the pollen collection period ranged from 15.6–31.7 °C (mean: 23.9°) and total precipitation was 10.9 mm (all of which occurred the day before pollen collectors were retrieved). Wind speeds taken 2 m above ground ranged from 0–6.2 m/s (mean: 2.3 m/s) and although wind came predominantly from the south (57%), it also came from the west (13%), the north (17%), and the east (14%). Temperature and precipitation were close to the twenty year average for the time of year (National Climate Data Center, 2013).

4. Discussion

4.1. Impact of local plants on airborne pollen

We found that plant populations in the urban environment had a significant effect on airborne pollen concentrations on two spatial scales (10 m and 1 km). We came to these findings because of two nontraditional approaches to our methodology: first, we used 31 pollen collectors and second, we sampled air at 1.5 m above ground. Although the importance of land use and plant abundance to spatial heterogeneity in airborne pollen concentrations have not been reported in the peer reviewed literature, they are corroborated by both theoretical and experimental work (Raynor et al., 1970; Sugita, 1993). They are also supported by those studies which have found spatial differences in airborne pollen within a city (e.g., Bricchi et al., 2000; Koessler and Durham, 1926), within a region (e.g., Kotelarits et al., 2004; Zink et al., 2012), or even within the same city when airborne pollen concentrations were recorded on multiple rooftops 15 m above ground or higher (e.g., Arobb et al., 2000; Velasco-Jiménez et al., 2012). The results also fit with those of Stuart et al. (2006), who found that ragweed pollen concentrations were higher in desert sediments, where there was more ragweed growing, than in surrounding agricultural land or urban areas.

![Fig. 2. Pollen grain density as a function of the proportion of lots within 1 km that are vacant.](image)

Table 1

| Pollen density on slides (n = 31) as explained by ragweed cover within 10 m of the pollen collector and the percentage of vacant lots at three spatial scales. Model fit is shown in the R² column and the generalized linear model with the lowest AIC value was selected as the best ranked model and is in bold. |
|-----------------|-----------------|-----------------|
| Explanatory variables | R²  | p-Value | AIC  |
| Ragweed 10 m | 0.27 | 0.003 | 137.47 |
| Vacant lots 0.5 km | 0.18 | 0.019 | 141.02 |
| Vacant lots 1.0 km | 0.16 | 0.028 | 141.84 |
| Vacant lots 1.5 km | 0.13 | 0.046 | 142.73 |
| Ragweed 10 m + vacant lots 0.5 km | 0.48 | <0.001 | 129.03 |
| Ragweed 10 m + vacant lots 1.0 km | 0.48 | <0.001 | 128.57 |
| Ragweed 10 m + vacant lots 1.5 km | 0.43 | <0.001 | 131.44 |
urban areas. Thus, our finding that local pollen production causes extensive heterogeneity in airborne pollen within a city, is strongly supported by the literature.

4.2. Why understanding dispersal is important

Understanding the role of local plant populations on airborne pollen concentrations is required to understand what pollen densities people experience in their day to day lives, and researchers have pointed to the need for more detailed spatial sampling (e.g., Breton et al., 2006). This is a prerequisite for understanding the medical consequences of allergenic rhinitis on smaller spatial scales and is a necessary first step towards assessing whether local or regional management of allergenic pollen producing plants has the potential to meaningfully reduce exposure to airborne pollen. As argued by Cariñanos and Casares-Porcel (2011), a lack of planning and management has dramatically intensified allergenic pollen burdens in many cities. We found that the plants which are the most important sources of allergenic pollen are at small enough spatial scales that they could potentially be managed by municipalities, neighborhoods, or even individuals. Reducing populations of allergenic pollen producing plants could therefore be an effective way to reduce allergenic pollen exposure, and perhaps an alternative to the current paradigm of treating symptoms experienced by individuals after pollen exposure.

We also expect that management of pollen producing plants will become increasingly important over the coming decades, as temperatures and carbon dioxide concentrations continue to increase, which will result in more ragweed pollen production (Ziska et al., 2003, 2011) and ragweed pollen that is more allergenic (Singer et al., 2005). In fact, increased temperatures have been shown to directly increase pollen production in many plant species (Dapul-Hidalgo and Bielory, 2012). Global warming can also shift plant phenology, leading to earlier flowering dates and longer flowering seasons (D’Amato et al., 2007; Darbah et al., 2008; Rogers et al., 2006; Yli-Panula et al., 2009; Ziska et al., 2011). Indeed, analysis of long term pollen datasets suggest that climate change-induced increases in pollen production have already occurred over the last three decades in Europe (Cristofori et al., 2010; Yli-Panula et al., 2009).

4.3. Allergenic pollen and environmental justice

Because vacant lots are spatially correlated with low income neighborhoods in Detroit (Yun, 2008), which also tend to have large minority populations, our results suggest that local production of ragweed pollen disproportionately affects these communities. The literature contains evidence that there are racial inequities in the allergenic impact of ragweed within Detroit (Wegienka et al., 2012a,b). Results from the Wayne County Health, Environment, Allergy and Asthma Longitudinal Study found that black women in the Detroit metropolitan area were almost twice as likely as white women to be sensitized to ragweed pollen (Wegienka et al., 2012a) and that black children in Detroit were more sensitized to ragweed pollen than white children by more than 3 times, although in this case the sample size was small and the results were not significant (Wegienka et al., 2012b). Although some of this could be explained by the correlation between socio-economic factors and the frequency and severity of allergies and asthma (Johnson et al., 2010; Wright and Subramanian, 2007), environmental factors also play a large role and should not be underestimated (Eggleston, 2007; Wright and Subramanian, 2007). Thus, it is plausible that locally produced pollen from herbaceous plants is contributing to the allergy and asthma rates in urban areas, where they are disproportionately high (Crain et al., 1994; Eggleston, 2007; Johnson et al., 2010). This is corroborated by work by Breton et al. (2006) who found that low income residents in Montreal were more likely to seek medical attention for allergic rhinitis following days with high levels of ragweed pollen, compared to higher income residents of Montreal. These researchers also speculated that this link could be related to the proximity of low income residents to vacant lots (Breton et al., 2006).

4.4. Management implications

Our results offer new insight into the importance of management on smaller spatial scales; because production of pollen is important on scales ranging from 10 m to 1 km, reducing populations of ragweed and other allergenic pollen producing plants has the potential to effectively reduce airborne pollen and exposure. Perhaps, in part because of a lack of focus on local pollen production, comprehensive local management of ragweed to reduce pollen concentrations has not been discussed for urban areas, at least in the realm of peer-reviewed literature (which is not to say that it has not been tried; see Falck (2010) for a detailed history of ragweed control attempts in New York City in the early 1900s). While the pollen load of many cities could be managed by choosing plants which do not produce allergenic pollen (Cariñanos and Casares-Porcel, 2011), applying these lessons to privately owned vacant lots may prove more difficult.

There is a long history of attempting to control ragweed for health and economic reasons (e.g., Grigsby, 1945; Mitman, 2007). Mechanical removal of ragweed usually involves mowing, but although this may reduce pollen production if done multiple times a year (e.g., Bohren et al., 2008; Simard and Benoit, 2011; Vincent and Ahmim, 1985), it increases ragweed’s competitiveness and dominance within early successional communities (Wan et al., 2002). In fact, in our field surveys we found high ragweed densities in vacant lots which were mowed regularly or occasionally.

We instead call attention to an alternative strategy for reducing ragweed in vacant lots: permit secondary succession and promote reforestation (e.g., by planting tree seedlings). This will allow other successional plants to out compete ragweed (Raynal and Bazzaz, 1975), as it is a poor competitor in the conditions produced by succession (Leskovšek et al., 2012; Pickett and Baskin, 1973). Vincent and Bergeron (1985) found that vacant lots with high densities of ragweed tended to have a far lower proportion of perennial plants, presumably because they were more recent. Moreover, in additional vegetation surveys we observed that vacant lots which were going through secondary succession had far fewer ragweed plants (Katz et al. unpublished data). This approach would also reduce management costs, instead of increasing them. Reforestation of vacant lots is supported by community groups (e.g., The Greening of Detroit and LEAP), municipal government (e.g., Detroit Works), and private entities (e.g., Hantz Woodlands), and would have many benefits beyond reducing ragweed pollen allergies.

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