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Levels and determinants of tree pollen in New York City

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Abstract

Exposure to allergenic tree pollen is a risk factor for multiple allergic disease outcomes. Little is known about how tree pollen levels vary within cities and whether such variation affects the development or exacerbation of allergic disease. Accordingly, we collected integrated pollen samples at uniform height at 45 sites across New York City during the 2013 pollen season. We used these monitoring results in combination with adjacent land use data to develop a land use regression model for tree pollen. We evaluated four types of land use variables for inclusion in the model: tree canopy, distributed building height (a measure of building volume density), elevation, and distance to water. When included alone in the model, percent tree canopy cover within a 0.5 km radial buffer explained 39% of the variance in tree pollen (1.9% increase in tree pollen per one-percentage point increase in tree canopy cover, $p < 0.0001$). The inclusion of additional variables did not improve model fit. We conclude that intra-urban variation in tree canopy is an important driver of tree pollen exposure. Land use regression models can be used to incorporate spatial variation in tree pollen exposure in studies of allergic disease outcomes.

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Supplementary Information

Supplementary information is available at the Journal of Exposure Science and Environmental Epidemiology's website.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

pollen; aeroallergens; urban trees; tree canopy; allergic disease

Introduction

Exposure to allergenic tree pollen is associated with a range of allergic disease outcomes, including the development of allergic sensitization to tree pollen (1–3), exacerbation of allergic rhinitis (4–7), and exacerbation of allergic asthma (6, 8–12). Allergic rhinitis and asthma are highly prevalent and costly illnesses with large impacts on quality of life. In 2012, the prevalence of asthma in the United States was 8% among adults and 10% among children, while the prevalence of allergic rhinitis was 7% among adults and 9% among children (13, 14). Asthma resulted in approximately \$56 billion in medical expenditures, missed work and school days, and early deaths in 2007 (15). The estimated costs of health services and prescription medication sales for allergic rhinitis in the U.S. was \$11.2 billion in 2005 (16).

Many studies of the population health impacts of tree pollen are based on exposure data from a single site, as most cities in the U.S. have only one pollen monitoring station (17). Consequently, little is known about the spatial distribution of tree pollen within cities and the relevance of this distribution to health. In a systematic literature review, we identified 13 studies that measured intra-urban tree pollen variation. 12 of these studies found heterogeneity in tree pollen levels within cities, possibly arising from differences in local vegetation (18–28). However, most of these studies used a small number of sampling sites (typically four or fewer), and many have other design limitations such as non-uniform height of sampling (29). Recent work has evaluated intra-urban variation in grass pollen levels at 16 sites in the Helsinki metropolitan area, but did not include tree pollen measurements (30).

The health implications of intra-urban gradients in tree pollen exposure may be substantial. In New York City (NYC), tree canopy density within a 0.25 km radial buffer of a child's prenatal address was associated with a significantly increased risk of developing allergic sensitization to a group of common tree pollen allergens by age 7 (31). However, no information on pollen exposure was available in that study. Furthermore, while the 0.25 km buffer was more strongly associated with allergic sensitization than a 1.0 km buffer, little evidence was available to guide the scale of measurement. As urban tree planting programs are increasingly adopted to provide ecological, social, and public health benefits in cities (32–36), it is timely to systematically assess the distribution of tree pollen and its relationship to the urban tree canopy.

Here, we describe results from the first year of the New York City Pollen Survey (NYCPS), one of the largest intra-urban pollen monitoring networks worldwide. In the NYCPS, pollen is monitored at 45 sites across NYC using the monitoring framework of the New York City Community Air Survey (NYCCAS), a study of intra-urban spatial variation of air pollutants (37). We further describe the development of land use regression (LUR) and kriging models for total tree pollen and several individual allergenic pollen types using the NYCPS monitoring results.

Methods

Site Selection

New York City is made up of five boroughs: the Bronx, Brooklyn, Manhattan, Queens and Staten Island. We measured pollen at 45 sites distributed throughout the five boroughs (Figure 1). We selected these sites from among the 100 active monitoring sites of the NYCCAS, one of the largest ongoing studies of spatial variation in air pollution within an urban area (37). To maximize potential variability in tree pollen across sites, we used a GIS to overlay the NYCCAS sites with a 2010 land cover map that includes a state-of-the-art measure of tree canopy coverage derived from Light Detection and Ranging data (38). We divided the NYCCAS sites into terciles (low, medium, and high) of tree canopy cover within a 0.25 km radial buffer. To choose 45 sites, we first included 10 sites at which we had conducted a pilot study in 2012, assigning each of these sites to the appropriate terciles. We then randomly selected from the remaining NYCCAS sites until we reached 15 sites in each tercile. We also used a stratified random sample to select 10 sites at which to install replicate samplers, such that four replicate sites fell in the high tree canopy tercile, three in the medium tercile, and three in the low tercile.

Pollen Collection

We took a single, integrated pollen sample at each monitoring site using Tauber traps (39) that we modified for mounting on utility poles. Tauber traps depend on gravity and a 50% glycerol base (mixed with one gram of thymol to slow fungal growth) to collect and measure pollen deposition (in grains per cm², hereafter referred to as “influx”) over periods of weeks or months. Despite the varying and sometimes extended length of time for which Tauber traps are commonly deployed, different pollen types do not appear to be differentially preserved (40). We installed the traps in late February 2013 and removed them in November 2013 in order to capture the entire 2013 pollen season (March to October) (41). To facilitate comparisons across the city, we installed all traps as close to 8 feet off the ground as possible (range: 7.3 to 9.6 feet) and facing west (into the dominant wind direction) unless conditions were prohibitive (n = 38 samplers facing due west). We selected 8 feet as the installation height as it is close to the human breathing zone but still high enough to minimize the likelihood of accidental or intentional damage. We installed replicate samplers at 10 sites. Replicate samplers were separated by a height of approximately nine inches, both facing west. In subsequent analysis, we considered the sampler installed closest to 8 feet to be the main sampler.

Pollen Processing

We processed Tauber trap contents using laboratory methods that are well-established in the preparation of both fossil and modern pollen samples (42–45). The purpose of these methods is to concentrate the sample and to remove extraneous material. Briefly, sampling bottles were rinsed into 15 mL tubes, centrifuged, and decanted. Concentrated samples were sieved and subjected to a series of chemical washes. One tablet of *Lycopodium* spores (batch no. 1031, 20,848 ± 1,546 grains per tablet, Department of Quaternary Geology, Lund University, Sweden) was added to each sample during the chemical wash steps. Sample residues were plated on glycerine jelly slides and stained with phenosafranine.

A National Allergy Bureau-certified pollen counter (Dr. Weinberger) carried out microscopic analysis of the processed samples, classifying pollen to the genus level when possible. A proportion of each sample was counted (range: 1.5 – 2.1%), as the total amount of pollen in a Tauber trap is typically too large to count in its entirety. Each sample was counted until at least 400 pollen grains were identified, consistent with common practice (40, 46). The proportion of the sample counted was tracked using the *Lycopodium* spore spike, and this quantity was used to calculate the total amount of pollen in the sample (47). Pollen data were reported as influx in units of grains per cm².

Statistical Analysis

Spatial Distribution of Pollen—We used Pearson correlation to quantify differences in spatial patterns between pollen types. The pollen types we considered included total tree pollen (our main exposure) as well as four tree pollen genera that are clinically meaningful allergens, have well-established sensitization patterns in the Northeastern United States, and are included in a test for allergic sensitization to tree pollen used in a major NYC asthma study population (48–50). These pollen types are: maple (*Acer spp.*), birch (*Betula spp.*), oak (*Quercus spp.*), and sycamore (*Platanus spp.*).

Replicates—We quantified variation between pairs of replicate samplers by calculating the standard error of imprecision (51), which is equal to the square root of one half the variance of the differences between the 10 pairs of replicate samplers. We expressed this error as a percent of the mean influx measured in the replicate samplers.

Land Use Variables—We considered the following variables for inclusion in a LUR model for total tree pollen: percent tree canopy cover; distributed building height (a measure of building volume density); minimum, maximum and mean elevation in the area surrounding the monitoring site; point elevation of the monitoring site; and monitoring site distance to water. We selected percent tree canopy cover as an indicator of the source of pollen, distributed building height as it may act as a barrier to pollen dispersion (52), distance to water to reflect the absence of barriers to dispersion, and the elevation measures as pollen concentrations have been shown to vary with height (53). Additional information on the definitions and data sources of the land use variables is provided in Table 1. With the exception of monitoring site elevation and distance to water, which are characteristics of points, each variable was considered in five radial buffer sizes around the monitoring site: 0.05, 0.1, 0.25, 0.5, and 1 km.

LUR Model Building—Total tree pollen influx was log-transformed to more closely approximate normality of the LUR model residuals. We examined these data for outliers, defined as plus or minus three times the standard deviation. To select predictor variables for the LUR, we began by evaluating Pearson correlation coefficients for each variable in each buffer size with log-transformed total tree pollen (hereafter referred to as “total pollen”). For each variable (except the point characteristics), we considered the most highly correlated buffer size for inclusion in the LUR, unless no buffer sizes were significantly correlated with total pollen (54). Similarly, we considered the point characteristics for inclusion if they were significantly correlated with total pollen. We then selected variables for inclusion in the

model in order of the strength of correlation with total pollen, beginning with the source variable, percent tree canopy cover. Next, we considered distributed building height and the interaction of tree canopy cover and distributed building height, followed by the elevation variables. We kept variables in the model if they were statistically significant ($p < 0.05$), increased the adjusted R^2 , and had a variance inflation factor of less than 2.0.

Cross-Validation and Sensitivity Analysis—Because the number of monitoring sites was relatively small, we built the LUR model using data from all sites and evaluated model performance using leave-one-out-cross validation and the root mean square error (RMSE) using the ‘boot’ package in R (55, 56). We first assessed model performance for the main model, then examined a model using data only from monitoring sites facing due west.

Individual Taxa Models—We examined correlations of tree canopy with log-transformed influx of the four individual allergenic tree pollen types described earlier to assess the feasibility of building additional LUR models. We built LUR models for taxa that were significantly correlated with tree canopy following the same procedure used for total pollen.

Kriging—Kriging is a spatial interpolation technique in which predictions at unmonitored sites are made based on values at surrounded monitored sites. We examined variograms of LUR model residuals using the ‘gstat’ package in R (57) to assess whether kriging the residuals would further improve model predictions. For tree pollen taxa that had no significant predictors in an LUR model, we examined variograms of log-transformed influx and modeled their spatial distributions using ordinary kriging.

Software—All analyses were conducted using the R statistical package version 3.02 (R Core Team, Vienna, Austria, 2014). Land use variables were calculated using ArcGIS Desktop version 10.1. All statistical tests were two-tailed and based on an alpha of 0.05.

Code Availability—The R code used to build the LUR and kriging models can be obtained by contacting the corresponding author.

Results

Pollen Sampling Results

Data Quality—At the conclusion of the 2013 pollen season, one sampler was damaged to the point of being unusable, reducing the number of data points to 44.

Spatial Distribution of Pollen—Across monitoring sites, total tree pollen influx ranged from 2,942 grains per cm^2 to 17,463 grains per cm^2 (Table 2). Oak and sycamore were the most abundant allergenic pollen types measured. Some individual taxa exhibited an even greater degree of spatial variability than total tree pollen. For example, sycamore pollen influx varied by a factor of 70. Individual tree pollen types also exhibited distinct spatial patterns. For example, sycamore pollen influx was not significantly correlated with several other tree pollen taxa, including oak (Pearson $r = 0.29$) and birch (Pearson $r = 0.07$) (Supplemental Material, Table S1).

Replicates—The standard error of imprecision for total tree pollen was 1,474 grains/cm², or 20.6% of the mean total tree pollen influx measured in the replicate samplers (Supplemental Material, Figure S1a). There was no apparent difference in influx as a function of height when comparing the lower sampler to the upper sampler (separation distance = 9 inches) at replicate sites (Supplemental Material, Figure S1b).

Modeling Results

Land Use Variables—The distribution of land use variables at the five buffer sizes across monitoring sites is shown in Supplemental Material, Table S2. Tree canopy and the elevation measures were significantly positively correlated with total tree pollen at all buffer sizes (Pearson r for the most highly correlated buffer size: tree canopy (0.5 km) = 0.63, minimum elevation (0.5 km) = 0.39, maximum elevation (0.05 km) = 0.32, mean elevation (0.05 km) = 0.31, point elevation = 0.31), while distributed building height was significantly negatively correlated with total tree pollen (Pearson r = -0.41 for a 0.1 km buffer). Distance to water had a weakly positive but non-significant correlation with total tree pollen (Pearson r = 0.13).

LUR Model Building—There were no outliers in total pollen. When included alone in the LUR, percent tree canopy cover within a 0.5 km radial buffer explained 39% of the variance in total pollen (Table 3). Once the tree canopy variable was included in the model, no other land use variables improved the model fit. Subsequent analyses utilized tree canopy within a 0.5 km radial buffer as the only predictor for total tree pollen (hereafter referred to as the “main model”). Figure 1 shows the distribution of tree pollen as estimated by the main model.

Cross-Validation—The RMSE from leave-one-out cross-validation for the main model was 0.322 log-transformed pollen grains per cm² (Table 3). The RMSE improved slightly to 0.303 when the model was built using only sites where the sampler faced due west (n = 38).

Individual Taxa Models—We removed one outlier from the birch pollen dataset (n = 43) and two outliers from the maple pollen dataset (n = 42). Oak pollen was the only individual pollen type that was significantly correlated with percent tree canopy at any of the five buffer sizes (Supplemental Material, Table S3). The most highly correlated tree canopy buffer size was 0.5 km (Pearson r = 0.60). After including percent tree canopy within a 0.5 km radial buffer in an LUR model for oak pollen, no additional land use variables improved the fit (Table 3). Percent tree canopy explained less of the variance in oak pollen than it did in total tree pollen.

Kriging—There were no trends in the semivariance in variograms of the main model and oak model residuals. Consequently, we were unable to improve these models with kriging techniques. We did observe trends in variograms of both sycamore and maple influx, which we then modeled using ordinary kriging with an exponential fit. Supplemental Material, Figure S2 shows the prediction and variance surfaces derived from these kriging models. For both models, predictions for the eastern edge of the city had the largest variance due to the lack of monitoring sites. The RMSE from leave-one-out cross validation was 0.926 log-

transformed grains per cm² for the sycamore pollen model and 0.635 log-transformed grains per cm² for the maple pollen model.

Discussion

Here, we have described monitoring results from one of the largest intra-urban pollen monitoring studies to date. We found that total tree pollen varies substantially across NYC (2,942 grains per cm² to 17,463 grains per cm²), with some individual pollen types exhibiting an even greater degree of spatial variation. We expanded on these findings by building what we believe is the first LUR model for tree pollen. In the LUR, tree canopy cover within a 0.5 km radial buffer explained 39% of the variance in total pollen, suggesting that intra-urban variation in tree canopy at this scale is an important predictor of local tree pollen levels.

The density of the monitoring network (45 sites) is almost unprecedented. Ishibashi et al. (22) measured pollen at 78 sites in Tokyo, Japan in 2006, but the sampling period was limited to a single 24-hour period and the distribution of only two pollen species – Japanese cedar (*Cryptomeria japonica*) and Japanese cypress (*Chamaecyparis obtusa*) – was characterized. In contrast, our integrated samples spanned the 2013 pollen season, allowing us to examine the variability in the magnitude of the entire pollen season for multiple pollen taxa within NYC as well as investigate drivers of this variation.

Our 2013 monitoring results are consistent with previous work suggesting that tree pollen levels vary substantially within cities. Celenk et al. (19) measured daily tree pollen concentrations with a Hirst-type (58) sampler at two sites within Istanbul, Turkey and found that the total number of tree pollen grains captured over the course of a year was 1.3 times larger at one site than the other. Larger differences were observed for some individual pollen types; notably, sycamore pollen counts at the two sites varied by a factor of six. Similarly, Emberlin and Norris-Hill (20) measured influx of several pollen types at 12 sites in North London over a two-year period and found substantial variation across sites. For example, sycamore pollen influx varied by more than a factor of six across sites, while grass pollen (Poaceae) influx varied to a lesser extent. The authors suggest that the heterogeneous distribution of sycamore trees within the sampling area and the small, dense nature of sycamore pollen grains could give rise to this variability.

While the factors governing pollen dispersion over long distances (i.e., regions, continents) are well-characterized (59), less is known about pollen dispersion within small, urban areas, in which both potential sources of pollen (i.e., urban trees) and barriers to dispersion (i.e., buildings) are present (52). In this study, we found that percent tree canopy cover within a 0.5 km radial buffer explained nearly 40% of the variance in total pollen. While this result suggests that the spatial scale at which tree canopy influences pollen levels is larger than previously assumed, the buffer size used in earlier work (0.25 km) was also highly correlated with tree pollen (31). In addition to measurement error, the unexplained variance in tree pollen could arise from several factors. First, the tree canopy may have changed between when it was assessed in 2010 and when pollen was measured in 2013. Second, the heterogeneous distribution of different tree species and sex within the canopy and their

contributions to total tree pollen could account for some of the unexplained variance. Third, there may be additional land use characteristics that account for the remaining variance that we were unable to capture in our model. In future research, a more complex measure of air flow accounting not only for distributed building height but also street and wind direction could prove useful in predicting tree pollen influx. Finally, the reduction in the RMSE when the model was restricted to sites with samplers facing due west suggests that non-uniform sampler direction contributed to the remaining variance as well.

A limitation of the model for total tree pollen is that it provides information on pollen levels only on a coarse timescale (i.e., an entire pollen season). However, exposure estimates from this LUR model could be used to weight daily pollen concentrations measured with a Hirst-type (58) sampler at a regional monitoring station in Manhattan, NYC to develop daily pollen time series that are relevant on an intra-urban scale. While the units of the measurements taken with the modified Tauber traps (grains/cm²) are not directly comparable to those taken with volumetric Hirst-type samplers (grains/m³), previous work suggests that relative amounts of different pollen types observed over the course of a year are highly correlated between the two sampler types (46).

Tree canopy was more strongly related to total tree pollen than to any individual tree pollen type. Oak was the only pollen type individually correlated with percent tree canopy cover. A limitation of this study is that we were unable to use speciated tree canopy measures to improve our individual pollen type models, as we did not have complete information on the distribution of individual tree types within the canopy. While tree canopy appears to be a poor proxy for exposure to some individual taxa, we were able to model the spatial distribution of both sycamore and maple pollen with ordinary kriging, which relies on the correlation structure of measured values of pollen through space rather than on land use characteristics. These models predict the highest sycamore and maple influx in parts of Brooklyn and Queens, where the London planetree (*Platanus sp.*) and Norway maple are the top two most common street trees (60). However, the prediction errors from the kriging models were much larger than the error for the total tree pollen land use regression model. Thus, accurate modeling of the distribution of sycamore and maple pollen across NYC will require better information on pollen sources.

Strengths of this study include the density and number of sampling sites, the collection of samples at uniform height, and the use of high-resolution tree canopy data to systematically investigate the scale of the relationship between trees and pollen within a city. Planned future monitoring will attempt to answer several key remaining questions, including determining if the patterns we observed in 2013 are stable across years and systematically evaluating the effect of sampler direction on pollen influx.

In summary, we have shown that tree canopy on a small scale (0.5 km) influences the distribution of tree pollen. The results of this study are particularly relevant in light of the massive urban tree planting campaigns currently underway both in the United States and abroad. While these programs are expected to have substantial health benefits (32–36), they could also increase exposure to allergenic tree pollen. If intra-urban variation in tree pollen exposure is confirmed to contribute to the development or exacerbation of allergic disease,

future tree planting campaigns could consider modifications to their species selection strategies in favor of less allergenic species.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.
Location of NYCPS monitoring sites and land use regression-estimated total tree pollen influx using the main model in 0.1 km by 0.1 km grid cells (log-transformed grains per cm²)

Table 1

Land use variable definitions and data sources

Variable	Definition (unit)	Source
Tree canopy	Percent of buffer area covered by tree canopy (%)	2010 LIDAR mission (61)
Distributed building height	Building volume within the buffer divided by buffer area (meters)	NYC Building Footprints 2013-09 release from NYC Open Data with Roof Height and Ground Elevation (62)
Minimum elevation	Minimum elevation within the buffer area (feet)	NYC 1-foot resolution digital elevation model from 2010 LIDAR mission (63)
Mean elevation	Mean elevation of the buffer area (feet)	NYC 1-foot resolution digital elevation model from 2010 LIDAR mission (63)
Maximum elevation	Maximum elevation within the buffer area (feet)	NYC 1-foot resolution digital elevation model from 2010 LIDAR mission (63)
Point elevation	Elevation of the pollen site (feet)	NYC 1-foot resolution digital elevation model from 2010 LIDAR mission (63)
Distance to water	Distance to nearest body of water (feet)	NYC Hydrography layer from NYC Department of Information Technology and Telecommunications - Infotech/GeoDecisions, May 2008 (64)

Table 2

Descriptive statistics for total tree pollen and four individual pollen types measured at the 44 NYCPS monitoring sites

Pollen type	Minimum	p25 th	p50 th	p75 th	Maximum	Geometric mean (standard deviation)
Oak (grains/cm ²)	490	1,510	1,948	2,578	6,989	2,061 (1.7)
Sycamore	114	454	716	1,275	8,031	770 (2.7)
Birch	113	208	277	325	979	264 (1.5)
Maple	5	40	52	79	775	59 (2.3)
Total tree pollen	2,942	4,951	5,786	8,105	17,463	6,083 (1.5)

th p25 = 25th percentile, p50 = 50th percentile, p75 = 75th percentile

LUR models for log-transformed total tree pollen and log-transformed oak pollen. Results for total tree pollen are presented for both the full dataset ($n = 44$) as well as a restricted dataset limited to samplers facing due west ($n = 38$).

Table 3

Model	Predictor	Estimate	SE	p-value	R ²	RMSE ²
Total tree pollen, all observations ($n = 44$)	Tree canopy (0.5 km)	0.0189	0.0036	< 0.0001 ¹	0.392	0.322
Total tree pollen, west-facing samplers only ($n = 38$)	Tree canopy (0.5 km)	0.0194	0.0039	< 0.0001 ¹	0.408	0.303
Oak pollen	Tree canopy (0.5 km)	0.0232	0.0047	< 0.0001 ¹	0.364	0.418

¹ $p < 0.05$

² Root mean square error calculated using leave-one-out cross validation