



Urban-scale variation in pollen concentrations: a single station is insufficient to characterize daily exposure

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Received: 31 May 2019 / Accepted: 7 April 2020
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Abstract Epidemiological analyses of airborne allergenic pollen often use concentration measurements from a single station to represent exposure across a city, but this approach does not account for the spatial variation of concentrations within the city. Because there are few descriptions of urban-scale variation, the resulting exposure measurement error is unknown but potentially important for epidemiological studies. This study examines urban-scale variation in pollen concentrations by measuring pollen concentrations of 13 taxa over 24-h periods twice weekly at 25 sites in two seasons in Detroit, Michigan. Spatiotemporal variation is described using cumulative distribution functions and regression models. Daily pollen concentrations across the 25 stations varied considerably, and the average quartile coefficient of dispersion was 0.63. Measurements at a single site explained 3–85% of the variation at other sites, depending on the taxon, and 95% prediction intervals of pollen concentrations generally spanned one to two orders of magnitude. These results demonstrate

considerable heterogeneity of pollen levels at the urban scale and suggest that the use of a single monitoring site will not reflect pollen exposure over an urban area and can lead to sizable measurement error in epidemiological studies, particularly when a daily time step is used. These errors might be reduced by using predictive daily pollen levels in models that combine vegetation maps, pollen production estimates, phenology models, and dispersion processes, or by using coarser time steps in the epidemiological analysis.

Keywords Aeroallergens · Allergenic pollen · Allergic rhinitis · Exposure misclassification · Exposure measurement error

1 Introduction

Exposure to allergenic pollen can trigger allergic rhinitis, allergic conjunctivitis, and asthma attacks (Bousquet et al. 2008; La Rosa et al. 2013; Linneberg et al. 2002; Salo et al. 2011). Sensitization to pollen is common, and estimates of allergic rhinitis prevalence range from 10 to 30% (D’Amato et al. 2007; Mims 2014). Suffering individuals endure substantial reductions in quality of life and economic productivity (Blais et al. 2018; Meltzer 2016; Meltzer et al. 2009), and estimates of the health burden range to 5 million

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s10453-020-09641-z>) contains supplementary material, which is available to authorized users.

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lost school and work days annually in the USA (Nathan 2007). In Sweden, the economic cost of allergic rhinitis alone has been estimated at €1.3 billion annually (Cardell et al. 2016). Epidemiological analyses have linked ambient pollen concentrations to emergency department visits (Darrow et al. 2012; Sun et al. 2016), medication purchases (Ito et al. 2015), allergy symptoms (Werchan et al. 2018), and suicides (Qin et al. 2013).

Most epidemiological studies of allergenic pollen have implicitly assumed that pollen concentrations are uniform across the study area, typically a metropolitan area (Darrow et al. 2012; Guilbert et al. 2016; Osborne et al. 2017; Sakata et al. 2017; Sun et al. 2016) or a larger region (Gleason et al. 2014; Ito et al. 2015). These studies usually compare a time series of pollen concentrations monitored at a single location with health outcomes aggregated across the study area, typically using a daily time step. Although rarely considered (but see Werchan et al. 2018), intra-urban differences in pollen concentrations can result in substantial exposure measurement error, defined here as the difference between observed and estimated pollen levels at a location. For air pollutants, spatial variability and temporal misalignments associated with the use of a single monitoring station have been long recognized as issues that can bias results (Wilson et al. 2005). Exposure measurement error for airborne pollen can arise for a number of reasons, and information on spatial and temporal variability in pollen concentrations is needed to assess the potential for such effects.

Spatial variation of pollen concentrations has been documented in several studies (Table 1). Three studies collected brief (15 min to 3 h) measurements sequentially at 6–16 sites within a city (Charalampopoulos et al. 2018; Hjort et al. 2015; Katz et al. 2019). Such data can help describe average differences between sites, but not how pollen concentrations vary within a city on a particular day since the measurements are brief and taken at different times. Several other studies used long sampling integration periods (e.g., 5 days–8 months with gravitational samplers) (Emberlin and Norris-Hill 1991; Katz and Carey 2014; Weinberger et al. 2018; Werchan et al. 2017), which does not show short term variability, e.g., on the daily basis that is commonly used in health studies. Ishibashi et al. (2008) sampled at 78 sites in a city for a 24-h period; however, sampling was conducted on only 2 days, and

the gravitational samplers used do not measure airborne concentrations and are considered an inaccurate sampling method (Levetin 2004). Several other studies have assessed correlations in airborne pollen concentrations at a handful of sites (Fernández-Rodríguez et al. 2014a; Weinberger et al. 2015), but it is difficult to draw large conclusions about intra-municipal spatial heterogeneity from a small number of sampling sites. Thus, spatial variation on the daily time step important for health studies remains largely unknown.

The temporal variability of pollen levels measured at a single site (and a few sites in several cases) has been well documented, but studies examining how spatial patterns at the urban scale vary over time (i.e., spatiotemporal variation) have mostly been conducted at weekly time steps (Emberlin and Norris-Hill 1991; Werchan et al. 2017). We have recently examined effects of intra-urban temperature gradients on the timing of peak pollen release within Detroit, Michigan, which led to differences in pollen concentrations between sites (Katz et al. 2019). However, that study was not designed to describe how spatial patterns of pollen concentrations changed between days. More empirical data are required to describe spatiotemporal variation, such as simultaneous measurements of pollen concentrations at numerous locations over repeated 24-h periods. If the variation is high, then measurements from a single monitoring location may be a poor proxy for concentrations at other sites.

This study evaluates spatial and spatiotemporal variability of allergenic pollen concentrations by simultaneously measuring airborne pollen concentrations at 25 locations across Detroit, Michigan, USA, on 21 sampling days. These data are used to investigate how pollen concentrations differ throughout the city on a daily basis, whether the same sites have consistently higher concentrations, and how well measurements at one site represent levels elsewhere. This information provides insight into the extent of exposure measurement error that can affect epidemiological studies and into the design of and interpretation of data from pollen monitoring networks.

Table 1 Studies that have quantified spatial variation in airborne pollen concentrations on the municipal scale at more than five sites

Study	Plant type	Number of locations	Sampling approach	Sample integration period	Sampler used
Emberlin and Norris-Hill (1991)	Trees, grass	14	Simultaneous	7 days	Hyde (gravitational)
Bricchi et al. (2000)	Tree	12	Simultaneous	7 days	Durham (gravitational)
Ishibashi et al. (2008)	Tree	78	Simultaneous	1 day ^a	Durham (gravitational)
Katz and Carey (2014)	Ragweed	34	Simultaneous	5 days	Durham (gravitational)
Hjort et al. (2015)	Grass	16	Sequential	30 min	Rotorod (rotating impactor)
Werchan et al. (2017)	Trees, grass, herbaceous	14	Simultaneous	7 days	Durham (gravitational)
Weinberger et al. (2018)	Trees	45	Simultaneous	8 months	Tauber (gravitational)
Charalampopoulos et al. (2018)	Trees	6	Sequential	15 min	Portable Hirst (suction impactor)
Katz et al. (2019)	Trees	13	Sequential	3 h	Rotorod (rotating impactor)

^aIshibashi et al. (2008) deployed 78 samplers for a 24-h period, but this was only done once in 2005 and once in 2006

2 Materials and methods

2.1 Study area

The study was conducted in Detroit, Michigan, USA. Tree canopy covers 21.6% of Detroit and vacant lots occupy 16% of land area (Katz and Batterman 2019). Focal taxa (Table 2) include several trees (*Acer*, *Betula*, Cupressaceae, *Gleditsia*, *Juglans*, *Morus*, Pinaceae [including *Pinus* and the morphologically similar genera *Abies* and *Picea* but not the morphologically distinct *Tsuga*], *Platanus*, *Populus*, *Quercus*, *Salix*, and *Ulmus*), grasses (Poaceae), and ragweed (*Ambrosia*); other taxa had low pollen concentrations and are not included. Several taxa (e.g., *Acer*, *Ulmus*, and *Gleditsia triacanthos*) are common street trees in Detroit, whereas others are rare (e.g., *Juglans*). Plant cover has increased in Detroit neighborhoods as building vacancy has increased over the last 3 decades (Endsley et al. 2018), and preliminary data from the Urban Forest Inventory and Analysis (Richard McCullough, *personal communication*) suggest that early successional genera such as *Ulmus*, *Populus*, and *Morus* are especially common among non-street trees in Detroit. The annual average temperature in Detroit is 10.6 °C, and the average precipitation is 940 mm/year. Weather during the sampling period is provided in SI 1.

2.2 Pollen collection, samplers, and processing

Pollen was measured at 1.5 m height at 25 sites on volunteers' property in or immediately adjacent to Detroit (Fig. 1a). While the locations of our sampling sites were constrained to volunteers' locations (and thus were not randomly selected), they are distributed across a large portion of the city. Sampling locations were more than 5 m from the nearest building (excluding small sheds). Tree pollen sampling was conducted twice weekly for a total of 17 sampling events (from April 2–May 31, 2018). This period included the beginning of the grass pollen season. Ragweed pollen was sampled four times (August 22–23, 27–28, 30–31, and September 6–7, 2018). Samples were collected using rotorods; to prevent overloading, this sampler type is generally operated intermittently over 24-h periods (e.g., cycling on for 30 s of spinning and cycling off for 690 s, for a total of 1 h of active sampling out of 24 h). Here, we used a cycling period of 15 s on followed by 345 s off for a total of 1 h of sampling over 24 h; this cycle frequency is double the standard sampling frequency (Levetin 2004), which may better allow detection of brief episodes of elevated pollen. Samplers were deployed for a total of 29 h (deployment and retrieval each took ~ 5 h and were conducted in the same order); sampler deployment began at 7:30, and sampling

Table 2 Focal taxa including trees, ragweed, and Poaceae

Focal taxa	Common name	Major pollen-producing species	Relative basal area street trees (%)
<i>Acer</i>	Maple	<i>A. saccharinum</i> , <i>A. rubrum</i> , <i>A. saccharum</i> , <i>A. negundo</i>	46.9
<i>Betula</i>	Birch	<i>B. papyrifera</i> , <i>B. nigra</i>	0.1
Cupressaceae	Juniper, arborvitae	<i>Juniperus virginiana</i> , <i>Thuja occidentalis</i>	> 0.1
<i>Gleditsia</i>	Honey locust	<i>G. triacanthos</i>	10.2
<i>Juglans</i>	Walnut	<i>J. nigra</i>	0.1
<i>Morus</i>	Mulberry	<i>M. alba</i> , <i>M. rubra</i>	0.4
Pinaceae	Pine	<i>Pinus nigra</i> , <i>P. sylvestris</i> , <i>P. strobus</i> , <i>Picea abies</i>	0.2
<i>Platanus</i>	Sycamore, London planetree	<i>P. occidentalis</i> , <i>P. x acerfolia</i>	9.1
<i>Populus</i>	Poplar	<i>P. deltoides</i> , <i>P. alba</i>	2.0
<i>Quercus</i>	Oak	<i>Q. palustris</i> , <i>Q. rubra</i> , <i>Q. macrocarpa</i> , <i>Q. alba</i> , <i>Q. robur</i>	5.6
<i>Salix</i>	Willow	<i>S. matsudana</i> , <i>S. babylonica</i>	0.2
<i>Ulmus</i>	Elm	<i>U. pumila</i> , <i>U. americana</i> , <i>U. rubra</i>	10.4
<i>Ambrosia</i>	Ragweed	<i>A. artemisiifolia</i> , <i>A. trifida</i>	–
Poaceae	Grasses	<i>Dactylis glomerata</i> , <i>Elymus repens</i> , <i>Panicum dichotomiflorum</i> , <i>Poa annua</i> , etc., ^a	–

Tree abundance in Detroit is based on street tree data and does not include trees on private property or in parks

^aPersonal observation; graminoids were not quantitatively surveyed

began at 13:00 and ended at 13:00 on the next day. While sampling events technically spanned two dates, for brevity we refer to these 24 h periods as “days.” The custom samplers used (Fig. 1b) featured a self-supporting tripod mount, rain shield, two revolving motor-operated sampling rods, battery operation, and microprocessor control (Arduino Pro Mini 328, Sparkfun, Boulder, CO, USA) that enabled programmable and simultaneous sampling. Sampler speed was adjusted to 2400 (± 25) RPM, and speed was checked several times over the sampling season. To ensure reproducibility, we compared different rods on the same sampler and also compared pollen measurements of colocated commercial and custom-built rotorod samplers (SI 2: Sampling QA/QC). Samplers used in the spring for tree and grass pollen sampling were not equipped with automatically retracting rods, so passive deposition could have occurred on the sampling surface outside of active sampling periods when measuring tree and grass pollen. Passive deposition of tree and grass pollen was assessed by placing a stationary deposition rod adjacent to the sampler. To control for passive deposition, the number of pollen grains on the

deposition control rod was subtracted from those on the sampling rod for each taxon (SI 2). If the deposition control rod was lost ($n = 21$ of 361), values were imputed (SI 2). Samples deployed in the fall for ragweed pollen were equipped with automatically retracting rods.

Pollen was collected on acrylic rods coated with silicone grease. Samplers were transported in airtight containers that attached directly to the rain shield (i.e., bucket lid). After retrieval, rods were glued to microscope slides and stored in slide storage cases pending analysis. Rods were stained with Calberla solution and viewed at $400\times$ using a Meiji ML2000 microscope. Although some survey the entire rod sampling surface (35 mm^2 for a standard rod), this was not feasible given the large number of rods and high pollen concentrations encountered. Because pollen tends to accumulate on rods fairly evenly (Frenz et al. 1996), we surveyed a subsection of the sampling surface (Darrow et al. 2012; Hugg and Rantio-Lehtimäki 2007; Katz et al. 2019; Peel et al. 2014) using five latitudinal transects, each measuring $2.90 \times 0.46\text{ mm}$, for a total 6.67 mm^2 per rod and 13.34 mm^2 per sampler. The surveyed area represents



Fig. 1 **a** Map of sampling locations and tree canopy cover within Detroit. **b** Custom rotorod sampling device and rain shield. The symbols for sampling points are not to scale

a sample volume of 0.52 m^3 , compared to 0.49 m^3 collected in a single transect on a 24-h Burkard slide. The high correlation between duplicate rods ($r = 0.98$; SI 2) suggests that sampling error was a negligible contributor to the variation reported in this study. Airborne pollen concentrations (pollen grains m^{-3}) were calculated following standard procedures (Frenz et al. 1996; Katz et al. 2019; Wang et al. 2017).

Sampling volume was the product of the air volume sampled per revolution ($\text{m}^3/\text{revolution}$), the rotational speed (RPM), and the sampling duration (minutes). Pollen was identified to the genus level with the exception of Cupressaceae, Pinaceae, and Poaceae. Identification was confirmed by comparison to reference samples and with pollen identification guides (Hepworth et al. 1983; Smith 1984).

2.3 Data visualization and statistical analysis

The main pollen season for each taxon was defined as the period of days in which 99% of pollen was measured. This definition of the pollen season is only approximate since pollen concentrations were measured twice a week, but is still useful for restricting the period of analysis. Two alternate common definitions of the pollen season are the periods when 95% or 100% of pollen was measured; sensitivity of analyses to alternate pollen season definitions was also explored (described in the results). Distributions and cumulative distributions of pollen concentrations during each sampling event were visualized.

The variation in pollen concentrations for each taxon on each date was visualized with cumulative distribution functions and quantified with the quartile coefficient of dispersion metric, qCOD. Its definition

is: $qCOD = \frac{(Q_3 - Q_1)}{(Q_3 + Q_1)}$, where Q_1 and Q_3 are the first and third quartiles of measured pollen concentrations; higher qCOD scores indicate a more dispersed distribution. This metric of dispersion is used because it is robust to extreme values and non-normal distributions (Bonett 2006), and because it could be calculated for other studies that report pollen concentration quartiles. (More formal analyses were not conducted because there were few days where pollen concentrations were high for most taxa.) The spatial variation of pollen concentrations for each sampling event was mapped using the R package *ggmaps* (Kahle and Wickham 2013), and spatial autocorrelation was assessed with variograms using the R package *gstat* (Gräler et al. 2016).

To assess how well pollen concentrations at one site predicted pollen concentrations at another site, we compared pollen concentrations between all unique pairs of sites. To do so, the pollen concentration time series from each pair of sites were log-transformed and plotted (e.g., site A on the x axis and site B on the y axis where each point is a sampling day); the plot includes all unique pairs of sites. Linear regression models (ordinary least squares) quantified the relationship across all unique site pairs and were used to estimate prediction intervals. A similar analysis using correlation matrices was explored, and it provided qualitatively similar results to the linear regression models (data not shown). This manuscript provides a descriptive analysis of spatial and temporal variability and does not utilize formal hypothesis tests of differences between particular sites and sampling days.

Data were visualized with *ggplot2* (Wickham 2016), and all analyses were conducted in R 3.5.0 (R Core Team 2018); additional maps were made in ArcMap 10.6 (ESRI, Redlands, CA).

3 Results

3.1 Quality assurance and pollen levels

Sampler reproducibility was high (SI 2): the two rods on the same sampler were highly correlated (Pearson's $r = 0.98$), and pollen measurements from co-located samplers were strongly correlated (Pearson's $r = 0.98$). Active sampling rods had a median of 5.5 times more pollen than passive deposition rods (SI 2).

Trends of airborne pollen concentrations (Fig. 2) show that *Morus* and *Quercus* exhibited distinct peaks in pollen concentrations; other taxa exhibited more variable temporal patterns in pollen concentrations. The main pollen season was captured for most taxa with the exceptions of Pinaceae, Poaceae (their pollen concentrations were still rising at the end of the spring sampling period), and *Ambrosia*. Other traditional definitions of pollen seasons (95% and 100% of pollen collected) are also shown in Fig. 2.

3.2 Spatial heterogeneity

Pollen concentrations at the different sites in Detroit varied dramatically within a sampling event, often by 1–2 orders of magnitude. Figure 3 represents this variability by showing measurements from each sampling event as an individual cumulative distribution function (CDFs, i.e., the cumulative proportion of measurements below each pollen concentration). Spatial variability depends on the taxa and pollen concentrations (or pollen season). Taxa with higher variability include *Gleditsia* (qCOD = 0.96), *Betula* (qCOD = 0.83), *Platanus* (qCOD = 0.87), Pinaceae (qCOD = 0.80), and *Acer* (qCOD = 0.67). Taxa with more uniform concentrations included *Ambrosia* (qCOD = 0.18) and *Morus* (qCOD = 0.42). Across all taxa and days, qCOD was 0.63. Even on the highest pollen day for each taxon, pollen varied considerably among the 25 sites, and the average qCOD across taxa was 0.41. Days with higher pollen concentrations tended to have less spatial variability, shown by steeper slopes in Fig. 3 (as described in the previous paragraph), and lower qCODs in SI 3 for 11 of 12 taxa, except *Morus* (but sample sizes were small for each taxon).

Spatial autocorrelation was inconsistent, and nearby sites often had very different pollen concentrations (semivariograms for each taxon and day are provided in SI 4). The strength of autocorrelation varied among taxa and sampling events; the taxa exhibiting the strongest evidence for spatial autocorrelation were Cupressaceae and *Quercus*.

3.3 Spatiotemporal heterogeneity

For several taxa (e.g., *Acer*, *Ulmus*, and *Platanus*), the site with the highest pollen concentration frequently changed between days, and it was common for a site

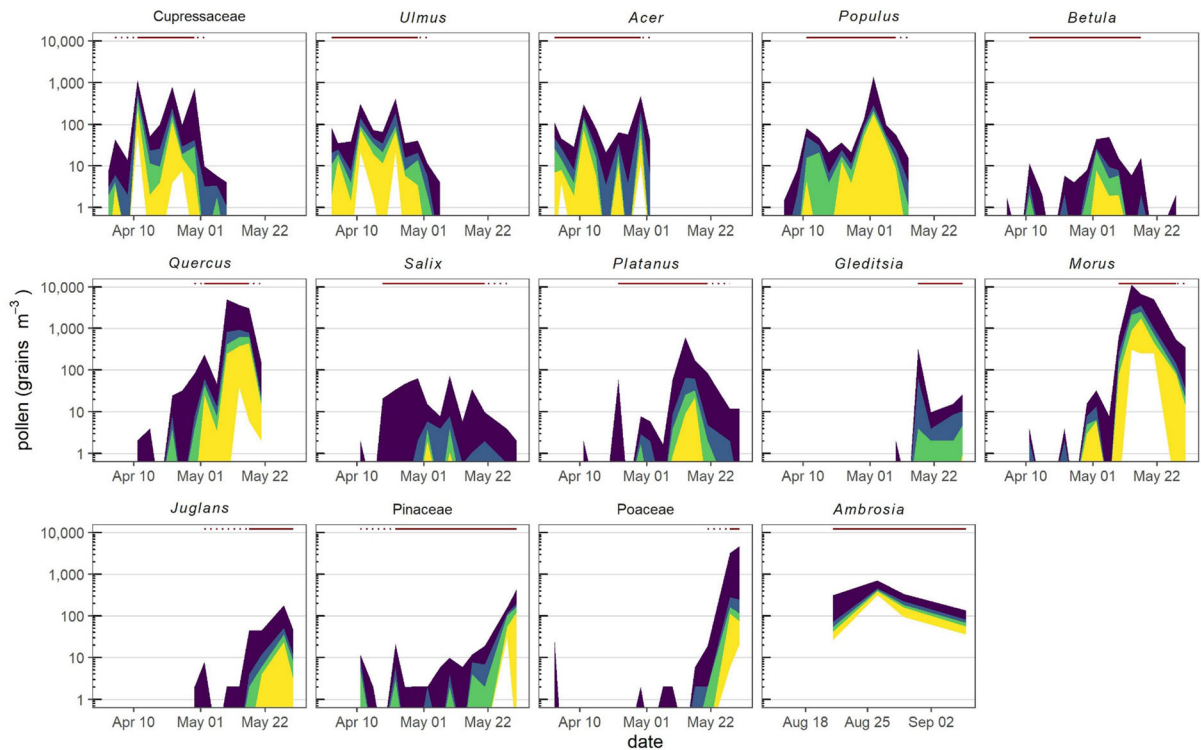


Fig. 2 Distributions of pollen concentrations during each sampling event for each taxon. Quartiles are indicated by color (top quartile is dark blue, and bottom quartile is yellow). Three common pollen season definitions are shown: the 95% season definition (solid red line at top of panel), the 99% season

definition (dotted red line), and the full pollen season definition (first to last observed pollen); note that these definitions are based on the available data and are not comprehensive. Taxa are displayed in general phenological order (based on data from a regional pollen monitoring station)

that had relatively low pollen concentrations on one day to have relatively high pollen concentrations on the subsequent sampling day (SI 5). In contrast, for Cupressaceae, *Morus*, and *Ambrosia*, some sites tended to have consistently high pollen concentrations and other sites tended to have consistently low pollen concentrations. Example maps of airborne pollen concentrations including relative and absolute pollen concentrations are provided in SI 5.

The Detroit data show the extent to which pollen concentrations at a single location predict pollen concentrations at other sites. Figure 4 is a scatter plot of all observations from each unique pair of sites. Stronger associations between sites are shown by observations closer to the 1:1 line and by narrower prediction intervals (dashed lines). For example, if 100 pollen grains m^{-3} were observed at one site, the 95% predicted interval at other sites was 4–1087 pollen grains m^{-3} for *Quercus* and 45–312 pollen grains m^{-3} for *Ambrosia*. Model fits as R^2 ranged from 0.03

(*Salix*) to 0.85 (Pinaceae and Poaceae); the average R^2 across tree taxa was 0.37. Analyses using the 95% and 100% pollen season definition, give an average R^2 of 0.27 and 0.46, respectively. Across the entire season, the 95% predicted intervals often spanned two orders of magnitude.

4 Discussion

4.1 Urban-scale variation of pollen

Other studies have measured pollen concentrations at the urban scale that correspond to qCOD values ranging from 0.21 to 0.57, with an average qCOD of 0.34 (Bricchi et al. 2000; Charalampopoulos et al. 2018; Emberlin and Norris-Hill 1991; Hjort et al. 2015; Katz and Carey 2014; Weinberger et al. 2018; Werchan et al. 2017). Our Detroit data show considerably higher variability, e.g., qCOD across taxa here

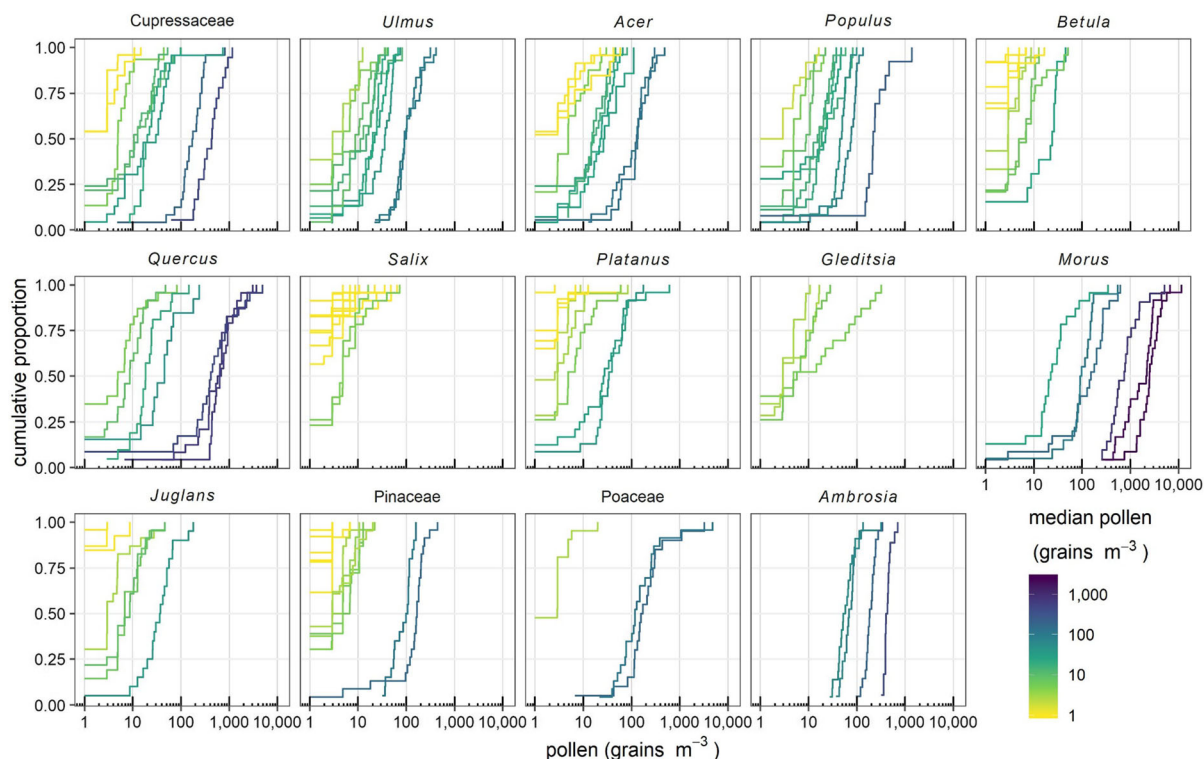


Fig. 3 Cumulative distribution of pollen concentrations for each taxon during each sampling event within the 99% pollen season. Each line is a sampling event, and each step on the line is a site; the x-axis is the pollen concentration at that site and the y-axis the proportion of sites that had less pollen than that site.

averaged 0.63. For focal taxa, qCOD reported elsewhere was generally far lower than reported here, e.g., 0.26 and 0.21 versus 0.46, respectively, for *Quercus*, 0.42, 0.47, and 0.48 versus 0.87 for *Platanus*, 0.35 and 0.22 versus 0.83 for *Betula*, 0.33 and 0.42 versus 0.67 for *Acer*, 0.26 and 0.21, and 0.42 versus 0.48 for *Poaceae*, 0.09 versus 0.57 for *Cupressaceae*, 0.42 versus 0.80 for *Pinaceae*, 0.29 versus 0.54 for *Populus*, 0.14 versus 0.42 for *Morus*, and 0.51 versus 0.52 for *Ulmus*. Here, qCOD for *Ambrosia* was 0.18; in a previous study we conducted in Detroit qCOD for *Ambrosia* was 0.42, but in that study, a portion of samplers were deliberately placed near *Ambrosia* patches. Potential causes for the relatively higher spatial variation reported here are described below. These results provide strong evidence that pollen concentrations measured at one location are not an effective proxy for concentrations elsewhere within a city or region. This is corroborated by the sharp pollen concentration gradients associated with individual

Sampling events are color coded by median pollen level (cumulative proportion = 0.5). Steeper lines show more uniform pollen concentrations, and shallower lines more dispersed distributions. Slopes of lines at low concentrations (e.g., < 10 grains m^{-3}) may be less meaningful

trees at distances of ~ 100 m in Worcester, UK (Adams-Groom et al. 2017) to hundreds of meters in Perugia, Italy (Bricchi et al. 2000), and from data from a similar study in Toronto, Canada (Lavigne et al., manuscript in prep).

The higher degree of spatial variability reported here than elsewhere may be due to methodological differences. First, we used a daily time step while the comparison studies used weekly or seasonal time steps that would tend to miss variability caused by peak flowering occurring on different days within the study area. Second, we sampled at 1.5 m height; in comparison, the recommended height for (permanent) pollen monitoring stations is 5–15 m in the USA and 15–20 m in Europe. Pollen concentrations near the ground are generally more variable than concentrations measured at greater heights (Rojo et al. 2019; Soldevilla et al. 1995; Spieksma et al. 2000) and can display differences in diurnal timing (Fernández-Rodríguez et al. 2014b), but 1.5 m is approximately

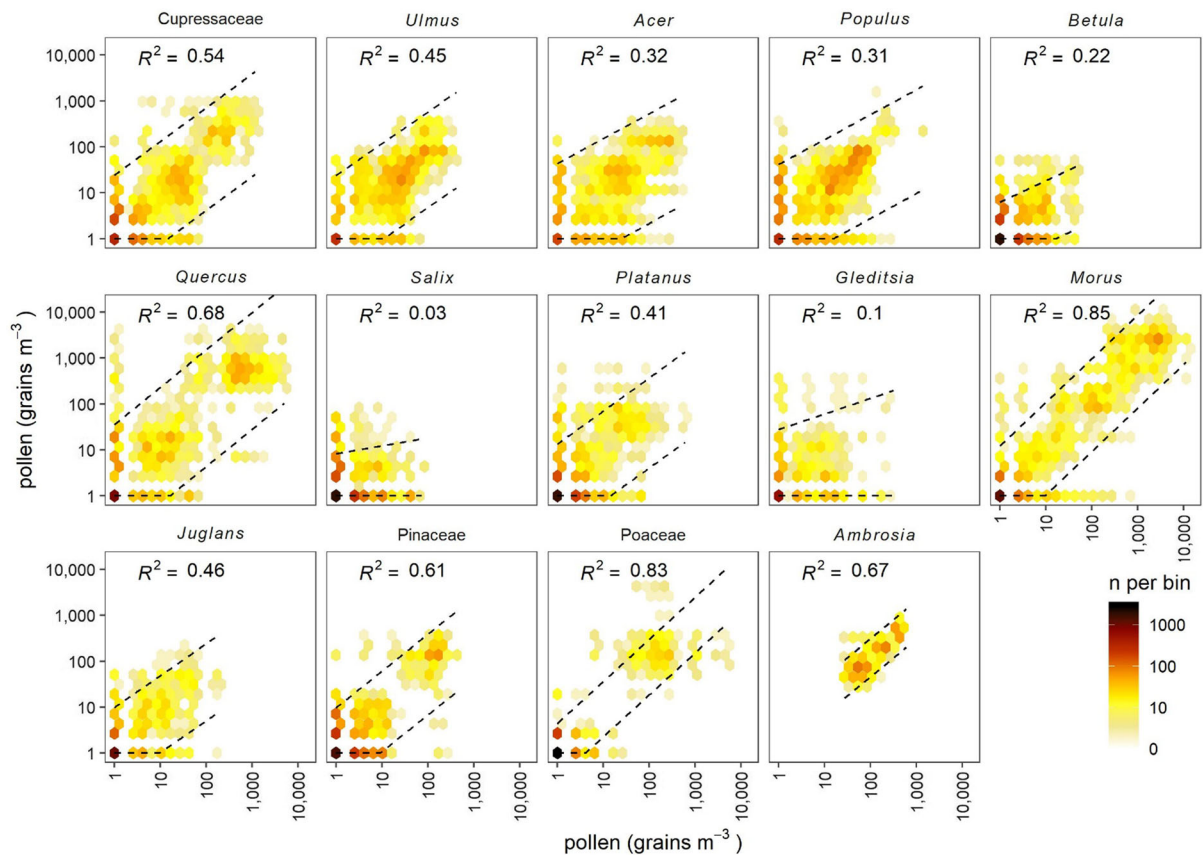


Fig. 4 Comparison of pollen concentrations between sites across the sampling period for the time-series from each unique pair of sites. The number of observations in each bin is indicated

by color, and the 95% prediction interval (using the linear model and the log transformed data) is shown for each taxon with dashed lines

breathing height. Several other studies of spatial variation in airborne pollen have also sampled near the ground (Charalampopoulos et al. 2018; Hjort et al. 2015; Ishibashi et al. 2008; Katz et al. 2019; Katz and Carey 2014; Weinberger et al. 2018; Werchan et al. 2017). While many studies that sampled at only a few locations have sampled at elevated heights (Fernández-Rodríguez et al. 2014a; Weinberger et al. 2015), we are only aware of one study that sampled at many locations at elevated heights (Emberlin and Norris-Hill 1991). Furthermore, truncating the time period of an analysis can change how well one site predicts another, e.g., including the periods at the start and end of the pollen season when pollen concentrations were near zero resulted in stronger correlations between sites. In other words, a single station is better at indicating whether the city is in the main pollen season than it is for predicting daily concentrations at other locations during the main pollen season.

4.2 Causes of variation

The spatial variability of pollen concentrations at the urban scale can result from several factors, including spatial variation in plant composition and abundance, the time of flowering and pollen release, and meteorological influences on pollen release and dispersal. Spatial variability in plant composition has been shown to affect pollen concentrations at distances from 100 m (Werchan et al. 2017) to 200 m (Charalampopoulos et al. 2018); the effects of plant composition at larger scales are seldom tested. More comprehensive linkages between plant composition and spatial variability is limited by information on plant location; only a single study had locations of all intra-municipal sources (Bricchi et al. 2000). Other surrogates for plant composition and abundance, including total tree cover (Weinberger et al. 2018), land use type (Hjort et al. 2015), and habitat type

availability (Katz and Carey 2014), also have been used to predict airborne pollen. However, urban plant composition results from several complex mechanisms (Roman et al. 2018), limiting the generalizability of indirect proxies for plant abundance. Plant composition within genera can also affect variation in pollen concentrations (Brennan et al. 2019); while pollen of congeneric plants are lumped together during identification, they can have distinct flowering phenology (e.g., distinct peaks in *Acer* pollen could potentially be caused by *Acer saccharinum* and *A. negundo*, which we have observed flowering several weeks apart in this area, Katz unpublished data).

Differences in flowering phenology cause lags and leads in pollen concentrations at different sites leading to spatial variability. In the spring of 2017, we monitored flowering phenology of *Quercus* and *Morus* trees in Detroit and found substantial variation in the timing of flowering within the city, which was very well explained by spatial differences in average land surface temperature during February (Katz et al. 2019). These differences in flowering time within the city explained 46% and 70% of the variation in relative pollen levels for *Quercus* and *Morus*, respectively. It is plausible that the phenological differences between sites could flip their relative pollen concentrations even on time scales of days (e.g., the 3 or 4 day sampling interval used here). The range of average February temperatures within Detroit (6 °C) is similar to that in other epidemiological studies (average of 5 °C), so phenology is likely to be a principal cause of spatiotemporal variation elsewhere too (Katz et al. 2019).

Meteorological variables can affect pollen release and dispersal, including wind speed, wind direction, and turbulence (Auer et al. 2016; Huang et al. 2015; Klein et al. 2003; Kuparinen 2006). Wind direction will influence the direction of dispersal, and higher wind speeds can increase the distance pollen will travel. Temperature (as discussed) and humidity can affect the timing of pollen release (Martin et al. 2010). These meteorological variables can vary considerably over time and space, potentially causing variation at both local and regional scales. For example, winds could transport air masses from areas with high pollen production on one day; the next day may bring air masses from areas with low pollen production (Hernández-Ceballos et al. 2011; Maya-Manzano et al. 2017). Physical structures such as buildings

and tree cover can affect wind patterns and therefore pollen concentrations (Auer et al. 2016). Taxon-related differences in spatial variability of pollen could also be caused by pollen release height (Klein et al. 2003), the relative contributions of local versus regional sources (Hernández-Ceballos et al. 2011), or pollen settling rates (Borrell 2012). Quantitative analyses of the relative contributions of these processes to the variability observed in this study are beyond the present scope, but these data are useful for hypothesis generation. For example, the greater spatial variability seen for *Gleditsia triacanthos* could hypothetically be driven by its relatively large pollen size ($\sim 37 \mu$), which could result in faster settling rates (Borrell 2012). In another example, the high spatial variability of *Betula* could hypothetically be due to its relative infrequency in the landscape; sites with higher pollen concentrations may simply have been near source trees. Knowledge of many taxon-specific processes, from plant location and phenology to meteorology and pollen traits, are required to understand the spatiotemporal patterns of pollen observed here and to predict them in other cities. Knowing the circumstances in which a monitoring station is or is not expected to be representative of its area would be useful for both researchers and the public.

4.3 Implications for epidemiological investigations

Epidemiological studies using longitudinal designs may be robust to spatial variation if pollutant concentrations fluctuate in unison within the study area (Wilson et al. 2005). However, the Detroit data show that pollen levels did not increase (or decrease) by the same amount across the sites, or even necessarily change in the same direction. Conducting analyses on a weekly basis (Qin et al. 2013; Werchan et al. 2017, 2018) in which a greater portion of the study area would attain peak pollen levels together, instead of a daily time step, may prevent a false level of precision in pollen concentrations.

The extensive spatial and spatiotemporal variation found in this study suggests that the use of a single monitoring station can result in considerable measurement error in epidemiological analyses that use a daily time step; such errors can lead to incorrect conclusions. However, the variability in pollen levels must be considered with respect to levels that may

cause symptoms and adverse health effects. Despite longstanding study of the relationship between pollen concentrations and allergic responses Frenz (2001), population-level responses to pollen vary considerably between epidemiological studies (e.g., Darrow et al. 2012; Erbas et al. 2012; Ito et al. 2015; Sun et al. 2016), so the exact effect of the potential misclassification documented here is unknown. Still, these studies at the population level, as well as studies at the individual level (Frenz 2001), suggest that responses to pollen are continuous and do not saturate at high pollen concentrations, thus misclassification is expected to be important across a broad range of pollen concentrations.

4.4 Implications for pollen monitoring

For many air pollutants, a single monitor does not provide sufficient exposure information and alternate approaches are required (Dionisio et al. 2016). The variability observed in Detroit suggests that any single monitoring station, even if located at NAB or EAN recommended height, will not represent near-ground pollen concentrations across an urban area. Additionally, if the pollen monitoring station is located away from population centers, then it may provide incorrect exposure estimates due to differences in the timing of pollen release (Katz et al. 2019). One approach for reducing exposure misclassification is to monitor pollen at multiple locations within a city (e.g., Werchan et al. 2018). However, large differences in pollen concentrations were frequently observed at nearby sites in Detroit and elsewhere (Adams-Groom et al. 2017; Bricchi et al. 2000), suggesting that even dense sampling networks will only partially explain pollen concentrations.

Mechanistic models of pollen concentrations offer a promising approach to improving urban-scale predictions of pollen concentrations. A major barrier has been a lack of comprehensive maps of urban plants. While such maps are rare, they are becoming feasible for trees due to advances in remote sensing (Wang et al. 2019) and are already fully operational for grass (Skjøth et al. 2013). Taxa with distinct habitat preferences, such as ragweed, can also be mapped and modeled effectively (Katz and Batterman 2019). Plant maps could be combined with pollen production estimates (Katz et al. 2020), phenology models, and

atmospheric dispersion models to more accurately predict and forecast airborne pollen concentrations.

4.5 Sampler variability

Measurements reported here were collected over 24 h periods and escape the limitations imposed by sequential sampling and gravitational sampling. Wind speed can affect sampler efficiency, but effects are expected to be < 20% for speeds commonly observed during sampling (Frenz 2000). Rotorod samplers are one of two sampler types widely used by the National Allergy Bureau pollen monitoring network and in epidemiological analyses. Differences between rotorods and the other most commonly used active sampler, Burkards, are generally small for pollen (< 20% difference in means), although differences do depend on wind speed and particle size (Di-Giovanni 1998; Frenz 2000; Miki et al. 2017). It should also be noted that pollen concentrations observed in Detroit are generally in the same range as concentrations reported in epidemiological analyses (e.g., Darrow et al. 2012; Guilbert et al. 2016; Ito et al. 2015; Sun et al. 2016), with the exception of *Ambrosia* concentrations, which were substantially higher at 709 pollen grains m^{-3} (maximum recorded), compared to ~ 60 pollen grains m^{-3} (Darrow et al. 2012), ~ 50 pollen grains m^{-3} (Gleason et al. 2014), and < 30 pollen grains m^{-3} (Sun et al. 2016).

4.6 Study limitations

Spatiotemporal variation in pollen concentrations was evaluated in only one city, and results may vary between cities. Sampling was conducted in a single year, but the quantity of pollen produced and the timing of release could vary between years. Urban plant distributions are determined by complex processes that are expected to vary between cities, likely resulting in distinct spatial patterns of pollen release in each city. Still, urban vegetation is generally becoming more similar among cities (Groffman et al. 2014), and tree composition in Detroit (as per street tree data) does not appear unusual. Results for ragweed, which thrives in vacant lots and disturbed soils that are common in Detroit, may be less generalizable, although findings for this taxon may still apply to other depopulating cities. Additionally, the results for *Ambrosia* and Poaceae were based on only four and

two sampling events, respectively, so results for these taxa should be interpreted with some caution.

5 Conclusion

Based on a comprehensive set of 24-h measurements of 13 taxa, spatial and spatiotemporal variability of airborne pollen concentrations was high in Detroit. This novel dataset demonstrates that pollen measurements from a single site are unlikely to represent exposure over an urban area. The amount of variability varied between taxa, and pollen concentrations were generally more homogenous on high pollen days. The spatiotemporal variation of pollen concentrations can represent a potentially important source of exposure measurement error in epidemiological analyses, particularly for studies using a 24-h time step. Such errors might be reduced by using longer time steps (e.g., 1 week), or by applying new methods that model pollen concentrations over space and time.

Acknowledgements This work was supported by the National Institute of Environmental Health Sciences through a NRSA postdoctoral fellowship (Grant Number F32 ES026477). It was also supported by the Michigan Institute for Clinical Health Research through the Postdoctoral Translational Scholars Program (Grant Number UL1 TR002240). S. Batterman also acknowledges support from Grant P30ES017885 from the National Institute of Environmental Health Sciences, National Institutes of Health. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. We thank John Kost for his considerable effort on this project and the volunteers that allowed us to sample pollen on their property.

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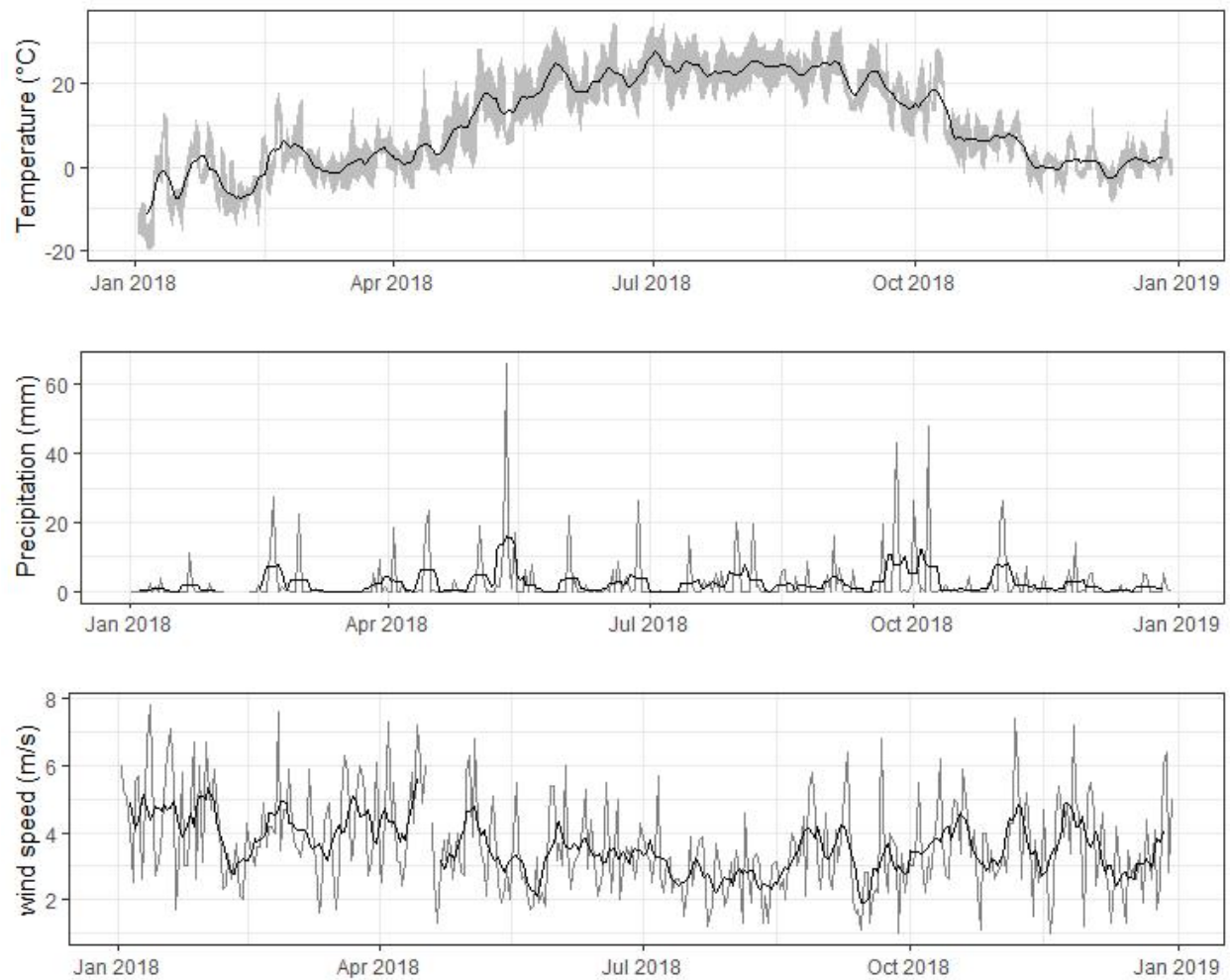
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Supporting Information

Supporting information 1: Local weather station measurements from Detroit City Airport in 2018. Daily measurements are shown in gray and one week moving averages are shown in black.



SI 2: Sampling QA/QC

Custom-built rotorod measurements were validated against a commercial rotorod (Sampling Technologies Inc., Model 40) in a collocation experiment (Fig. SI 2A). Samplers were adjacent to each other (40 cm apart) and sampling occurred on 10 days between May 25 and June 18 2019, for approximately 24 hours per sampling event. The sampling cycle of our rotorod was adjusted to match the commercial rotorod (60 seconds on, 553 seconds off) to ensure simultaneous sampling. Total pollen concentrations were measured by microscopy at 400 $\times$. We compared total pollen concentrations between samplers; mean and standard deviations for the matching samples are provided. Pearson's correlation coefficient between measurements was 0.9997.

To compare differences caused by intra-sampler stochasticity, we also compared concentrations between the two duplicate rods from each rotorod sampler for all data collected for this study (Fig SI 2B).

21 out of 361 deposition rods from the spring sampling were not recovered. The number of pollen grains on missing rods were imputed based on the observed median ratio between control rods and deposition rods (5.5; the full distribution of values for rods are shown in Fig. SI2C). This ratio was used across all taxa; differences between taxa were minimal (data not shown).

Fig. SI 2A: Comparison of a custom built and a commercial rotorod. Mean and standard deviation of pollen concentrations on each date are shown, as is a 1:1 line.

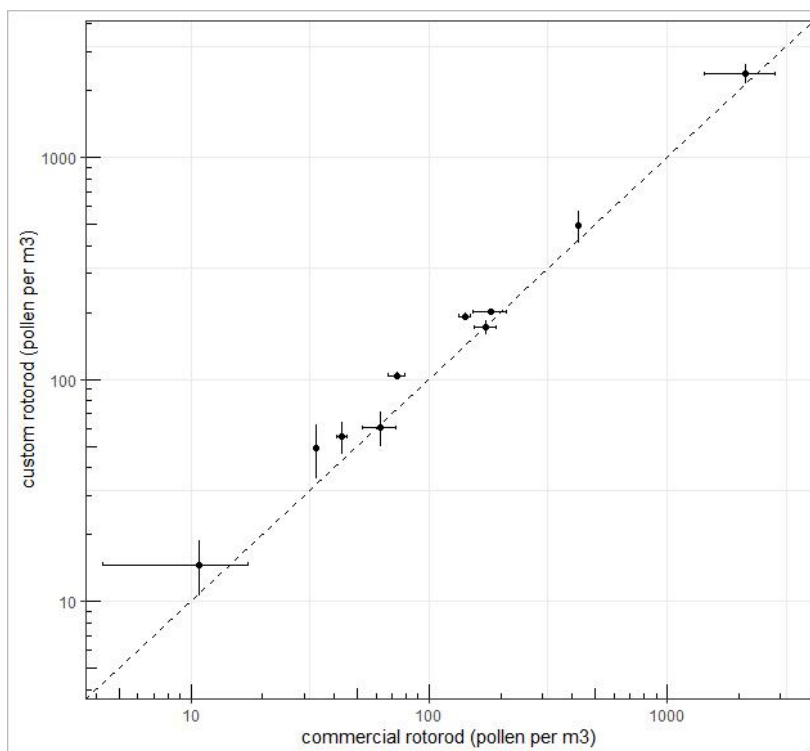


Fig SI 2B Comparison between pollen grains counted on the two rods of a sampler. All rods analyzed in the study are included. The 1:1 line is shown and the correlation (Pearson's r) is 0.98.

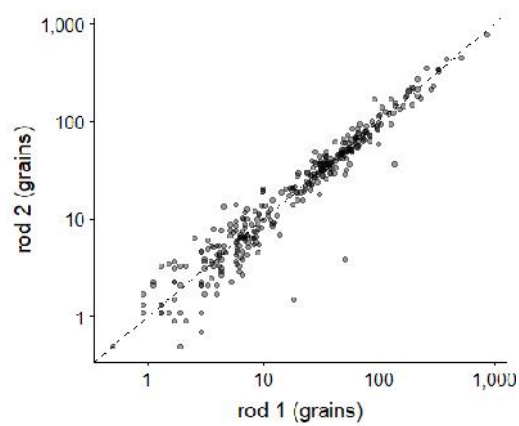
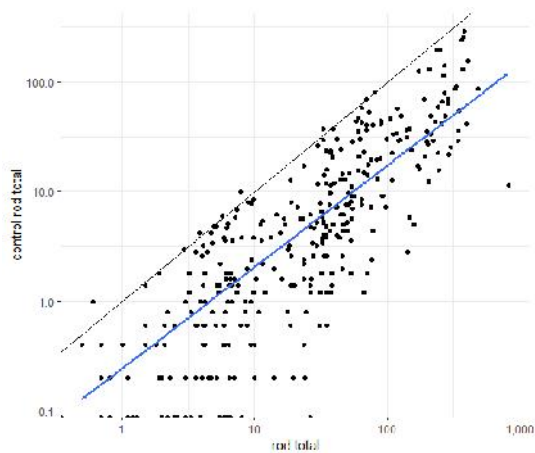


Fig SI 2C Relationship between pollen grains counted on the active sampling rod and the control rod. A one:one line and linear regression are included.



SI 3: Spatial variability (qCOD) as a function of median pollen concentrations across sampling days across all taxa (Fig SI 3A) and within each taxon (Fig SI 3B). A negative association shows that there is less variability between sites on high pollen days.

Fig SI 3A. Quartile COD as a function of median pollen concentration for each taxon on each day (low pollen days, where more than a quarter of sites had less than 1 pollen grain /m³ are not included here). A linear regression is provided ($R^2 = 0.27$, $p < 0.001$).

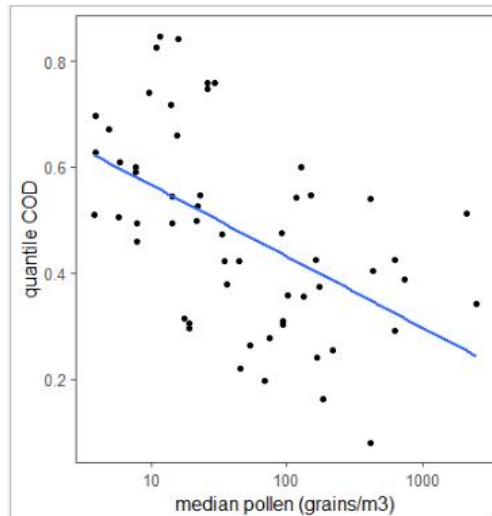
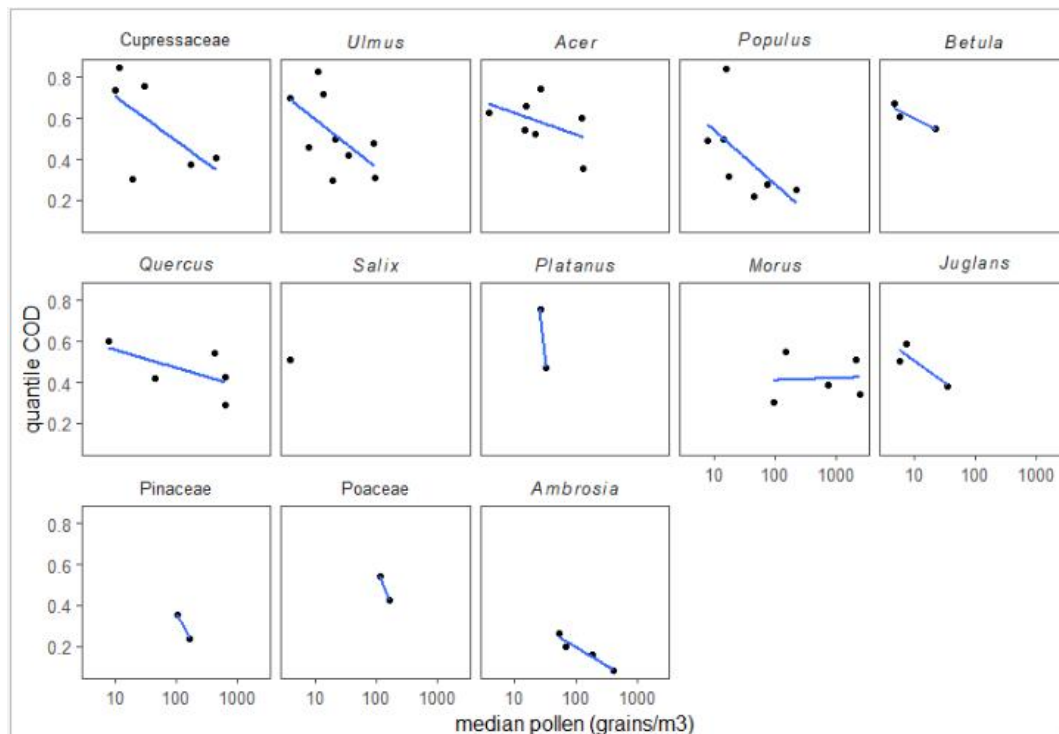


Fig SI 3B. Quartile COD as a function of median pollen concentration for each taxon on each day (low pollen days, where more than a quarter of sites had less than 1 pollen grain /m³ are not included here). Exploratory linear regressions are shown, but sample sizes are too small for meaningful conclusions to be drawn for individual taxa.



SI 4: Semivariograms of pollen concentrations on each day that median pollen concentrations were > 10 grains/ m^3 . Differences between points (gamma values, on y axis) are log transformed ($\log 10 + 10$) and distance between sites are provided in km. Loess regression fits are provided. Separate figures are provided for each focal taxon.

Fig. SI 4A

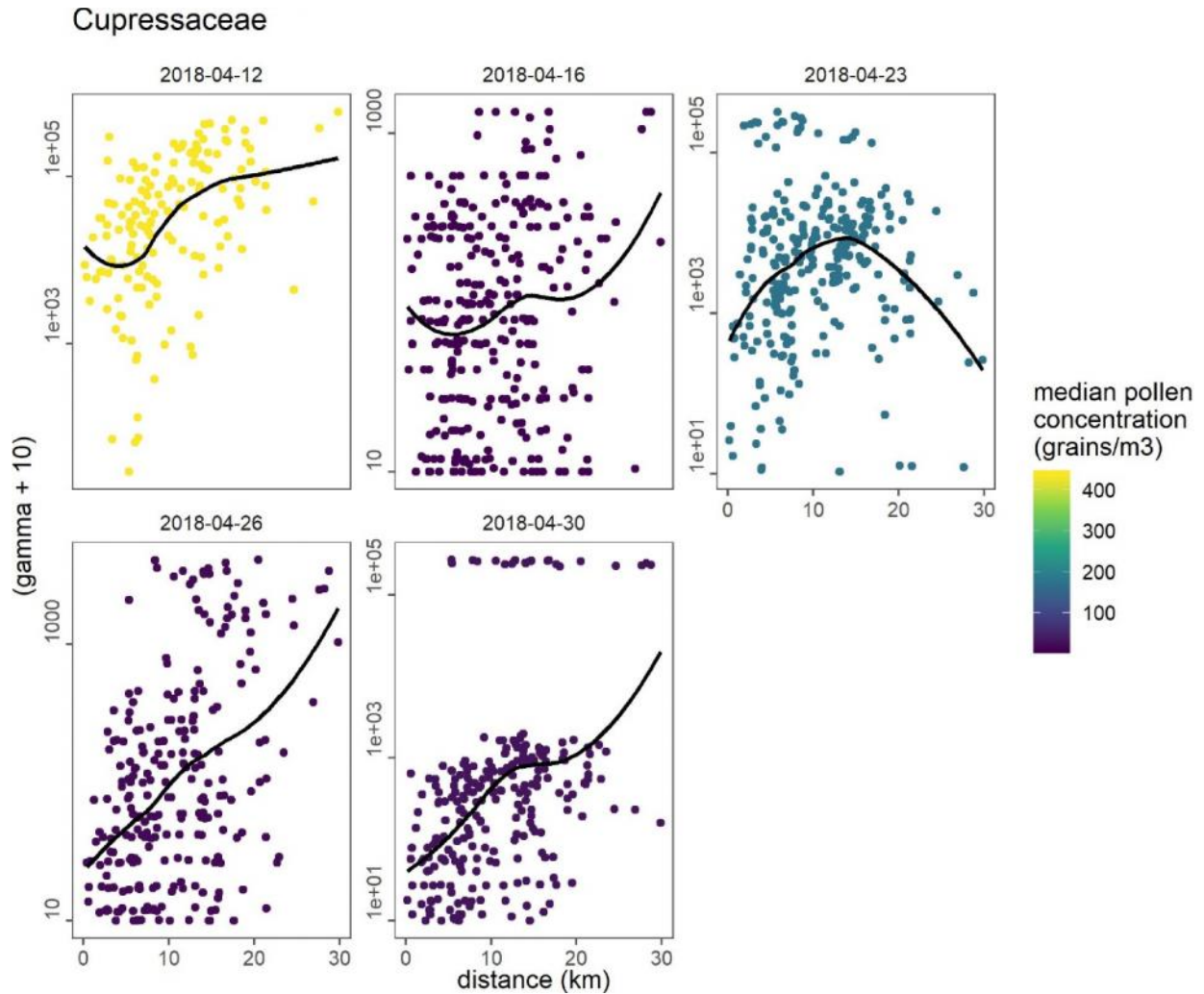


Fig. SI 4B
Ulmus

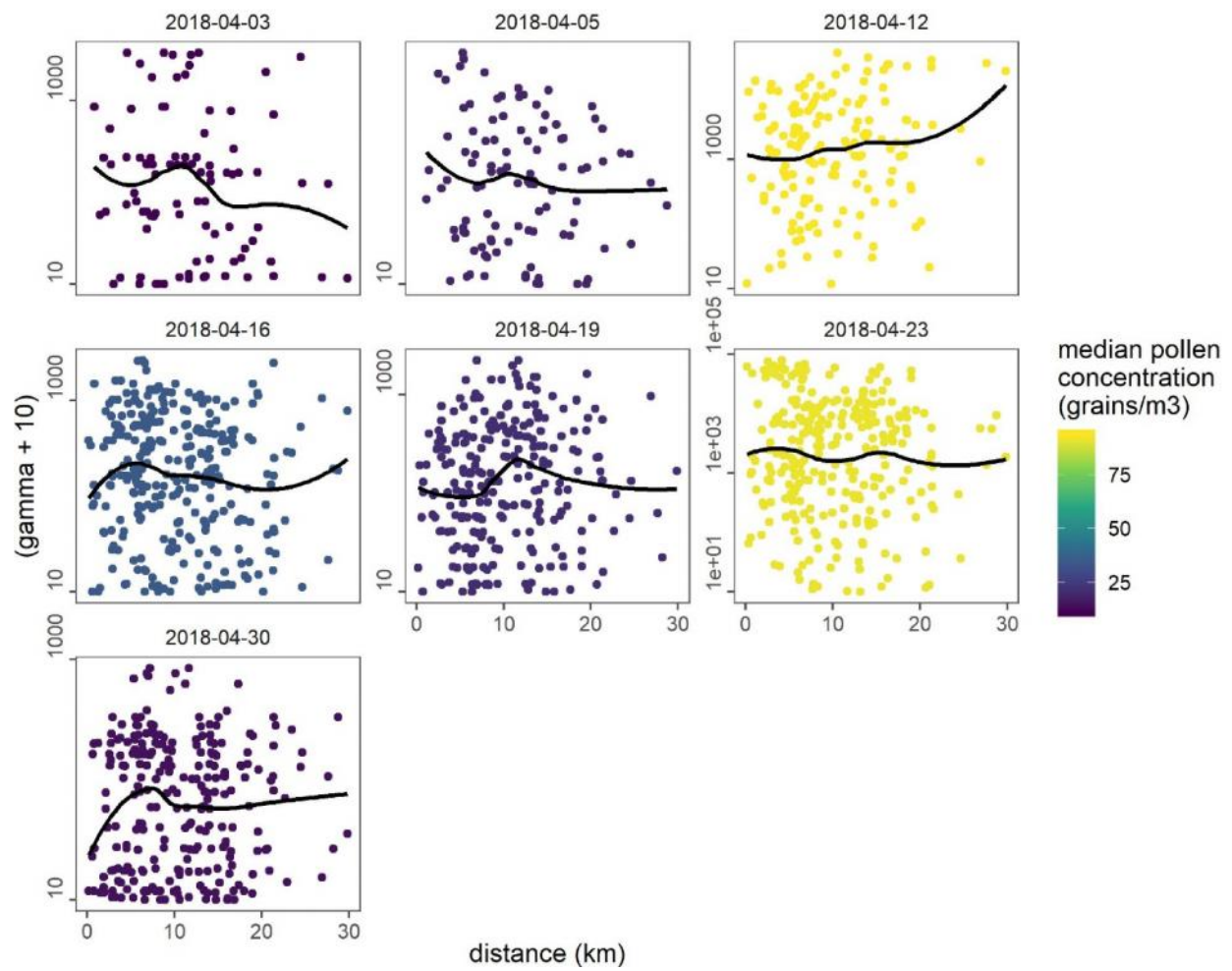


Fig. SI 4C

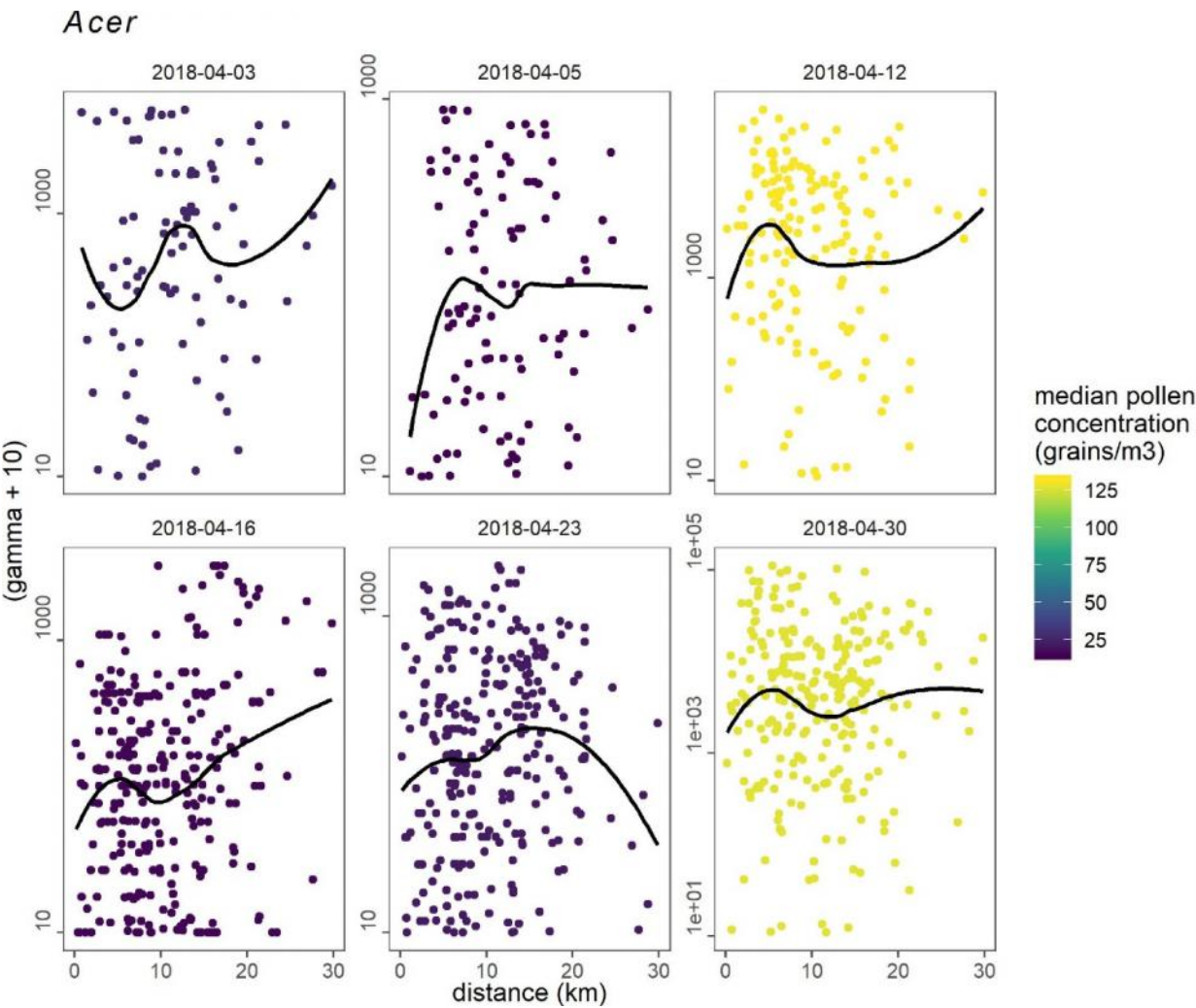


Fig. SI 4D

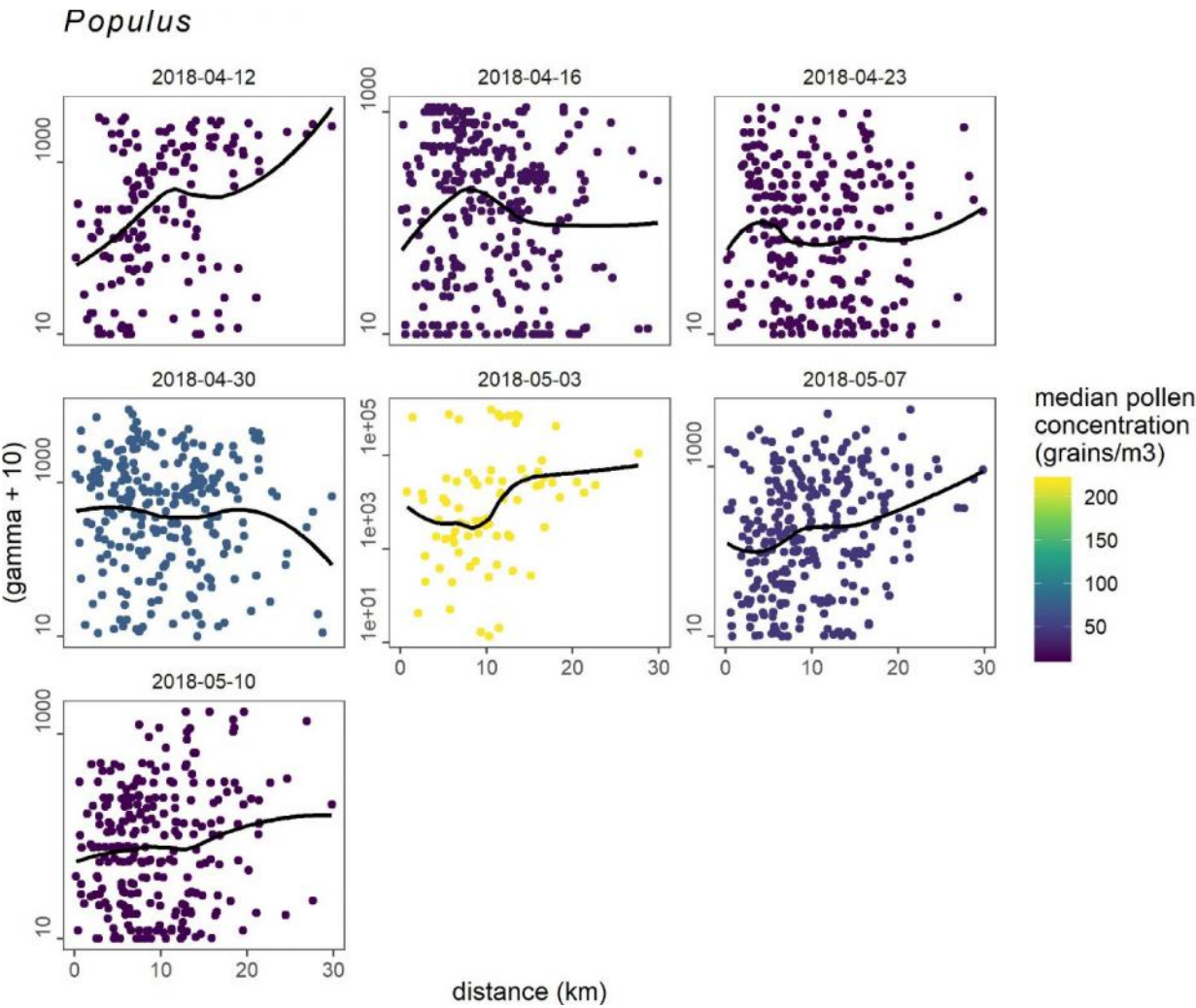


Fig. SI 4E

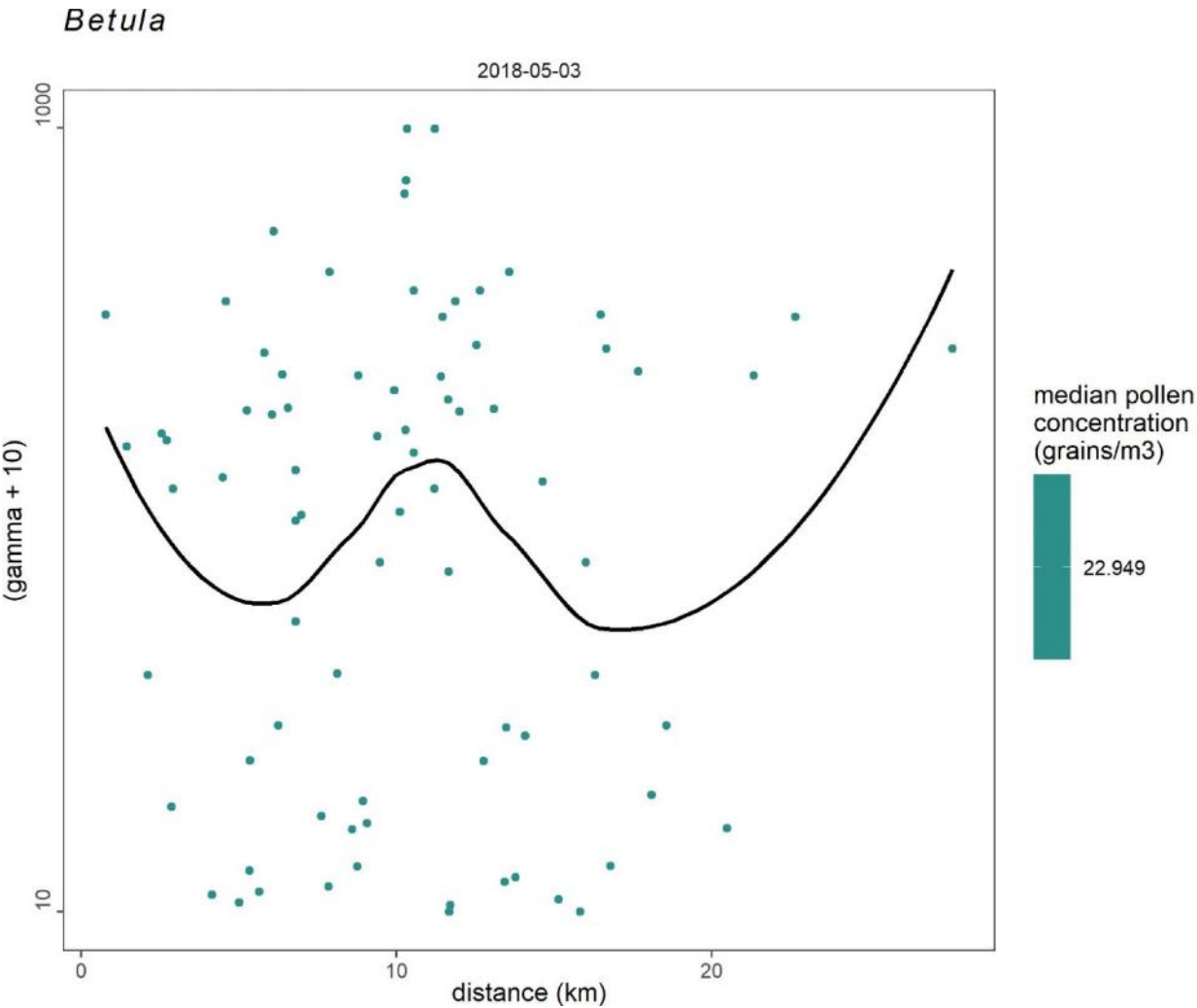


Fig. SI 4F

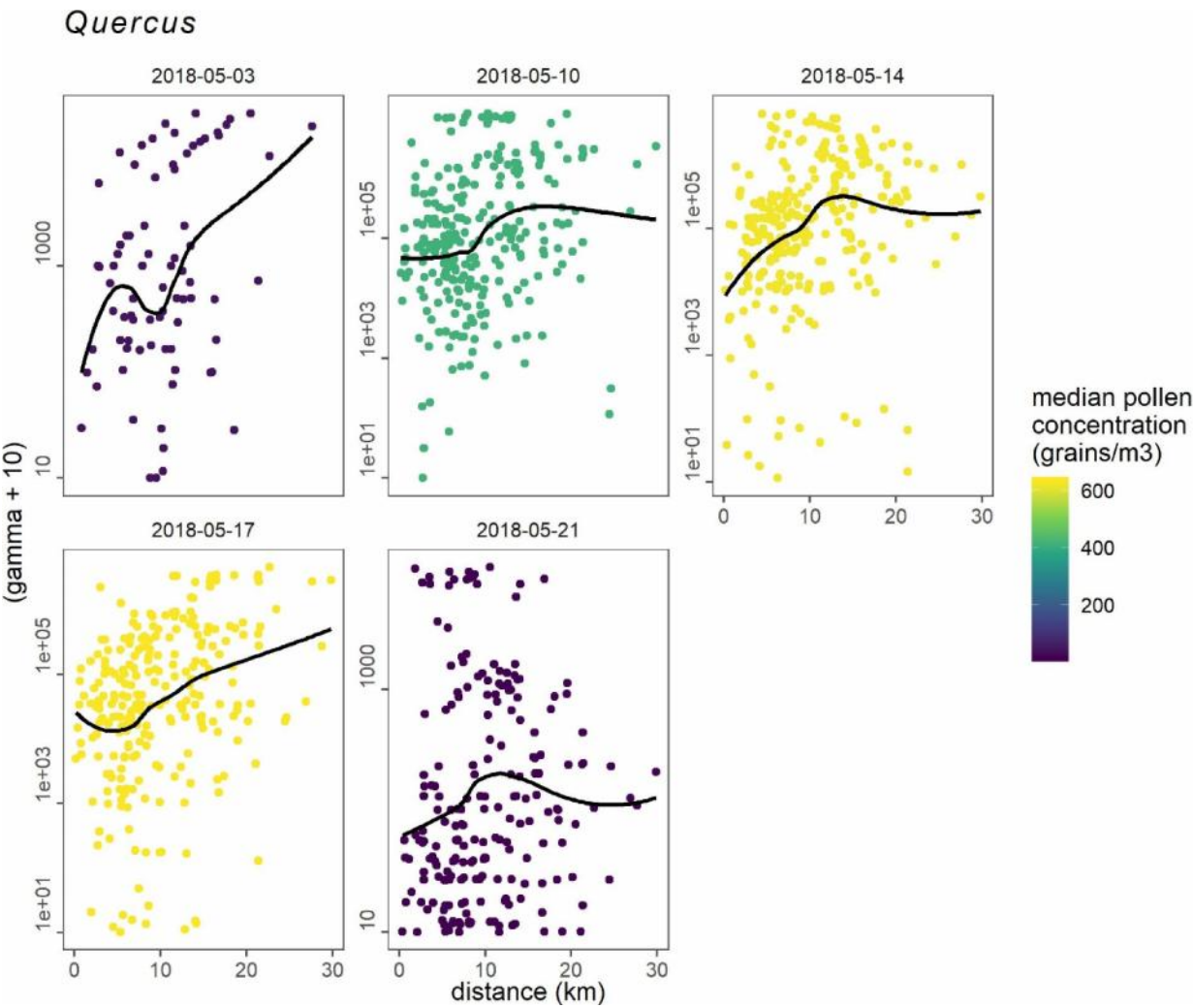


Fig. SI 4G

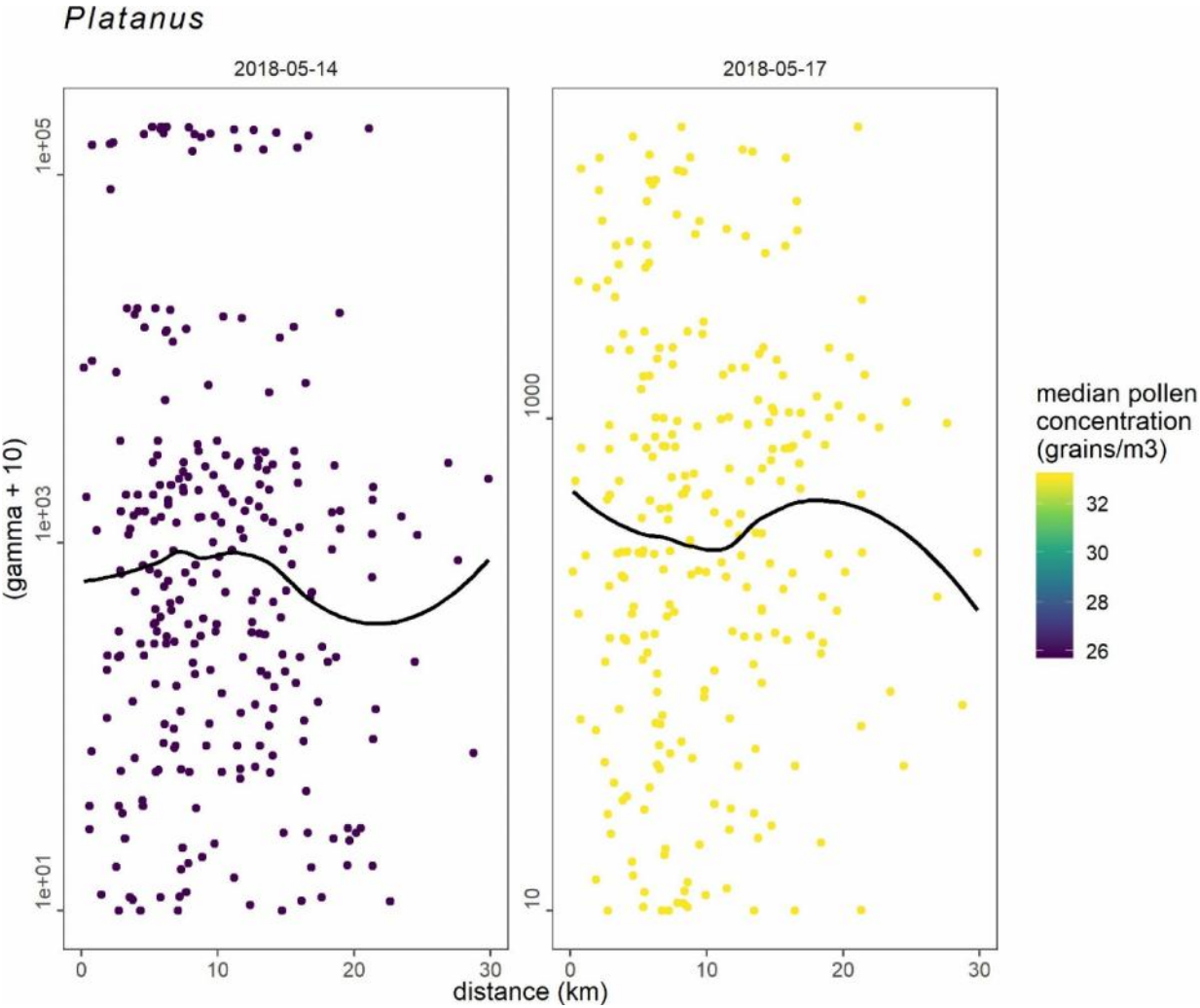


Fig. SI 4H

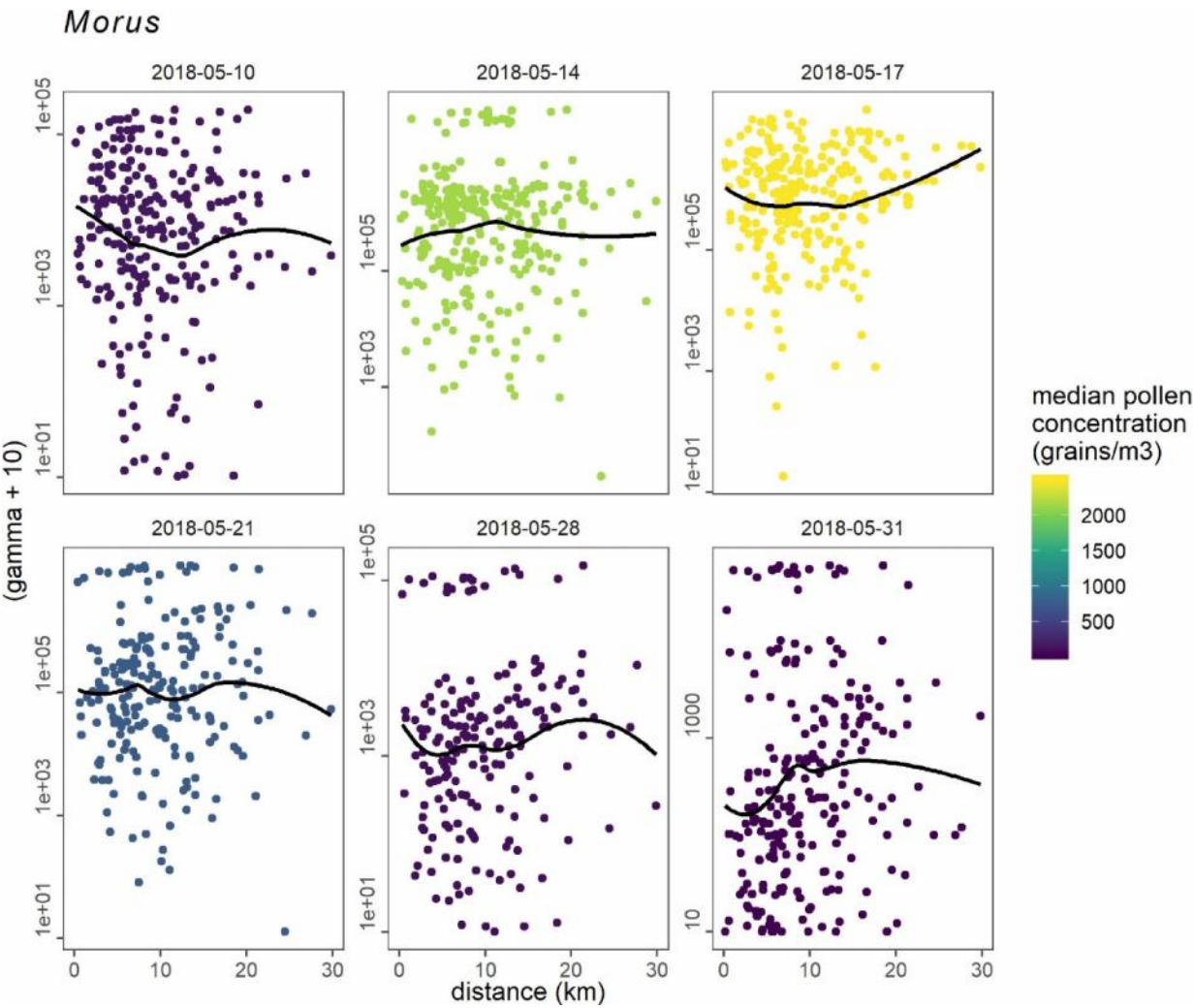


Fig. SI 4I

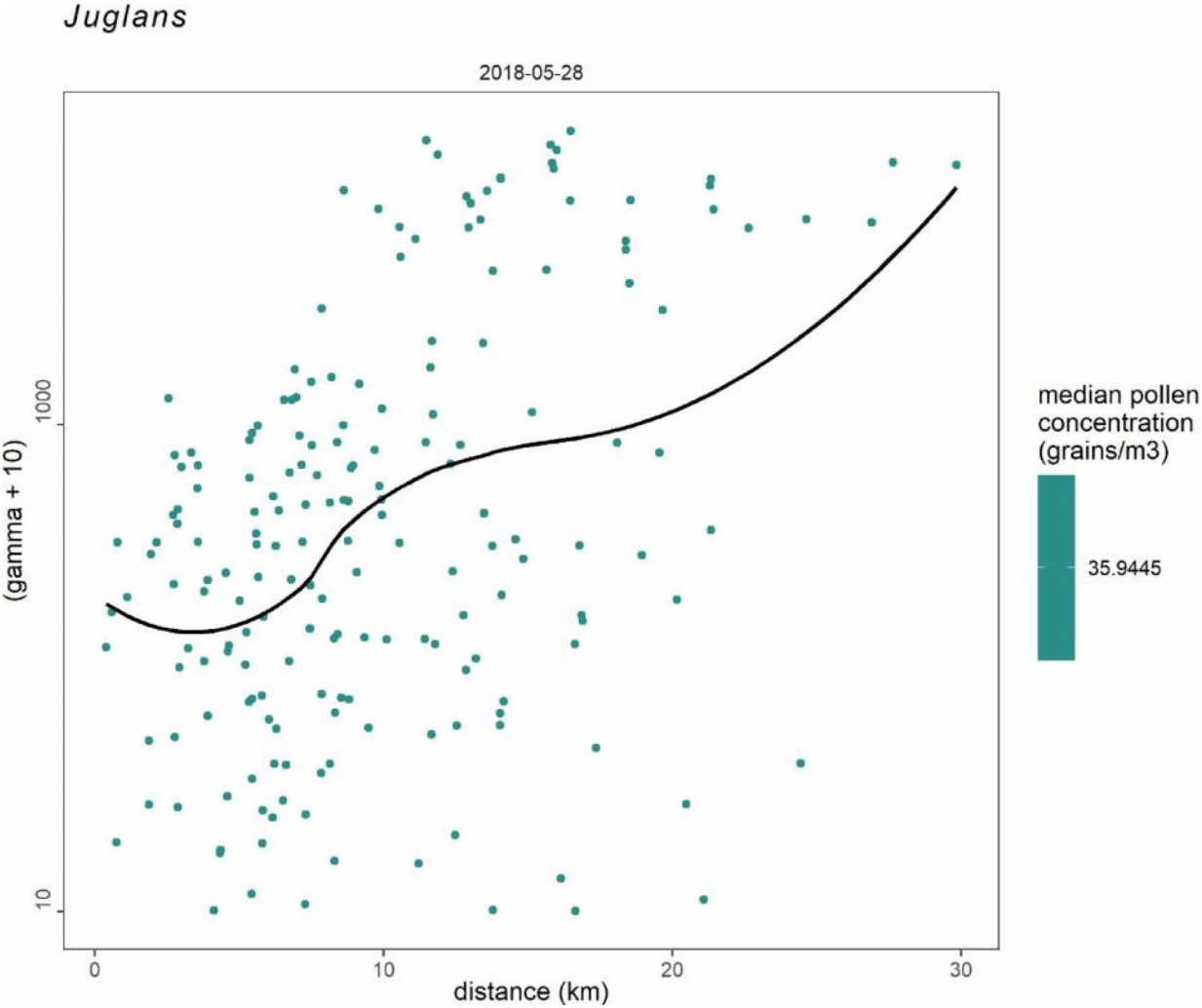


Fig. SI 4J

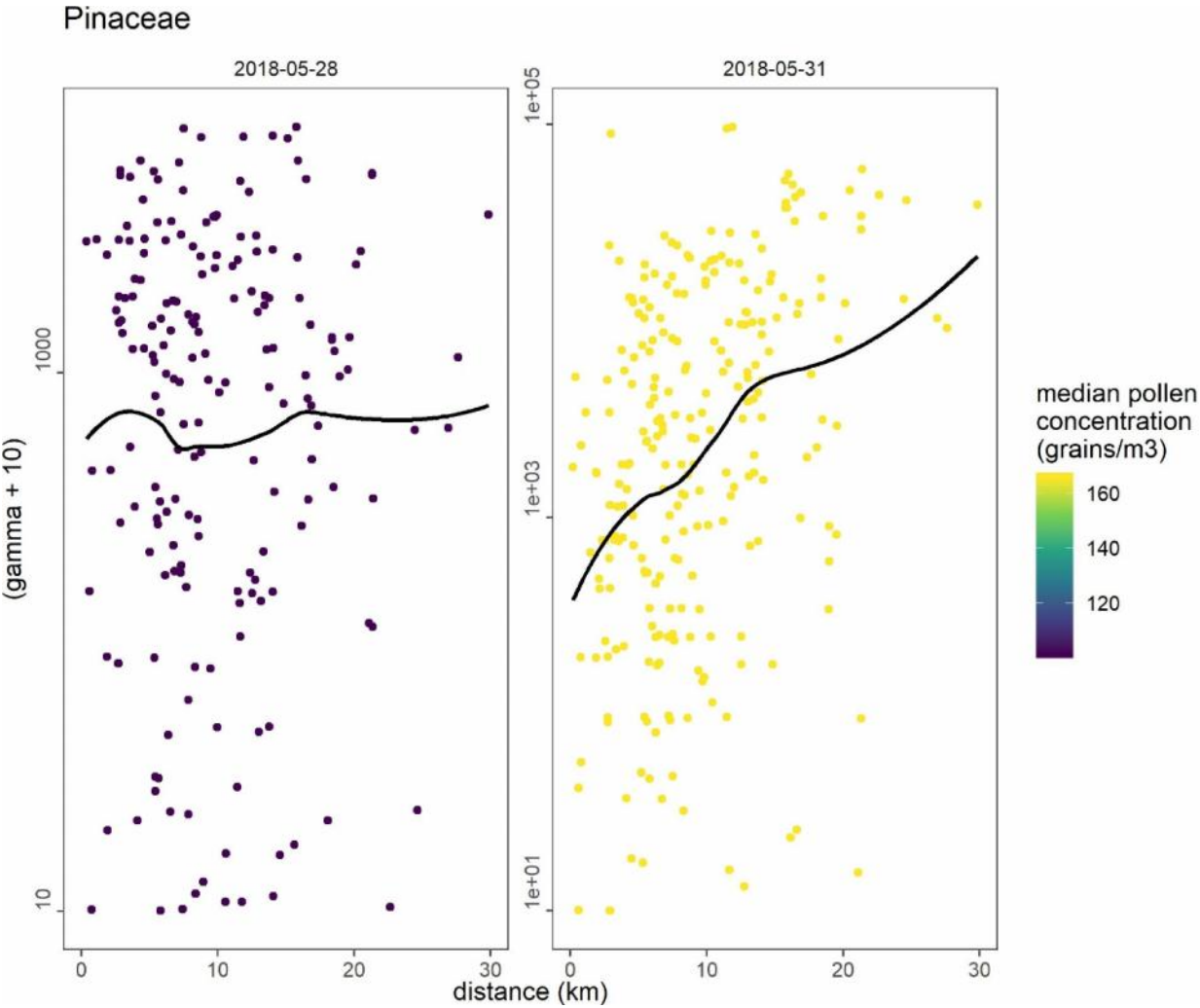


Fig. SI 4K

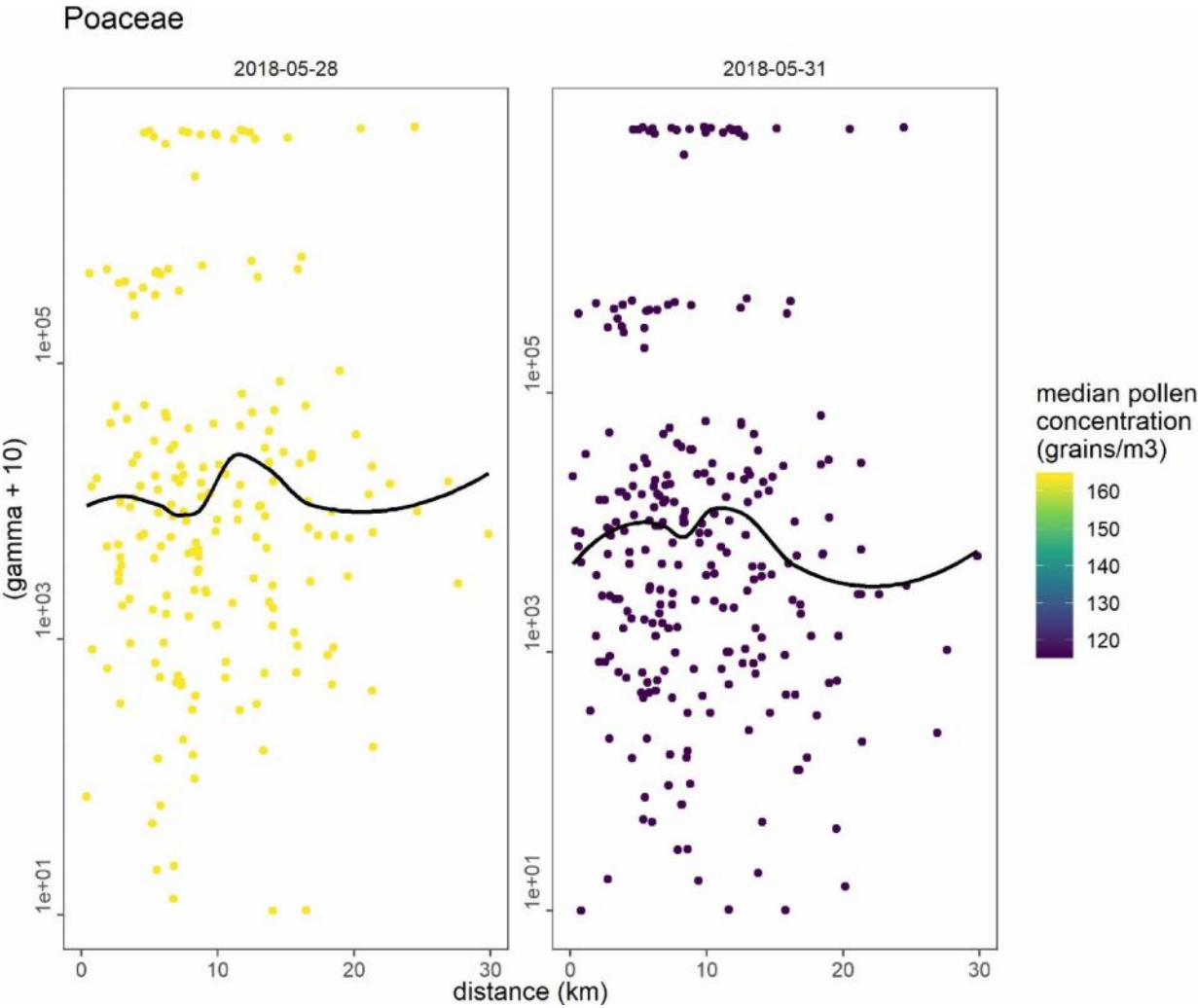
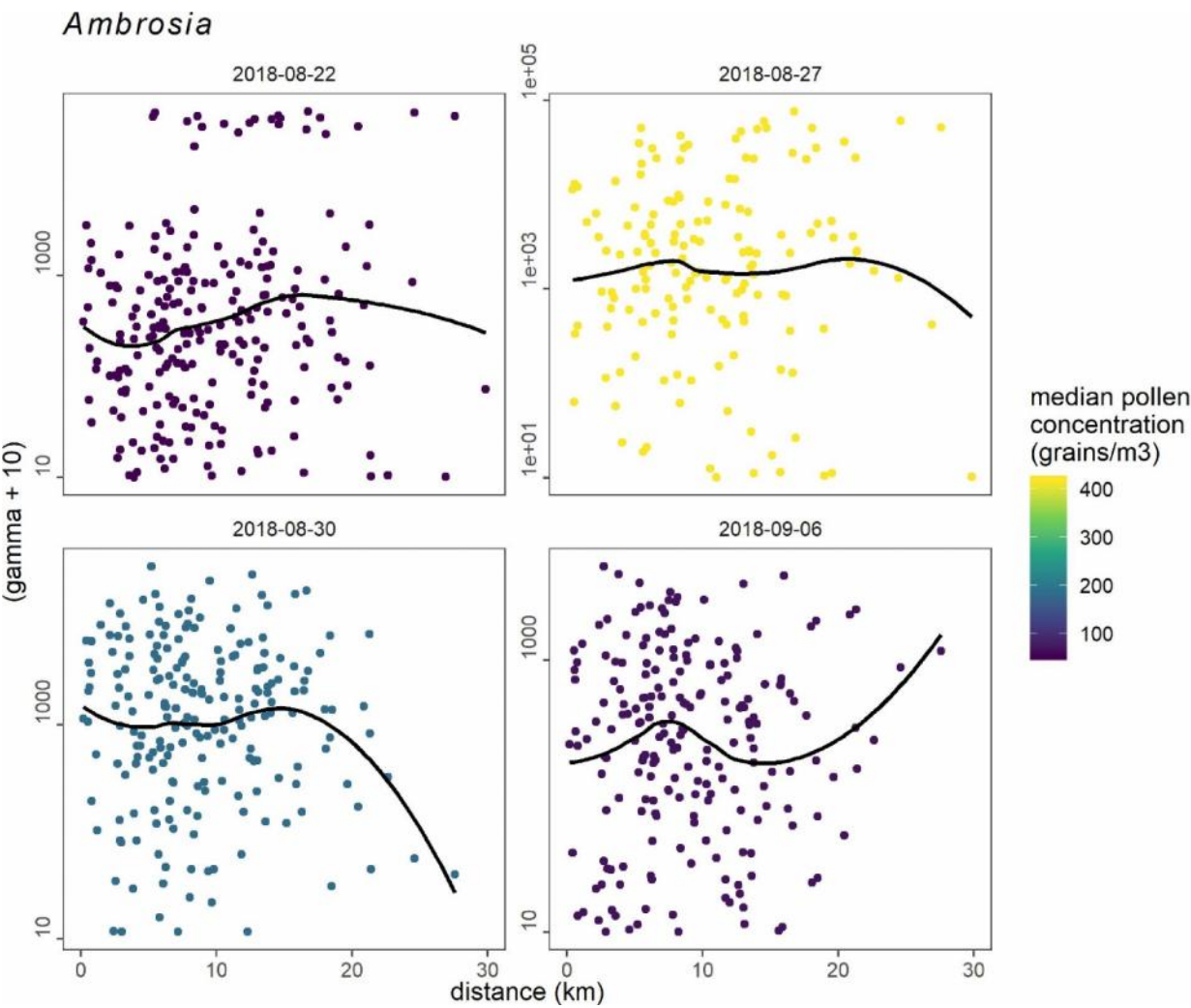


Fig. SI 4L



SI 5: Absolute and relative pollen concentrations at the site level for each taxon. Maps of pollen concentrations are coded by absolute pollen concentration (point size, in grains/m³) and relative concentration among sites on that day (color; blue = lower than other sites on that day, red = higher than other sites on that day).

Fig. SI 5A



Fig. SI 5B

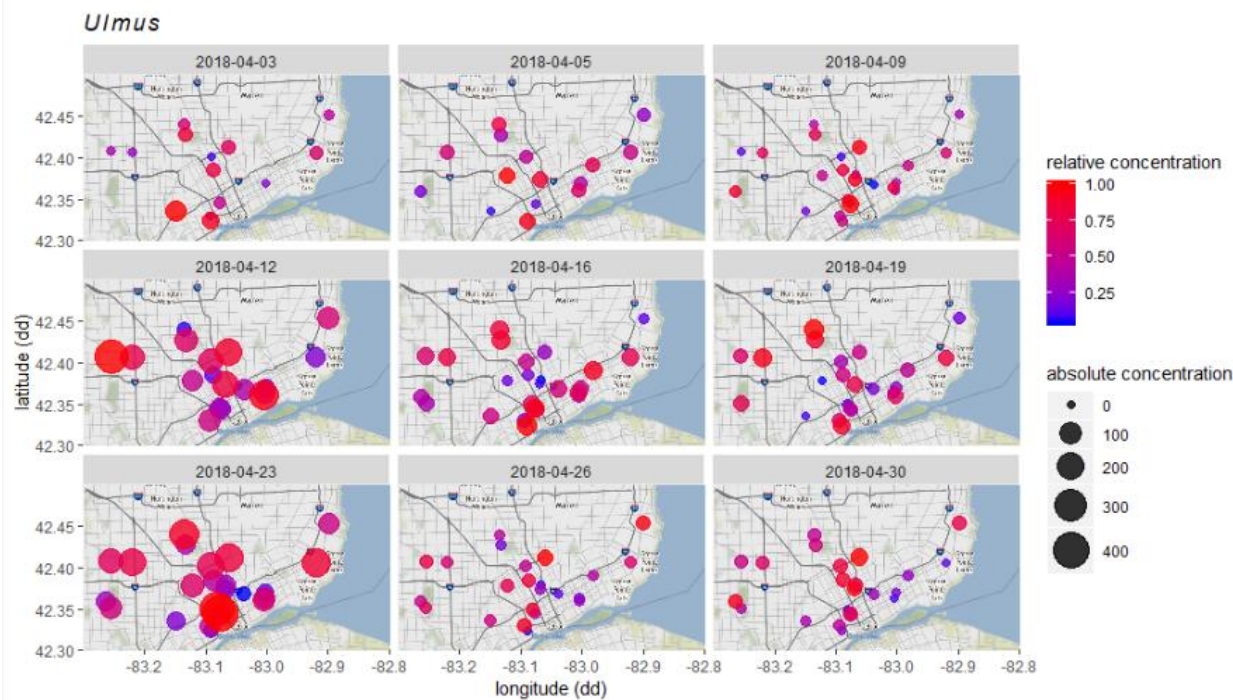


Fig. SI 5C

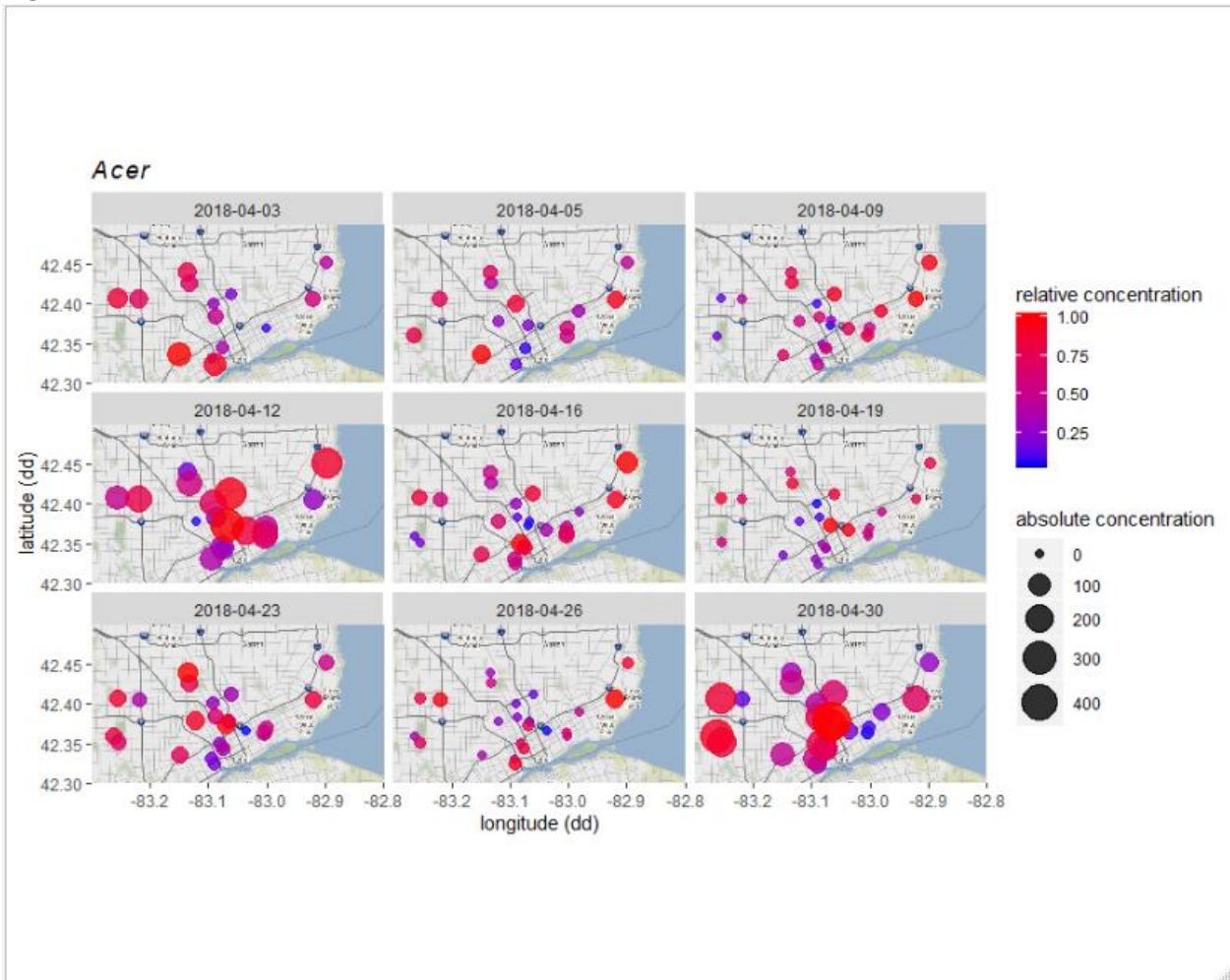


Fig. SI 5D

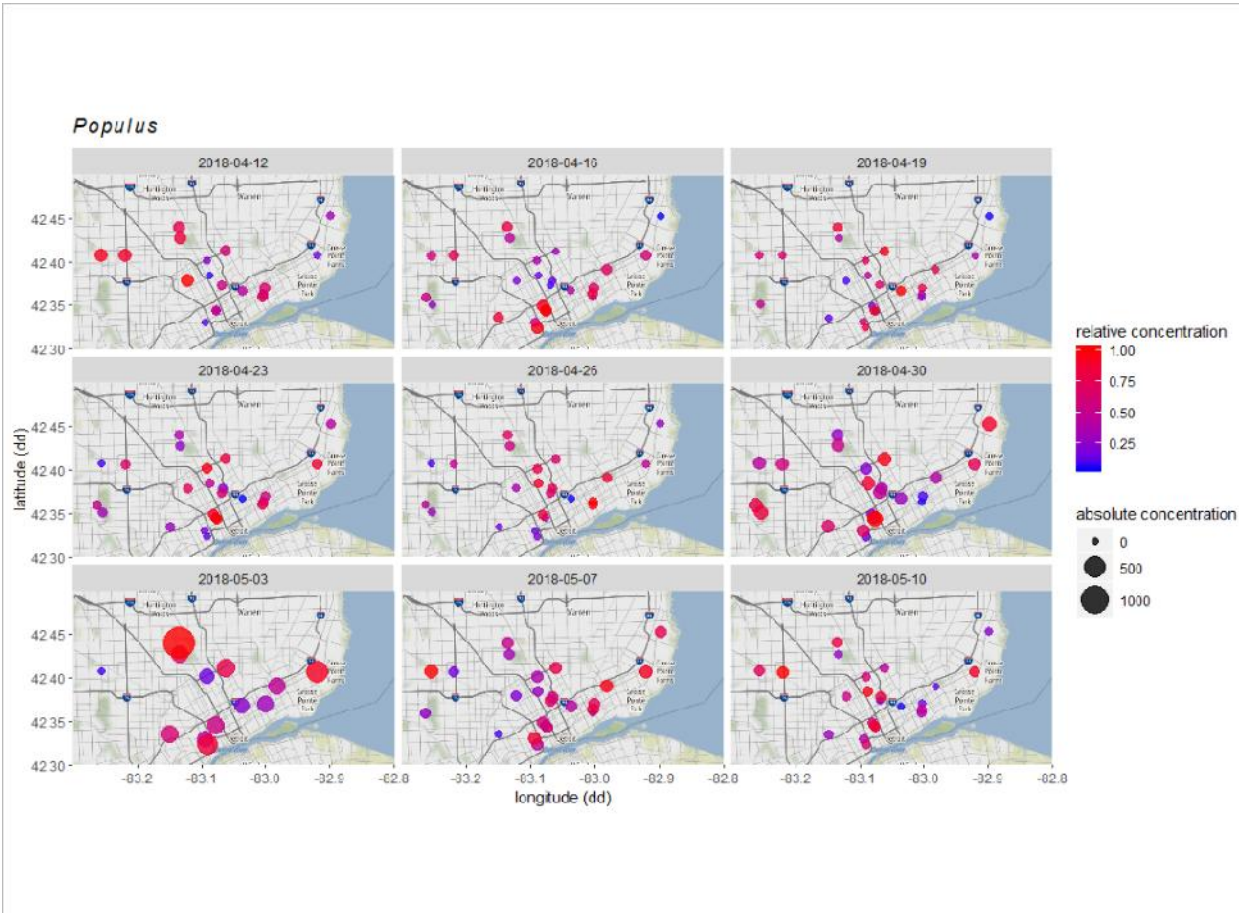


Fig. SI 5E

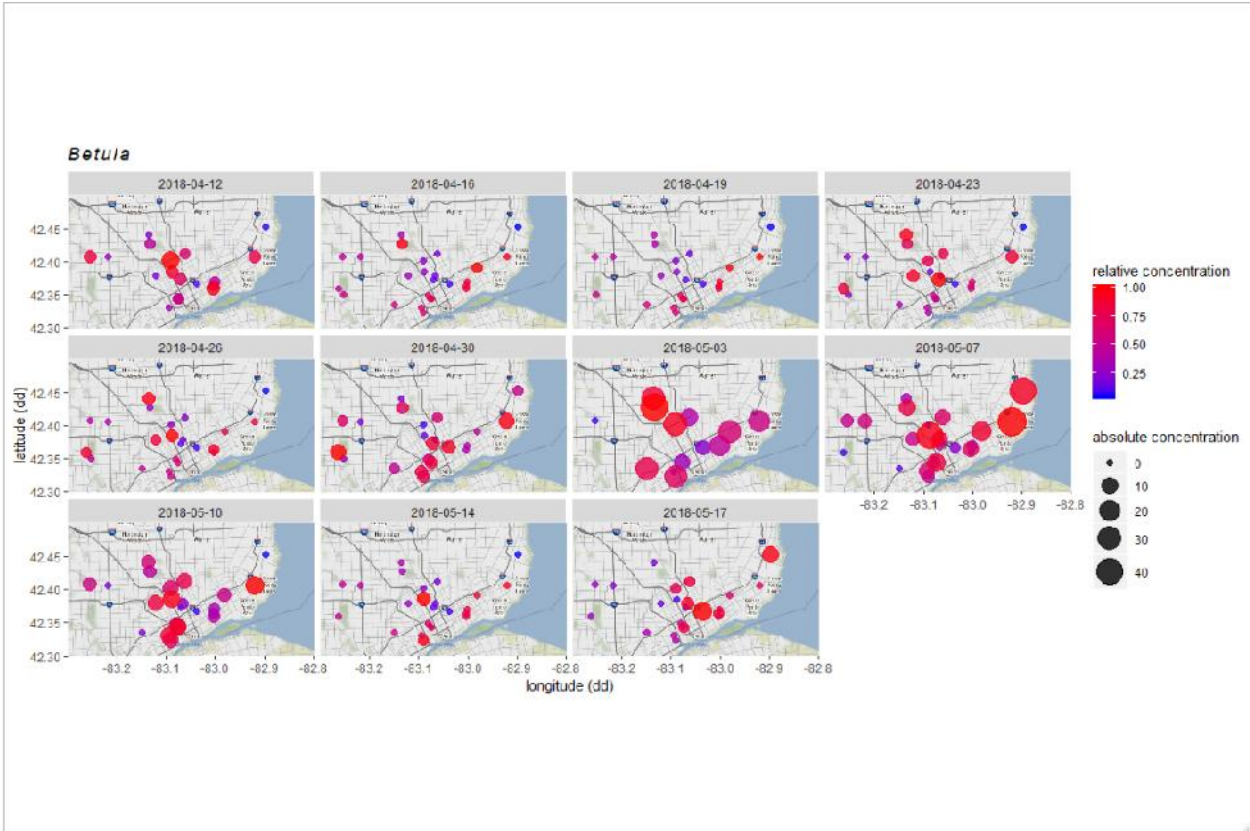


Fig. SI 5F

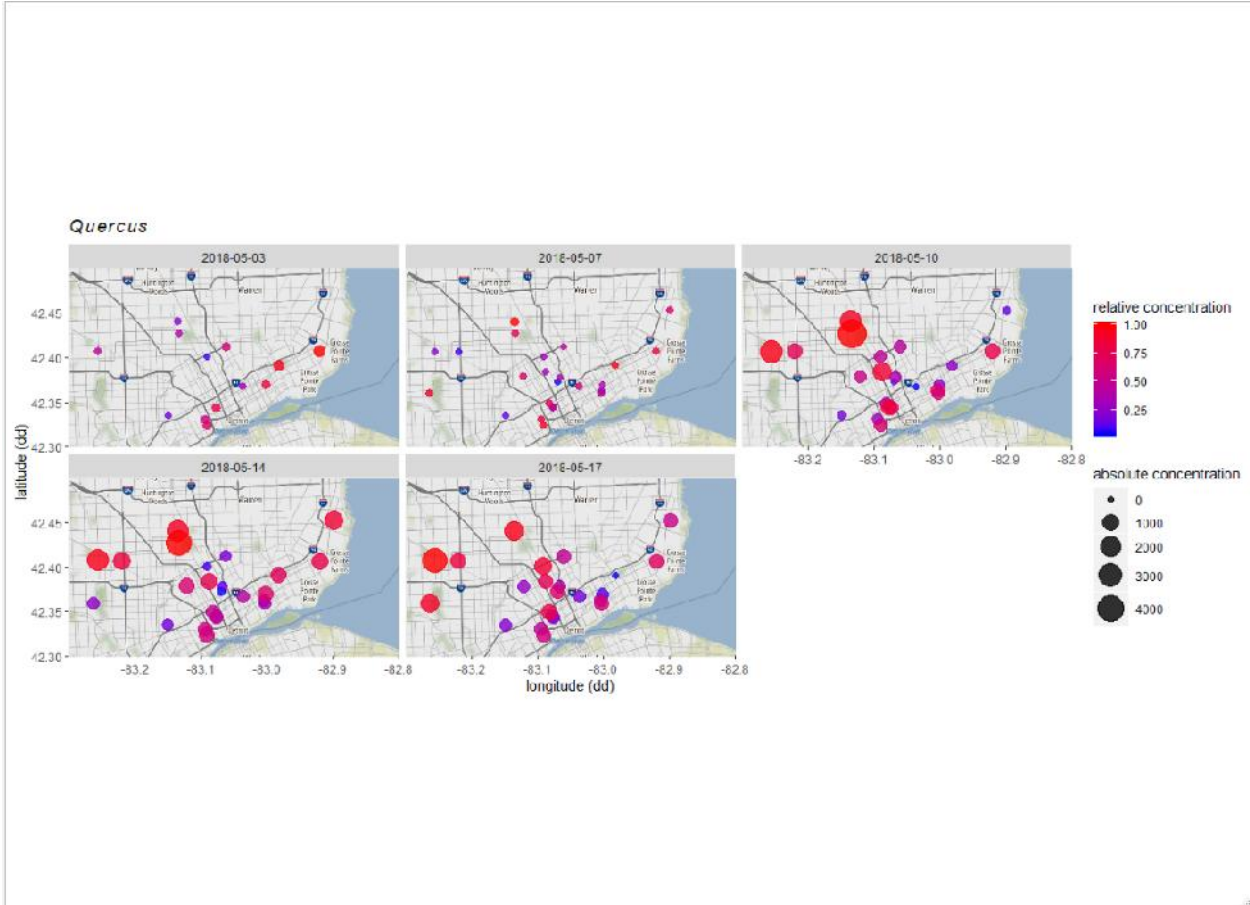


Fig. SI 5G

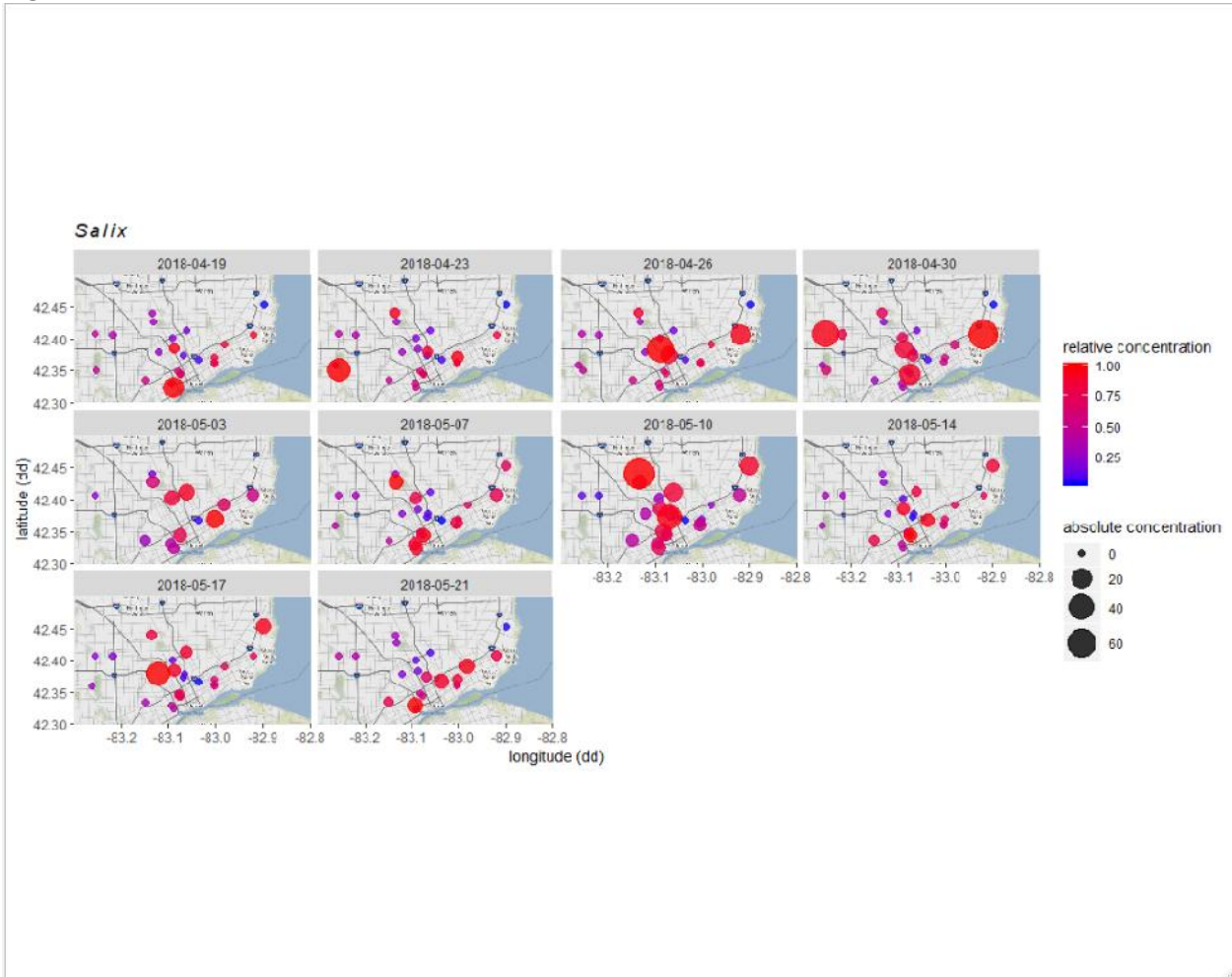


Fig. SI 5H

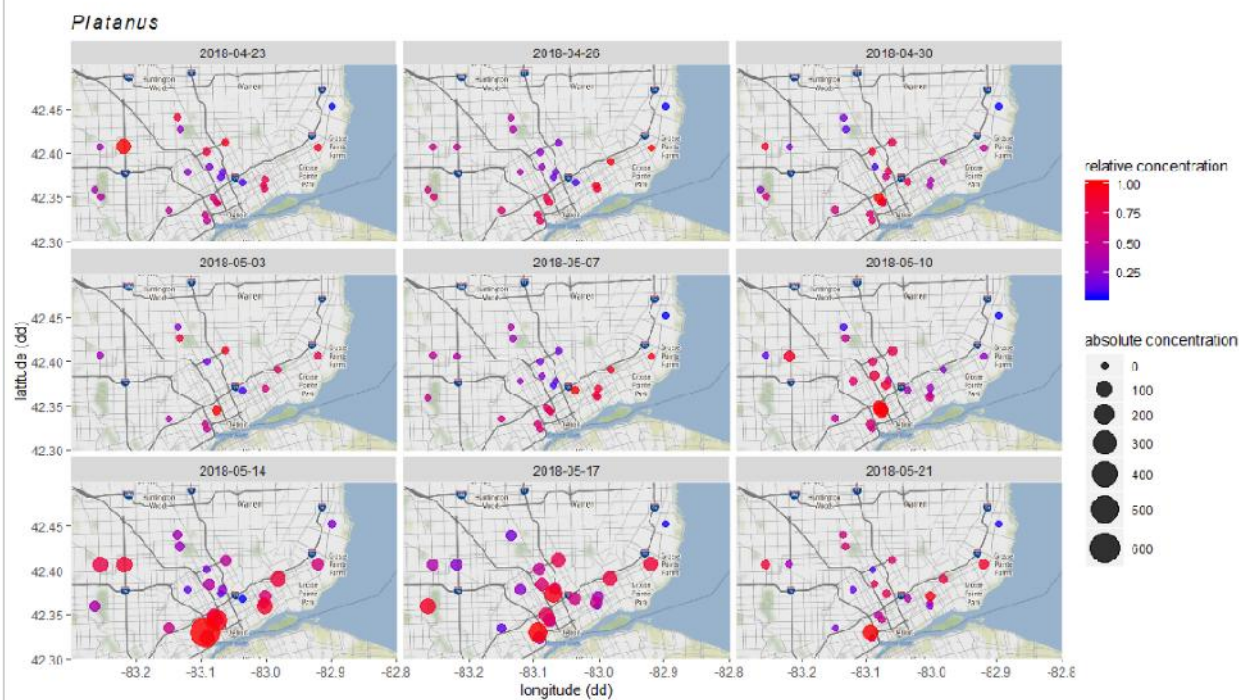


Fig. SI 5I



Fig. SI 5J

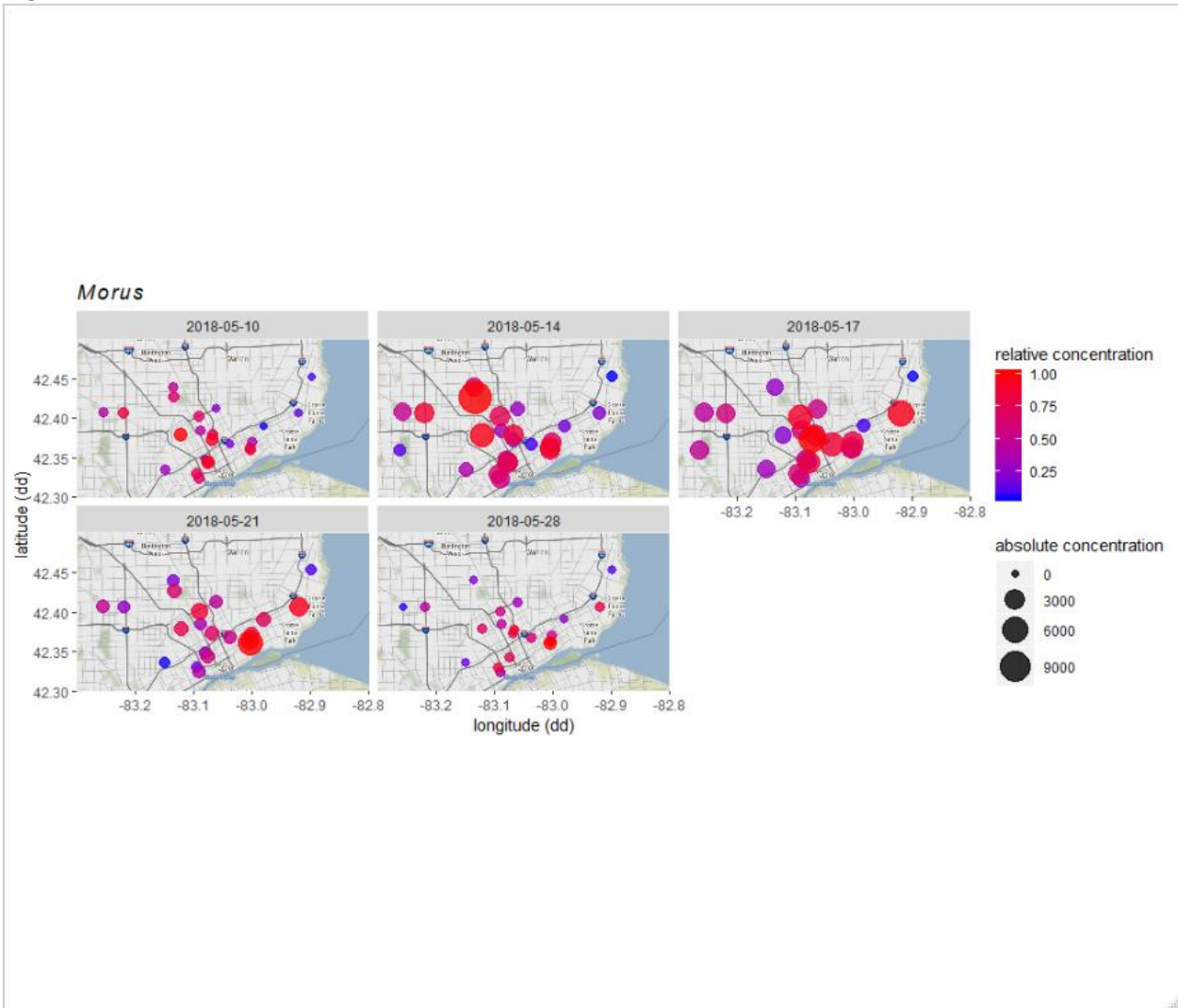


Fig. SI 5K

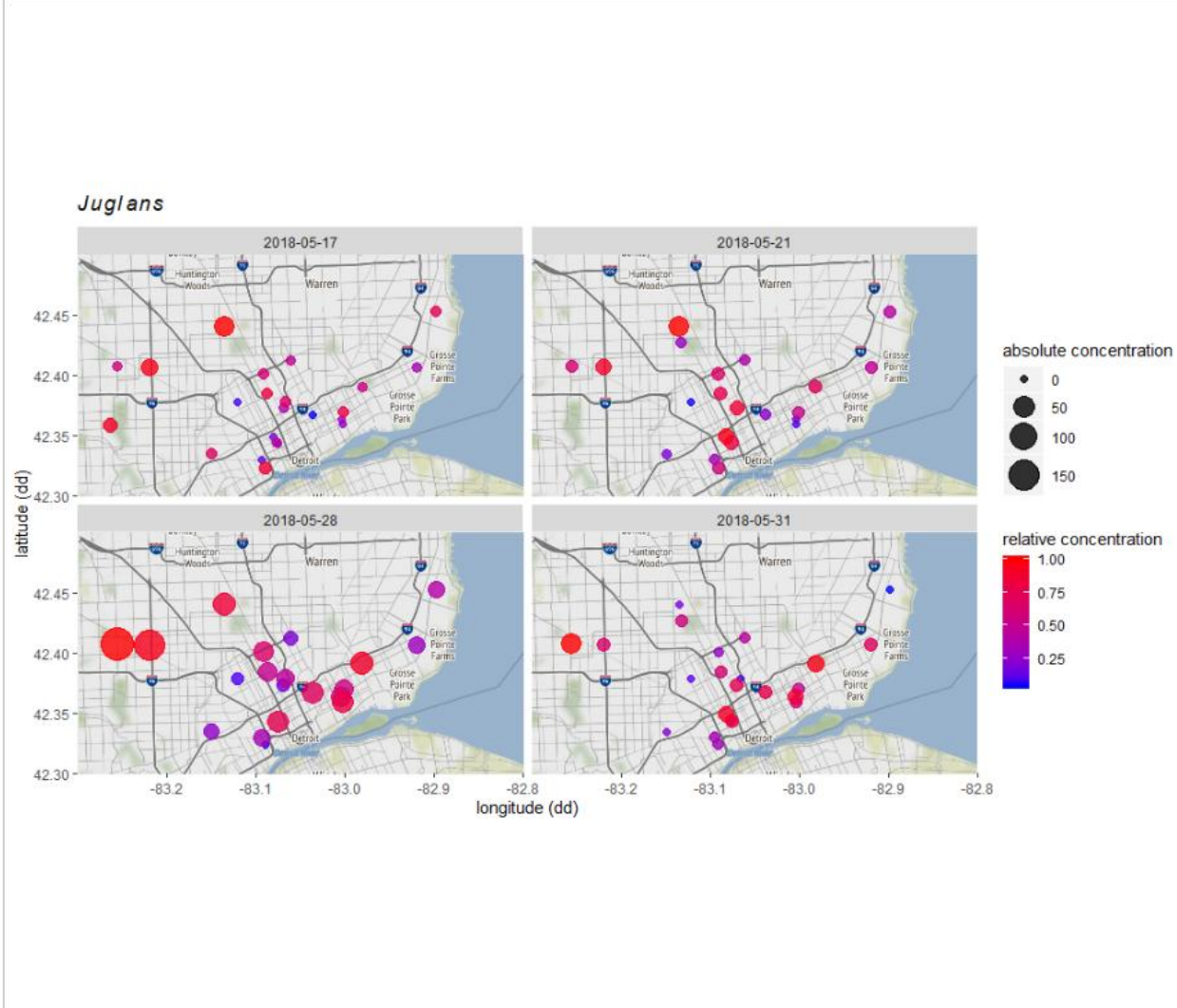


Fig. SI 5L

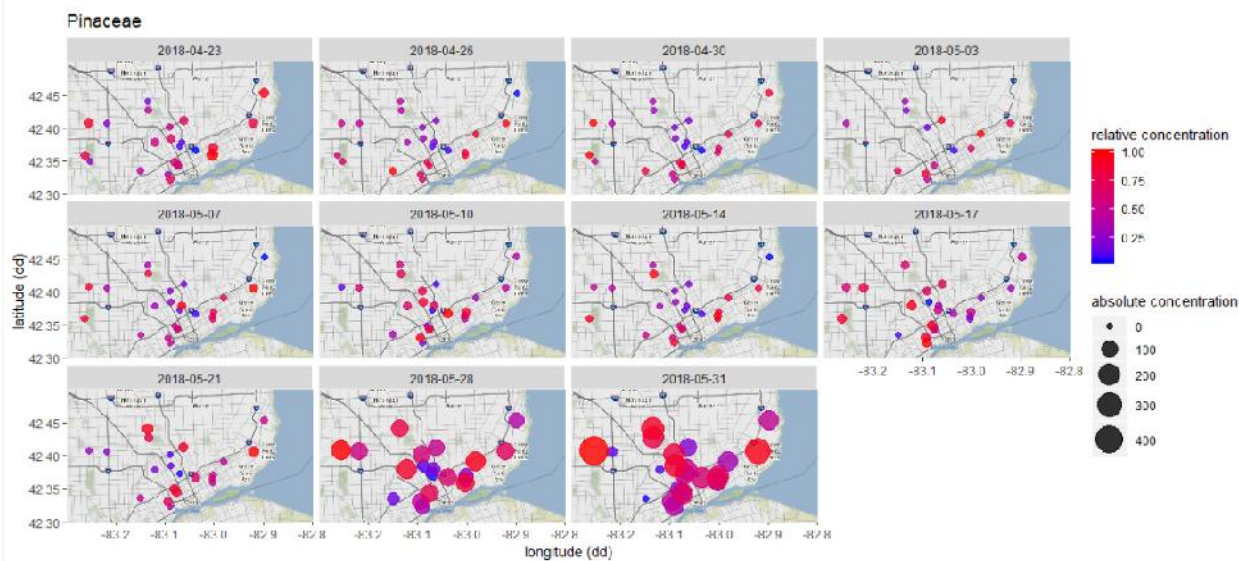
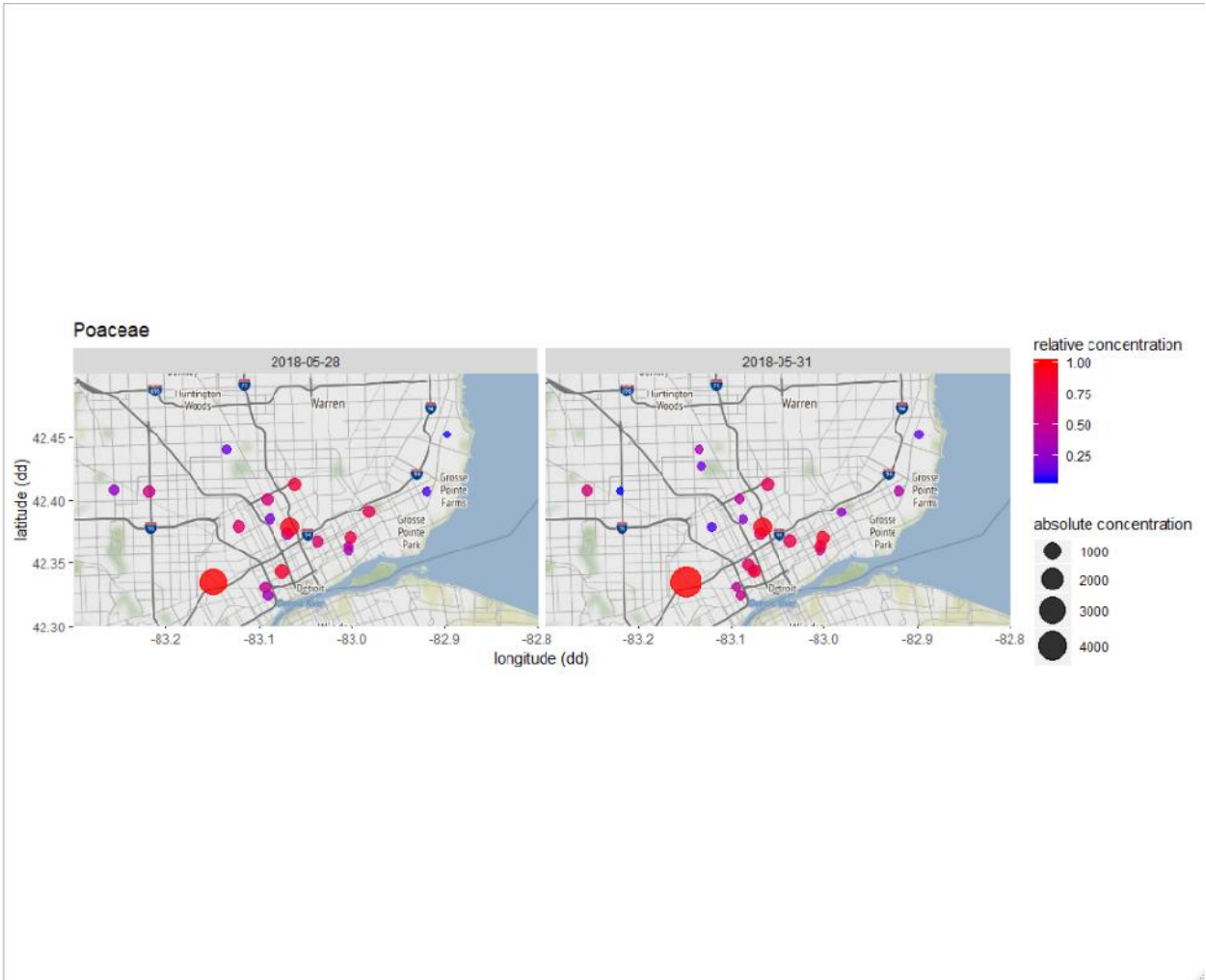


Fig. SI 5M



Ambrosia

2018-08-22

2018-08-27

2018-08-30

2018-09-06

absolute concentration

- 200
- 400
- 600

relative concentration

- 1.00
- 0.75
- 0.50
- 0.25

latitude (dd)

longitude (dd)

