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REVIEW PAPER

Diurnal variations of airborne pollen concentration and the effect of ambient temperature in three sites of Mexico City

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Abstract Pollen is an important cause of allergic respiratory ailments in the Mexico City Metropolitan Area (MCMA). However, very little is known if ambient air temperature correlates with the early blooming of plants observed in other urban areas around the world. A research study was conducted during the dry season of 2012–2013 at three representative sites of the MCMA with different urban characteristics with the aim to understand the relationships between the profusion and diversity of pollen against temperature and other meteorological variables and degree of urbanization. Pollen samples were collected using a Hirst-type trap sampler in the sites: Merced (highly urbanized), Iztapalapa (medium-high urbanized) and Coyoacan (moderately urbanized). Urbanization levels were determined using a composite index based on population density, proportion of surface covered by construction and asphalt, and urban heat island intensity. A set of representative pollen sampling tapes were assayed under a light microscope at magnification of ×1,000 and converted to grains per cubic meter. The most representative pollen types found in the three sites were, regardless of urbanization levels were: *Fraxinus*, Cupressaceae/Taxodiaceae, *Casuarina*, *Alnus*, Myrtaceae, and *Pinus*. Total pollen concentration was greatest in the moderately urbanized area, although earlier blooming took place at the highly urbanized zone. Total pollen concentration in the medium-high urbanized site has the lowest because the green areas in this zone of MCMA are few. In a diurnal basis, the most abundant pollen types peaked near midday or in the afternoon evening at the three sites. A Spearman test showed a positive correlation among bihourly pollen concentrations, temperature and relative humidity in all sites, but wind speed just correlated in Iztapalapa and Coyoacan. The results obtained suggest that Urban Heat Island Intensity can disturb flowering periods and pollen concentrations, largely in the highly urbanized areas. A principal components analysis established that the concentrations of each pollen type differed across the urbanization gradients. Additionally, it was found that a large number of allergenic pollens are produced by ornamental trees, some only recently introduced by urban planners.

Keywords Airborne pollen · Ambient temperature · Urban heat island · Urbanization · Mexico City

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Introduction

Urban green spaces provide a wide range of environmental enhancements that improve the quality of life and health of city dwellers (Wolch et al. 2010; Dahmann et al. 2010; Baran et al. 2014). These health benefits, notwithstanding, green spaces also inflict certain adverse effects on city dwellers (Lyytimäki and Sipilä 2009; Cariñanos and Casares-Porcel 2011; Escobedo et al. 2011). Pollen released by trees contributes to biotic air pollution (Buseck and Posfai 1999) and causes enormous direct costs (e.g., consultations, medications, and clinical tests), indirect costs (e.g., absenteeism from work and school, early retirement), and intangible costs (e.g., social isolation and lesser quality of life) (Small et al. 2013; Baran

et al. 2014). Moreover, there is strong evidence that city dwellers are more often afflicted with pollinosis than those living in the rural–urban fringe; and that sensitization to pollen allergens can be exacerbated by co-stressors such as gaseous and/or particle-phase air pollutants, an effect that might be linked to the degree of urbanization (Bartra et al. 2009; Bosch-Cano et al. 2011; Després et al. 2012; Zhang et al. 2014). Exposure to pollen and pollen allergen loaded fine particles has been related to allergic airway response in pollen-sensitized children and adults suffering from rhinitis and/or bronchial asthma (Ziello et al. 2012).

Unfortunately, much of the symptoms-causing airborne pollen comes from species most commonly used by urban planners in the design and plantation of urban forests and green areas. These plant species blossom more readily and earlier than those native in the surrounding countryside (Hruska 2003; Zhang et al. 2004; Mimet et al. 2009; D'Amato and Cecchi 2010). Moreover, the buildings prevent pollen grain dispersion by the wind, leading indirectly to the increase of the pollen concentrations in urban surroundings (McKinney 2008).

In order to facilitate diagnosis and treatment of allergies, it is important to gain an understanding of the spatial and temporal airborne pollen concentrations for diverse cities and within different sectors of the same city (D'Amato and Cecchi 2008). The latter is important because airborne pollen concentration depends on the location and extension of the green area and on the meteorological factors that induce pollen release and dispersion (D'Amato et al. 2007). Grimm et al. (2008) have pointed out that the knowledge of diurnal variation of pollen patterns and its association with meteorological variables in cities is important to allergy patients. For instance, it is known that some dehiscence mechanisms are controlled by cohesive forces in which water loss increases tension on cell walls, thus rupturing anthers and releasing pollen; therefore, this mechanism is largely associated with changes in air humidity and temperature (Puc 2011). Diurnal changes in pollen counts are also modified by other meteorological factors, such as wind speed, convection flows and precipitation (Jones and Harrison 2004). While wind speed variations influence horizontal particle dispersion and affect the hourly distribution of pollen concentration, wind direction explains which areas are most affected. Similarly, pollen counts may have a significant positive correlation with the daily maximum temperature; they are negatively correlated to precipitation (Tarragó 1996; Pérez-Badia et al. 2011; Veriankaité et al. 2011). Another very important climate factor directly related with the degree of urbanization is the effect of the so-called urban heat island (UHI). As the urbanization increases from the urban outskirts inward, the environment becomes warmer than the rural surroundings, thereby forming an "island" of higher temperatures in the landscape (Rajasekar and Weng 2009). Surface urban heat islands are typically present day and night and exhibit daily and annual variations (Kardinal Jusuf et al.

2007; Buyantuyev and Wu 2010). These generally warmer temperatures in the urban area, of course, encourage the release of pollen from plants.

The Mexico City Metropolitan Area (MCMA) is one of the largest urban areas in the world, with approximately 24.8 million inhabitants, living across 1,500 km^2 of the so-called Valley of Mexico at 2,240 m above sea level in a subtropical region surrounded by mountains. The city boasts robust urban activity with over 40,000 industrial facilities and more than five million vehicles burning more than 40 million liters of gasoline and diesel fuel per day, which produce thousands of tons of pollutants (Molina et al. 2010). Despite several actions taken by the local government to improve the air quality, MCMA residents remain exposed to concentrations of airborne pollutants frequently exceeding local ambient air quality standards, especially with regard to particulate matter (PM) and ozone, the two most important pollutants from the standpoint of public health. The PM composition includes a large fraction of organics, but black carbon, crustal matter, sulfates, and nitrates are also significant (Parrish et al. 2011). Although the proportion of biogenic particles in PM concentrations in MCMA is very low, they can be of relevance with regard to human health, since pollen or fungi can also be found in the fine PM fraction (Tarragó 1996; Osornio-Vargas et al. 2003; De Vizcaya-Ruiz et al. 2006).

Pollen is major cause of allergic respiratory disease in Mexico City (Terán et al. 2009). Aerobiological studies have shown that during the mild, dry winter there are many types of pollens in the environment, with tree pollens most abundant. In contrast, grassland weed pollens prevail during the summer (rainy season). Terán et al. (2009) have suggested that the high air pollution levels in MCMA might increase pollen allergenicity, because pollutants could directly cause pollen grains to release antigens, which then enter the human respiratory tract and cause disease. Thus, it might be presumed that the heavily polluted air in MCMA in conjunction with meteorological factors, such as wind, temperature, and UHI, provide favorable conditions for the release of pollen and, indeed, induce longer pollen seasons.

Although many aerobiological studies have been carried out in Mexico City (Rosas et al. 1987, 1989, 1990, 1992, 1993, 1997; Rivera et al. 1987; Santos-Burgoa et al. 1994; Calderon et al. 1995, 1997;) and pollen monitoring in MCMA is currently in place (http://www.atmosfera.unam.mx/rema/estaciones_muestreo.html), the relationship to meteorological parameters has not been examined in depth on Mexico City (Ramírez-Arriaga et al. 1995; Argáez Márquez 1996; Tarragó 1996; Rocha-Estrada et al. 2008; Gonzalez-Diaz et al. 2010). Ramírez-Arriaga et al. (1995) conducted a study in southwest Mexico City identifying a total of 80 pollen types, of which *Acacia*, *AInus*, *Casuarina*, *Salix*, *Eucalyptus*, *Fraxinus*, and *Tithonia* were the dominant taxa. Tarragó (1996) carried out a study of the seasonality and diurnal variation of airborne pollen in northern Mexico City. Employing an Olmsted-Tukey

analysis, this researcher found 24 taxa and identified the prevailing species of trees, weeds, and grasses. Pollen grains peaked during the dry season and the foremost taxa were *Alnus*, *Callistemon*, *Casuarina*, Cupressaceae, *Eucalyptus*, *Fraxinus*, *Quercus*, *Pinus*, Amaranthaceae, Asteraceae, and Poaceae. For the rainy season, the dominant taxa were *Casuarina*, Cupressaceae, *Pinus*, Amaranthaceae, Asteraceae, and Poaceae. Tarragó (1996) found that the increase of pollen concentration was related to higher temperatures, low relative humidity, and high wind speed.

The objective of this study is to examine the relationship between pollen taxa abundance in three areas with differing degrees of urbanization in Mexico City and to explore the temperature, relative humidity, wind speed, and wind direction influencing concentrations.

Material and methods

Study area

Currently, MCMA encompasses 16 administrative delegations of the Federal District, 37 municipalities of the State of Mexico, and 1 municipality of the State of Hidalgo. The climate of the Valley of Mexico is semi-humid and temperate, and can be divided into three climatic seasons, i.e., the dry-warm season from March to May, the rainy season from June to September and the dry-cold season from October to February. The daily temperature oscillates with an amplitude of 15 to 18 °C, whereas monthly averages differ little between the coldest (January, monthly average 11–13 °C) and warmest (April, 15–17 °C) months depending on the specific location within the city (Jauregui 1997; Lafragua et al. 2003). The MCMA experiences an UHI that is closely dependent on the time of day and the time of year. The UHI effect is greatest at night during the dry season, weakening during the wet season (Jauregui 1997). During the day, the effect is reversed with a cool island occurring during the dry season, with daytime UHI that exceeds the nighttime value during the wet season.

Mexico City (Federal District) has approximately 44.7 km^2 of green areas (INEGI 2010). There is a noticeable process of decline in the quantity and diversity of native flora and other vegetation, brought about by pressure for development. Synanthropic vegetation is predominant throughout the urban area, where green space is made up of numerous parks, lawns and home gardens. Velasco (2003) points out that vegetation in urban parks might be 33 % pine, 33 % *Eucalyptus*, and 34 % grasslands. Weeds are an important part of the urban flora in Mexico City. Vibrans (1998) documented the ruderal vegetation of Mexico City finding 256 species. According to Vibrans (1998), Asteraceae is the most leading weed family, followed in prevalence by the Poaceae, Brassicaceae, and Amaranthaceae families, whereas Fabaceae is quite sparse.

Sampling sites

Three sampling sites were set up in areas representing differing degrees of urbanization in Mexico City (Fig. 1). The degree of urbanization was classified on an arbitrary composite urbanization index constructed by combining three frequently used urbanization indicators.

These indicators are as follows: the proportion of population living in an urban sector, the proportion of one unit of area covered by hard surfaces such as concrete or asphalt within an urban sector, and the urban heat island intensity (Neil and Wu 2006; Organisation for Economic Co-Operation and Development and China Development Research Foundation 2010). The expression of the composite index is shown in Eq. (1).

$$\mathrm{UI} = \frac{\dfrac{\mathrm{DP_i}}{\mathrm{DP_{max}}} + \dfrac{\mathrm{HSC_i}}{\mathrm{HSC_{tot}}} + \dfrac{T_{\mathrm{amb\ i}}}{T_{\mathrm{ambmax}}}}{3} \qquad (1)$$

Where UI is the composite urbanization index ranging from 0 to 1, with higher figures indicating higher degree of urbanization. $\mathrm{DP_i}$ and $\mathrm{DP_{max}}$ are the population density in the sector i, and the maximum population density reported in the urban area. $\mathrm{HSC_i}$ and $\mathrm{HSC_{tot}}$ are the area covered with hard surfaces in the sector i, and the total extension in the urban area covered with hard surfaces (in units of area), respectively; while T_{amb} and $T_{\mathrm{amb\ max}}$ are the ambient temperature in the sector i, and the maximum ambient temperature in the center of the urban area (in degree Celsius), respectively.

While the first two indicators in the equation provide and intuitive sense of the degree of urbanization, the third figure resembles the urban heat island intensity (UHII) effect, which is an important indicator for evaluating the density of the urbanization in a given area (Neil and Wu 2006; Rizwan et al. 2008). Typically, the UHII for an urban area is determined as the spatially averaged temperature difference between an urban and its surrounding rural area. Table 1 shows a summary of the characteristics of the sampling areas and their urbanization index. It was assumed that the area defined by a circle with a radius of 2.5 km centered on the sampling site would be representative of the degree of urbanization of each area and of the influence of pollen production within the same sector. This assumption was made on the basis of a review of pollen dispersion modeling experiments and US EPA criteria to delineate the representativeness of monitoring stations for PM$_{10}$ and PM$_{2.5}$. Pollen dispersion modeling experiments shows that spore concentrations emitted from either a group of trees or individual species at different heights and wind speed conditions follows either a relatively steadily or a semi-logarithmic decline from the point of emission out to about 2 km. At greater distances (>2 km), the dispersal curve becomes quite flat at very low concentrations (MacInnis

Fig. 1 Location of the three Federal District monitoring stations (*black points*). The area defined by a *circle* with a radius of 2.5 km centered on the sampling site is the zone of the influence of pollen production
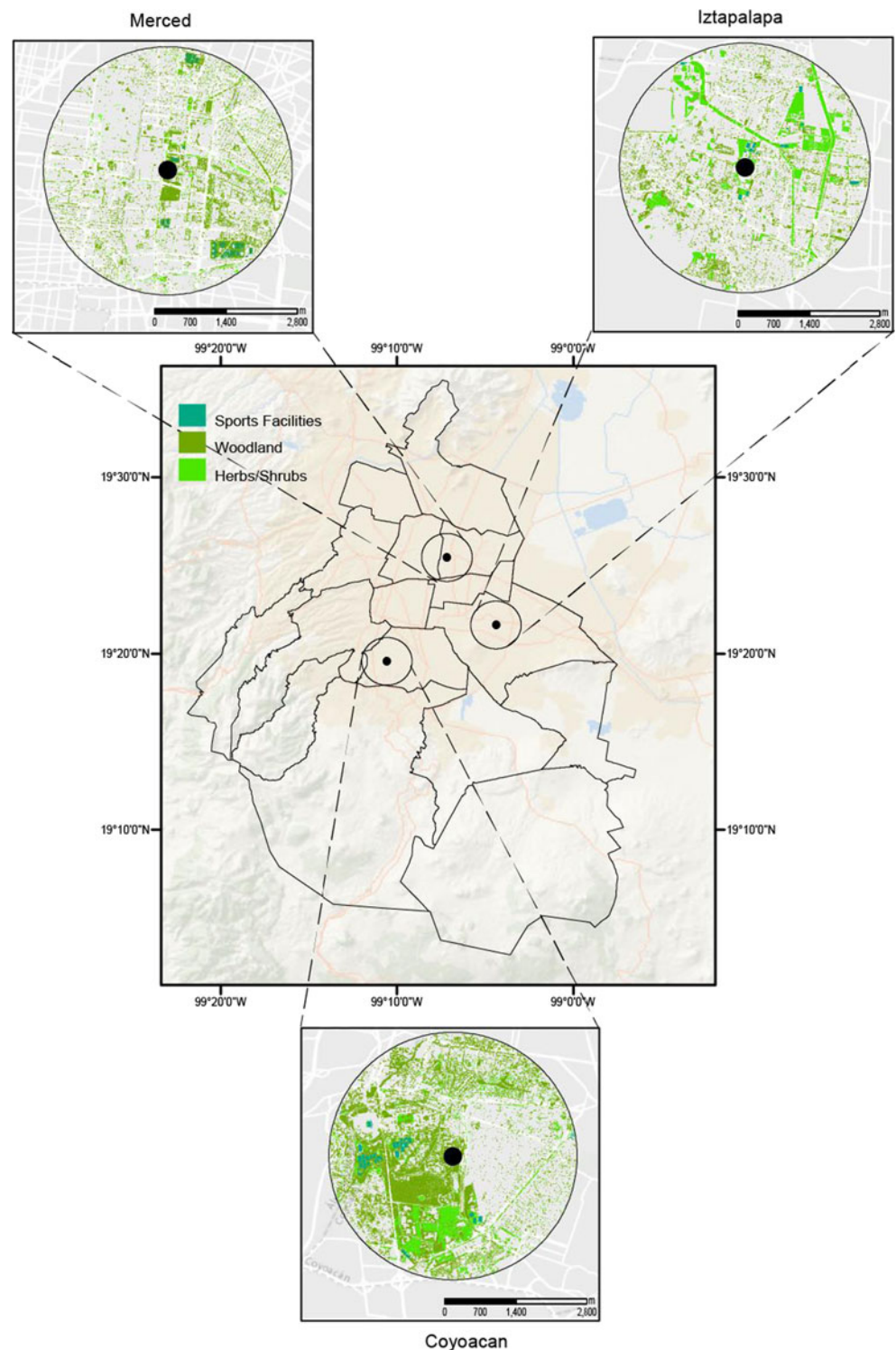
2012). On the other hand, the US EPA criteria for sitting PM_{10} or $PM_{2.5}$ monitoring stations recommends the measurement of these air pollutants under the category of a neighborhood scale when the objective is to get concentrations data representative of a reasonably homogeneous urban sub-region with dimensions of a few kilometers (US EPA 2014).

Sampling and measuring methods

Airborne pollen sampling was carried out during the 2012–2013 dry season (October–April) using three 7-day-recording Burkard volumetric spore traps (Hirst 1952). The Burkard traps were located near air quality monitoring stations

Table 1 Characteristics of the three sampling areas

Characteristics of urban sectors	Downtown Merced	Southeast Iztapalapa	Southwest Coyoacan
Geographic coordinates	19.421633°, −99.120541°	19.361389°, −99.072778°	19.324994°, −99.1856°
Percentage of green area (%)	11	17	34
Population density (individuals/km^2)	16,552	14,280	7,031
Hard surface covered (km^2)	15.8	17.4	14.1
Mean annual temperature (°C)	17.2	16.9	17.2
UHII equivalent ($T_{amb\ i}/T_{amb\ max}$)	1	0.89	0.78
Mean annual rainfall (mm)	600	619.4	817
Urbanization index	0.5 (high)	0.44 (medium-high)	0.33 (moderate)

belonging to the official Automatic Air Quality Monitoring Network (RAMA). There were no notable obstructions to horizontal airflow at samplers height in all sites. The first sampler was placed at about 6-m height on the roof-top of a building where the Merced RAMA station is located. The site is very close to downtown of Mexico City where heavy vehicular traffic and bustling commercial activity is common. In general, the green areas within the 2.5-km radius consist largely of grasses and shrubs growing in parks and private gardens. Synanthropic plant populations are also in evidence. The second pollen sampler was located 20 m above ground level on the roof-top of a school building in the Iztapalapa delegation, where anthropization favors specific vegetation, mainly grasses, and weeds with short annual cycles. The third spore trap was placed 15 m above ground level on the roof of a research building in the National Autonomous University of Mexico campus within the Coyoacan delegation, where 75 % of the green space is covered by trees. In the three sampling sites the samplers were operated continuously, and the sampled tapes were changed on a weekly basis. The tapes were cut into 48-mm segments, representing the previous 7 days. Since the information about the diversity of anemophilous pollen in Mexico City is not extensive and is not updated regularly, we assumed that the standard technique used in airborne pollen measurements of counting along a single longitudinal traverse were unsuitable for obtaining of a thoroughly identification of pollen types. Therefore, pollen was identified and counted at ×1,000 magnification (Zeiss, Axio Lab.A1) on 12 transverse strips every 2 h, according to the method described by British Aerobiology Federation guidelines (1995). Daily average pollen concentrations were expressed as grains per cubic meter. The total area counted was 336 mm^2, which is 50 % of the total area of the slide, equivalent to the number of pollen grains in 14.4 m^3 of air.

Around 500 Burkard sampled slides were obtained during the campaign, but not all were counted. From the total sampled slides, only 144 were analyzed in deep. The reason for this was that the objective of the study was to investigate the influence of meteorological variables on the pollen concentrations and

their distribution and that the counting of all the sampled tapes would have required a very large observing-microscope time. The criterion for the selection was based on the hypothesis that it would have short-term changes on pollen concentrations only when the wind speed will show a sudden change. Ambient temperature was no used as the main criterion because changes in the typical trend of ambient temperature oscillation in Mexico City are observable only on longer periods. Therefore, it was decided to analyze the days with the four highest and, the four lowest wind conditions above the mean wind registered for each month at each one of the monitoring sites. The high wind conditions are related to strong unstable conditions and the low wind conditions to relatively stable conditions. The above hypothesis was tested by taking at random concentration data with the corresponding meteorological information for several continuous days. The results showed that both temperature and pollen concentrations did not changed significantly from 1 day to another, but sudden changes in wind speed did affect the pollen levels.

Hourly averages of wind speed, wind direction, air temperature, and relative humidity data at the Merced and Coyoacan sites were obtained from the nearby RAMA monitoring stations, and at the Iztapalapa site the same information from the Red Universitaria de Observatorios Atmosféricos (PEMBU) meteorological stations, respectively. Pollen wind roses were constructed for each site to identify the possible area source of the sampled pollen. A set of "pollen wind roses" were constructed using the pollen concentration of the most abundant arboreal pollen types and wind direction data of each sampling station with the MatLab sofware. The reasons for constructing these diagrams were to depict for each wind direction the mean pollen concentration and to infer the distribution and strength of pollen emissions sources around the sampling station.

Statistical analyses were made using MatLab and Tilia software. Non-parametric Spearman's correlation coefficients were used to establish the relationship between bihourly pollen counts and the associated meteorological variables. The non-parametric method was used because data did not exhibit normal distribution. One of the difficulties inherent to

Aeropalynology is how to visualize relationships between diverse variables, such as pollen types and meteorological parameters, since many variables are measured simultaneously. When this happens, one can take advantage of information redundancy and simplify the problem by replacing a group of variables with a new variable (Wilks 2011). The main object of components analysis (PCA) is to describe the initial variables $X1$, $X2$, …, Xp in terms of m linearly independent indices ($m<p$), the so-called components, measuring different "dimensions" of the initial data set. Each variable X can be expressed as a linear function of the m factors:

$$X_i = \sum_{j=1}^{m} \alpha_{ij} F_j \qquad (2)$$

where α_{ij} are constants called component loadings. The square of α_{ij} represents the part of the variance of X_i that is accounted for by the component F_j (Sindosi et al. 2003). To avoid skewing the analysis with rare types, only the major taxa were included in the PCA. Before the analysis was performed, the data were standardized in order to eliminate differences resulting from the differences in measurement units and give all variables equal weight, whereas the original variables may have extremely different variances. The optimum number m of the retained component can be determined by a variety of statistical criteria (Overland and Preisendorfer 1982). Perhaps the most common method is to specify a least percentage (74 % in this study) of the total variation in the original variables that has to be achieved. Loadings lower than 0.25 are not statistically significant at the threshold of 0.05 and, therefore, have been omitted (Jolliffe 1993).

Results

Pollen counts

The pollen count and contribution of individual pollen types to the total counts at the three sampling stations are shown in Table 2. During the dry season of 2012–2013, a total of 62,097 pollen grains were collected in the highly urbanized area (Merced) and 90,572 in the moderately urbanized area (Coyoacan), but only 11,991 in the medium-high urbanized area (Iztapalapa). 29 taxa were identified, of which 20 pollen types were arboreal and 9 herbaceous. A significant percentage of the pollen in all three areas pertained to arboreal taxa (89.3–92.7 %). The most abundant pollen count from native trees was observed in Coyoacan (51,651), followed by Merced (23,888) and Iztapalapa (2,961), while the highest pollen count from introduced trees was Merced (3,378), followed by Coyoacan (2,600) and Iztapalapa (892). Pollen from introduced herbaceous plants dominated over those from native plants. The higher count from introduced herbaceous plants was observed in Coyoacan (5,553), followed by Merced (1,129) and Iztapalapa (319), while the count from native herbaceous followed the order: Merced (1,271), Coyoacan (748) and Iztapalapa (374).

The results reflect the effects of the degree of urbanization in MCMA and the dominant taxa at each area. In the moderately urbanized Coyoacan site, *Fraxinus* made up almost 60 % of the total pollen count, *Alnus* only 5 %, *Casuarina* 3 %, and Myrtaceae 2 %. At the high urbanized Merced site, pollen from native taxa was dominated made for *Fraxinus* (38 %) followed by Cupressaceae/Taxodiaceae (17 %). *Pinus* and *Alnus* were very close with 8 and 11 % respectively, while *Quercus* represented only 3 %. The higher pollen counts at the medium highly urbanized Iztapalapa site were for Cupressaceae/Taxodiaceae (24 %), *Pinus* (20 %), *Fraxinus* (17 %), and *Alnus* (15.2 %). Pollen from introduced plants did not exhibit high percentages. The Australian taxa, *Casuarina*, and Myrtaceae, represented between 2 and 7 % of the total pollen count in all sites. *Abies*, *Acacia*, *Buddleja*, Ericaceae, *Ligustrum*, *Liquidambar*, Moraceae, Palmae, *Ricinus*, *Salix*, *Schinus*, and *Ulmus* pollen types were weakly represented. Among herbaceous plants, the most abundant were Urticaceae, Poaceae, and Asteraceae.

Trend variation

Figure 2 shows the trends of daily pollen concentrations and number of taxa recorded from October to April in the three sampling sites. The trends showed a suddenly increase in total pollen concentrations and species richness in the cold month of January in all sites (Fig. 2). However, there were differences in the occurrence of the concentration peaks in the trees and herbaceous pollen grains among the sites. In the highly urbanized zone of Merced, the herbaceous pollen concentrations reached maximum concentrations in October, while almost disappearing throughout the remaining months. However, tree pollen levels had their maximum since December up to part of February (Fig. 2a). The most abundant taxa at this site pertained to *Fraxinus* followed by *Casuarina*, Cupressaceae/Taxodiaceae, and *Alnus*. Contrary to the trend observed in Merced, in the medium-high urbanized site of Coyoacan, pollen concentrations from trees peaked first than those from herbaceous origin (Fig. 2b). *Fraxinus*, Cupressaceae/Taxodiaceae, and *Alnus* pollen were highly concentrated in January, while *Liquidambar* and *Pinus* peaked in March. Poaceae was the dominant herbaceous pollen only during March. The Coyoacan area has the lowest urbanization index and the highest green area coverage. Therefore, the UHI did not influence an early blooming

Table 2 Pollen counts and percentage contribution of individual pollen types to the total counts at the three sampling stations

| | Taxa | Type | Urbanized area | | | | | |
			High (Merced)	%	Medium-High (Iztapalapa)	%	Moderate (Coyoacan)	%
Trees/Shrubs	*Abies* spp.	Native	26	0.042	39	0.325	35	0.039
	Acacia spp.	Introduced	264	0.425	0	0	0	0
	Alnus spp.	Native	6,973	11.229	1,825	15.22	4,436	4.898
	Buddleja cordata	Native	83	0.134	0	0	0	0
	Casuarina cunninghamiana	Introduced	3,378	5.44	892	7.439	2,600	2.87
	Cupressaceae/Taxodiaceae	Native	10,752	17.315	2,961	24.694	13,095	14.458
	Ericaceae	Native	4	0.006	0	0	0	0
	Fraxinus uhdei	Native	23,888	38.469	2,051	17.104	51,651	57.028
	Ligustrum spp.	Introduced	213	0.343	2	0.017	155	0.171
	Liquidambar styraciflua	Native	105	0.169	2	0.017	65	0.072
	Moraceae	Native	485	0.781	43	0.359	730	0.806
	Myrtaceae	Introduced	3,037	4.891	283	2.36	1,926	2.126
	Palmae	Introduced	354	0.57	0	0	0	0
	Pinus spp.	Native	4,896	7.884	2,472	20.615	7,590	8.38
	Populus spp.	Native	0	0	90	0.751	467	0.516
	Quercus spp.	Native	1,585	2.552	0	0	0	0
	Ricinus communis	Introduced	156	0.251	73	0.609	46	0.051
	Rosaceae	Native	101	0.163	0	0	2	0.002
	Salix spp.	Native	163	0.262	3	0.025	16	0.018
	Schinus molle	Introduced	1,063	1.712	14	0.117	248	0.274
	Ulmus spp.	Native	62	0.1	0	0	0	0
Herbaceous	Amaranthaceae	Native	469	0.755	213	1.776	597	0.659
	Asteraceae	Introduced	838	1.35	315	2.627	500	0.552
	Brassicaceae	Native	22	0.035	0	0	0	0
	Cyperaceae	Native	516	0.831	0	0	0	0
	Labiatae	Introduced	3	0.005	0	0	0	0
	Onagraceae	Native	8	0.013	0	0	0	0
	Poaceae	Introduced	1,129	1.818	319	2.66	5,553	6.131
	Rumex sp.	Introduced	70	0.113	0	0	14	0.015
	Urticaceae	Native	1,271	2.047	374	3.119	748	0.826
	Total arboreal		57,588	92.739	10,711	89.325	83,062	91.708
	Total herbaceous		4,326	6.967	1,264	10.541	7,412	8.184
	Others		183	0.295	16	0.133	98	0.108
	Total		62,097	100	11,991	100	90,572	100

in this area of MCMA. The pollen concentrations of both, tree and herbaceous taxa, followed the trend of the ambient temperature. On the other hand, much like the Merced area, the highest herbaceous pollen concentration in Iztapalapa was in October, but the maximum pollen levels from trees occurred in March (Fig. 2c). While the herbaceous pollen Urticaceae and Poaceae were the dominant herbaceous pollen, tree pollen from *Pinus* and Cupressaceae/Taxodiaceae

reached the highest concentrations. Iztapalapa has an intermediate urbanization index and a higher hard surface coverage. In addition, the surrounding green areas are dominated by herbaceous taxa. As shown in Fig. 2c, pollen concentrations of both taxa, herbaceous and trees are low and similar. It seems that in this area, the influence of the UHI effect and the ambient temperature has an equal effect on the blooming processes.

Fig. 2 Trend of the concentrations of each taxon at sampling sites during the dry season, expressed as pollen grains per cubic meter: **a** Merced, **b** Coyoacan, and **c** Iztapalapa. The concentration scales were adjusted for each case for a better visualization

Diurnal variation

Figure 3 shows the diurnal variation of total pollen concentrations at the sampling sites. In general, maximum concentrations were found in the afternoon, according to the typical diurnal ambient temperature diel pattern. Concentrations peaked between 1400 and 1800 hours in Merced and between 1400 and 2200 hours in Coyoacan. At Iztapalapa, there was a slight increase between 1400 and 1600 hours. At all sampling sites, the lowest diurnal concentrations were recorded in the night and morning hours (0200 to 1000 hours).

The diurnal pollen distribution patterns for each particular taxon showed a regular distribution at all sampling sites. Figure 4 shows a comparison of the pollen diel patterns for selected taxa at the three sampling sites. In Merced and Iztapalapa, the highest diurnal concentrations of *Alnus*, Cupressaceae/Taxodiaceae, *Pinus*, *Casuarina*, and Myrtaceae occurred between 1400 and 2000 hours, with the exception of Myrtaceae, which peaked around 2000 hours. Cupressaceae/Taxodiaceae and *Pinus* in the low urbanized area exhibited a pattern close to that recorded in the Merced site. Myrtaceae concentrations in Coyoacan were lower than in Merced and
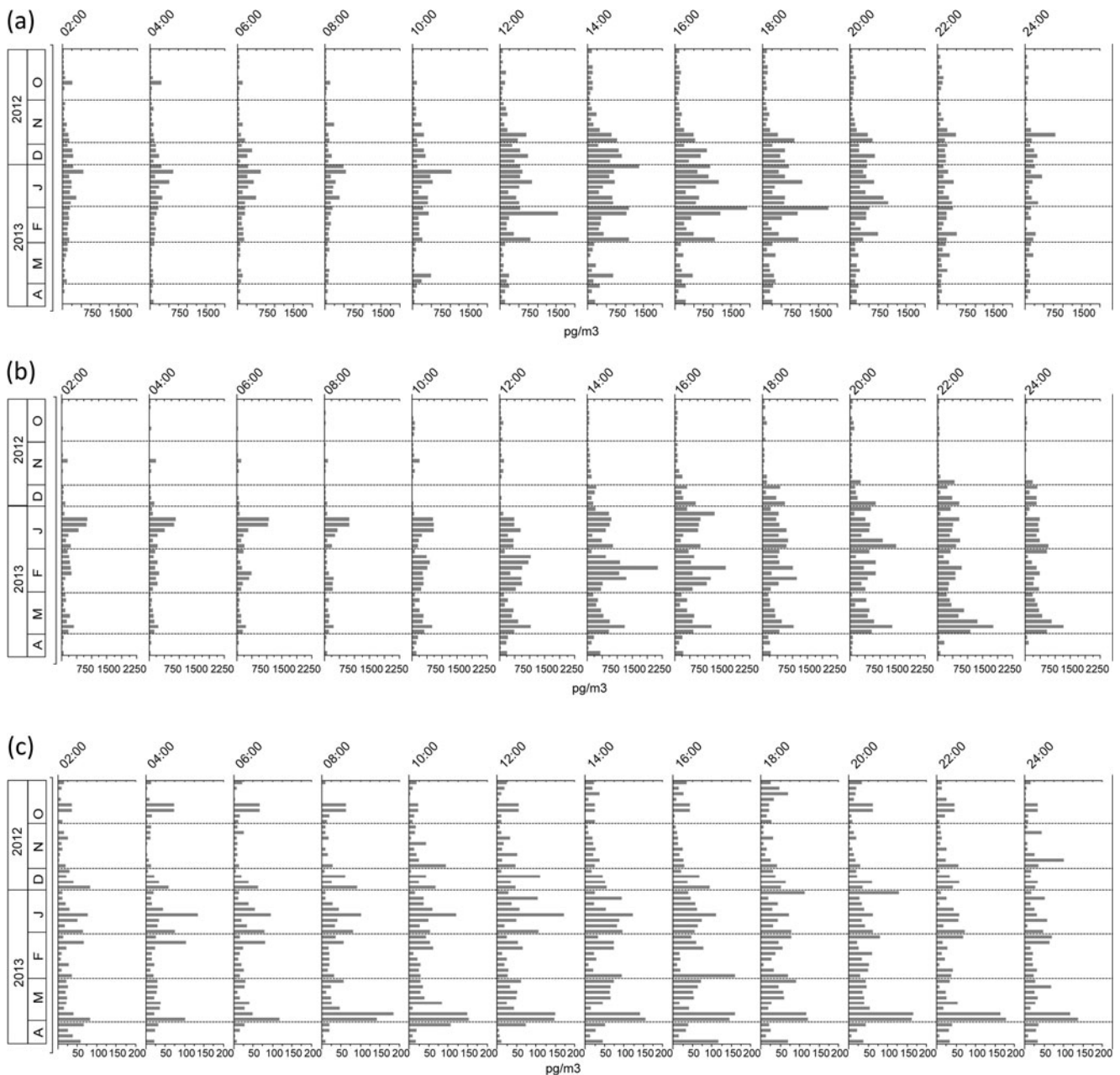

Fig. 3 Diurnal distribution of total pollen from sampling sites, expressed as pollen grains per cubic meter: **a** Merced, **b** Coyoacana, and **c** Iztapalapa. The concentration scales were adjusted for each case for a better visualization
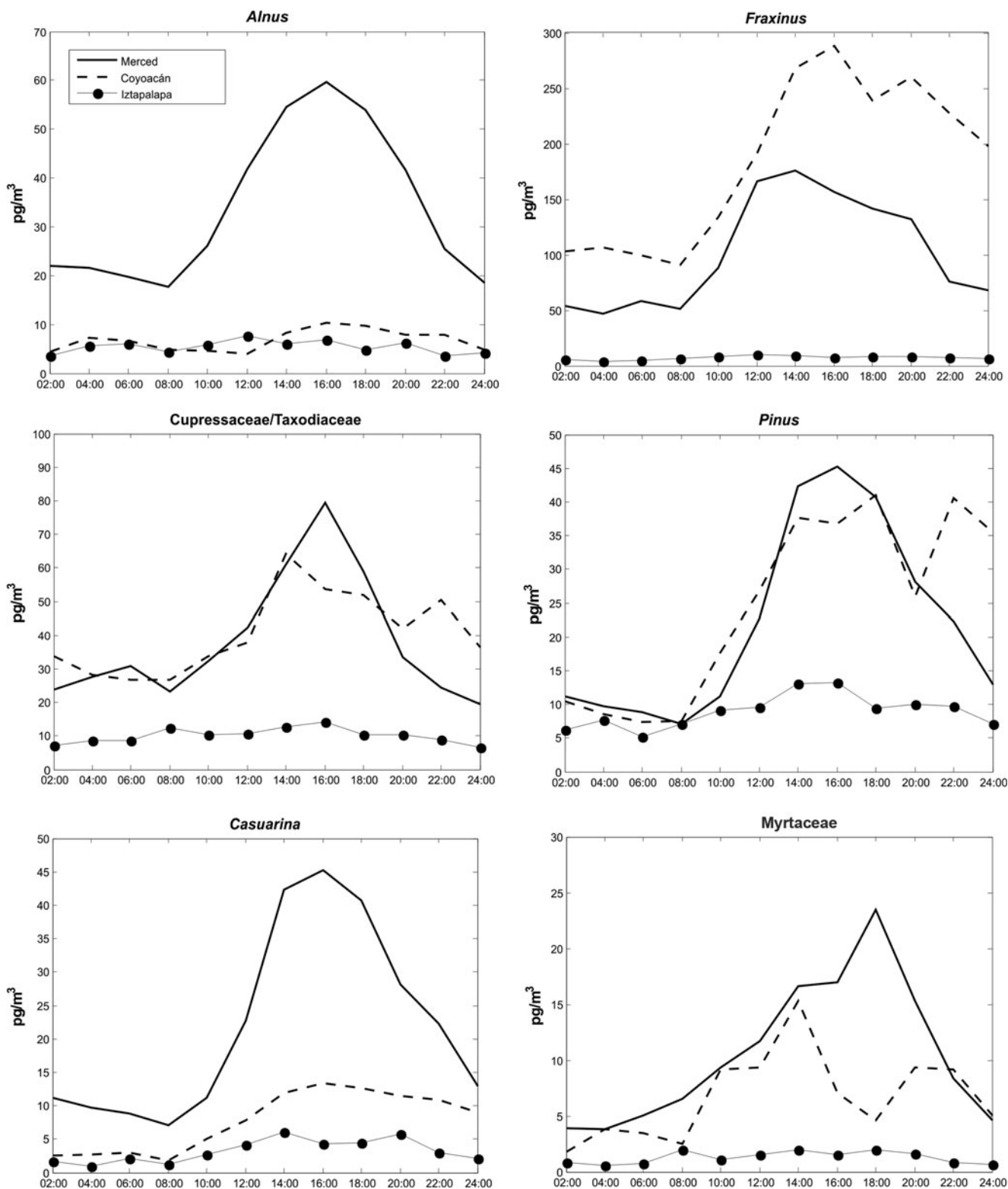
Fig. 4 Diurnal distribution of the most abundant taxa at the three sampling sites expressed in pollen grains per cubic meter. The concentration scales for each graph were adjusted for best visual representation

peaked earlier. In the moderately urbanized area, *Fraxinus* was the largest contributor to total pollen concentrations. It was the only taxa that exceeded the concentrations recorded

at the highly urbanized site. Counts reached peaks between 1400 and 1800 hours in Coyoacan and between 1200 and 1400 hours. in Merced. The lowest concentrations of all taxa

were consistently observed in the medium-high urbanized area, and in general did not show a significant change during the day, except for *Pinus* which showed a slight peak between 1400 and 1800 hours.

Meteorological variables and pollen concentration in the atmosphere

Table 3 shows the results of the Spearman's correlation analyses between meteorological variables analyzed and pollen concentration. In general, pollen concentrations were significantly correlated with temperature. Strong correlations were found in December, January, February, and April in the highly urbanized area. In the moderately urbanized area, the most significant correlations were obtained for the months of October, February, March, and April. However, low correlation coefficients were found for March and April in the medium-high urbanized area. Relative humidity seems to correlate negatively with the occurrence of pollen grains in both Merced and Coyoacan, perhaps because this meteorological variable anticorrelates with temperature. On the other hand, the correlations between pollen concentration and wind speed at all three sampling sites were in general lower. The most significant correlations were found in February, March, and April at the Merced site, while the higher correlations at the medium-high and moderate urbanized areas were only observed in April. In short, April was the month that exhibited the higher correlations between temperature, wind speed and pollen concentrations across the three sampling sites.

The resulting factor loadings of the rotated component matrix are shown in Table 4. Four factors were retained for the Merced and Coyoacan sites and five for Iztapalapa. The retained components explain 79 % of total variance of the 14 original variables in Merced, 75 % in Iztapalapa and 74 % in Coyoacan. Connections among the 14 variables

examined were analyzed in terms of the factor loadings for each sampling sites. In Merced, component 1 reveals the opposite relationship between arboreal pollen types and the herbaceous types. Since the factor loading of the meteorological parameters is not significant, no relation with the pollen types considered can be established. In the second component the factor loading of *Fraxinus* is relatively low; however, it is significant and is in direct proportion to the others variables. In component 3, only wind speed and *Schinus* are grouped. The component loading of wind speed is height and is correlated with *Schinus* pollen. Component 4 is the weakest, explaining about 11 % of the total variance. In Iztapalapa, the first component is prevalent as a function of the contrast between positive values of herbaceous taxa, and negative values of arboreal taxa. This component behaves contrary to the first component in the PCA of Merced. In component 2, Amaranthaceae has a low factor loading, because these components do not entirely represent this variable. Component 3 correlated positively to *Alnus*, *Casuarina*, Cupressaceae, *Schinus*, and Asteraceae. In component 4, we can see that the factor loading of temperature and relative humidity are significant, and there some relationship between these pollen types and this parameter. The last component explains only 8 % of the total variance. The principal components analysis in Coyoacan shows that the first component explains the most abundant taxa. The second component comprises the herbaceous taxa and *Pinus*. This component is correlated negatively with *Fraxinus*. In the same way, both component loadings of the meteorological parameters are not significant, the factor loading of relative humidity is correlated positively with component 3. The last component is correlated positively to *Schinus* and temperature, and negatively to *Casuarina*. High loadings of RH (0.728) and temperature (−0.524) indicate that only part of the variance of daily pollen concentration is controlled by the relative humidity temperature variable.

Table 3 Spearman's correlations among bihourly pollen concentrations and wind speed and temperature at all sampling sites

Month	Highly urbanizad			Medium-high urbanized			Moderately urbanized		
	(Merced)			(Iztapalapa)			(Coyoacán)		
	WS	T	RH	WS	T	RH	WS	T	RH
October	ns	0.475***	−0.239*	ns	ns	−0.174*	0.356***	0.528***	−0.601***
November	ns	0.437***	−0.482***	ns	ns	−0.197*	0.383***	0.443***	−0.561***
December	0.352*	0.800***	−0.572***	ns	ns	ns	ns	0.468***	ns
January	0.371***	0.713***	−0.662***	ns	0.248*	−0.483***	0.408***	0.439***	−0.453***
February	0.589***	0.827***	−0.700***	0.269**	0.369***	ns	0.423***	0.594***	−0.456***
March	0.562***	0.484***	−0.550***	ns	0.496***	ns	0.357**	0.642***	*ns*
April	0.591***	0.843***	−0.329**	0.675***	0.435**	ns	0.634***	0.820***	−0.741***

ns not significant

Correlation *p* values: **p<0.05; **p<0.01; ***p<0.001

Table 4 Component loadings of the rotated component matrix. (Component loadings lower than 0.25 are suppressed)

Variables	Merced				Iztapalapa					Coyoacán			
	PC1	PC2	PC3	PC4	PC1	PC2	PC3	PC4	PC5	PC1	PC2	PC3	PC4
Alnus	0.395				−0.368		0.254			0.335	−0.095	0.042	−0.121
Casuarina		0.315		−0.265			0.261	0.581					0.261
Cupressaceae/Taxodiaceae	0.254				−0.347	−0.337				0.410			
Fraxinusudhei	0.447	0.220			−0.353	0.427		0.296		0.486	−0.354		
Pinus spp.				0.457		−0.417					0.377		
Schinus molle	0.267		0.352			0.308	0.483	−0.403	0.553				−0.370
Myrtaceae	0.251								0.315	0.304			
Amaranthaceae/Chenopodiaceae		0.405			0.463		0.389				0.400		−0.295
Asteraceae		0.528		0.262	0.261		0.430				0.425	0.322	0.459
Poaceae	−0.294	0.498			0.380		0.263	−0.151			0.440		−0.303
Total pollen	0.491				−0.256	−0.339	0.265			0.508			
Temperature			−0.524	0.332				−0.326			−0.361		
Wind speed			0.552	0.535		−0.378			0.461		−0.360		0.287
RH				−0.257				0.410			0.728		
Explained variance (%)	38.697	18.556	11.172	10.523	24.795	16.414	14.056	11.333	8.279	37.494	18.159	10.170	7.883
Cumulative variance (%)	38.697	57.253	68.424	78.947	24.795	41.209	55.266	66.599	74.878	37.494	55.653	65.823	73.706

Wind direction varied greatly among the three sampling sites (Fig. 5). In Merced, low percentages occurred from the SW and NE with predominant winds from the SE. The highest concentration of buildings and retail stores are located in the SW and NE areas with respect to this site. In Coyoacan, low percentages occurred from the NE and NW; most of the winds were from the SW and SE sectors. Extensive green areas are located towards the last directions. The winds in Iztapalapa had high percentages from the NE and NW with a fairly even distribution from all other points. The highest pollen concentrations in Iztapalapa occurred from the north where some green areas are located.

Discussion

In this study, we examined the composition and abundance of pollen at three sites in Mexico City, representative of diverse degrees of urbanization, and the influence of several meteorological variables on the temporal and spatial distribution and concentration of the allergens. We also explored the applicability of several statistical tests for demonstrating associations between the set of measured variables, in such a way that this information could help improve estimates of airborne pollen concentrations in areas with differing degrees of urbanization

As expected, due to the relatively low degree of urbanization, pollen counts were higher in Coyoacan than in the other sampling areas. However, the observed pollen types in this area were similar to those observed at the more highly urbanized Merced site. Pollen counts from tree species were, in general, greater than those from herbs and shrubs. The observed predominance of pollen produced by tree species (*Alnus*, *Casuarina*, Cupressaceae, *Fraxinus*, *Pinus*, *Schinus*, and Myrtaceae) in the present study, has also been reported in previous studies, not only in Mexico but also other countries as in the western part of Turkey which has a typical Mediterranean climate, and Buenos Aires, Argentina, that exhibits similar climatic conditions as in Mexico City (Guvensen and Ozturk 2003; Murray et al. 2008; Gonzalez-Diaz et al. 2010). While some tree taxa (e.g. Cupressaceae, *Casuarina*) have been extensively used as ornamental plants in Merced and Iztalapa, the arboreal pollen from native *Fraxinus* is the most abundant tree at Coyoacan, an area by all accounts rich in native tree taxa.

On the other hand, all of the herbaceous taxa recorded were anemophilous varieties, but these were found relatively low density. This could be explained by the fact that the flowering period for these synanthropic herbs, usually the rainy season, is typically prolonged due to species diversity (Hejda 2012). Moreover, this study was carried out during the dry season.

The most common types of airborne pollen of herbaceous origin were similar for three sites in spite of the degree of urbanization. The lower pollen counts observed in Iztapala could be associated to the low diversity in the scant green areas in the zone and probably to weather conditions as Chacalo et al. (1994) also observed.

The influence of weather conditions on the pollen season was clearly observed. This study showed that tree pollen season starting dates can vary from several days to 2 weeks (Fig. 2). This can be explained by the influence of
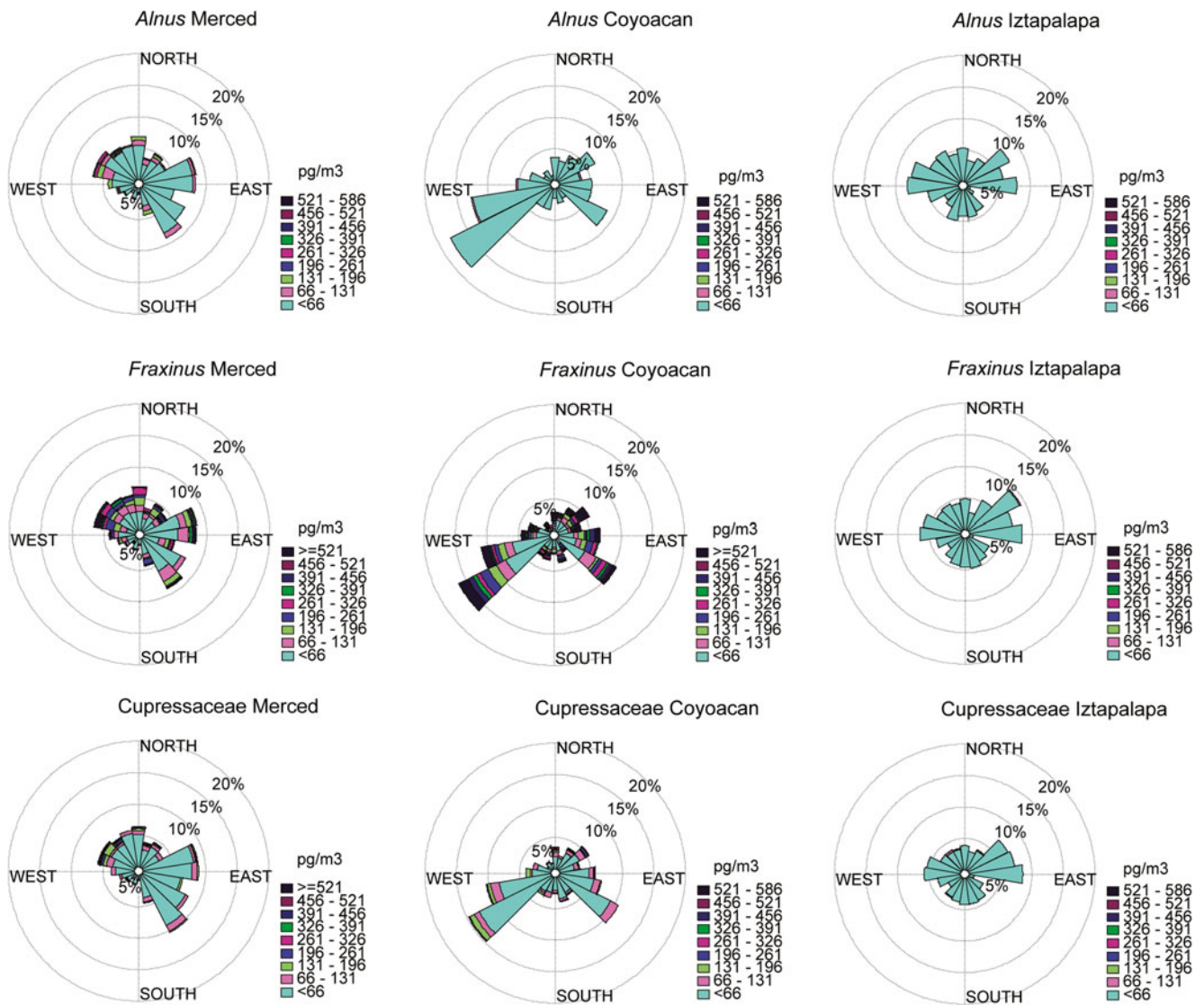
Fig. 5 Pollen wind-roses of the most abundant taxa at the three sampling sites expressed in pollen grains per cubic meter

meteorological variables analyzed, particularly the UHI effect and ambient air temperature, which exert considerable impact on both phenology and flowering (Jato et al. 2004; Rodriguez-Rajo et al. 2006; Kaszewski et al. 2008; Ziello et al. 2012; Kasprzyk et al. 2014). Warming of the urban atmosphere has been shown to increase in intensity and extent as cities grow. During the monitoring period, we found that the effect of urban heat island intensity upon sampling sites was as follows: Merced>Iztapalapa>Coyoacan. Such temperature differences could have caused earlier flowering of trees at Merced. In order to draw clearer conclusions, however, more extensive research into this effect will be necessary.

The pollen grain content in the Mexico City's atmosphere exhibited daily variation. The knowledge of this pattern allows one to understand the factors that determine the exacerbation of allergy symptoms (Baran et al. 2014). The analysis of bihourly pollen grain distribution showed that concentrations peaked near midday or in the afternoon at monitoring sites. Only in the Coyoacan site were maximum concentrations recorded at night from February to April.

We suggest that the evening and nocturnal downslope flows from the southern and southwestern mountains could be in part responsible for carrying pollen and other aged pollutants into the Mexico City basin. The Coyoacan site is located no more than 6 km from the piedmont of these forested mountains. This phenomenon has been previously documented for gases and particles (Bravo et al. 1988; Raga et al. 1999).

The most abundant airborne pollen types in sampling sites were most highly concentrated in the afternoon except for Myrtaceae pollen, which was most concentrated in the morning at the Merced and Iztapalapa sampling sites (Fig. 4).

Air temperature is believed to trigger pollen release, while dispersion is thought to be conditioned by wind speed (Després et al. 2012). It is known that pollen is dispersed at

speeds greater than 3 m/s (Jones and Harrison 2004; Šikoparija et al. 2013b), and this intensity was frequently recorded during our sampling trials. Pollen grains are carried away from the source and borne into the layers of the atmosphere (Pérez-Badia et al. 2011; Xu and Zhang 2011). Although the hours of major pollen liberation are genetically determined (Millerón et al. 2012), the analysis of a statistical correlation of meteorological variables with occurrence of pollen in the atmosphere of Mexico City during 2012 and 2013 shows that the most important variable studied was temperature, which markedly influenced the production of pollen grains in the atmosphere. Ribeiro et al.(2003); Gioulekas et al. (2004) studied the influence of temperature, and relative humidity on the occurrence of pollen grains in the atmosphere. They conclude that under normal weather conditions, temperature and relative humidity have minimal effects on the day-to-day pollen counts; however, unstable atmospheric

conditions, such as the passing of a cold front, had the greatest impact of all the weather-related events on airborne ragweed pollen counts. The PCA analysis also showed some degree of correlation among meteorological parameters analyzed and pollen concentrations. The first principal component in Merced reveals a negative correlation between the principal arboreal taxa and herbaceous taxa. This could be associated with the seasonality of the pollen; the results of components 3 and 4 showed a correlation among four arboreal taxa (*Schinus*, *Alnus*, *Pinus*, Myrtaceae) and one herbaceous (Asteraceae) with temperature and wind speed. These results agree with those found in previous studies (Makra et al. 2004; Rodriguez-Rajo et al. 2005; Frei and Gassner 2008). The first component in Iztapalapa exhibited behavior opposite to that observed at Merced. This is a densely populated zone in the center of the city where herbaceous plants are relatively scarce.
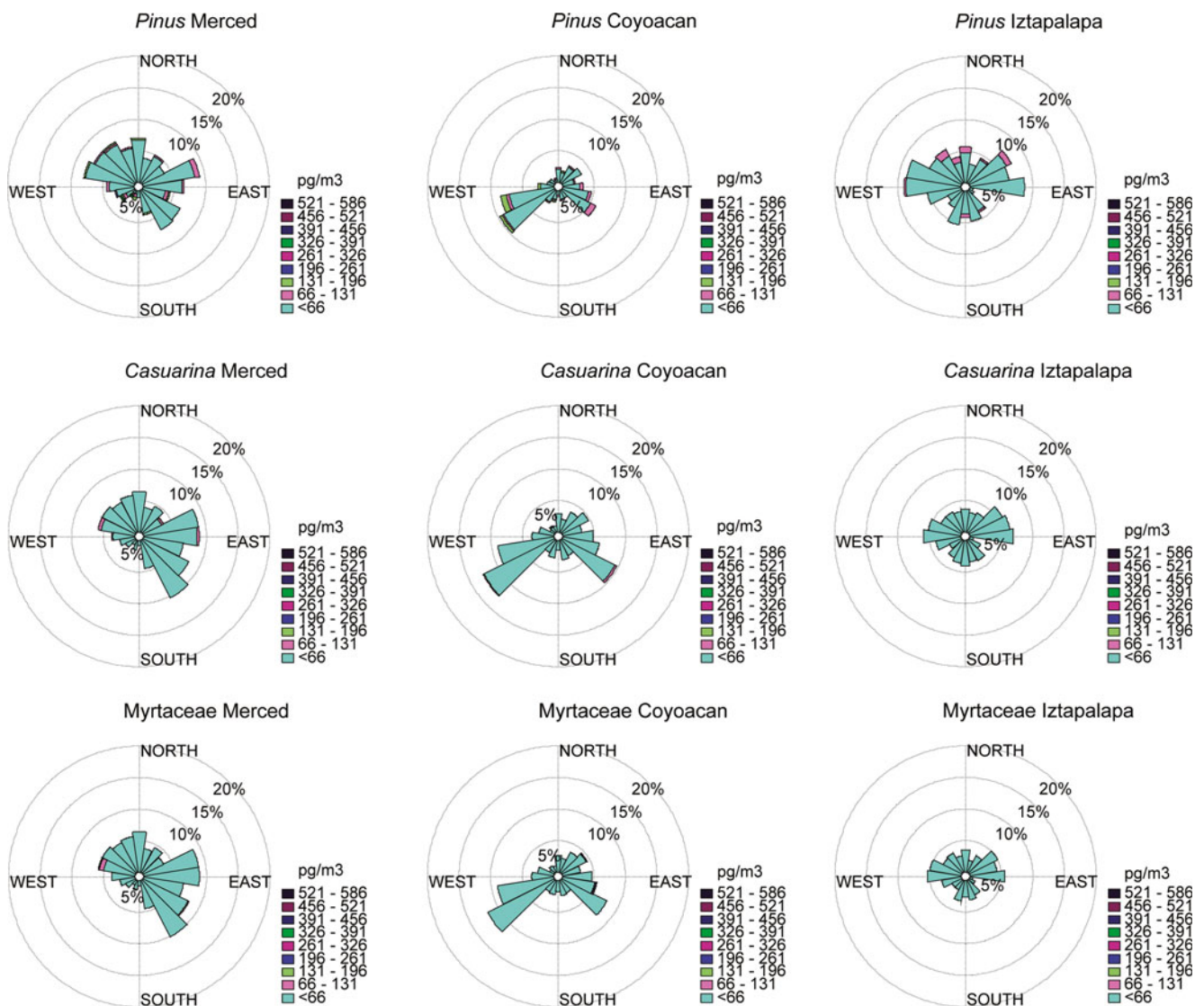

Fig. 6 Pollen wind-roses of the most abundant taxa at the three sampling sites expressed in pollen grains per cubic meter

The data indicate that the airborne pollen composition in the sampling site varies markedly with variations in vegetation composition, which in turn is influenced by the degree of surface area built or paved and climate conditions. Taken together these factors give rise to distinct pollination periods.

Analyzing the second and fourth components, we observed a weak correlation between meteorological parameters and *Pinus* and *Schinus*. This confirms the results obtained with linear regression, since these components only explain between 16 and 8 % of the total variance. Components 4 and 5 showed a correlation among three of the arboreal taxa and temperature. Components 1 and 2 in Coyoacan generally exhibited the same pattern observed in the Merced PCA.

Although all the pollen types studied appear frequently in the neighborhood of the trap (some meters), their preponderant location in one or another quadrant is determined by the dominant vegetation there. The action of the wind in concentrating greater or lesser amounts of pollen from these sources is manifest in the results expressed in Figs. 5 and 6. It can be seen that the wind not only is able to carry pollen from sources far from the sampling point, as has been demonstrated by different workers (Šikoparija et al. 2013a; Peel et al. 2014) , but may also modify pollen concentrations from sources closer to the trap.

Conclusions

Based on data gathered over 7 months, this paper presents preliminary results of a study of spatial and temporal pollen concentrations in Mexico City, showing that allergenic pollen exposure was more prominent at one moderately urbanized site, and that the most abundant pollen grains came from a single arboreal taxa. Furthermore, we found that the most abundant pollen types reached maximum concentrations in the evening, suggesting that allergy sufferers should outdoor activities during those hours.

The multivariate regression and principal components analysis performed resulted only in an approximate indication of which variables could be useful for predicting pollen concentrations. Results also showed that hourly and daily pollen concentrations at the sampling sites were linked to a set of urbanization indicators and climatic conditions, such as a composite urbanization index, the urban heat island intensity, temperature, and wind speed.

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