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ORIGINAL PAPER

# Behaviour of Quercus pollen in the air, determination of its sources and transport through the atmosphere of Mexico City and conurbated areas

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## Abstract

Pollen allergies have a remarkable clinical impact all over world. *Quercus* pollen is the main allergen in many parts of world. Due to the health impacts caused by exposure to oak pollen, the objectives of this study are to characterise the aerobiological behaviour of *Quercus* pollen and to determine its potential sources as well as their transport through the atmosphere of Mexico City and surrounding areas between January 2012 and June 2015. Airborne *Quercus* pollen monitoring was carried out simultaneously in five zones of Mexico City. The percentage of *Quercus* pollen of the total pollen collected from the air showed that the highest concentration was recorded in 2014, followed by 2012. The annual seasonal variation indicated that flowering and pollen emission into the atmosphere began between February and March. The maximum concentration of *Quercus* pollen was reached at Cuajimalpa. In 2012, the amount of pollen grains was distributed in March and April uniformly, whilst in 2014, the largest amount of pollen was concentrated in March. In 2012 and 2014 (years with the highest pollen concentrations), corresponding intraday variations were quite similar, with a low relative maximum in the morning and the highest concentrations in the evening. The largest values were recorded in 2014, and two processes can explain these. In the afternoon, pollen from secondary forest is carried by southwesterly converging winds, increasing the pollen concentration in Cuajimalpa. In the evening, there is an additional pollen contribution from primary forest via transport by NW winds.

**Keywords** Aerobiology · *Quercus*-pollen · Wind convergence · Transport · Daily cycle

## Introduction

*Quercus* (oak) is the only genus in the family Fagaceae that occurs naturally in Mexico. Of 160 *Quercus* species reported in Mexico, 13 species are distributed in the Metropolitan Area of the Valley of Mexico in forests of oak, pine and oak-pine (Valencia 2004; Rzedowski and Rzedowski 2005; Challenger and Soberon 2008) as well as in the urban green areas of Mexico City (SMADF 2011).

*Quercus* pollen represents 4.95% of all pollen types collected in the atmosphere of Mexico City (Calderón-Ezquerro et al. 2016); therefore, it is included amongst the main types of allergenic pollen to which the population is exposed. For this reason, determining its spatial distribution and seasonal and intraday variation, depending on biological and geographical differences, together with its mobility in the atmosphere will help to improve the prediction of the presence of this aeroallergen in regions with tropical climate like our area of study. The primary and secondary forests of *Quercus* are common in the mountains surrounding Mexico City and the State of Mexico (INEGI 2005).

For species of this genus, the release mechanism of the pollen grains is typically anemophilous (Trigo et al. 2008). Several authors have studied its aerobiological behaviour through its seasonal and diurnal characterisation showing that this varies by species and regions (Tormo-Molina et al. 1996;

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García-Mozo et al. 2000; Gómez-Casero et al. 2004; Jato et al. 2007; So et al. 2017). Likewise, it has been observed that the dynamics of the pollen season, such as those of *Quercus* and its relationship with meteorological factors, have been affected by the increase in temperature detected in recent years as a possible consequence of global climate change (García-Mozo et al. 2006a, b). Also, the impacts of oak pollen on allergic asthma and the potential influence of future climate change on these impacts have been determined (Lake et al. 2017; Anenberg et al. 2017).

The flowering of tree species depends largely on the increase of light and temperature to favour flowering. In Mexico City, the temperature drop and the reduction of daylight hours (at the end of June), combined with changes at the end of the rainy season (October), produce changes in the transcription of cascade repressors of floral induction genes. The absence of such repressors, together with the increase in daylight hours (from the beginning of the new year) and the constant increase in temperature (beginning in February), generates the necessary environmental conditions for the expression of chemical signals that induce the specialisation and development of the sexual reproductive structures; the flowering of Mexican oaks begins during the warm months of the dry season, towards the middle of February and beginning of March (Yang et al. 2009; Rzedowski and Rzedowski 2005; Linkosalo et al. 2006).

In geographical regions of mainly temperate and cold zones, such as Italy (Romano et al. 1988), Spain (Recio et al. 1999; Moreno-Grau et al. 2000), the USA (Dvorin et al. 2001), Germany, Netherlands, Belgium, United Kingdom (Spieksma et al. 2003) and Poland (Weryszko-Chmielewska and Piotrowska 2004), the seasons are well defined (spring, summer, autumn and winter). It has been determined that the period of flowering of *Quercus* pollen begins after the increase in temperature and hours of light during the spring season (March and June), whilst in the tropical and subtropical regions, the flowering period occurs between March and April (Rzedowski and Rzedowski 2005).

The range of movement of bioaerosols such as oak pollen in the air is wide. To determine the trajectories of the pollen grains in the atmosphere, models that simulate their transport in the air have been developed (Schueler and Schlünzen 2006; Wozniak and Steiner 2017). The different proposed models encompass both those based in simple backward trajectory analysis and those that include forward pollen dispersion, pointing to the simulation of the real life cycle of pollen. The result of the modelling is a set of maps of concentration and deposition of each specific type of pollen (Sofiev and Bergmann 2013). Therefore, in addition to determining the stationary nature of pollen, it is advisable to use numerical models that allow the tracing of its trajectory in the air from its sources (forest) to other regions, for example both suburban and urban. The analysis of this information allows space-time predictions of the presence of allergenic pollen types such as airborne oak.

Pollen allergies have a remarkable clinical impact all over the world. Exposure to allergens is a key factor amongst environmental determinants of asthma, which include air pollution (Eder et al. 2006). Due to this, developed countries such as USA, Canada and diverse European countries have studied and determined the presence, diversity and seasonality of the main types of airborne pollen. In Latin America, there are a reduced number of aerobiological studies (e.g. Tejera and Beri 2005; Bianchi and Olabuenaga 2006; Villegas and Nolla 2001; Duso et al. 2007). In particular, a group of researchers from the Mexican Network of Aerobiology have reported aerobiological studies characterising airborne fungal spores (Calderón et al. 1997) and bacteria (Frías-de León et al. 2016), as well as the first pollen calendar for Mexico City (Calderón-Ezquerro et al. 2016), which was based on pollen data collected from the air continuously for 5 years (2008–2015). In that same publication, Calderón-Ezquerro et al. (2016) refers to the history of aerobiological studies carried out in Mexico City since 1940. Likewise, Ríos et al. (2016) focused on the daily variation of pollen in Mexico City during a dry period (6 months), but analysing only a few days of each month. These studies are important, as they could make it possible to characterise and quantify the most abundant and frequent airborne pollen types, mainly those that cause allergic and respiratory diseases such as asthma.

For this purpose, aerobiological studies conducted in tropical and subtropical regions such as Mexico contribute to expanding knowledge on the presence of this airborne pollen in these regions, its relation with the meteorological conditions and the adequate time for to take efficient prevention and control measures to benefit the health of the population. The objectives of this study were to characterise the aerobiological behaviour of *Quercus* pollen in a tropical region and determine its potential sources as well as their transport through the atmosphere of Mexico City and surrounding areas between January 2012 and June 2015.

## Methods

### Study area and sampling sites

Mexico City is located in the south-central region of Mexico, and lies within the basin of the Valley of Mexico at the coordinates 19° 36′–19° 02′N and 98° 56′–99° 22′W at a height of 2240 m a.s.l. Mexico City has a tropical climate tempered by altitude (Jáuregui 2000). The northeast of the city tends to be dryer, with 400- to 500-mm annual precipitation (dry steppe; BS in the Köppen classification), whilst the centre and south, especially at the base of the mountains, receive 700- to 1200-mm precipitation annually (Jáuregui 2000; Estrada et al.

2009). Mountains surround the city, except to the northwest. Forty-five percent of the city are urbanised (north and central), whereas 55% of the city distributed to the south and east are rural with the land used for ecological reserves, forestry and agriculture (INEGI 2010).

Figure 1a shows the main forests and parks with broadleaf (*Quercus*) vegetation in Mexico City (red points 1 to 7) and surrounding areas (red points from 8 to 14), which are potential sources of the *Quercus* pollen that is transported from one place to another in the region. Aerobiological monitoring stations (yellow points) are also evident on the map. These were installed in five areas of Mexico City with different rates of urbanisation; the topography and the different areas exhibit diversity in vegetation and climate heterogeneity, and they divide the city into two climatic regions, mainly defined by topography and land use (Estrada et al. 2009).

The monitoring stations used for this study were selected based on the microclimatic and vegetation differences that occur in Mexico City (Estrada et al. 2009). These stations were the following: Coyoacan (Atmospheric Sciences Centre at the Universidad Nacional Autónoma de México (UNAM), Miguel Hidalgo (Museum of Natural History, located in Chapultepec Forest), Cuajimalpa (French English School), Iztapalapa (residential area) and Gustavo A. Madero (National School of Medicine and Homoeopathy, Instituto Politécnico Nacional).

## Pollen monitoring

Pollen sampling was performed using five Hirst-type volumetric spore traps (Burkard Manufacturing Co., Ltd., UK), from January 01, 2012 to January 06, 2015. The samplers were placed in open areas at an approximate height of 15 m from the ground. Air pollen samplings were performed simultaneously at all five stations throughout the study period. These stations are part of the Mexican Network of Aerobiology (REMA; http://rema.atmosfera.unam.mx/rema/), in which pollen is monitored continuously 365 days a year.

The sampler operated continuously and aspirated a constant flow of 10 L/min. After exposure, a Melinex tape that was impregnated with silicone fluid was cut into 24 fragments (48 mm) and mounted on slides using glycerine jelly stained with fuchsine. Counts of the different pollen types were performed with the aid of a light microscope, and four longitudinal sweeps per slide were performed at a magnification of ×400 according to the methodology proposed by the Spanish Aerobiology Network (REA) manual (Galán et al. 2007, 2014; Calderón-Ezquerro et al. 2016).

The pollen grains were examined under a microscope at a magnification of ×400, and the pollen was identified with the aid of pollen atlas (Erdtman 1952; Pla-Dalmau 1960, 1961; Kapp 1969; Bassett et al. 1978; Moore et al. 1991; Smith 2000; Lacey and West 2006; Trigo 2007; Trigo et al. 2008). And a pollen collection of the local floral from Mexico City is part of the palinoteque of the Mexican Aerobiological Network (REMA).

After the analysis of the pollen records of each monitoring station, we obtain five time series of pollen counts, with a time resolution of 1 h, as well as time series of daily values, which represent daily averages of the amount of pollen grains contained in a cubic meter of air (hereafter referred as pollen concentrations, which are expressed as a daily average of pollen grains/m$^3$ of air). With the hourly time series, we derived daily cycles, describing the hour-to-hour variation relative to a determined period, whereas daily values are used to analyse pollen variability at longer time scales (monthly and annual) (Calderón-Ezquerro et al. 2016).

The main pollen season (MPS) has been defined following Andersen (1991), considering 95% of the annual pollen, and the pollen season starts the first day with a cumulative daily

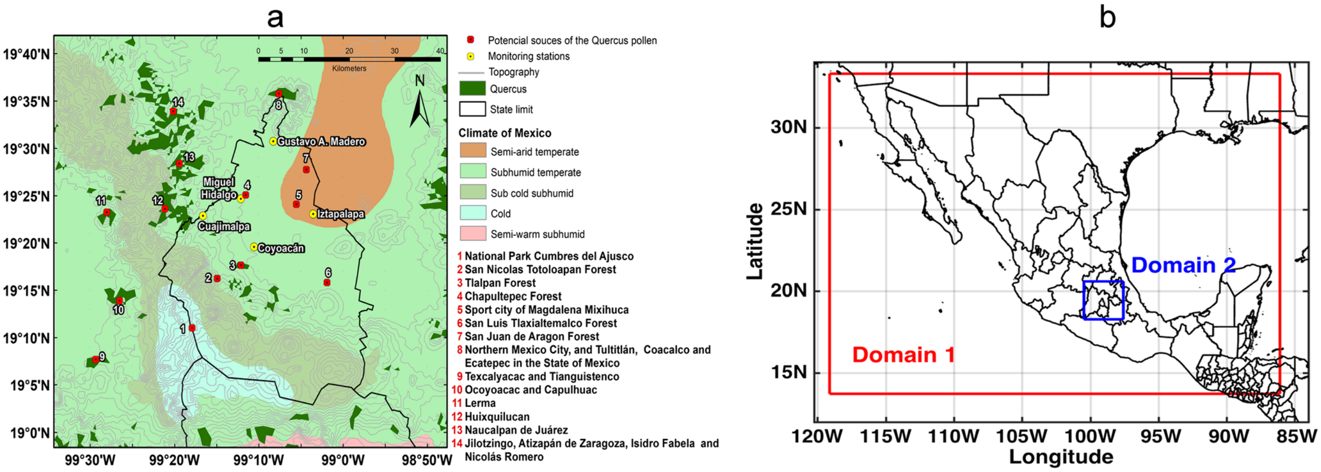

**Fig. 1** **a** Broadleaf (*Quercus*) forests in Mexico City and surrounding areas and sampling sites in Mexico City: Coyoacán, Miguel Hidalgo, Iztapalapa, Cuajimalpa and Gustavo A. Madero. **b** Domains defined for the numerical experiment. The first domain has dimensions of 375 × 245 points and a horizontal resolution of 9 km, and the second domain has dimensions of 100 × 85 points and a horizontal resolution of 3 km

pollen concentration of 2.5% of total pollen and finishes at 97.5%. The pollination period from the beginning of the MPS to the day with the highest pollen count is referred to as the pre-peak period, whereas the days following this period are referred to as the post-peak period. The annual pollen integral (APIn) was used for presenting inter-annual variations (Galán et al. 2017).

## Meteorological data

### Meteorological data and wind-modelling experiments

A time series for temperature (average, maximum and minimum), rainfall and relative humidity (RH) were obtained from weather stations of the "University High School Meteorological Station Program".

In order to estimate the wind field over central Mexico, a set of numerical simulations were performed with the Weather Research and Forecasting (WRF) model version 3.8 (Skamarock et al. 2008) with the Advanced Research WPS (ARW) core to calculate atmospheric dynamics. The numerical simulation used a nesting that is covering central Mexico with a grid of 100 points from west to east and 85 points from south to north. The nested domain (blue in Fig. 1b) has a horizontal resolution of 3 km and 35 vertical levels. The simulations were performed for March and April from 2012 to 2015. The interaction with the parent domain, which covers all of the Mexican Republic (red in Fig. 1b) with a horizontal resolution of 9 km, was two way (Kalnay 2003). Simulations of a day and a half in length were performed in forecast mode with outputs every 15 min. All simulations were initialized at 00:00 UTC, and the first 24 outputs of the forecast were not considered in the analysis. The subsequent 97 outputs of the forecast were used as they represent a simulation day in local time (UTC-6); thus, all analysis including daily variations are in local time. The initial and boundary conditions were taken from the NCEP FNL (Final) Operational Global Analysis, specifically 00:00 UTC data every 6 h with a 1° spatial resolution. The data is in a Mercator projection with a time step of 30 s. The schemes used in the model physics were as follows: the Kain-Fritsch cumulus parameterisation, the rapid radiative transfer model (RRTM) for longwave radiation, the Dudhia for shortwave radiation and the Yonsei University (YSU) scheme for the boundary layer (Skamarock et al. 2008). The Noah Land Surface Model (LSM) was used, and the land use and land cover data used was of MODIS with 21 classes. Hereafter, when we use the term "simulated wind", we refer to the wind field simulated by the WRF model for the specified period of time. Sometimes, when the context is very clear, we will simply use "wind" omitting the adjective "simulated" but meaning wind fields obtained from the numerical simulation using WRF.

In order to analyse daily behaviour of pollen and its relation to the wind, the daily cycle of wind at 10 m and its divergence (where is the wind field at 10 m, and is the nabla operator) at Cuajimalpa was computed for each March for the years 2012 to 2014 using hourly averages obtained from the closest WRF-grid point to this station (Fig. 4). As stated by Calderón-Ezquerro et al. (2016), "wind fields produce large areas of convergence which is an atmospheric condition that exists when the winds cause a horizontal net inflow of air into a specified region. On the other hand, divergence is the opposite, where winds cause a horizontal net outflow of air from a specified region. Thus, these large areas of convergence, closely related to the mountain-valley circulation, are favourable for the transport and accumulation of pollen".

## Statistical analysis

First, a typical meteorological year was built using all the available data for Mexico City, and a series of statistical analyses were carried out. For the correlations of pollen concentrations (MPS, pre-peak and post-peak, that is, from the beginning of the flowering period until the end of January to September) and climatic parameters, the Spearman *r* was calculated for samples distributed non-Gaussian (Rodriguez-Rajo et al. 2005; Köhler et al. 2007; Parrado et al. 2009). For the analysis, the arithmetic mean pollen concentration values of the monitored stations were used. The statistical analyses were performed with IBM-SPSS version 22.0.

# Results

## Pollen Quercus data

*Quercus* airborne pollen behaviour at the different sampling stations in Mexico City between January 2012 and June 2015 is shown in Table 1. Pollen concentrations with higher percentages of *Quercus* pollen were related to shorter periods of flowering, as occurred in 2012 when the flowering period duration was 3 months and the AQPIn fluctuated between monitoring stations. In 2014, the flowering period was 4–5 months (although the largest amounts of pollen were concentrated in March), with AQPIn values from 604 to 7333 pollen grains. In 2015, the flowering period of *Quercus* was 4–6 months. Meanwhile, in 2013, the year in which the lowest AQPIn values were recorded, the flowering period had a duration of 5–10 months (Table 1).

The percentage of pollen of *Quercus* with respect to the total of airborne pollen collected at the monitored stations generally showed that the highest concentrations were recorded in the years 2014 and 2012. The oak populations distributed in the study area with respect to the total collected pollen from the air provided an average of 7.0% (2012), 2.9%

**Table 1** Details of the following parameters: locality; year; and pollen indexes, including annual pollen integral (APIn), seasonal *Quercus* pollen integral (AQPIn), percentage (%) of pollen *Quercus* of the APIn, date of the beginning of flowering, date of the end of flowering, date of maximum concentration and maximum value (pollen grain/m$^3$ air)

| | Year | APIn | AQPIn | % of Quercus of the APIn | Date of the beginning of flowering | Date of the end of flowering | Date of maximum concentration | Maximum value (pollen grain/m$^3$ air) |
|---|---|---|---|---|---|---|---|---|
| Coyoacan | 2012 | 47,024 | 2,674 | 5.7 | 04/03/2012 | 24/05/2012 | 19/03/2012 | 156 |
| | 2013 | 22,420 | 385 | 1.7 | 24/02/2013 | 22/07/2013 | 28/03/2013 | 19 |
| | 2014 | 23,587 | 1,019 | 4.3 | 27/02/2014 | 21/05/2014 | 27/03/2014 | 72 |
| | 2015 | 22,954 | 953 | 4.2 | 27/02/2015 | 02/05/2015 | 17/04/2015 | 77 |
| Miguel Hidalgo | 2012 | 75,746 | 2,538 | 3.4 | 03/03/2012 | 25/05/2012 | 23/03/2012 | 136 |
| | 2013 | 44,451 | 1,034 | 2.3 | 28/02/2013 | 22/06/2013 | 19/04/2013 | 36 |
| | 2014 | 42,743 | 2,148 | 5.0 | 20/02/2014 | 26/05/2014 | 28/03/2014 | 147 |
| | 2015 | 41,819 | 1,506 | 3.6 | 23/02/2015 | 10/05/2015 | 13/04/2015 | 166 |
| Iztapalapa | 2012 | 16,421 | 1,352 | 8.2 | 29/02/2012 | 29/05/2012 | 23/03/2012 | 77 |
| | 2013 | 12,932 | 297 | 2.3 | 27/02/2013 | 20/11/2013 | 31/03/2013 | 13 |
| | 2014 | 12,909 | 604 | 4.7 | 23/02/2014 | 04/06/2014 | 24/03/2014 | 36 |
| | 2015 | 6,252 | 446 | 7.1 | 16/02/2015 | 05/05/2015 | 15/04/2015 | 23 |
| Cuajimalpa | 2012 | 58,550 | 7,355 | 12.6 | 02/03/2012 | 15/05/2012 | 20/03/2012 | 338 |
| | 2013 | 53,929 | 2,238 | 4.1 | 20/02/2013 | 26/06/2013 | 31/03/2013 | 88 |
| | 2014 | 54,591 | 7,333 | 13.4 | 27/02/2014 | 15/05/2014 | 24/03/2014 | 447 |
| | 2015 | 73,576 | 2,609 | 3.5 | 17/02/2015 | 07/05/2015 | 13/04/2015 | 205 |
| Gustavo A. Madero | 2013 | 19,193 | 445 | 2.3 | 18/02/2013 | 27/07/2013 | 18/04/2013 | 21 |
| | 2014 | 18,559 | 1,313 | 7.1 | 25/02/2014 | 24/05/2014 | 06/04/2014 | 172 |
| | 2015 | 17,767 | 976 | 5.5 | 09/02/2015 | 11/05/2015 | 15/04/2015 | 102 |

*APIn* annual pollen integral, *AQPIn* concentration for Quercus pollen, % percentage of concentration of Quercus pollen with respect to APIn

(2013), 8.8% (2014) and 4.0% (2015) in Mexico City (see figure on supplementary material).

Figure 2 shows the seasonal variation of *Quercus* pollen in the atmosphere of each of the five sampling sites (Cuajimalpa, Gustavo A. Madero, Chapultepec, Iztapalapa and Coyoacán) between 2012 and 2015. The seasonal variation indicates that the flowering and emission of pollen to the atmosphere began between February and March in all the sampling stations, constituting the months of March and April as the main flowering months, with concentrations that fluctuate strongly between the years and the sampling stations (Fig. 2). The maximum concentration of pollen of *Quercus* was recorded during March in Cuajimalpa in 2014, and in Coyoacan and Iztapalapa in 2012, whilst the maximum concentrations of airborne pollen obtained in the atmosphere of the delegations Gustavo A. Madero and Chapultepec were registered during April 2014 and 2015. The lowest concentrations of airborne pollen of *Quercus* were recorded during the months of March and April at all monitoring stations in 2013. The seasonal and intraday analysis was concentrated in the years of 2012 and 2014 because in these years, a large amount of *Quercus* pollen was found in the atmosphere of Mexico City (Fig. 3).

In 2012, the amount of pollen grains was distributed in March and April uniformly, whilst in 2014, it was concentrated in March. Interestingly, the total pollen amounts of the season (March and April) were quite similar at 15,772 pollen grains and 15,902 pollen grains in 2012 and 2014, respectively. The intraday variation computed for March (similar behaviour in both years) showed a maximum value at 20:00 h in 2012 and at 21:00 h in 2014, with the largest values recorded in 2014. Later, in the first hours of the morning between 5 and 6 am, there is a decreased concentration in the air until midday when it reaches a secondary maximum in both years.

## Quercus pollen and its relation to meteorological parameters

The analysis was performed for each of the study years. The correlation between *Quercus* pollen concentration during the MPS, pre-peak and post-peak periods and the main meteorological parameters (rainfall, relative humidity (RH), and the mean, maximum and minimum temperatures) in the atmosphere of Mexico City was significant in many cases (see table on supplementary material).

Generally, associations amongst airborne *Quercus* pollen and meteorological parameters were observed as follows: in 2012, significant correlations with temperature, rainfall and

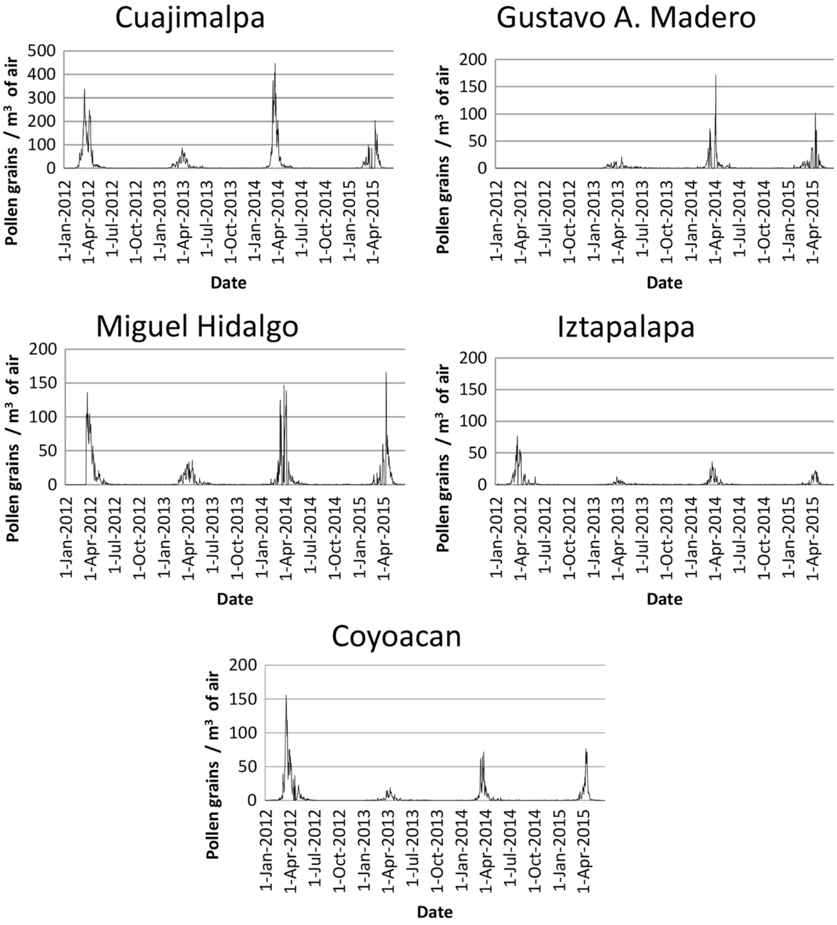

**Fig. 2** Seasonal variation of *Quercus* pollen in the atmosphere of Cuajimalpa, Gustavo A. Madero, Miguel Hidalg, Iztapalapa and Coyoacan during 2012 to 2015

humidity were negative, mainly in the MPS and post-peak periods. In 2013, the correlations for periods evaluated were significantly positive with temperature and negative with rainfall and RH for all three periods analysed. In 2014 and 2015, significant positive correlations were recorded for the average *T* during the MPS and post-peak periods, whilst the correlations with rainfall and RH were significantly negative for the same two periods.

## Daily Quercus pollen cycle and simulated wind conditions at Cuajimalpa for March 2012 and 2014

The surface circulation in Mexico City is dominated by a mountain-valley circulation, with down-slope converging winds that favour the transport and accumulation of pollen during the evening and night (Fig. 4, upper-left panel), and up-slope diverging weak winds from the morning to early

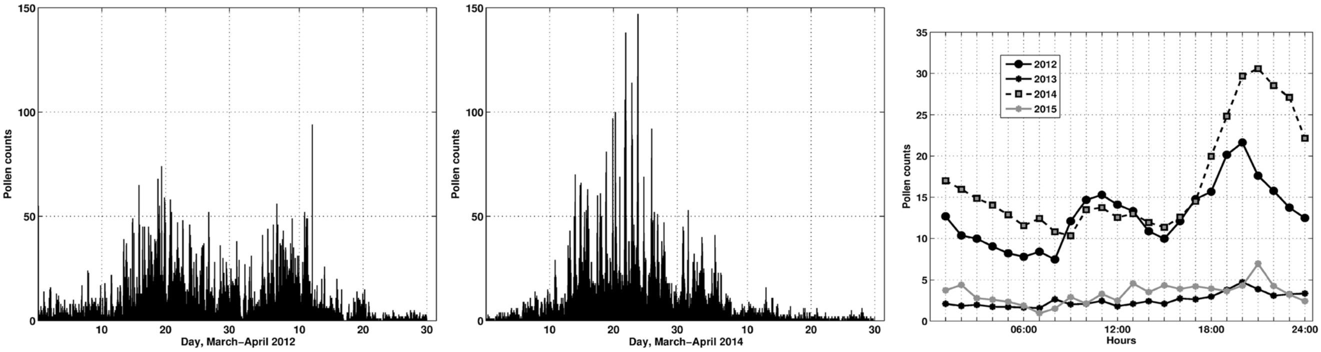

**Fig. 3** Hour-to-hour *Quercus* pollen variation at Cuajimalpa during the flowering months of March–April 2012 (*left panel*) and of March–April 2014 (*central panel*); each line corresponds to the pollen counts/hour/day. Daily cycles of pollen computed for March of years 2012 to 2015 (*right panel*). Note the largest pollen amounts registered in years 2012 and 2014

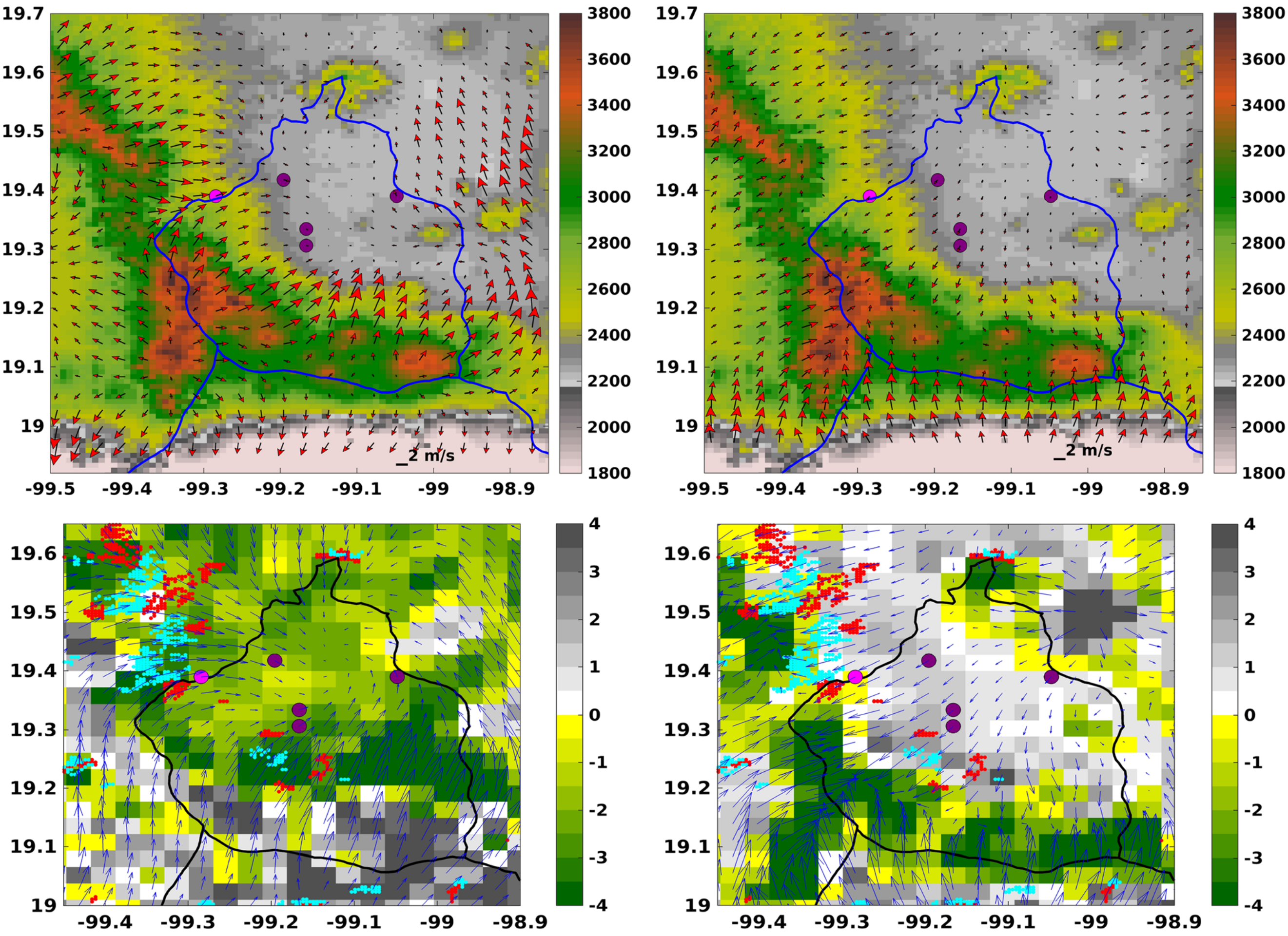

**Fig. 4** Simulated mean wind field for March 2014 at 02:00 h (*upper-left panel*) and 11:00 h (*upper-right panel*). In both panels, shading colours indicate altitude (m a.s.l.), which is used to illustrate the dominant mountain-valley circulation, with down-slope winds during the evening and night, and up-slope weak winds from the morning to early afternoon. The down-slope converging mean winds at 19:00 h (*lower-left panel*) favour the transport and accumulation of oak pollen from its primary (cyan dots) and secondary (red dots) forest towards Mexico City, whereas at 11:00 h, up-slope diverging winds dominate the surface circulation (*lower-right panel*). The Cuajimalpa monitoring station is indicated by the magenta circle. Other sampling stations are indicated by purple circles. The colour bar in the *lower panels* indicates divergence of the mean wind field (multiplied by $10^4$), with negative values meaning convergence of the wind field. Units are $s^{-1}$

afternoon that have the opposite effect on pollen transport and accumulation (Fig. 4, upper-right panel). Figure 4 (lower-left panel) shows the Quercus forests located in Mexico City and its surrounding areas (primary forest in cyan and secondary forest in red), with the simulated mean wind field at 19:00 h. It illustrates a possible way in which pollen released from anthers can be advected and dispersed by the wind and its convergence (areas in yellow to green colours). For example, pollen transported in the evening by down-slope converging winds towards Cuajimalpa (magenta circle) mainly comes from the closest forest located southwest and west from this sampling station. For the monitoring stations located in the central part of Mexico City (southernmost purple circles), pollen mainly comes from the forests located in the southwestern region, from where it is advected by down-slope southwesterly winds. At noon, a reversal of the surface circulation is evident (Fig. 4, lower-right panel), with northeasterly diverging winds dominating the surface circulation and precluding the pollen accumulation.

Figure 5 shows the daily cycles of pollen concentration registered at the Cuajimalpa station and of simulated wind vectors and their convergence for March 2012 and 2014. A visual inspection reveals that the pollen daily cycles are quite similar: they show two peaks of pollen concentration, a strong peak at approximately 20:00 h (local time) and a smaller one between 10:00 h and 11:00 h. There are, however, subtle differences that may be related to the simulated wind and its convergence, as this figure suggest. For example, pollen concentrations early in the morning were higher in 2014 than in 2012 and the main peak was also

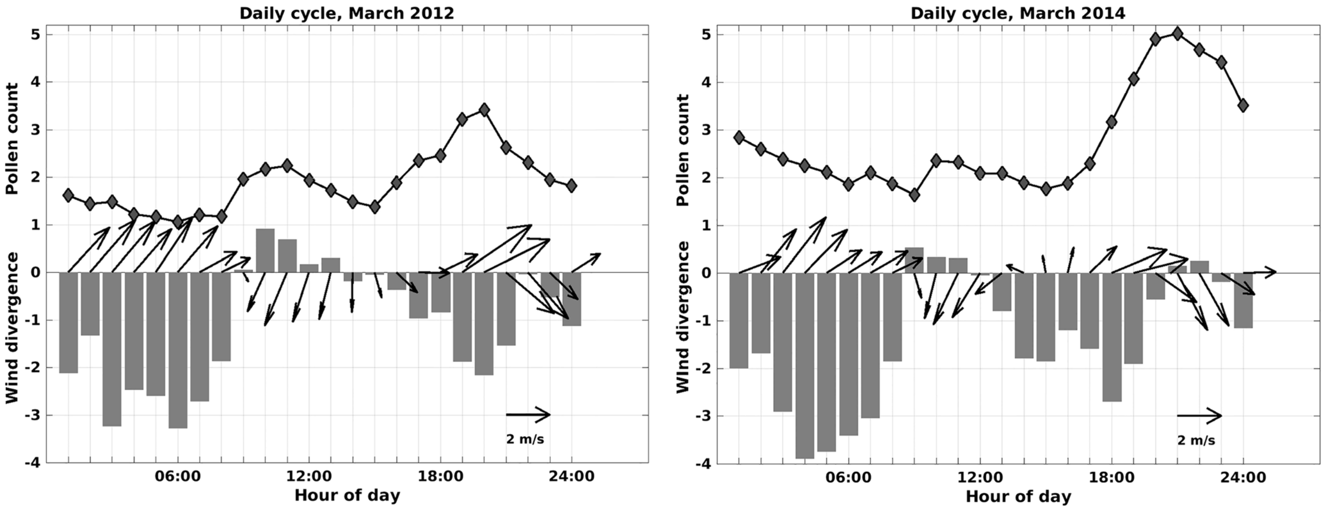

**Fig. 5** Daily cycle of pollen grain concentration (black line), surface winds (at 10 m, black arrows) and wind divergence (grey bars) at Cuajimalpa station for March 2012 (*left panel*) and for March 2014 (*right panel*). The *x* axis represents the hour of the day. The *y* axis represents both pollen grain concentration divided by 10 and wind divergence multiplied by $10^4$

significantly stronger in 2014, whilst the secondary peaks were of similar magnitude. From late night to morning, simulated SW winds with comparable magnitudes dominated Cuajimalpa in both years, but the wind convergence was also slightly higher in 2014 than in 2012.

In 2012 and 2014, the smaller peak in pollen concentration between 10:00 h and 11:00 h was associated with the change in both wind direction and magnitude that occurred at 09:00 h, when the weakest simulated SW winds switched to NW winds and then to NE winds at 10:00 h, increasing their magnitude (note that these NW and NE winds are divergent). NE wind reached a relative maximum magnitude at 11:00 h, coinciding with the lower peak in pollen concentration. In 2014, a period of simulated wind convergence began at noon and ended at 20:00 h (see Fig. 5), with the maximum peak pollen concentration occurring 1 h later. During this simulated convergence period, the wind changed in both magnitude and direction, blowing from the northeast at noon and then rotating clockwise from northeast to southwest in the subsequent hours, reaching its minimum magnitude at 15:00 h and then reaching its maximum in both magnitude and convergence at 18:00 h. In 2012, the simulated wind convergence was less prolonged, starting at 14:00 h with northerly winds before they rotated counterclockwise from north to southwest in the subsequent 6 h. The wind reached its maximum magnitude at 19:00 h and its maximum convergence at 20:00 h. Note that the simulated convergence maximum coincided with the pollen concentration maximum. Once the maximum was reached, the pollen concentrations started to decrease from 20:00 h (2012) and 21:00 h (2014), with lower values at night and early in the morning.

## Discussion

The quantities of oak pollen spread over the study area relative to the total collected pollen from the air showed annual variations in Mexico City. The annual *Quercus* pollen integral (AQPIn) showed variations in concentrations between localities and years, ranging from 297 to 7355 pollen grains/m$^3$ of air (annual). These concentrations of oak pollen are similar to those reported in other countries such as Spain between 2006 and 2008, where concentrations of oak pollen fluctuated between 3389 and 12,484 grains (Hernández Ceballos et al. 2011), as well as those reported by the University of Tulsa (http://pollen.utulsa.edu/Spring/Pollen/Quercus.htm) from 1987 to 1996, which reached maximum concentrations between 7656 (1994), 8862 (1991) and 10,271 (1996) annual pollen.

These variations are related to annual changes in the weather, to the phenology of such trees and also to the pollen of biennial species. Year 2011 was a very rainy year (1235 mm) with a low average minimum temperature (10.5 °C) (data not shown), which probably favoured the development of flower buds; as a result, in 2012, the flowering and pollen production in *Quercus* were high. In that year, the presence and dispersal of pollen in the air during the MPS and post-peak periods correlated with the decrease of both the prevailing temperature and the rainfall. In 2013, both precipitation (761.7 mm) and low temperature (12 °C) again favoured the development of pollen, which probably influenced the pollen production during flowering in 2014. In general, the presence of *Quercus* pollen in the atmosphere during that year was mainly associated with a decrease or absence of precipitation during the evaluated periods (pre-peak, MPS and post-peak). In brief, the main variables that had a positive effect on the emission and dispersion of pollen were the temperature and the hours of daylight, whilst the RH and rainfall had the highest negative effect. Likewise, in the present study, the association between the amount of airborne pollen of *Quercus* and the length of the flowering period (3–10 months) reflects the impact of the prevailing weather conditions before flowering. All this agrees with the findings reported by several authors (Recio et al. 1999; Rizzi-Longo et al. 2005; Rodriguez-Rajo et al. 2005; García-Mozo et al. 2006a, b; Calderón-Ezquerro et al. 2016).

Although the four well-defined seasons (spring, summer, autumn and winter) are not present in Mexico City and its conurbated areas, the conditions that favour the period of flowering of the oaks are reached during the hot dry season, and there is a similarity with the previously noted aerobiological reports for *Quercus* pollen. In this study, their MPS was recorded when there was a constant rise in temperature and extension of the photoperiod. Such conditions are analogous to the variation of light and temperature experienced by the populations of *Quercus* sp., prior to their flowering season, in other regions of the world.

These results are also consistent with those reported by several authors in studies that show that pollen release and dispersion depend on the microclimate, which explains the differences observed with respect to the beginning of flowering within the same species through the years (maximum concentration in 2014 and minimum in 2013; see Table 1) (Fernández-González et al. 1999; Galán et al. 2001; García-Mozo et al. 2007). In addition, there is the possibility of the influence of intrinsic physiological factors, and the observed accumulated annual differences observed maybe climate variability, which make it difficult to predict the level of pollen production (Galán et al. 1991). Also, the reproductive biology in *Quercus* species includes two different types of seed cycles, the "annual biotype", which requires only one season to complete its reproductive cycle, and the biennial biotype, which requires two full years (Varela and Valdiviesso 1996). Likewise, the findings found in this study coincide with what was reported for the floral phenology of many *Quercus* species, which is mainly influenced by temperature changes caused by the climate (Schwartz 2003).

The airborne oak pollen in Mexico City indicated that flowering and pollen emission into the air fluctuated between February and March until May and June, which is consistent with the findings reported in some aerobiological studies in Mexico City (Bronillet-Tarragó 1992; Salazar-Coria 1995; Torres-Valdos 2006) and in Monterrey (Rocha-Estrada et al. 2008), where the flowering period of oaks occurs from late February to late May.

In plants, dehiscence of the anthers is a mechanism regulated by the increase of temperature and by the decrease of the atmospheric humidity during the day. Together with this dehiscence, the exposure of pollen grains to air currents allows their release from the anthers and their dispersion into the atmosphere (Pacini 2008; Yang et al. 2009), conditions that determine the variation in the concentration of pollen in the air throughout the day. This phenomenon was also reported by other authors (Frenguelli et al. 1992; Bricchi et al. 1995; Rodriguez-Rajo et al. 2005), who determined that during the flowering period, meteorological conditions determine the opening of anthers and release of pollen, which is then dispersed in the air by the wind. Nevertheless, Rodriguez-Rajo et al. (2005), in their study on the "Factors affecting pollination ecology of *Quercus* anemophilous species", indicate that meteorological variables alone do not explain the aerobiological behaviour of pollen. Therefore, it is necessary to consider other variables that reflect factors that affect the plants and on which the production and release of pollen depend.

For Mexico City, the clear sky that predominates from February to May, the increase in temperature and the low humidity of the air make a difference in the amount of water present in the air during the morning and afternoon (Jáuregui 1963; Rzedowski and Rzedowski 2005). During the flowering season of the oaks, these conditions produced for *Quercus* are an intraday variation curve for Mexico City. In 2012 and 2014, when there were high concentrations of pollen in the air, it was possible to determine intraday variation observing variations throughout the day. This phenomenon seems to be due not only to the physiology of the plant and environmental parameters but also to the transport of airborne *Quercus* pollen from its primary and secondary sources (*Quercus* forest) (Fig. 1a).

Our results indicate that the subtle differences in the daily pollen cycles can be explained to a greater extent by the simulated wind fields and their convergence. In 2014, the simulated wind convergence was more intense and lasted longer than in 2012. From 16:00 h to 17:00 h, the wind convergence was dominated by simulated SW winds that favoured pollen transport from its closest secondary forest regions towards Cuajimalpa. At 20:00 h, the SW winds switched to NW winds, which were able to transport pollen from the primary forest (located in the north and northwest) towards Cuajimalpa. Thus, two processes can explain the pollen concentration maximum registered in 2014. First, pollen is carried by southwesterly converging winds from its nearby secondary forest towards Cuajimalpa. Afterwards, NW winds transport pollen from the more distant primary forest towards Cuajimalpa. Note that the simulated NW winds involved in the latter process converge only during the first hour (20:00 h) and then weakly diverge. Despite the favourable wind conditions late at night to further accumulate and transport pollen, the pollen amount decreases once the maximum is reached due to physiological and reproductive factors controlled by physical variables such as temperature and humidity (Galán et al. 1991; Rodriguez-Rajo et al. 2005). Clearly, this subject deserves a thorough study and this topic will be covered elsewhere.

In contrast, in 2012, transport of pollen by simulated SW winds from the closest secondary forest regions towards Cuajimalpa was possible only after 18:00 h. Two hours later, the maximum pollen concentration was reached without any apparent contribution from the primary forest located to the north and northwest of Cuajimalpa, despite the favourable wind conditions that could further increase the pollen amount. Thus, the timing of maximum pollen concentration seems to be strongly controlled by the pollen expulsion period. Regarding the maximum pollen concentration values, SW winds carrying pollen from secondary forest are crucial for the maximum values recorded in 2012 and 2014, also playing a key role in the advection of pollen from primary forest by NW winds in 2014, leading to the absolute maximum registered in that year.

## Summary

In this paper, we determine the aerobiological behaviour of *Quercus* pollen, and its transport by the simulated wind from the primary and secondary *Quercus* forests towards Mexico City and the surrounding areas between January 2012 and June 2015.

Airborne Quercus pollen monitoring was carried out simultaneously in five zones of the city: Coyoacan, Miguel Hidalgo, Iztapalapa, Cuajimalpa and Gustavo A. Madero. The percentage of *Quercus* pollen of the total pollen collected from the air showed that the highest concentration was recorded in Mexico City in 2014, followed by 2012. Oak populations distributed in the study area with respect to the total pollen collected from the air provided an average of 7.0% (2012), 2.9% (2013), 8.8% (2014) and 4.0% (2015) in Mexico City. The annual seasonal variation in airborne *Quercus* pollen indicated that flowering and pollen emission into the atmosphere began between February and March at all sampling stations, with the concentration strongly fluctuating amongst years and sampling stations. The maximum concentration of *Quercus* pollen was reached at Cuajimalpa, followed by Gustavo A. Madero, Miguel Hidalgo (Chapultepec), Coyoacán and Iztapalapa. In 2012, the amount of pollen grains was distributed in March and April uniformly, whilst in 2014, the largest amount of pollen was concentrated in March. The total pollen amounts of the season were quite similar, at 15,772 pollen grains and 15,902 pollen grains in 2012 and 2014, respectively. In general, the presence of *Quercus* pollen in the atmosphere during that year was mainly associated with meteorological parameters. In brief, the main variables with a positive effect on the emission and dispersion of pollen were the temperature and the hours of daylight, whilst the RH and rainfall had the highest negative effects.

In 2012 and 2014 (the years with the highest pollen concentrations), corresponding intraday variations were quite similar with a low relative maximum in the morning and the highest concentrations in the evening. The largest values were recorded in 2014, and two processes can explain these. In the afternoon, pollen from secondary forest is carried by the simulated southwesterly converging winds, increasing the pollen concentration in Cuajimalpa. In the evening, there is an additional pollen contribution from primary forest via transport by simulated NW winds.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

## References

Andersen TB (1991) A model to predict the beginning of the pollen season. Grana 30:269–275

Anenberg CS, Weinberger R, Roman H, Neumann J, Crimmins A, Fann N, Martinich J, Kinney P (2017) Impacts of oak pollen on allergic asthma in the United States and potential influence of future climate change. AGU Publications GeoHealth 1:80–92. https://doi.org/10.1002/2017GH000055

Bassett JI, Crompton CW, Parmelee JA.(1978) An Atlas of airborne pollen grains and common fungus spores of Canada. Que´bec: Supply and Services Canada

Bianchi M, Olabuenaga S (2006) A 3-year airborne pollen and fungal spores record in San Carlos de Bariloche, Patagonia, Argentina. Aerobiologia 22:247–257

Bricchi E, Frenguelli G, Mincigrucci G, Fornaciari M, Ferranti F, Romano B (1995) Time linkages between pol- lination onsets of different taxa over an 11-year period in Perugia, Central Italy. Aerobiologia 11:57–61

Bronillet-Tarragó I (1992) Estudio aeropolínico de la zona norte de la Ciudad de México en un ciclo anual. Tesis de Licenciatura. Facultad de Ciencias. Universidad Nacional Autónoma de México. México, D. F

Calderón C, Lacey J, McCartney A, Rosas I (1997) Influence of urban climate upon distribution of airborne Deuteromycete spore concentrations in Mexico City. Int J Biometeorol 40:71–80

Calderón-Ezquerro M, Guerrero-Guerra C, Martínez-López B, Fuentes-Rojas F, Téllez-Unzueta F, López-Espinoza E, Calderón-Segura M, Martínez-Arroyo A, Trigo-Pérez M (2016) First airborne pollen calendar for Mexico City and its relationship with bioclimatic factors. Aerobiologia 32:225–244

Challenger A, Soberón J (2008) Los ecosistemas terrestres, en Capital natural de México, vol. I: Conocimiento actual de la biodiversidad. Conabio, México

Duso M, Duso L, de Antoni Zoppas B, González M, Barrera R (2007) Airborne pollen calendar of Caxias do Sul (Rio Grande do Sul, Brazil), 2001-2002. Polen 17:51–65

Dvorin D, Lee J, Belecanech G, Goldstein M, Dunsky E (2001) A comparative, volumetric survey of airborne pollen in Philadelphia, Pennsylvania (1991-1997) and Cherry Hill, New Jersey (1995-1997). Ann Allergy Asthma Immunol 87:394–404

Eder W, Markus J, von Mutius E (2006) The asthma epidemic. N Engl J Med 355:2226–2235

Erdtman G (1952) Pollen morphology and plant taxonomy, angiosperms. Stockholm: Almqvist and Wiksell

Estrada F, Martínez-Arroyo A, Fernández-Eguiarte A, Luyando E, Gay C (2009) Defining climate zones in Mexico City using multivariate analysis. Atmosfera 22:175–193

Fernández-González D, Valencia-Barrera R, Vega A, Díaz de la Guardia C, Trigo M, Cariñanos P, Guardia A, Pertiñez C, Rodríguez-Rajo F (1999) Analysis of grass pollen concentrations in the atmosphere of several spanish sites. Polen 10:123–132

Frenguelli G, Bricchi E, Romano B, Mincigrucci G, Ferranti F, Antognozzi E (1992) The role of air temperature in determining dormancy release and flowering of *Corylus avellana* L. Aerobiologia 8:415–418

Frías-De León M, Duarte-Escalante E, Calderón-Ezquerro C, Jiménez-Martínez M, Acosta-Altamirano G, Moreno-Eutimio M, Reyes-Montes M (2016) Diversity and characterization of airborne bacteria at two health institutions. Aerobiologia 32:187–198

Galán C, Cariñanos P, Alcázar, P, Dominguez-Vilches E (2007) Spanish aerobiology network (REA) management and quality manual. Córdoba: Servicio de Publicaciones Universidad de Córdoba

Galán C, Cariñanos P, García-Mozo H, Alcázar P, Domínguez-Vilches E (2001) Model for forecasting *Olea europaea* L. airborne pollen in south-West Andalucia, Spain. Int J Biometeorol 45:59–63

García-Mozo H, Dominguez-Vilches E, Galán C (2007) Airborne allergenic pollen in a natural áreas Hornachuelos natural park, Córdoba. Southern Spain Ann Agric Environ Med 14:109–110

Galán C, Smith M, Thibaudon M, Frenguelli G, Oteros J, Gehrig R, Berger U, Clot B, Brandao R (2014) Pollen monitoring: minimum requirements and reproducibility of analysis. Aerobiologia 30:385–395. https://doi.org/10.1007/s10453-014-9335-5

Galán C, Ariatti A, Bonini M, Clot B, Crouzy B, Dahl A, Fernandez-González D, Frenguelli G, Gehrig R, Isard S, Levetin E, Li DW, Mandrioli P, Rogers CA, Thibaudon M, Sauliene I, Skjoth C, Smith M, Sofiev M (2017) Recommended terminology for aerobiological studies. Aerobiologia 33:293–295. https://doi.org/10.1007/s10453-017-9496-0

García-Mozo H, Galán C, Gómez-Casero M, Dominguez-Vilchis E (2000) A comparative study of different temperatura accumulation methods for predicting the start of the *Quercus* pollen season in Cordoba (south West Spain). Grana 39:194–199

García-Mozo H, Galán C, Jato V, Belmonte J, Díaz de la Guardia C, Fernández D, Gutierrez M, Aira M, Roure J, Ruiz L, Trigo M, Dominguez-Vilches E (2006a) *Quercus* pollen season dynamics in the Iberian peninsula: response to meteorological parameters and possible consequences of climate change. Ann Agric Environ Med 13:209–224

García-Mozo H, Pérez R, Fernández González F, Galán C (2006b) Airborne pollen sampling in Toledo, Central Spain. Aerobiologia 22:55–66

Galán C, Tormo CJ, Infante F, Domínguez E (1991) Theoretical daily variation patterns of airborne pollen in the southwest of Spain. Grana 30:201–209

Gomez-Casero MT, Hidalgp P, García Mozo HF, Domínguez E, Galán C (2004) Pollen biology in four mediterranean *Quercus* species. Grana 43:1–9

Hernández-Ceballos MA, García-Mozo H, Adame JA, Domínguez-Vilches E, Bolívar J, De la Morena BA, Galán C (2011) Determination of potential sources of *Quercus* airborne pollen in Córdoba city (southern Spain) using back-trajectory analysis. Aerobiologia 27:261–276

INEGI (2005) II conteo de poblacion y vivienda 2005. http://wwwinegiorgmx/est/contenidos/proyectos/ccpv/cpv2005/ Accessed January 2015

INEGI (2010) Mapa digital de México. Información de uso de suelo y vegetación. http://gaia.inegi.org.mx/mdm5/viewer. html. Accessed July 2015

Jato V, Rodriguez-Rajo F, Aira J (2007) Use of *Quercus ilex* subsp. ballota phenological and pollen production data for interpreting *Quercus* pollen curves. Aerobiologia 23:91–105

Jáuregui O (1963) Climatología. En Hidrología de la Cuenca del Valle de México. Comisión hidrológica de la cuenca del valle de México. Secretaría de Recursos Hidráulicos. México, D. F

Jáuregui E (2000) El clima de la ciudad de México. Instituto de Geografía, UNAM- Plaza y Valdés. México, 131 pp.

So HJ, Moon SJ, Hwang SY, Kim JH, Jang HJ, Jo JH, Sung TJ, Lim DH (2017) Characteristics of airborne pollen in Incheon and Seoul (2015–2016). Asia Pac Allergy 7:138–147

Kalnay E (2003) Atmospheric modeling, data assimilation and predictability: United States of America, Cambridge University Press

Kapp RO (1969) How to know pollen and spores. WM. In: C: Brown company publishers

Köhler W, Schachtel G, Voleske P (2007) Biostatistik Einführung für Biologen und Agrarwissenschaftler. In: Heidelberg: Springer-Verlag Berlin

Lacey ME, West JS (2006) The air Spora: a manual for catching and identifying airborne biological particles. Springer, Netherlands

Lake IR, Jones NR, Agnew M, Goodess CM, Giorgi F, Hamaoui-Laguel L, Semenov M, Solomon F, Storkey J, Vautard R, Epstein MM (2017) Climate change and future pollen allergy in Europe. Environ Health Perspect 125:385–391

Linkosalo T, Häkkinen R, Hänninen H (2006) Model of the spring phenology of boreal and temperate trees: is there something missing. Tree Physiol 20:1175–1182

Moore PD, Webb JA, Collinson ME (1991) Pollen analysis. 2da edicion. Blackwell Scientific Publications, London

Moreno-Grau S, Angosto J, Elvira-Rendueles B, Bayo J, Moreno J, Moreno-Clavel J (2000) Effects of meteorological parameters and plant distribution on Chenopodiaceae-Amaranthaceae, *Quercus* and *Olea* airborne pollen concentrations in the atmosphere of Cartagena (Spain). Aerobiologia 16:17–20

Pacini E (2008) Pollination. In Jorgensen S, Fath B (eds) Encyclopedia of ecology. 2nd edition. Elsevier 2857 – 2861pp

Parrado ZG, Barrera R, Rodriguez C, Maray A, Romero R, Fraile R, Gonzalez D (2009) Alternative statistical methods for interpreting airborne Alder (*Alnus glutimosa* (L.) Gaertner) pollen. Int J Biometeorol 53:1–9

Pla-Dalmau JM (1960) Estudios palinológicos y precisiones morfológicas sobre los granos de polen de quinientas especies bota nicas del extremo NE de España. PhD thesis. Facultad de Farmacia Universidad de Barcelona, Barcelona, España

Recio M, Trigo M, Toro J, Cabezudo B (1999) Incidencia del polen de *Quercus* en la atmósfera de Málaga y su relación con los parámetros meteorológicos. Acta Bol Malacitana 24:77–88

Ríos B, Torres-Jardón R, Ramírez-Arriaga E, Martínez-Bernal A, Rosas I (2016) Diurnal variations of airborne pollen concentration and the effect of ambient temperature in three sites of Mexico City. Int J Biometeorol 60:771–787

Rizzi-Longo L, Pizzulin-Sauli M, Ganis P (2005) Aerobiology of Fagaceae pollen in Trieste (NE Italy). Aerobiologia 21:217–231

Rocha-Estrada A, Alvarado-Vázquez M, Torrres-Cepeda T, Foroughbakhch-Pournavab R (2008) Principales tipos polínicos presentes en el aire de la zona norte del área metropolitana de Monterrey, Nuevo León. Ciencia UANL 11:69–76

Rodriguez-Rajo F, Méndez J, Jato V (2005) Factors affecting pollination ecology of *Quercus* anempophilious species in north-West Spain. Bot J Linn Soc 149:283–297

Romano B, Mincigrucci C, Frenguelli G, Bricchi E (1988) Airborne pollen content in the atmosphere of Central Italy (1982-1986). Cell Mol Life Sci 44:625–626

Rzedowski G, Rzedowski J (2005) Flora fanerogámica del Valle de México. Instituto de Ecología, AC. Y Comisión Nacional para el Conocimiento y Uso de la Biodiversidad. Pátzcuaro, Michoacán. (Digital Edition: INECOL2010). http://www.biodiversidad.gob.mx/publicaciones/librosDig/librosDig2.html Accessed December 2014

Salazar-Coria L (1995) Estudio anual de polen atmosférico en la zona sur de la Ciudad de México. Tesis de Licenciatura. Escuela Nacional de Estudios Profesionales Iztacala, Universidad Nacional Autónoma de México. México, D. F

Schueler S, Schlünzen KH (2006) Modeling of oak pollen dispersal on the landscape level with a mesoscale atmospheric model. Environ Model Assess 11:179–194

Schwartz H (2003) Phenology: an integrative environmental science. Kluwer Academic Publishers, Netherlands

Skamarock W, Klemp J, Dudhia J, Gill D, Barker D, Wang W, Powers J (2008) A description of the advanced research WRF version 3 (No. NCAR/TN-475+ STR). National Center For Atmos Res Boulder Co Mesoscale and Microscale Meteorology Div

SMADF (2011) Secretaría del Medio Ambiente del Distrito Federal. Catálogo de especies vegetales producidas en los viveros Nezahualcóyotl y Yecapixtla. Árboles http://www.sma.df.gob.mx/plantas/index.php?op=consultas&ext=php&sub=tipo&selec=2. Accesed july 2015

Smith E G (2000) Sampling and identifying allergenic pollen and molds. An illustrated identification manual for air samplers. Texas, USA

Sofiev M, Bergmann K (2013) Allergenic pollen: a review of the production, release, distribution and health impacts. Springer, Netherlands

Spieksma F, Corden M, Etandt M, Millington W, Nikkels H, Nolard N, Schoenmakers C, Wachter R, de Weger L, Willems R, Emberlin J (2003) Quantitative trends in annual totals of five common airborne pollen types (*Betula*, *Quercus*, Poaceae, *Urtica*, and *Artemisia*), at five pollen-monitoring stations in western Europe. Aerobiologia 19: 171–184

Tejera L, Beri A (2005) First volumetric airborne pollen sampling in Montevideo City, Uruguay. Aerobiologia 21:33–41

Tormo-Molina R, Silva Palaciso I, Muñoz Rodríguez A, Gallardo López F (1996) Pollen production in anemophilous trees. Grana 35:38–46

Torres-Valdos J (2006) Determinación de los agentes principales de polinosis en la Ciudad de México. Tesis de Posgrado. Universidad Nacional Autónoma de México. México D. F

Trigo M (2007) El polen en la atmósfera de Vélez-Málaga Concejalía de Medio Ambiente. España: Ayuntamiento de Vélez-Málaga

Trigo M, Jato V, Fernández D, Galán C (2008) Atlas aeropalinológico de España. España: Secretariado de publicaciones de la Universidad de León

Valencia A (2004) Diversidad del género *Quercus* (Fagaceae) en México. Bol Soc Bot Méx 75:33–53

Varela M, Valdiviesso T (1996) Phenological phases of *Quercus suber* L. Flowering For Genet 3:93–102

Villegas G, Nolla J (2001) Atmospheric pollen in Santiago, Chile. Grana 40:126–132

Weryszko-Chmielewska E, Piotrowska K (2004) Airborne pollen calendar of Lublin. Poland Ann Agric Environ Med 11:91–97

Wozniak M, Steiner A (2017) A prognostic pollen emissions model for climate models (PECM1.0). Geosci Model Dev 10:4105–4127

Yang C, Song J, Marshal A, Bradley G, Wilson Z (2009) Establishing regulatory models for anther endothecium development and the regulation of dehiscence. In: 20th International Conference on Arabidopsis Research Edinburgh, UK