



Five-year airborne pollen calendar for a Sonoran Desert city and the relationships with meteorological variability

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Abstract

Aerobiological studies are still scarce in northwestern Mexico where allergenic pollen have great impacts on health. Current global pollution and climate change problems are closely related to many allergic diseases, enhancing the need to continue researching these issues and improve life quality. This study provides the first Pollen Calendar for Hermosillo, Sonora, México. Airborne pollen were continuously collected for 5 years (2015–2019). The standardized methodology with a Hirst-type spore trap proposed for global aerobiological studies was used. Weather data were also taken from a station located in the city and used to explore correlations between climate and airborne pollen concentrations in different seasons. The most important pollen taxa recorded in air belongs to herbaceous pollen, such as Poaceae, *Ambrosia*, Asteraceae, Chenopodiaceae-Amaranthaceae, and some shrub trees typical of this arid region, such as Nyctaginaceae, *Prosopis*, *Parkinsonia*, and Fabaceae. The most critical herbaceous pollen related to allergies have a long mean pollen season throughout the years, and the most critical periods with high pollen concentration in air occur in two seasons, spring (March–April) and summer–fall (August–October). In these 5 years, the correlation analyses for these two peaks indicate that a link exists between pollen in the air and decreases in precipitation and temperatures, and an increase in relative humidity. An inter-annual variability in pollen concentrations was recorded related to different weather conditions. Although pollen calendars are location-specific, they are useful for future research on biological air quality scenarios in different cities. Using this standardized method for other regions can provide pollen calendars that have been proven clinically important in allergic disease management worldwide.

Keywords Aerobiology · Pollen calendar · Desert city · Meteorological variability · Allergies · Human health

Introduction

Allergy prevalence has been rising in recent decades (D'Amato et al. 2015). Allergic rhinitis affects humans globally, including 10–30% of adults and up to 40% of children, which accounts for 400 million people worldwide (Pawankar

et al. 2011). Allergenic pollen is the most important cause of these diseases (Sénéchal et al. 2015; Sofiev and Bergmann 2013). Pollen—one of the most common sources of outdoor allergens—is too big (10 to 100 μm) to penetrate the airways, but it can release cytoplasmic granules following contact with water. Due to the small size (3 μm) of pollen granules, they can form a respirable aerosol capable of reaching deep airways (Motta et al. 2006). A normal person inhales approximately 14–15 m^3 of air daily, which contains many atmospheric and biological constituents, including O_3 , SO_2 , NO_2 , CO particulate matter, pollen, and spore grains. Thus, air contaminants are associated with diseases, such as asthma and hay fever, and older and younger populations are at the highest risk from these pollutants (Rahman et al. 2019).

For instance, increased carbon dioxide (CO_2) atmospheric concentration jointly with temperature increases due to climate change have been observed to promote allergenic plant

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productivity and thus allergenic pollen production (Ariano et al. 2010; Ghiani et al. 2012). In this sense, the variability of pollen concentrations in the air should be monitored for long periods in urban areas to obtain accurate information about what allergenic pollen types are the most important, and overall, the season of the year these aeroallergens reach higher concentrations (Buters et al. 2018). Furthermore, this information is crucial for clinical studies to establish the prevalence and possible allergen contributions to allergic disorders, such as allergic rhinitis and pollinosis, occurring in the population (Camacho et al. 2019). Aerobiological studies are a type of multidisciplinary research that involves principally sampling air quality and public health, but their applications also include immunology research, environmental protection, agriculture, beekeeping, meteorology, or monument protection (Myszkowska 2020). The importance of aerobiology related to public health is the possibility of obtaining pollen calendars from cities that show the temporal and spatial distributions of allergenic pollen types, which are important in the diagnosis and management of allergic diseases (Lo et al. 2019). The relevance of pollen calendars is that they show, in a simple way, the different kinds of allergenic pollen, their distribution, timing, and concentration in a given area. Additionally, they are helpful for allergy sufferers and clinicians to identify potential triggers, guide diagnostic testing, and initiate appropriate therapies (Katotomichelakis et al. 2015). Thus, a pollen calendar should be constructed and include at least 5 years of continuous data for one region (Galán et al. 2017; Sofiev and Bergmann 2013).

Pollen calendars in different cities and countries (e.g., Camacho et al. 2019; Martínez-Bracero et al. 2015; Rodríguez-de la Cruz et al. 2015) have shown to be most useful with at least 5 years of continuous data. In Mexico, two of them have been published for Mexico City, one in Coyoacan Town Hall (Calderón-Ezquerro et al. 2015) and another one in Miguel Hidalgo Town Hall, (Calderon-Ezquerro et al. 2018). This study is the first pollen calendar for the desert city of Hermosillo in the northwestern state of Sonora, Mexico, and is useful for public health officials, academics, and allergic individuals in the community. Thus, this research aims to provide information that helps the public health sector and population, in general, to develop prevention strategies and promote therapy in advance of high allergenic pollen loads in the air.

For the state of Sonora, the rates of rhinitis or allergic-related diseases are higher compared to other cities in Mexico (López-Romero et al. 2017). One study of children (from 5 to 17 years old) showed that from 125 patients undergoing an allergic sensitization test, 47.2% had allergies, with asthma being a common diagnosis. Furthermore, the extramural allergens showed greater sensitization when compared to other allergens. The prevalence of sensitization in pediatric patients in Mexican states is above the World Health

Organization (WHO) statistics worldwide (around 20%). The population in Hermosillo is exposed to many allergens, and the manifestations of sensitization involve frequent visits to the emergency services, and in some cases, prolonged hospital stays (Lopez-Romero et al. 2017). Therefore, this research aims to provide accurate information about the types, concentrations, and pollen seasons for the public health sector and allergenic population through the publication of a pollen calendar.

The relationships between weather variables and airborne pollen concentration in the atmosphere are also included since they are useful for future research on biological air quality scenarios within cities with variable environmental conditions. Particularly, the variables of temperature, relative humidity, and precipitation are emphasized. These variables are important because they directly impact plant phenology with the potential to also affect airborne pollen concentrations and distribution and influence pollen season length (Schramm et al. 2021; Garcia-Mozo 2017). Additionally, due to the environmental characteristics of this desert city, the climate is a determinant of air quality.

Materials and methods

Study region

This study was developed in Hermosillo, the capital city of Sonora located within the Sonoran Desert (29° 05.02' N, 110° 57.56' W) (Fig. 1). The geomorphology of this area comprises valleys, hills, and mountains aligned NNW-SSE, where peaks of up to almost 700 m high can occur. The Sonoran Desert harbors a high biodiversity (Van Devender and Reina-Guerrero 2021) because of its geographical location between the Holarctic and Neotropical zones. The aerobiological monitoring station is located in the northern part of the city at UES (Universidad Estatal de Sonora) on the roof (~20 m above ground level) of a building (Fig. 1). The climate in Hermosillo is a transition of two types (García 2004): very dry and very warm BW(h') and very dry and semi-warm (BWh). Climate data from the most complete station (54 years: 26139 Hermosillo II) shows that the average annual temperature is 24.9 °C; the annual thermal oscillation is 14.5 °C with July being the hottest month with an average of 31.9 °C and December the coldest month with an average of 17.4 °C. The annual precipitation is 363.5 mm with summer rains dominating and winter rains representing only 10.4% of the total. The most important vegetation types in the surroundings of the city are thornscrub and sarcocaul scrub with representative species including *Prosopis glandulosa*, *Parkinsonia microphylla*, *P. praecox*, *Olneya tesota*, *Larrea tridentata*, *Celtis pallida*, *Encelia farinosa*, *Lophocereus schottii*, and *Opuntia fulgida*, and many different grass

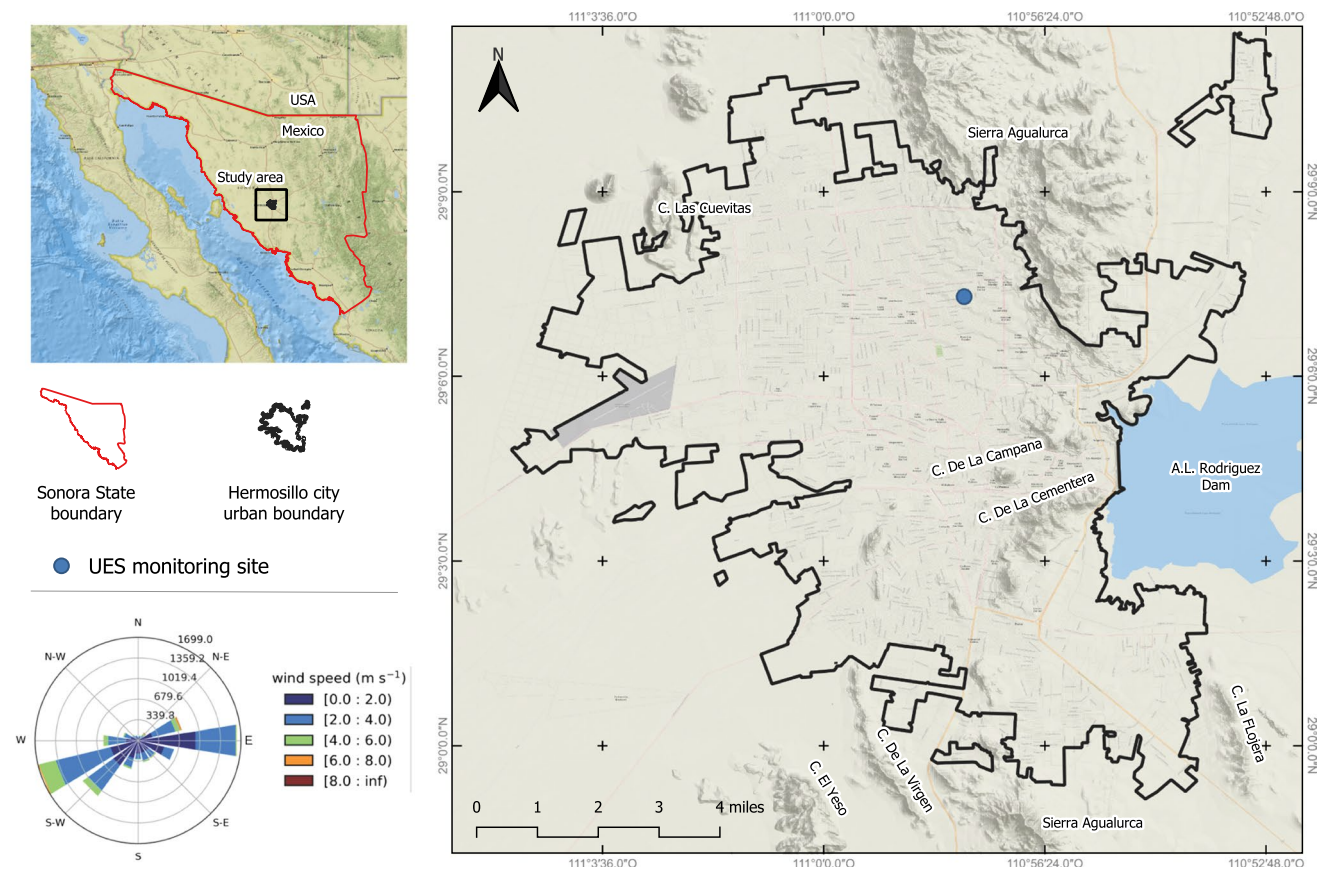


Fig. 1 Map of the study site showing the state of Sonora in northwestern Mexico (made by the authors) and the wind rose for 30-year data from Hermosillo (made by the authors with meteorological data from an automatic weather station close to the sampling site)

species, of which the most important is *Pennisetum ciliare* (introduced buffel grass) (INEGI 2020).

Sampling airborne pollen

A standard sampling method proposed by REA (Red Española de Aerobiología, in English Spanish Aerobiology Network) (Galán et al. 2007) and used by REMA (Red Mexicana de Aerobiología, in English Mexican Aerobiology Network) was applied. Atmospheric pollen and spores were sampled daily from January to December for 5 years (2015–2019), using a Hirst-type (Hirst 1952) volumetric spore trap (Burkard; <http://www.burkard.co.uk>). The Hirst-type spore trap was adjusted to aspirate 10 L air min⁻¹. Pollen were trapped on a Melinex (DuPont Teijin Films™, Tokyo, JP) tape coated with adhesive (silicone fluid). Pollen on Melinex tape segments were counted daily using an optical microscope with four longitudinal sweeps per slide and 400× magnification. Therefore, daily concentrations of pollen were obtained expressed as pollen grains/m³ (Galán et al. 2017). Additionally, the Annual Pollen Integral (API_n)—defined as the amount of recorded airborne pollen during a

year (Sofiev and Bergmann 2013; Galán et al. 2017)—was calculated.

The main pollen season (MPS) was calculated and defined as the duration of time when pollen is present in the atmosphere in significant concentrations at a location (Galán et al. 2017). In this case, the MPS for the most abundant pollen types was obtained based on Andersen (1991). The MPS represented 95% of the annual total, beginning on the first day with a cumulative daily calculation of 2.5% of the annual figure and ending when 97.5% of the annual total had been accounted for. For this region the range of daily values determined for pollen in the air was based on the percentiles of total concentrations: from 1–15 pollen grains/m³ (low level, below the 50th percentile), 16–50 pollen grains/m³ (moderate level, between the 50th and 75th percentile), 51–400 pollen grains/m³ (high level, between 75 and 99th percentile) and > 400 pollen grains/m³ (very high level, above the 99th percentile) (Table 3 supplementary material). This range is based on the method reported for Mexico (Calderón-Ezquerro et al. 2015) and data from previously published studies which have found that mild allergy symptoms are observed at relatively low pollen concentrations of 10–20 pollen grains/m³, moderate symptoms at 50–90 pollen

grains/m³, and severe symptoms at 80–90 pollen grains/m³ (Lo et al. 2019; Rapiejko et al. 2007; de Weger et al. 2013).

Pollen calendar construction

The pollen calendar was constructed by following Spieksma's model (Spieksma and Wahl 1991). It transforms 10-day mean pollen concentrations into a series of classes according to Stix and Ferretti (1974) and represents the series in a pictogram that includes columns of a different color according to the concentration shown (the higher the concentration is, the darker the color is). Each month is divided into three parts, and the average for each year is calculated. Only taxa that showed a minimum 10-day mean equal to or greater than 1 pollen grains/m³ of air were included.

Weather variables

Data was collected from a weather station close to the sampling site. Automated measurements include precipitation (PREC), relative humidity (RH), pressure (PRS), dew point (Td), mean maximum temperature (Tmax) and mean minimum temperature (Tmin) wind speed (ws), and wind direction (dir), taken once every 10 min. Daily mean values were computed from available records. Zonal wind (along latitude parallels) was calculated as $UWN = ws \times \cos(\text{dir})$, while meridional wind (along longitude meridians) as $VWN = ws \times \sin(\text{dir})$.

Correlation analysis

Spearman correlation coefficients were calculated between pair of samples of daily average pollen concentrations collected from the air (i.e. Poaceae, Ambrosia, Nyctaginaceae, Chenopodiaceae-Amaranthaceae, Ulmaceae, Cupressaceae, Urticaceae, and Parkinsonia) and the following daily meteorological variables: precipitation (PREC), relative humidity (RH), pressure (PRS), dew point temperature (Td), zonal wind (UWN), meridional wind (VWN), maximum temperature (Tmax) and minimum temperature (Tmin). Calculations were made considering all total accumulated pollen concentrations.

Additionally, for more detail, Spearman's correlation analyses were performed using lagged data between pollen type records and RH, and pollen type records and UWN and VWN. Computations were performed allowing a delay from 0 to 90 days between the predictor (i.e. RH and UWN, VWN) and the criterion (airborne particles) in the following cases: (1) daily values for the whole period (1 January 2015–31 December 2019, $n = 364 \times 4 + 366 = 1826$ sample pairs); (2) annual cycle (1 January–31 December daily climatology, $n = 365$); (3) cold months (1 November–31 March daily climatology in winter, $n = 151$); and (4) warm months

(1 July–31 October daily climatology in summer, $n = 123$). In the last three cases, daily climatology results (i.e. averages of daily meteorological variables) were obtained by averaging each calendar day from 2015 to 2019 period to get 365 mean daily values. Correlations were performed in this manner because statistically significant relationships between two variables do not result from the zero-lag correlations. Instead, some lag-time correlations may explain significant correlations between variables when zero-lag correlations show no statistical significance. Thereby, the strength of the linear correlation between variables is lagging n -days. This case explains, for example, that samples of airborne particles result from air transport that took place some days before.

Results

A total of 41 different pollen types were recorded in the atmosphere of Hermosillo, Sonora, México from 2015 to 2019. However, only 16 pollen taxa of allergenic importance were recorded with high concentrations in the air (Table 1, Supplementary material). Among the most important dominant airborne pollen concentration taxa were: Nyctaginaceae mean 12.5%, Ulmaceae and Cupressaceae with 4% each, Urticaceae 3.8%, *Parkinsonia* 3.2% and *Prosopis* 2.3%. For the herbaceous plants, the most important taxa were: Poaceae 33%, *Ambrosia* 16%, and Chenopodiaceae-Amaranthaceae 12%; these herbaceous taxa accounted for 61% of 5-year average Annual Pollen Integral (APIn).

The average APIn for the 5 years studied was 12,647. The highest total pollen level was attained in 2015, with an APIn of 32,887 (Table 1). Overall, high variability was observed regarding monthly pollen concentrations. Monthly and annual values of total pollen during the sampled years are shown in Table 1 and Fig. 2. The 5-year average airborne pollen shows two periods with the highest allergen concentrations in the air (Fig. 2) during spring (March) and late summer (August–September). Some interannual changes were detected (Table 2 supplementary material, Fig. 2): the highest monthly pollen concentrations occurred in August 2015 (24%) and 2016 (36%), whereas for 2017 it occurred in March (45%), and for 2018 (21%) and 2019 (24%) the highest concentrations occurred in September (Table 1).

The characteristics of the Main Pollen Season (MPS) for the most important taxa are shown in Table 2. The annual variation of airborne pollen indicates that concentrations increase from February to April primarily for herbaceous species whereas for tree species they increase both from February to April and from August to October (for example, see Nyctaginaceae and Cupressaceae, Table 2).

The most commonly collected airborne herbaceous pollen types were those of Poaceae (33%), *Ambrosia* (16%), and Chenopodiaceae-Amaranthaceae (12%), which are present

Table 1 Monthly and annual values (total and percentages) of total pollen in Hermosillo, Sonora, Mexico during the years (2015–2019) studied and 5-year averages

	POLLEN											
	2015		2016		2017		2018		2019		Average (2015–2019)	
	Total	%	Total	%	Total	%	Total	%	Total	%	Total	%
January	284	0.86	22	0.31	107	1.11	167	2.29	93	1.45	135	1.07
February	1065	3.24	107	1.53	465	4.82	155	2.12	115	1.79	381	3.02
March	6104	18.56	379	5.42	4357	45.17	1352	18.50	465	7.24	2531	20.01
April	2555	7.77	419	6.00	935	9.70	274	3.75	1317	20.55	1100	8.70
May	794	2.41	104	1.48	178	1.84	123	1.68	159	2.48	271	2.15
June	1382	4.20	351	5.03	143	1.48	320	4.38	76	1.19	454	3.59
July	2895	8.80	783	11.21	418	4.33	302	4.14	133	2.08	906	7.17
August	8029	24.41	2498	35.78	1127	11.68	792	10.84	439	6.84	2577	20.38
September	2969	9.03	403	5.77	1366	14.16	1542	21.09	1545	24.10	1565	12.37
October	5297	16.11	1571	22.51	325	3.37	1153	15.77	1444	22.52	1958	15.48
November	1093	3.32	273	3.91	131	1.36	974	13.32	479	7.47	590	4.66
December	421	1.28	73	1.04	94	0.97	155	2.12	146	2.28	178	1.41
APIn	32887	100	6981	100	9645	100	7311	100	6412	100	12647	100

Note: Bold numbers indicates the month where the highest percentage of airborne pollen concentration is reached for each year of monitoring

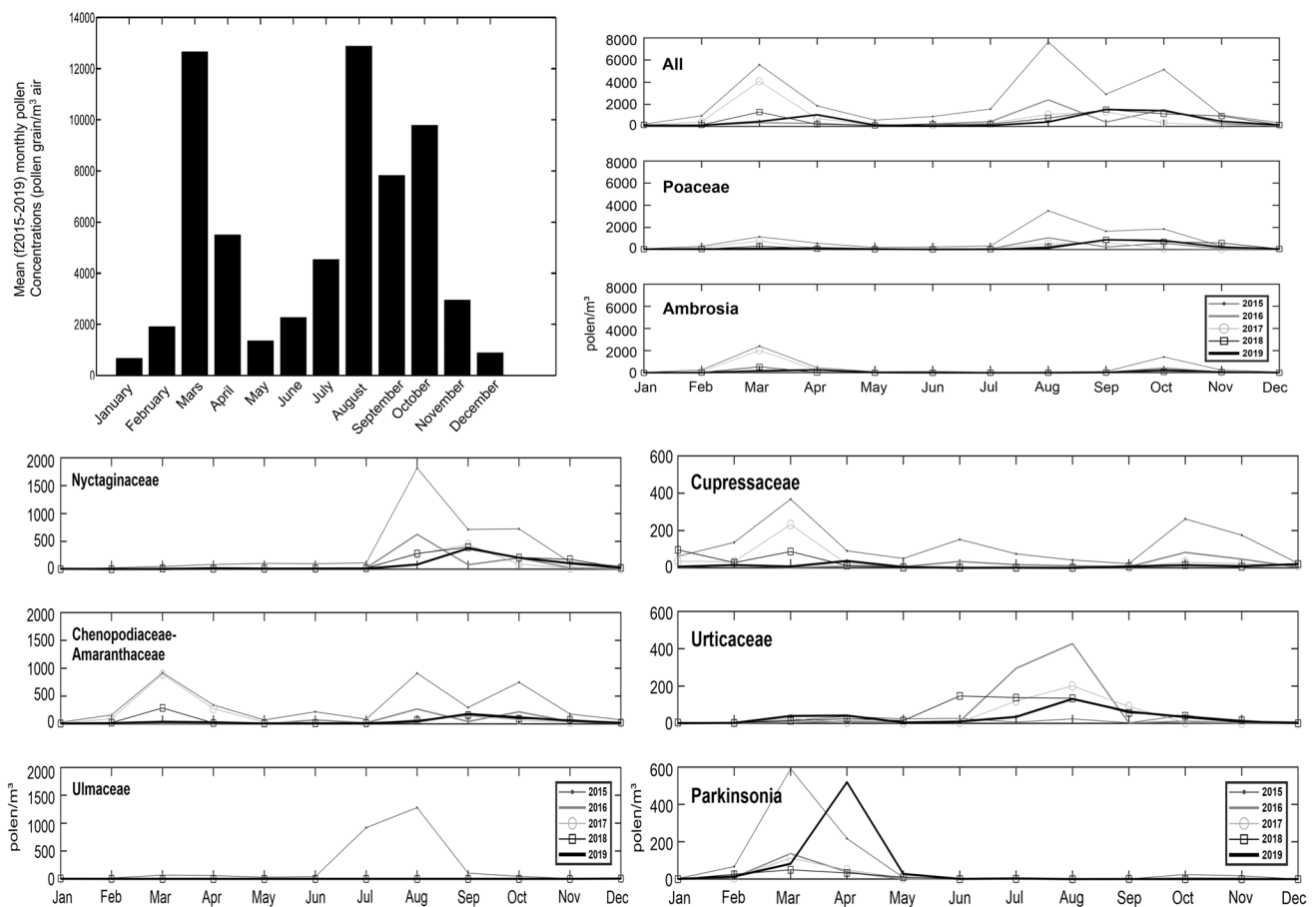


Fig. 2 Upper left-graph shows Mean annual pollen concentrations (pollen grain/m³ air) in Hermosillo, Sonora, México by month for the period 2015–2019. The rest of the graphs show frequencies of the most important allergenic taxa in Hermosillo, Sonora, México from

2015 to 2019. Y-values represent mean total pollen concentrations by month (pollen grain/m³ air). Each curve represents each year of analysis

Table 2 Characteristics of the main pollen season (MPS) for the most important taxa in Hermosillo, Sonora, Mexico starting and ending dates, season length, maximum daily value and date, and number of days with daily pollen concentrations over an allergenically significant value

Pollen taxa / Year	POLLEN				
	2015	2016	2017	2018	2019
Poaceae					
Pollen season	4 Feb-22 Nov	13 Feb-4 Apr; 1 Aug-10 Nov	08 Feb-14 Apr; 21 Jul-2 Oct	26 Feb-19 Mar; 19 Aug-14 Dec	22 Mar-14 Apr; 27 Aug-27 Nov
Season length	272 days	18 days; 76 days	66 days; 74 day	19 days; 104 days	24 days; 81 days
Maximum daily value (Date)	31 Aug (400.96 pg/m ³)	30 Aug (134.4 pg/m ³)	15 Sep (66.98 pg/m ³)	1 Sep (105.32 pg/m ³)	2 Sep (101.54 pg/m ³)
Annual Pollen Index (API _n)	5329 pg/m ³	2413 pg m ³	2626 pg/m ³	3093 pg/m ³	2542 pg/m ³
Five-year average (%)	33%	33%	33%	33%	33%
No. of days 3–50 pg/m ³	242 days	117 days	65 days	149 days	137 days
No. of days >50 pg/m ³	59 days	8 days	7 days	9 days	8 days
Ambrosia sp.					
Pollen season	13 Feb-3 Jul 27 Sep-18 Dec	14 Feb-6 Mar; 26 Sep-9 Nov	22 Feb-1 May	26 Feb-20 Mar; 26 Oct-13 Nov	23 Mar-20 Apr; 8 Oct-15 Nov
Season length	117 days; 56 days	12 days; 45 days	69 days	16 days; 16 days	29 days; 33 days
Maximum daily value (Date)	11 Mar (255.36 pg/m ³)	4 Oct (34.72 pg/m ³)	11 Mar (318.13 pg/m ³)	2 Mar (118.29 pg/m ³)	31 Mar (39.43 pg/m ³)
Annual Pollen Index (API _n)	5332 pg/m ³	766 pg/m ³	2513 pg/m ³	788 pg/m ³	847 pg/m ³
Five-year average (%)	16%	16%	16%	16%	16%
No. of days 3–50 pg/m ³	158 days	60 days	63 days	34 days	63 days
No. of days >50 pg/m ³	26 days	0 days	11 days	4 days	0 days
Nyctaginaceae					
Pollen season	20 Apr-21 Nov	2 Aug-23 Oct	8 Aug-9 Oct	13 Aug-29 Nov	1 Sep-29 Oct
Season length	142 days	57 days	63 days	96 days	55 days
Maximum daily value (Date)	25 Aug (158.48 pg/m ³)	24 Aug (72.24 pg/m ³)	7 Sep (34.57 pg/m ³)	28 Aug (49.15 pg/m ³)	2 Sep (28.09 pg/m ³)
Annual Pollen Index (API _n)	3921 pg/m ³	1025 pg/m ³	948 pg/m ³	1166 pg/m ³	865 pg/m ³
Five-year average (%)	12%	12%	12%	12%	12%
No. of days 3–50 pg/m ³	154 days	52 days	66 days	93 days	74 days
No. of days >50 pg/m ³	20 days	2 days	0 days	0 days	0 days
Chenopodiaceae-Amaranthaceae					
Pollen season	14 Feb-26 Nov	12 Aug-1 Nov	21 Feb-1 May; 26 Aug-6 Oct	26 Feb-20 Mar; 22 Aug-13 Nov	25 Aug-3 Sep
Season length	203 days	56 days	60 days; 42 days	11 days; 65 days	66 days
Maximum daily value (Date)	21 Jul (161.84 pg/m ³)	10 Jun (32.48 pg/m ³)	14 Mar (233.33 pg/m ³)	15 Mar (113.43 pg/m ³)	12 Sep (18.36 pg/m ³)
Annual Pollen Index (API _n)	4034 pg/m ³	714 pg/m ³	1701 pg/m ³	798 pg/m ³	548 pg/m ³
Five-year average (%)	12%	12%	12%	12%	12%
No. of days 3–50 pg/m ³	222 days	62 days	101 days	67 days	61 days
No. of days >50 pg/m ³	15 days	0 days	2 days	1 days	0 days
Ulmaceae					
Pollen season	14 Mar-18 Mar; 1 Jul-10 Sep	1-22 Jul	4-31 Mars	4-30 Mars	27-30 Dec
Season length	5 days; 68 days	22 days	27 days	26 days	3 days
Maximum daily value (Date)	21 Jul (161.84 pg/m ³)	8 Jul (19 pg/m ³)	28,29,30 Sep (1.08 pg/m ³)	4 Jan (3.24 pg/m ³)	28,29,30 Dec (61.57 pg/m ³)
Annual Pollen Index (API _n)	3302 pg/m ³	136 pg/m ³	43 pg/m ³	17 pg/m ³	6 pg/m ³
Five-year average (%)	4%	4%	4%	4%	4%
No. of days 3–50 pg/m ³	85 days	0 days	0 days	1 days	0 days
No. of days >50 pg/m ³	15 days	0 days	0 days	0 days	0 days
Cupressaceae					
Pollen season	9 Feb-27 Jun; 6 Oct-19 Nov	16-26 Apr; 20 Oct- 16 Nov	8 Mar-19 Mar	12 Mar-17 Mar	31 Mar-21 Apr
Season length	43 days; 35 days	10 days; 28 days	12 days	6 days	22 days
Maximum daily value (Date)	14 Mar (62.72 pg/m ³)	21 Oct (29.12 pg/m ³)	14 Mar (60.49 pg/m ³)	4 Jan (17.82 pg/m ³)	19 Apr (11.88 pg/m ³)
Annual Pollen Index (API _n)	1462 pg/m ³	237 pg/m ³	406 pg/m ³	279 pg/m ³	124 pg/m ³
Five-year average (%)	3%	3%	3%	3%	3%
No. of days 3–50 pg/m ³	128 days	16 days	29 days	25 days	8 days
No. of days >50 pg/m ³	1 days	0 days	1 days	0 days	0 days
Urticaceae					
Pollen season	13 Oct-17 Oct	18 Jul-16 Aug	30 Jul-22 Aug	22 Jun-4 Sep	31 Jul-4 Aug
Season length	5 days	17 days	24 days	42 days	5 days
Maximum daily value (Date)	14 Oct (6.16 pg/m ³)	20 Jul (90.72 pg/m ³)	12 Aug (25.39 pg/m ³)	27 Jun (50.23 pg/m ³)	15 Aug (17.82 pg/m ³)
Annual Pollen Index (API _n)	190 pg/m ³	780 pg/m ³	465 pg/m ³	597 pg/m ³	377 pg/m ³
Five-year average (%)	3%	3%	3%	3%	3%
No. of days 3–50 pg/m ³	15 days	26 days	41 days	57 days	39 days
No. of days >50 pg/m ³	0 days	5 days	0 days	1 days	0 days
Parkinsonia sp.					
Pollen season	19 Feb-18 Apr	1 Mar-17 Mar	21 Mar-8 Apr	10 Feb- 30 Mars	27 Mar-26 Apr
Season length	54 days	13 days	19 days	48 days	31 days
Maximum daily value (Date)	15 Mar (79.52 pg/m ³)	14 Mar (27.44 pg/m ³)	28 Mar (11.88 pg/m ³)	30 Mar (16.20 pg/m ³)	15 Apr (37.81 pg/m ³)
Annual Pollen Index (API _n)	932 pg/m ³	196 pg/m ³	178 pg/m ³	121 pg/m ³	648 pg/m ³
Five-year average (%)	3%	3%	3%	3%	3%
No. of days 3–50 pg/m ³	58 days	19 days	21 days	6 days	38 days
No. of days >50 pg/m ³	2 days	0 days	0 days	0 days	0 days

Table 2 (continued)

Pollen taxa / Year	POLLEN				
	2015	2016	2017	2018	2019
<i>Prosopis sp.</i>					
Pollen season	2 Mar-18 Aug	1-11 Mars	23 Mars-24 Apr	12-28 Apr	7-16 Apr
Season length	121 days	11 days	32 days	16 days	9 days
Maximum daily value (Date)	27 Apr (36.40 pg/m ³)	5 Mar (3.92 pg/m ³)	1 Apr (6.48 pg/m ³)	12 Apr (16.94 pg/m ³)	10,11 Apr (2.16 pg/m ³)
Annual Pollen Index (API _n)	1281 pg/m ³	17 pg/m ³	34 pg/m ³	77 pg/m ³	15 pg/m ³
Five-year average (%)	2%	2%	2%	2%	2%
No. of days 3–50 pg/m ³	125 days	1 days	1 days	8 days	0 days
No. of days >50 pg/m ³	0 days	0 days	0 days	0 days	0 days
<i>Bursera sp.</i>					
Pollen season	19 Apr-26 Apr;7 Jul-13 Aug	6 Jul-24 Jul	6 Jul-26 Aug	22 Jun-26 Jul	10 Jul-24 Aug
Season length	8 days; 38 days	19 days	51 days	34 days	45 days
Maximum daily value (Date)	10 Jul (96.32 pg/m ³)	9 Jul (33.60 pg/m ³)	26 Jul (8.10 pg/m ³)	29 Jun (10.26 pg/m ³)	18 Aug (5.4 pg/m ³)
Annual Pollen Index (API _n)	887 pg/m ³	199 pg/m ³	120 pg/m ³	104 pg/m ³	47 pg/m ³
Five-year average (%)	2%	2%	2%	2%	2%
No. of days 3–50 pg/m ³	55 days	20 days	9 days	12 days	4 days
No. of days >50 pg/m ³	2 days	0 days	0 days	0 days	0 days

in the air throughout most of the entire year (61% of the total pollen with these three taxa). A higher inter-annual variability compared to intra-annual one in the MPS start and end dates, season length, and daily maximum values was recorded (Table 2; Fig. 2). It should be noted that the highest values of airborne pollen were recorded in 2015.

Pollen calendar

The first atmospheric pollen calendar for Hermosillo is shown in Fig. 3, with the pollen types ordered alphabetically. Only taxa reaching a ten-day mean of ≥ 1 pollen grains/m³ were included, which included 16 pollen types. The greatest diversity of pollen types was detected from March to April including *Ambrosia*, Asteraceae, Chenopodiaceae-Amaranthaceae, Poaceae, Cupressaceae, and *Prosopis*, which predominated until the summer in the main pollen season. Pollen peak concentrations were detected from March to April and from August to October. Airborne pollen concentrations remained at lower levels during late autumn and early winter (Fig. 3).

In general, pollination periods of arboreal taxa (Cupressaceae, *Parkinsonia*, Burseraceae) were observed to be shorter than those of herbaceous taxa (Asteraceae, *Ambrosia*, Chenopodiaceae-Amaranthaceae, and Poaceae) (Table 2, Fig. 3). The annual behavior of the eight principal allergenic pollen types for Hermosillo is shown in Figs. 3 and 4.

Poaceae Pollen concentration of grasses is observed year-round from moderate to higher and the highest concentrations (see Table 3 Supplementary material for thresholds). Nevertheless, Poaceae pollen begins to increase from March to April and after July–November; this last period shows very high concentrations (> 3100 pollen grains/m³) mean from July to November from 2015 to 2019, Table 4 Supplementary material).

Ambrosia This pollen type includes all the species of the genus *Ambrosia* present in the city; it was observed the whole year round but the levels remained moderate. Only increases were recorded from March to April and October to November with very high levels (> 1247 pollen grains/m³ and 536 pollen grains/m³ air, respectively mean from 2015 to 2019, Table 4 Supplementary material).

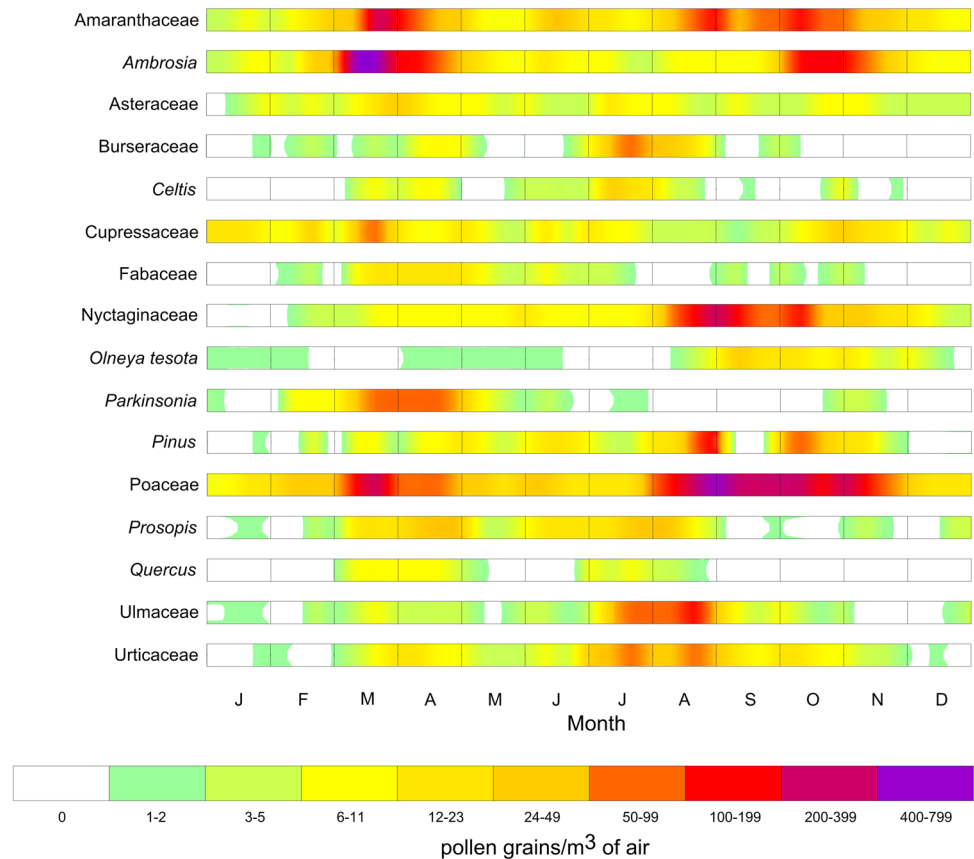
Nyctaginaceae This kind of pollen—represented primarily by the bougainvillea shrub—is present from March until December, but pollen increases in the air from August to November with high levels (1396 pollen grains/m³) mean from 2015 to 2019 (Table 4 Supplementary material).

Chenopodiaceae-Amaranthaceae This group of pollen is found year-round with moderate to high and very high levels; it begins to increase from March to April and October to November with very high levels in both seasons (564 pollen grains/m³ and 766 pollen grains/m³, respectively, mean from 2015 to 2019, Table 4 Supplementary material).

Ulmaceae This arboreal pollen type with high allergenicity is found only from March to April with low levels; then, it begins to increase during summer from July to September with moderately-high levels (459 pollen grains/m³) mean from 2015 to 2019, Table 4 Supplementary material).

Cupressaceae This arboreal tree, also highly allergenic, is present during the whole year with low levels; it begins to increase in winter from January to April with moderate to high levels (mean of 257 pollen grains/m³ from 2015 to 2019) also recording a slight increase from October to November with moderate levels (mean of 139 pollen grains/m³ from 2015 to 2019, Table 4 Supplementary material).

Fig. 3 Pollen Calendar for Hermosillo, Sonora, México from 2015 to 2019, reporting the most important allergenic pollen. Color scale shows pollen concentrations expressed in pollen grain/m³ air following Spieksma and Wahl's model (Spieksma and Wahl 1991) classified into a series of classes according to Stix and Ferretti (1974)



Urticaceae This weed pollen type is also highly allergenic and present from March to November, but it begins to increase during summer from July to September with moderate to high levels in air (mean of 345 pollen grains/m³ from 2015 to 2019), Table 4 Supplementary material).

Parkinsonia Although this kind of tree pollen is considered a minor cause of allergies around the world, it is reported here because of its importance in this desert city as a principal component of urban vegetation related to allergies for the population of Hermosillo (López-Romero et al. 2017). This pollen type includes at least 3 species of the genus *Parkinsonia* that are distributed in Hermosillo and present in the air from February to June mainly with low concentration levels. It increases from March to April with high levels in air (mean of 365 pollen grains/m³) from 2015 to 2019, Table 4 Supplementary material).

In general, pollen types in the atmosphere of Hermosillo have shown long MPS (more than six months duration) with some pollen types occurring throughout the year (Poaceae, *Ambrosia*, Asteraceae, Cupressaceae, and Chenopodiaceae-Amaranthaceae). For the most important peaks with concentration values in very high levels (> 50 pollen grains/m³ daily value), Table 2 shows that Poaceae pollen was present 59 days in 2015, 8 days in 2016, 7 days in 2017, 9 days in 2018 and 8 days in 2019 with extremely high concentration

values. *Ambrosia* pollen-type was at high levels for 26 days in 2015, 11 days in 2017, and 4 days in 2018 (Table 2). Nyctaginaceae was at high levels for 20 days in 2015, but only 2 days in 2016. Chenopodiaceae-Amaranthaceae pollen type was at high levels for 15 days in 2015, 2 days in 2017, and only 1 day in 2018 (Table 2). Finally, Ulmaceae pollen was at high levels for 15 days in 2015 and only 1 day in 2018. The rest of the pollen types did not show days with daily concentrations higher than 50 pollen grains/m³ of air.

Associations between airborne pollen concentrations and weather characteristics (Spearman's correlations)

Table 3 shows Spearman's correlations between daily pollen and weather characteristics for summer and winter periods (2015–2019) (Table 3). In summer, there were significant negative correlations between the following pollen types and meteorological variables:

Airborne pollen concentrations of Poaceae, and *Parkinsonia* and precipitation (PREC); airborne Chenopodiaceae-Amaranthaceae pollen concentration and air pressure (PRS); airborne daily total pollen types and zonal wind (UWN); airborne Chenopodiaceae-Amaranthaceae pollen concentration and dew point

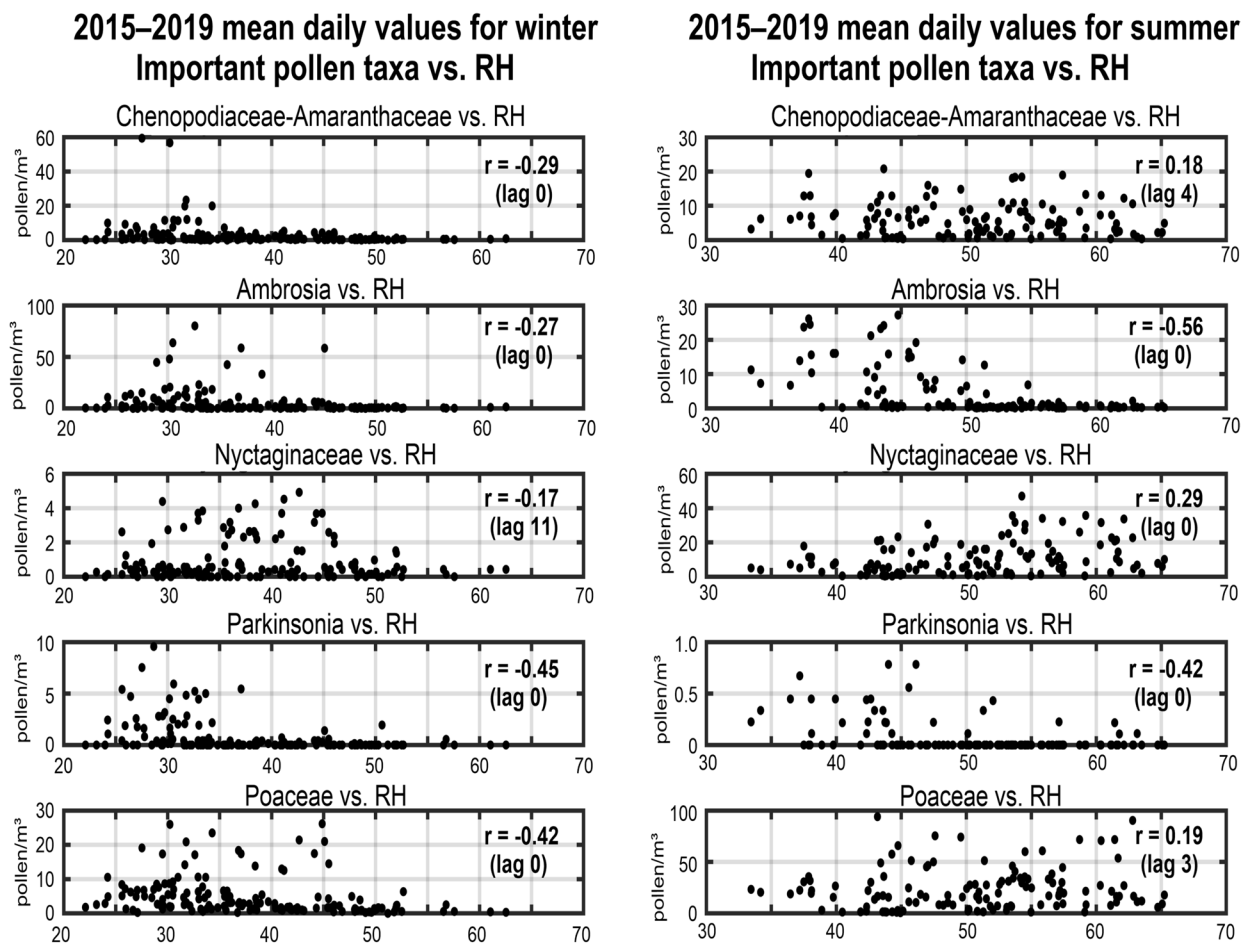


Fig. 4 Scatter diagrams for Hermosillo, Sonora, México, displaying the relationship between important pollen taxa and relative humidity (RH) taking samples of 2015–2019 mean daily values for (left) winter

(from 1 November 1 to 31 March, $n = 151$) and (right) summer (from 1 July to 31 October, $n = 123$). Inset in each case is the absolute maximum correlation and its lag in parenthesis

temperature (Td); airborne pollen concentration of Poaceae, Chenopodiaceae-Amaranthaceae, and *Parkinsonia* and meridional wind (VWN). Finally, airborne pollen concentration of Poaceae, and *Parkinsonia* and maximum temperature (Tmax), and minimum temperature (Tmin). Whereas, there were significant positive correlations between the following sample pairs in winter: airborne pollen concentrations of Ulmaceae, and Urticaceae and PREC; airborne Nyctaginaceae pollen concentration and relative humidity (RH); airborne *Parkinsonia* pollen concentration and PRS; airborne Nyctaginaceae pollen concentration and Td; airborne Cupressaceae pollen concentration and UWN.

In winter, there were significant negative correlations between the following sample pairs: almost all-important airborne pollen concentrations (Poaceae, *Ambrosia*, Chenopodiaceae-Amaranthaceae and *Parkinsonia*) and PREC; airborne pollen concentration of *Ambrosia*, Cupressaceae, and Urticaceae and RH; airborne pollen concentration of Nyctaginaceae, and Cupressaceae and PRS; airborne pollen concentration of Poaceae and *Ambrosia*, and VWN; airborne

Ulmaceae pollen concentrations and Tmax. Whereas, there were significant positive correlations between the following sample pairs in winter: airborne Ulmaceae pollen concentrations and PRS; airborne Chenopodiaceae-Amaranthaceae pollen concentrations and UWN; airborne pollen concentrations of Poaceae, and *Ambrosia* and VWN; airborne Nyctaginaceae pollen concentrations and Tmax.

In summary, Spearman's correlations between pollen and meteorological variables imply that the presence of the main pollen types in the atmosphere of Hermosillo is generally influenced in both peak periods (MPS) of summer and winter by decreases in precipitation and temperatures and increase in relative humidity.

The relationship between relative humidity (RH) and composite series of pollen taxa in different periods (Fig. 1, supplementary material) and by pollen species (Fig. 4) shows an increase between a pair of samples in whole and annual periods and a decrease in winter (Fig. 1, supplementary material). In the analysis by species, all the average series showed

Table 3 Spearman's correlations between pollen and weather characteristics for 2015–2019: (A) summer series and (B) Winter series. Numbers in boldface with an asterisk are significant correlations*(p* < 0.05). *PREC*, precipitation; *RH*, relative humidity; *PRS*, pressure; *Td*, dew point; *UWN*, zonal wind; *VWN*, meridional wind; *Tmax*, maximum temperature; *Tmin*, minimum temperature

Variable	PREC	RH	PRS	Td	UWN	VWN	Tmax	Tmin
A. Spearman's correlations: mean daily summer series from July to October (2015–2019)								
Total-pollen types	-0.256*	0.045	-0.271*	0.007	-0.185*	-0.156	-0.277*	-0.235*
Poaceae	-0.22*	0.106	-0.33	0.056	-0.153	-0.185*	-0.275*	-0.201*
<i>Ambrosia</i>	-0.533	-0.562	-0.105	-0.633	0.172	-0.319	-0.457	-0.513
Nyctaginaceae	-0.085	0.285*	-0.363	0.22*	-0.179*	-0.087	-0.203*	-0.118
Chenopodiaceae-Amaranthaceae	-0.388	-0.103	-0.245*	-0.15*	-0.081	-0.188*	-0.325	-0.314
Ulmaceae	0.305*	0.317	0.118	0.597	-0.019	0.393	0.711	0.652
Cupressaceae	-0.523	-0.662	0.055	-0.653	0.204*	-0.126	-0.218*	-0.376
Urticaceae	0.242*	0.268*	0.025	0.478	-0.074	0.296*	0.592	0.596
<i>Parkinsonia</i>	-0.297*	-0.415	0.201*	-0.406	0.08	-0.209*	-0.184*	-0.307*
B. Spearman's correlations: mean daily winter series from November to March (2015–2019)								
Total-pollen types	-0.067	0.062	-0.342	0.446	-0.027	-0.005	0.311	0.424
Poaceae	-0.225*	-0.419	-0.549	0.108	0.3	0.181*	0.709	0.672
<i>Ambrosia</i>	-0.207*	-0.274*	-0.578	0.132	0.375	0.207*	0.548	0.453
Nyctaginaceae	-0.119	0.04	-0.272*	0.403	-0.058	-0.072	0.265*	0.375
Chenopodiaceae-Amaranthaceae	-0.235*	-0.291	-0.377	0.106	0.195*	0.055	0.493	0.438
Ulmaceae	0.111	0.295	0.212*	0.108	-0.157	-0.161*	-0.253*	-0.291
Cupressaceae	-0.101	-0.237*	-0.242*	0.115	-0.071	-0.056	0.391	0.395
Urticaceae	-0.145	-0.27*	-0.344	0.042	0.298	0.257*	0.446	0.378
<i>Parkinsonia</i>	-0.203*	-0.445	-0.526	-0.038	0.41	0.345	0.678	0.551

Note: Numbers in boldface with an asterisk are significant correlations ($p < 0.05$)

decreased relationships with RH and negative significant correlations at lags from 0 to 11 days (Fig. 4, left panels).

In summer (Fig. 1, supplementary material), the high dispersion of points in the scatterplot shows no relationship between series at 0-day lag ($r = 0.04$). However, as lags increase, the correlations between the series become significant from 5-day lags ($r = 0.25$) to 21-day lags ($r = 0.47$), indicating that a time lag exists between RH increase and total pollen increase. The analysis by species shows that some of them (airborne pollen concentrations of Amaranthaceae, Nyctaginaceae, and Poaceae) display an increasing relationship with RH (Fig. 4, right panels), while others (airborne pollen concentrations of *Ambrosia* and *Parkinsonia*) show a decreasing relationship with RH.

Figures 5 and 6 show scatterplots displaying the relationship between important pollen taxa and zonal (east–west flow or UWN), and meridional (north–south flow or VWN) wind components, respectively.

In winter, an increasing relationship was observed between UWN and airborne pollen concentrations of *Ambrosia*, *Parkinsonia*, and Poaceae, which is in accordance with the significant positive correlation between the series from 0-day lag (Fig. 5, left panels).

In summer, the 0-day lag correlation between UWN and pollen taxa is close to zero (Fig. 5, right panels) suggesting no relationship. The largest mean records are found in airborne pollen concentrations of Chenopodiaceae-Amaranthaceae, *Ambrosia*, and Nyctaginaceae when wind flows from the west (positive UWN) between 0 and 2 m/s mean velocities. Conversely, the highest pollen concentrations are observed in Poaceae pollen concentrations when wind flows from the east (negative UWN) between 0 and 0.5 m/s mean velocities.

In winter (Fig. 6), the correlation between VWN and airborne *Ambrosia* pollen concentrations, and VWN and airborne *Parkinsonia* pollen concentrations is positive at 0-day lag (left panels), but the relationship is negative in summer (right). The scatterplots show that in winter, the largest mean pollen records for these types are observed when the wind flows from the south (positive VWN), and the smallest when the wind flows from the north (negative VWN). In summer, the decreasing relationship between a pair of samples shows that the largest mean pollen records are observed for *Ambrosia* when light meridional wind (< 1 m/s) flows from the south (positive VWN), and for *Parkinsonia* when it flows from the north (negative VWN). These results indicate that the largest mean pollen records for these pollen types delay

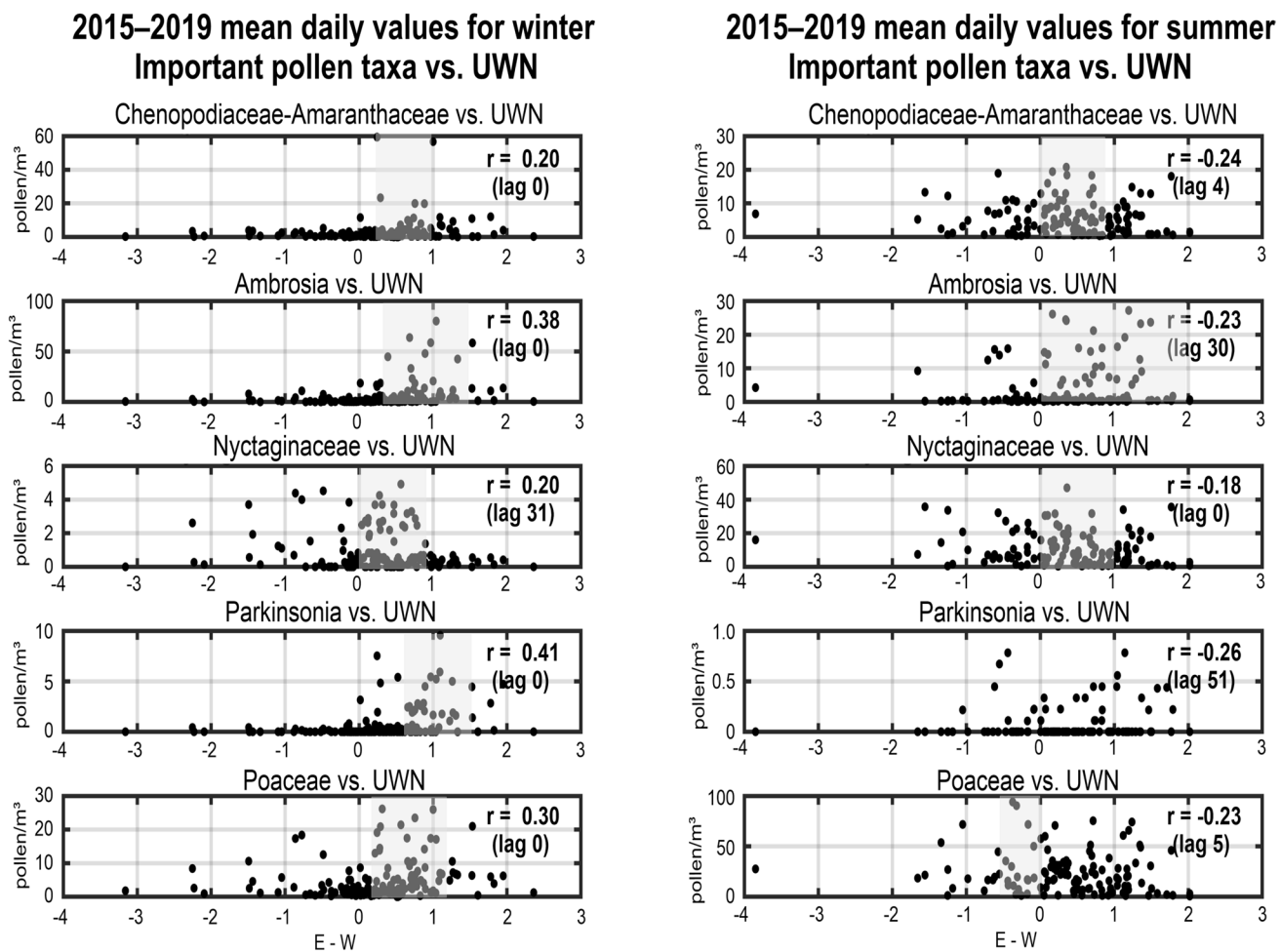


Fig. 5 Scatter diagrams for Hermosillo, Sonora, México, displaying the relationship between important pollen taxa and zonal wind (UWN) taking samples from 2015 to 2019 mean daily values for (left) winter (from 1 November to 31 March, $n=151$) and (right)

summer (from 1 July to 31 October, $n=123$). Inset in each case is the absolute maximum correlation and its lag in parenthesis. The shadow bars show the largest pollen records at different wind velocities

several days before coming to the station when the wind tends to flow from the south in winter and from the north in summer. The correlation between VWN and Nyctaginaceae is near zero from 0-day to 30-day lags in both winter and summer suggesting that wind does not influence Nyctaginaceae pollen records at the station (Fig. 6).

Discussion

Airborne pollen monitored in the city of Hermosillo reveals a great diversity with 41 pollen types, similar to values observed in Mexico City (Calderón-Ezquerro et al. 2015). Nevertheless, the most important pollen types that reach more than 1% of the total pollen concentration in air correspond only to 16 types, of which 61% are herbaceous species and 39% are arboreal (see Tables supplementary

material), with the most abundant representing species in this desert city being Poaceae, Chenopodiaceae-Amaranthaceae, *Ambrosia* and Nyctaginaceae. The seasonal variation of collected pollen types was correlated with differences in weather conditions throughout the year and determined by the flowering plant periods. In this region, most of the plant flower during spring and summer (Molina-Freaner and Van-Devender 2000).

Substantial interannual variation in pollen concentration in air was detected for Hermosillo (Fig. 2). The largest concentration of the total pollen in the air was recorded in 2015 with an APIn of 32,887 pollen * day/m³ followed by 2017 with an APIn of 9645 pollen * day/m³. The rest (2016, 2018, and 2019) recorded similar APIn of around 7000 pollen * day/m³. These values were much lower than those reported for more temperate regions such as Mexico City (Calderón-Ezquerro et al. 2015). Nevertheless, the range of

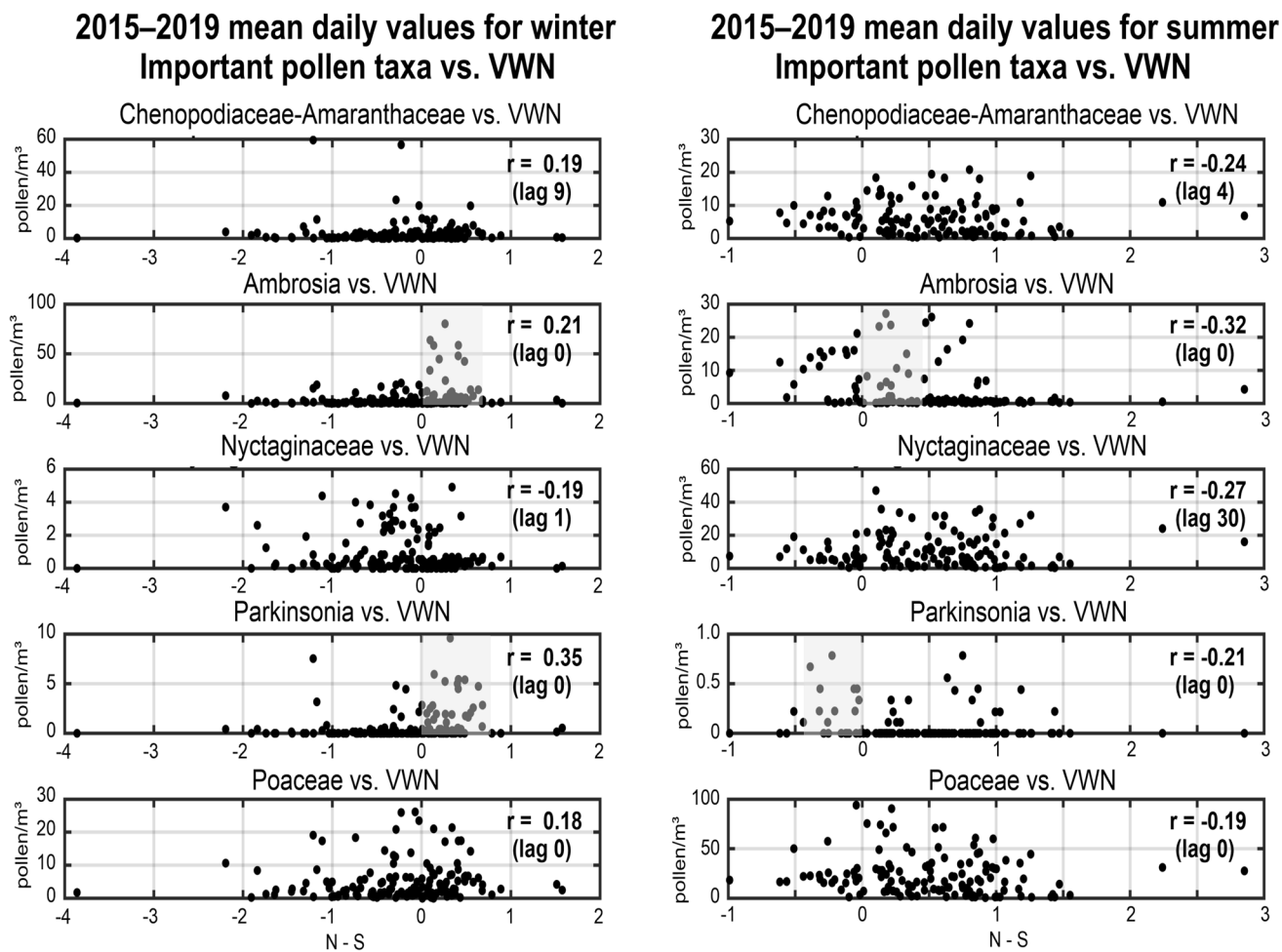


Fig. 6 Scatter diagrams for Hermosillo, Sonora, México, displaying the relationship between important pollen taxa and meridional wind (VWN) taking samples from 2015 to 2019 mean daily values for (left) winter (from 1 November to 31 March, $n = 151$) and (right)

summer (from 1 July to 31 October, $n = 123$). Inset in each case is the absolute maximum correlation and its lag in parenthesis. The shadow bars show the largest pollen records at different wind velocities

values found at Hermosillo is common for this kind of desert environment where APIn values range from 3500 to 34,000 pollen * day/m³ (Al-Nesf et al. 2020).

The interannual variation in pollen quantity means variations in source abundance, linked to changes in reproductive plant process and environmental conditions (Sofiev and Bergmann 2013). Meteorological data for the city show variations in the most common variables related to airborne pollen, such as PREC, Tmax, and Tmin and RH (Fig. 2 supplementary material). For 2015, precipitation was higher (401 mm) compared to the other years monitored (the annual normal from Hermosillo is 391 mm, INEGI 2021), which was related to more winter precipitation in 2015 (Fig. 2 supplementary material).

Thus, higher winter rains present during 2015 stimulated growing and bloom during spring of the most important desert herbs and grasses, recording a higher

production and pollen release compared with the other years (Table 1). In this sense, the APIn can provide an indicator of the effects on desert plant phenology, specifically on changes in flowering and pollen production periods caused by changes in temperature and precipitation patterns (Anderegg et al. 2021). The highest RH values are centered from July to September and are related to monsoon rains. We detected a variation in the length of this period of humidity among the years. For example, in 2018 the humid season extended until November (Fig. 2 supplementary material).

Aerobiologists (e.g. Rodríguez-Solà et al. 2022; Schramm et al. 2021) have widely accepted that the washing effect of rainfall is one of the causes of a fall in pollen concentrations in air. For example, this effect could explain lower airborne pollen concentrations recorded at Hermosillo during July and August in 2017, 2018, and 2019. These results

are related to the rainy season with higher precipitation from July to September (Fig. 2 Supplementary material), which is the period of monsoon influence in this region. Spearman's correlation shows a significant negative correlation between PREC and total-pollen concentrations in the air during summer (Table 3), showing also that pollen plant source in summer might be located mainly to the east of the station. In 2015 and 2016 higher total pollen was recorded in the air during March when lower precipitation is recorded (Fig. 2 Supplementary material). This season in Sonora is considered the driest one when no rains occur. To corroborate the hypothesis that rains decrease pollen in the air, the difference in the pollen peak between years could be a response to increasing temperatures and changes in precipitation related to phenology as previous research has found (Zachmann et al. 2021). This phenomenon could explain the variation between years of airborne pollen onset at Hermosillo and the long MPS for these desert taxa, as suggested for airborne pollen in North America, where increases in mean temperatures may increase pollen concentrations and extend pollen seasons (Anderegg et al. 2021).

Significant intra-annual variation in airborne pollen concentrations was observed in Hermosillo, with high loads of pollen in the air being recorded in different seasons (Fig. 5 and 6). In summer and winter, the largest mean pollen concentrations are observed at around 1 m/s wind mean velocity (Fig. 5). Particularly in winter, for some taxa (*Ambrosia*, *Parkinsonia*, and *Poaceae*) pollen concentrations are higher when the wind is from the west, which suggests that the pollen plant source of these species in winter might be located to the west of the station. For summer, the time lag correlation between a pair of samples indicates that measuring pollen types delays several days before pollen comes to the station.

In the case of the meridional wind component (i.e. VWN), pollen concentrations of *Ambrosia* are higher when the wind is from the south in both winter and summer (Fig. 6). For airborne *Parkinsonia* pollen, concentrations are higher when the wind is from the south in winter and from the north in summer.

In this sense, the most important airborne pollen of Hermosillo related to allergies in the population can be associated with variations in meteorological data (López-Romero et al. 2017; Ortega-Rosas et al. 2019). The first peak for *Poaceae* occurs from March to April (Figs. 2 and 3); Spearman's correlations reveal negative significant correlations with PREC and positive with VWN (Table 3); for these months, low values in precipitation can be observed for all the years, except for 2015 (Fig. 2 supplementary material). Lastly, no rain and wind reversal from east to west is linked to higher grass pollen concentrations in the air. The other peak in *Poaceae* pollen occurs from October to November (Figs. 2 and 3), correlated with the end of the monsoon rainy season

(July–September, Fig. 2 supplementary material). For *Poaceae*, the most important pollen taxa in the atmosphere, its presence and abundance in the air, was negatively correlated with PREC, VWN, Tmax, and Tmin. Therefore, conditions of lower precipitation, wind reversal from south to north, and mild temperature conditions stimulate pollen grass abundance in the air.

For both *Ambrosia* and *Chenopodiaceae-Amaranthaceae*, the most-important peak occurs in March–April (Table 4 supplementary material; Figs. 2 and 3) and Spearman's correlations showed a significant negative correlation with PREC and RH and a positive significant correlation with VWN. Thus, low precipitation occurs during these months, low RH, and wind reversal from east to west are associated with higher pollen concentrations of these herbs in the air.

In the case of arboreal pollen, *Ulmaceae* type is related principally to the genus *Celtis*, which is very common in city parks and gardens (Ortega Rosas et al. 2022). The pollen-season peak occurs from July to September (Table 4, supplementary material, Figs. 2 and 3), Spearman's correlations show (Table 3) a significantly positive correlation with PREC for summer (Table 3), so in the rainy season, higher concentrations of *Celtis* can be found in the air. Another arboreal pollen type of interest related to allergies in Hermosillo (López-Romero et al. 2017; Ortega-Rosas et al. 2019) is *Parkinsonia* (palo verde). The season for this pollen is centered in spring (March–April) in the drier period (Fig. 2 supplementary material). Spearman's correlation shows (Table 3) a significantly negative correlation with PREC. Therefore, in those months with lower rains, higher concentrations of *Parkinsonia* are found in the air.

Recent studies have shown that as the global climate warms, events such as flowering can occur earlier in the year (Prevéy 2020). In drier water-limited ecosystems, most plant species flower multiple times throughout the year, as recorded for many taxa at Hermosillo, such as *Poaceae*, *Chenopodiaceae-Amaranthaceae*, *Ambrosia*, and *Asteraceae* (Fig. 3). Increases in temperature were associated with early flowering, whereas precipitation decreases were associated with late flowering. Thus, precipitation is an important factor in flowering changes in desert regions (Prevéy 2020). A trend of earlier starting dates for many allergenic pollen taxa from North America (Crimmins et al. 2010; Lo et al. 2019) has been observed in past decades (van Vliet et al. 2002; Zhang et al. 2014). In this case, the beginning of the MPS was detected earlier every year for some taxa, such as *Parkinsonia* (Fig. 2), which has been documented to bloom in March (Molina-Freaner and Van-Devender 2000), but in recent years flowers of *Parkinsonia* have been observed starting in February (personal observation).

Five years of data show also the allergenic potential reaction of airborne pollen taxa at Hermosillo, in which

herbaceous pollen was dominant in the air, principally related to Poaceae, *Ambrosia*, Chenopodiaceae-Amaranthaceae, as found previously (Ortega-Rosas et al. 2021). Poaceae (grasses) pollen contributed 33% of the API_n (5-year mean) in this city. In a previous work (Ortega-Rosas et al. 2021), 29% of the people tested from Hermosillo ($n = 151$), showed a positive reaction to pollen grasses. In fact, Poaceae pollen is a serious health problem causing allergies around the world (García-Mozo 2017). The main source of Poaceae pollen into the city comes from the surrounding landscape and is related to buffelgrass (*Pennisetum ciliaris*) and Bermuda grass (*Cynodon dactylon*), which are reported by Hermosillo allergists as highly reactive in the allergic population (López-Romero et al. 2017). *Ambrosia* pollen (ragweed) accounted for 16% of total API_n (5-year mean) for Hermosillo and presented in higher concentrations during spring; this genus is also considered a highly potent aeroallergen worldwide (Grewling et al. 2019). For example, according to Arbes et al. (2005), about 26% of the US population is sensitized to ragweed pollen and 17% of the population tested at Hermosillo is also sensitive to this pollen type (Ortega-Rosas et al. 2021). The third abundant pollen type of the 5-year data belongs to the family Nyctaginaceae with 12% of API_n (mean), represented mostly by Bougainvillea shrub reported by the Allergen Encyclopedia (2021) as a plant species producing pollen, which may infrequently induce hay fever, asthma, and conjunctivitis in sensitized individuals. No scientific information has been published about the aerobiology of Bougainvillea, nevertheless, its pollen does not appear to be a major component in the atmosphere, as shown by aerobiological monitoring in North America. However, it may uncommonly induce symptoms of asthma, rhinitis, and conjunctivitis in sensitized individuals (Allergen Encyclopedia 2021). Bougainvillea are immensely popular for their toughness and adaptability, qualities that place them among the world's most familiar garden plants. At Hermosillo, this plant is distributed everywhere, with flowering that starts early in spring and lasts until the first cold spells. Although this airborne pollen is not as allergenic as grasses or ragweed, its high concentrations in the air make it a care agent for allergy sufferers.

In the case of arboreal pollen, desert trees such as *Prosopis* sp., *Parkinsonia* sp., and *Olneya tesota* (all Fabaceae) were recorded in the air during the 5 years. In brief, these taxa account for around 8% of total API_n (see Table 1). A previous work (Ortega-Rosas et al. 2021) reported 12% of people tested, showed a positive reaction to these pollen types. The highest peaks in concentrations recorded for all these pollen types were in April, corresponding to the flowering season. Fabaceae pollen is reported to be one of the most important allergenic pollen from trees in Mexico (Rosas-Alvarado et al. 2011); *Prosopis* is also reported with high allergenic potential in Mexican population (Batista-Roche

and Huerta-Ocampo 2021) with 21% ($N = 529$) of positive sensitization test (Larenas-Linnemann et al. 2014).

The pollen calendar for this desert city provides knowledge about how airborne pollen affects the allergic population. Overall, it helps the health sector to improve knowledge and medical treatment according to the pollen types present in the air and the periods when allergenicity increases. All these data can help prevent episodes of allergic-pollen reactions in the population. In addition to allergens, particulate air pollution is increasing worldwide, and this issue can exacerbate the airborne pollen-allergenic reactions of populations. Recently some studies have shown that air pollution impacts the prevalence and symptom severity of pollen allergies in populations around the world (D'Amato et al. 2015; Kim et al. 2013; Calderon-Ezquerro et al. 2018; Ortega-Rosas et al. 2021). For instance, grass pollen from rural areas causes less damage than the same grass pollen in urban regions (Rahman et al. 2019), where humans are also exposed to a polluted environment. Scientific studies have shown that predisposed subjects have increased respiratory reactivity induced by air pollution and increased bronchial responsiveness to inhaled pollen allergen (Di Menno di Buchianico et al. 2019). Airborne pollen for this study region has been previously reported with a high charge of micro and nanoparticles adhered to the pollen wall (Ortega-Rosas et al. 2021). Thus, the importance to continue with airborne pollen monitoring at this desert city and explore the effect of increasing temperatures on vegetation and pollen production as well as on pollution.

Conclusion

This research shows the first Pollen Calendar for the state of Sonora in the desert city of Hermosillo. A great variety of airborne pollen was detected related to important allergenic pollen. Most of the taxa recorded belong to herbaceous plants, such as Poaceae, *Ambrosia*, and Chenopodiaceae-Amaranthaceae typical of this desert ecosystem that is recognized in the region for being highly allergenic and causing severe reactions on the Sonoran population. Most of the grass pollen in the air are related to Bermuda grass, Buffelgrass, and *Lolium*, as well as some arboreal and shrub tropical taxa, such as *Parkinsonia*, *Prosopis*, Fabaceae, and Nyctaginaceae families. From those trees, *Prosopis* (Mezquite), high sensitization in the population has been reported.

Thus, government efforts to eradicate or control introduced grasses, such as buffelgrass, could help people that are highly allergenic to reduce allergenic reactions and associated medical complications. Although the results in this study are specific to this area in northwestern Mexico,

they are helpful for future research on biological air quality scenarios in different city environments. Using this standardized method for other regions can provide pollen calendars that have been proven clinically meaningful in allergic disease management worldwide. Therefore, monitoring airborne pollen should continue to reduce the burden of allergenic pollen on human health, besides updating the pollen calendar because of the rapidly changing weather conditions.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00484-023-02546-9>.

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Data Availability Data sets generated during the current study are available from the corresponding author on reasonable request. Airborne pollen counts from 2016–2019 are available at the Red Mexicana de Aerobiología <http://rema.atmosfera.unam.mx/rema/Default.aspx>.

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