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Temporal Variation of Airborne Cupressaceae, Pinus, and Quercus Pollen and Their Relationship with Environmental Variables in Three Sites of Mexico City

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Abstract

Climatic factors influence plant physiology and distribution, thereby affecting pollen production and its aerobiological processes. We analyzed the relationship between the reproductive phenology of Cupressaceae, *Pinus* sp., and *Quercus* sp. Airborne pollen was sampled using a Hirst-type volumetric spore trap at three locations: Coyoacán, Cuajimalpa, and Desierto de los Leones. For the three pollen types, the main pollination period (MPP), seasonal variation, and peak pollen emission dates were determined. The relationship between meteorological parameters and the MPP was assessed using Spearman's correlation test, while the Kruskal–Wallis test (Dunn's post hoc) was applied to compare pollen types and sampling sites. Wind trajectory and pollen grain deposition were analyzed using the HYSPLIT model. The pollination period of the Cupressaceae family began in July–August and ended in February. *Pinus* sp. started between August and December and concluded between May and July, whereas *Quercus* sp. began between February and March and ended between May and June. Spearman's analysis revealed positive correlations with temperature and solar radiation, and negative correlations with precipitation and relative humidity. The number of pollination days for Cupressaceae and *Pinus* sp. was similar between Coyoacán and Cuajimalpa, but differed significantly from Desierto de los Leones. In contrast, *Quercus* sp. showed no significant differences among the three sampling areas. The HYSPLIT model indicated that wind currents at different altitudes originated from varying directions, highlighting potential emission sources of the different pollen types. Cupressaceae pollen was present in the atmosphere throughout the year, whereas *Pinus* and *Quercus* pollen exhibited interannual and seasonal fluctuations due to their biennial periodicity and the flowering patterns of different species.

1 Introduction

In Mexico City (CDMX) (2240 m a.s.l.), its geographic location favors a wide variety of ecosystems that host numerous species from both arboreal and herbaceous strata, such as *Abies–Pinus–Quercus* forests, grasslands, xerophilous scrublands, and wetland areas (Rzedowski *et al*., 2005; Castillo, 2007). In addition, introduced species are commonly used in green areas, residential and commercial complexes, as well as along roadways.

The considerable release of allergenic pollen into the atmosphere, resulting from the great diversity of plant species in Mexico City, is a frequent cause of disorders such as asthma, rhinitis, and allergic conjunctivitis among its inhabitants. (Pawankar *et al*., 2011). In this context, pollen calendars have been a fundamental tool for visualizing and understanding the distribution, timing, and concentration of different pollen taxa (Calderón et al., 2015; Katotomichelakis *et al*., 2015), with the aim of informing the population about periods of high atmospheric pollen concentrations and thus promoting prevention and health care.

For the release of pollen grains through the anthers of different tree species to occur and subsequently affect the health of the inhabitants, several factors are required, such as time of day, biological parameters, and meteorological conditions, among which temperature, relative humidity, precipitation, and wind speed are particularly relevant (Nowosad, 2015; Ojrzyn´ska, 2020).

The rupture and opening of anthers are usually controlled by a cohesion mechanism. As a result of water loss, tension increases in the cell walls, allowing pollen release; therefore, this mechanism is closely associated with air humidity (Puc, 2012). In this context, various aerobiological studies have demonstrated the influence of daily temperature on pollen release, indicating that even small changes in temperature can have a significant impact on flowering (Alvarado *et al*., 2002; Ziello *et al*., 2012; Cavieres *et al*., 2021).

It has been evidenced that plants are sensitive to climate change, as they respond with variations in their different phenological phases, affecting pollen production. Consequently, aerobiological processes have been modified in terms of the onset, duration, and intensity of the pollen season (Frenguelli, 2002a; Galán *et al*., 2008; Cecchi *et al*., 2010; Morales *et al*., 2016).

There is evidence of an earlier onset of the pollination period, influenced by temperature in various tree species such as *Alnus* sp., *Betula* sp., *Castanea* sp., Cupressaceae, *Olea* sp., *Pinus* sp., and *Quercus* sp. (Frenguelli *et al*., 2002b; Jato *et al*., 2002; Fernández-González *et al*., 2021). Ziska *et al*. (2019) conducted a comprehensive analysis of pollen intensity datasets from Europe and North America over the past 20 years, highlighting an increase in the duration of the pollen season (on average 0.9 days per year), which was associated with rising temperatures. It is also important to note that in urban areas, temperature is exacerbated by the urban heat island effect, resulting in an earlier start of the pollen season (D'Amato *et al*., 2014).

Another factor associated with diurnal changes in pollen concentration is wind. During the day, pollen clouds are easily transported upward by convection currents, and no selection occurs based on pollen grain size or mass. However, at night, larger and heavier grains settle more rapidly than smaller ones (Puc, 2012).

This study aimed to develop a pollen calendar for Cuajimalpa and to analyze the interaction of environmental factors with the seasonal variation of Cupressaceae, *Pinus* sp., and *Quercus* sp. pollen in three areas of Mexico City.

2. Methods

2.1 Sampling Site and Study Period

Pollen grain monitoring was carried out using a Hirst-type spore trap (Burkard Manufacturing Co., Ltd., UK) in two urban zones and one forest zone located in Mexico City. The urban zones included the municipality of Cuajimalpa (Santa Fe) (19°22'50.88" N; 99°16'38.56" W, 2590 m a.s.l.) (2010–2023), and the municipality of Coyoacán (Ciudad Universitaria) (19°19'18.2" N; 99°11'7.8" W, 2273 m a.s.l.) (2008–2023). The forest zone corresponded to Parque Nacional Desierto de los Leones (PNDL) (Cuajimalpa municipality) (19°18'59" N; 99°18'22" W, 2960 m a.s.l.) (2016–2023) (Fig. 1).

Fig 1.

2.2 Pollen Calendar Development for Cuajimalpa

The pollen calendar model was constructed following the method proposed by Spieksma and Andersen (1991). It was based on data collected from the Mexican Aerobiology Network (REMA-UNAM) database (2010–2023) (REMA, 2021). Data were organized by year, and only those pollen types exceeding 1% of the total pollen grains collected were included. The number of pollen grains per cubic meter of air (pollen grains/m³, daily mean concentration) was calculated. The pictogram of the pollen calendar was prepared using Surfer 11 software (Golden Software Inc., CO, USA).

2.3 Phenological Analysis of Cupressaceae, *Pinus*, and *Quercus*

The criterion for defining the start and end dates of the pollination period, as well as the duration of the Main Pollen Period (MPP), was established following the method of Andersen (1991). This method is based on excluding the tails of the cumulative percentage curve for each taxon, retaining 95% of the total. Thus, the onset of the flowering period is defined as the day on which 2.5% of the total annual pollen has accumulated, and the end is the day on which 97.5% of the total is reached (Nilsson and Persson, 1981). The duration of the pollination period was defined as the number of days between the start and end of the MPP. The peak day was considered the date on which the highest value (peak concentration) was recorded. The pre-peak period was defined as the interval between the beginning of the MPP and the peak day, while the post-peak period was defined as the interval between the peak day and the end of the MPP. This approach was used to show the interannual variation in pollen levels of Cupressaceae, *Pinus* sp., and *Quercus* sp. throughout the study years.

2.4 Data Analysis

Meteorological records from the nearest stations were used for each site, corresponding either to University Network of Atmospheric Observatories (RUOA, 2023) or High School Meteorological Station Program (PEMBU 2023).

2.5 Statistical Analysis

To compare the total number of days of the main pollen period in each locality across the different pollen types, the Kruskal–Wallis test was applied, followed by Dunn's multiple comparison test for mean comparisons, using Prism V6.0 (GraphPad Software Inc., MA, USA). In addition, Spearman's correlation was performed to assess the relationship between pollen concentrations and environmental factors such as temperature (maximum, minimum, and mean), relative humidity, solar radiation, and precipitation. Also, the Correlation and linear regression analyses were applied to examine the relationships between Main Pollen Period, temperature (maximum, minimum and mean) and relative humidity. The non-parametric Mann–Kendall test was used to determine temporal trends in the Annual Pollen Integral (API) and other Main Pollen Period (MPP) parameters (onset, end, duration, peak day, and peak value), following the approach proposed by Galán et al. (2017). These analyses were conducted using Statgraphics XVII (Statgraphics Technologies, Inc., VA, USA). Furthermore, for the three pollen types and for each locality, a summary was perform to the most relevant daily pollen concentrations (Table 7). To identify the potential sources of emission and resuspension of the different pollen grains, the HYSPLIT model (NOAA, Hybrid Single-Particle Lagrangian Integrated Trajectory, 2023) was applied to simulate wind direction and possible pollen dispersion trajectories at different altitudes (30, 50, and 200 m). The analysis highlighted the dates with the highest pollen emission across the different study periods and localities. Subsequently, Duncan's multiple range test was performed with Statgraphics XVII (Statgraphics Technologies, Inc., VA, USA) to identify the likely distance of wind trajectories.

3. Results

3.1 Pollen Calendar

The main percentages of pollen types recorded at the Cuajimalpa station corresponded to the families and genera: Cupressaceae, *Fraxinus* sp., *Alnus* sp., *Quercus* sp., *Pinus* sp., Urticaceae, Poaceae, and *Casuarina* sp. All other pollen types were represented with less than 1% of the total collected (Table 1).

Table 1. Airborne pollen types collected in Cuajimalpa over 13 years.

Taxa	%
Cupressaceae	46.35
Fraxinus sp.	18.59
Alnus sp.	9.97
Quercus sp.	7.82
Pinus sp.	3.86
Urticaceae	2.67
Poaceae	1.63
Casuarina sp.	1.44
Myrtaceae	0.87
Moraceae	0.78
Schinus sp.	0.76
Amaranthaceae	0.58
Asteraceae-Anthemidae	0.57
Rosaceae	0.31
Buddleia sp.	0.29
Populus sp.	0.27
Ricinus sp.	0.26
Ambrosia sp.	0.24
Asteraceae-Helianthus	0.21
Liquidambar sp.	0.19
Ligustrum sp.	0.19
Rumex sp.	0.17
Celtis sp.	0.14
Mimosa sp.	0.10
Artemisia sp.	0.06

The concentration of pollen grains collected from 2010 to 2023 showed fluctuations throughout the year. The months with the highest pollen concentrations were from November to February (*Alnus* sp., Cupressaceae, and *Fraxinus* sp.), followed by March to May (*Quercus* sp. and *Pinus* sp.) (Fig. 2).

Fig. 2

3.2 Phenology

3.2.1 Quantitative analysis of interannual and seasonal variation

Monitoring of *Cupressaceae*, *Pinus*, and *Quercus* pollen grains in the atmosphere was conducted in Coyoacán during the period 2008–2023, in Cuajimalpa from 2010–2023, and in PNDL from 2016–2023. The Annual Pollen Integral (API) of the pollination period differed across sampling periods and among the stations.

In the Coyoacán station, Cupressaceae showed that the pollination period with the highest concentration occurred in 2009–2010 (21,718 pg/m³), while the lowest concentration was recorded in 2012–2013 (4,719 pg/m³). In the Cuajimalpa station, the highest atmospheric pollen concentration was observed in 2014–2015 (64,647 pg/m³), whereas the lowest abundance was in 2021–2022 (5,655 pg/m³). Finally, in the PNDL station, the highest value of airborne pollen was recorded in 2017–2018 (23,223 pg/m³), and the lowest in 2021–2022 (1,592 pg/m³) (Table 2).

Table 2. Flowering periods of the Cupressaceae family at the three monitoring stations.

Locality	Year	APIN*	Date of the beginning of flowering	Date of the end of flowering	Pollen seasons	Date of maximum concentration	Maximum value (pollen grain/m3 air)
Cupressaceae (A)							
Coyoacán	2008-2009	12,740	14/09/2008	29/05/2009	257	24/01/2009	504
	2009-2010	21,718	19/09/2009	18/04/2010	211	20/01/2010	2146
	2010-2011	11,344	04/11/2010	06/07/2011	244	06/02/2011	381
	2011-2012	12,163	15/09/2011	02/06/2012	261	12/02/2012	553
	2012-2013	4,719	01/09/2012	28/06/2013	300	15/01/2013	84
	2013-2014	10,204	12/10/2013	21/07/2014	282	11/03/2014	84
	2014-2015	7,919	10/08/2014	28/06/2015	322	21/01/2015	139
	2015-2016	12,911	10/09/2015	14/07/2016	308	26/01/2016	323
	2016-2017	13,072	21/08/2016	29/06/2017	312	29/11/2016	242
	2017-2018	6,932	09/10/2017	09/07/2018	157	05/02/2018	235
	2018-2019	7,607	25/08/2018	06/07/2019	315	22/01/2019	73
	2019-2020	7,249	04/09/2019	12/07/2020	310	02/01/2020	115
	2020-2021	5,809	16/08/2020	17/07/2021	308	25/01/2021	82
	2021-2022	6,285	20/08/2021	13/07/2022	302	31/01/2022	112
	2022-2023	4,941	25/08/2022	23/07/2023	242	31/01/2023	109
Cuajimalpa	2010-2011	23,251	12/11/2010	11/07/2011	241	08/01/2011	755
	2011-2012	25,478	19/10/2011	22/05/2012	216	18/02/2012	1202
	2012-2013	31,530	06/10/2012	03/07/2013	270	01/07/2013	1908
	2013-2014	17,812	10/10/2013	07/06/2014	240	10/01/2014	644
	2014-2015	64,647	19/10/2014	21/03/2015	153	11/01/2015	6270
	2015-2016	24,493	20/09/2015	26/05/2016	249	31/01/2016	1125
	2016-2017	23,243	13/11/2016	13/06/2017	212	28/11/2016	2626
	2017-2018	12,704	16/09/2017	11/05/2018	198	02/02/2018	597
	2018-2019	8,050	10/09/2018	17/06/2019	172	15/12/2018	320
	2019-2020	9,389	29/10/2019	24/02/2020	98	01/02/2019	1415
	2020-2021						
	2021-2022	5,655	21/11/2021	06/06/2022	145	01/05/2022	594
	2022-2023	26,340	10/10/2022	13/06/2023	237	21/02/2023	990
PNDL	2016-2017	9,573	28/12/2016	10/05/2017	123	20/01/2017	689
	2017-2018	23,223	13/09/2017	18/02/2018	79	06/12/2017	2156
	2018-2019	19,612	01/09/2018	30/05/2019	258	15/10/2018	587
	2019-2020	10,732	06/09/2019	06/03/2020	183	08/11/2019	330
	2020-2021						
	2021-2022	1,592	07/02/2022	01/07/2022	129	10/02/2022	45
	2022-2023	24,837	10/09/2022	13/05/2023	177	23/10/2022	974
*AIPn The Annual Pollen Integral							

For *Pinus* sp., it was observed that in the Coyoacán station, the highest representation of airborne pollen grains occurred in 2009–2010 (7,301 pg/m³), while the lowest concentration was in 2020–2021 (539 pg/m³). In contrast, in the Cuajimalpa station, the most abundant period was 2011–2012 (4,768 pg/m³), and the lowest concentration was recorded in 2021–2022 (1,125 pg/m³). Monitoring at Desierto de los Leones showed that the season with the highest pollen presence was 2018–2019 (2,245 pg/m³), whereas the lowest was in 2017–2018 (118 pg/m³) (Table 3).

Table 3. Pollination periods of *Pinus* sp. at the monitoring stations.

Locality	Year	APIN*	Date of the beginning of flowering	Date of the end of flowering	Pollen seasons	Date of maximum concentration	Maximum value (pollen grain/m3 air)
Pinus sp. (B)							
Coyoacán	2008-2009	2,390	02/12/2008	28/05/2009	177	19/02/2009	94
	2009- 2010	7,301	14/01/2010	31/05/2010	137	19/02/2010	249
	2010-2011	1,688	17/11/2010	19/05/2011	183	09/03/2011	51
	2011-2012	4,110	29/12/2011	10/06/2012	164	08/03/2012	84
	2012-2013	1,133	21/10/2012	24/06/2013	246	30/04/2013	26
	2013-2014	1,441	02/09/2013	12/07/2014	313	30/04/2014	42
	2014-2015	1,010	06/08/2014	01/07/2015	329	13/04/2015	34
	2015-2016	2,004	10/11/2015	11/07/2016	244	08/05/2016	73
	2016-2017	1,303	30/11/2016	27/06/2017	209	10/05/2017	31
	2017-2018	1,068	08/12/2017	28/06/2018	162	15/04/2018	37
	2018-2019	647	21/08/2018	17/07/2019	202	07/04/2019	23
	2019-2020	647	22/08/2019	17/07/2020	202	07/04/2020	23
	2020-2021	539	16/08/2020	20/07/2021	208	29/04/2021	18
	2021-2022	954	25/09/2021	22/07/2022	206	04/05/2021	33
	2022-2023	2,013	08/09/2022	23/06/2023	223	17/03/2023	72
Cuajimalpa	2010-2011	1,487	01/11/2010	23/05/2011	203	08/03/2011	83
	2011-2012	4,768	16/12/2011	31/05/2012	167	20/03/2012	159
	2012-2013	3,547	20/12/2012	16/06/2013	178	09/03/2013	73
	2013-2014	3,491	14/12/2013	07/06/2014	175	16/03/2014	88
	2014-2015	2,158	16/11/2014	04/06/2015	200	21/04/2015	69
	2015-2016	3,272	13/12/2015	08/06/2016	178	13/04/2016	91
	2016-2017	1,530	05/12/2016	05/06/2017	182	29/04/2017	52
	2017-2018	1,142	19/11/2017	13/05/2018	110	09/03/2018	74
	2018-2019	1,690	18/01/2019	20/06/2019	118	01/05/2019	54
	2019-2020	117	07/08/2019	14/03/2020	79	27/01/2020	6
	2020-2021						
	2021-2022	1,125	07/12/2021	09/06/2022	120	20/03/2022	51
	2022-2023	3,967	07/11/2022	14/06/2023	198	14/03/2023	198
PNDL	2016-2017	2,310	22/02/2017	26/05/2017	79	01/04/2017	177
	2017-2018	118	14/08/2017	15/06/2018	82	28/11/2017	5
	2018-2019	2,245	17/02/2019	24/06/2019	125	03/04/2019	60
	2019-2020	189	06/08/2019	14/03/2020	99	08/03/2020	15
	2020-2021						
	2021-2022	1,363	08/03/2022	18/06/2022	93	18/03/2022	79
	2022-2023	2,213	25/09/2022	28/05/2023	124	04/04/2023	120

***AIPn The Annual Pollen Integral

The *Quercus* sp. pollen grains identified at the Coyoacán station indicated that the period with the highest airborne concentration occurred in 2009–2010 (5,671 pg/m³), while the lowest concentration was recorded in 2020–2021 (106 pg/m³). At the Cuajimalpa station, monitoring of this pollen type showed that

the highest concentration was in 2011–2012 (9,705 pg/m³), whereas the lowest was in 2018–2019 (1,370 pg/m³). In the Desierto de los Leones site, the period with the highest representation occurred in 2021–2022 (1,515 pg/m³), and the lowest abundance was observed in 2017–2018 (36 pg/m³) (Table 4).

Table 4. Pollination periods of *Quercus* sp. at the monitoring stations.

Locality	Year	APIN*	Date of the beginning of flowering	Date of the end of flowering	Pollen seasons	Date of maximum concentration	Maximum value (pollen grain/m3 air)
***Quercus* sp.**							
Coyoacán	2008-2009	1,389	14/12/2008	13/06/2009	181	14/03/2009	48
	2010	5,671	01/03/2010	24/04/2010	54	23/03/2010	329
	2011	1,382	19/02/2011	18/05/2011	88	08/03/2011	90
	2012	3,562	03/03/2012	24/05/2012	82	19/03/2012	167
	2013	507	24/02/2013	09/06/2013	105	28/03/2013	24
	2014	1,246	23/02/2014	19/05/2014	85	27/03/2014	81
	2015	1,193	03/03/2015	01/05/2015	59	17/04/2015	87
	2016	1,087	24/03/2016	15/05/2016	52	14/04/2016	87
	2017	654	22/02/2017	29/05/2017	96	09/04/2017	51
	2018	2,248	06/03/2018	28/04/2018	54	28/03/2018	147
	2019	1,262	03/03/2019	30/04/2019	59	10/03/2019	74
	2020	1,074	03/03/2020	24/05/2020	81	23/03/2020	43
	2021	106	26/02/2021	27/06/2021	123	14/03, 07/06/ 2021	7
	2022	1,181	17/03/2022	15/05/2022	60	05/04/2022	75
	2023	1,379	07/03/2023	06/06/2023	59	26/03/2023	101
Cuajimalpa	2011	2,765	18/02/2011	15/05/2011	86	07/03/2011	218
	2012	9,705	02/03/2012	15/05/2012	74	20/03/2012	412
	2013	3,679	19/02/2013	17/06/2013	118	31/03/2013	125
	2014	8,253	27/02/2014	16/05/2014	78	24/03/2014	445
	2015	3,357	18/02/2015	07/05/2015	78	13/04/2015	215
	2016	4,405	15/03/2016	23/05/2016	69	11/04/2016	253
	2017	2,139	13/02/2017	30/05/2017	106	09/04/2017	112
	2018	5,799	05/03/2018	21/04/2018	38	18/03/2018	568
	2019	1,370	13/02/2019	30/06/2019	100	09/04/2019	120
	2019-2020	252	28/08/2019	14/03/2020	55	13/03/2020	30
	2020-2021						
	2022	1,738	07/02/2022	20/05/2022	76	03/04/2022	127
	2022-2023	4,589	18/12/2022	12/06/2023	133	12/03/2023	276
PNDL	2017	422	02/02/2017	04/06/2017	97	09/04/2017	25
	2017-2018	36	08/09/2017	11/06/2018	70	25/02/2018	5
	2019	933	26/02/2019	08/05/2019	67	12, 13, 14/04/2019	45
	2020	384	28/02/2020	14/03/2020	14	03/03/2020	76
	2020-2021						
	2022	1,515	09/03/2022	15/05/2022	58	17/03/2022	99
	2023	1,386	22/04/2023	15/05/2023	32	11/05/2023	170

***AIPn The Annual Pollen Integral

The start and end dates of the MPP for the Cupressaceae family were determined (Figure 3A). In Coyoacán (2008–2023), the MPP began between August and November and ended between May and July. The longest period lasted a total of 322 days (2014–2015), while the shortest was 157 days (2017–2018). In Cuajimalpa (2010–2023), the MPP started between September and November, ending between March and July. The longest period lasted 270 days (2012–2013), and the shortest lasted 98 days (2019–2020). At the PNDL station, the onset of the MPP was more variable: in 2016–2017 it began in December, whereas between 2017–2020 it started in September, ending between February and July. The longest period was 258 days (2018–2019), while the shortest was 79 days (2017–2018). In addition, the months of maximum concentration were December–February, corresponding to the cold-dry season, in all three monitoring stations, averaging between 6 and 9 months of the MPP.

At the Coyoacán station, the onset of *Pinus* sp. pollination varied each year, beginning between August and January and ending between May and July (Figure 3B). The longest period lasted 329 days (2014–2015), while the shortest lasted 137 days (2009–2010). At the Cuajimalpa station, the pollination season of *Pinus* sp. occurred between August and January, ending between March and June. The longest period lasted 203 days (2010–2011), whereas the shortest lasted 79 days (2019–2020). In PNDL station, *Pinus* sp. showed that pollination began between August and February and ended between March and June. The MPP lasted approximately 6 months, with the longest period being 125 days (2018–2019) and the shortest 79 days (2022–2023). In addition, pollination periods of *Pinus* sp. are prolonged, lasting between 5–8 months, with the highest abundance observed in March–April, coinciding with the onset of the warm-dry season.

The onset and end of the *Quercus* sp. pollination period were established (Figure 3C). In Coyoacán (2008–2023), the onset of the pollination periods was mainly in February–March, with the exception of December in 2008–2009, ending between April and June. The longest period lasted a total of 181 days (2008–2009), while the shortest was 52 days (2015–2016). In Cuajimalpa (2010–2023), the onset of pollination periods occurred in February–March, with the exception for two periods beginning in August (2019–2020) and December (2022–2023), which ended between March and June. The longest period lasted 118 days (2012–2013), and the shortest 38 days (2017–2018). In PNDL station, the onset of pollination was observed between September and April, concluding between March and June. The longest period lasted 97 days (2016–2017), while the shortest was 14 days (2019–2020). Similarly, in all three monitoring stations, maximum concentrations occurred from March to May, averaging 2–3 months of the MPP, with the highest levels during the warm-dry season.

The maximum concentration of pollen grains from members of the Cupressaceae family (Fig. 4A) reached 2146 pg/m³ in Coyoacán in January (2009-2010). At the Cuajimalpa station, the highest peak was recorded in 2014-2015, with a concentration of 6270 pg/m³. While in PNDL station, the most representative peak occurred in 2017-2018, with a value of 2156 pg/m³.

For *Pinus* sp. (Fig. 4B), the maximum concentration values in Coyoacán reached during 2009–2010, 249 pg/m³, while at the Cuajimalpa station the highest concentration was recorded in 2022–2023 with 198 pg/m³. In PNDL station the maximum concentration was observed in 2016–2017, corresponding to 177 pg/m³.

On the other hand, *Quercus* sp. (Fig. 4C) showed that at the Coyoacán station the highest pollen concentration during 2009–2010 was 329 pg/m³. At the Cuajimalpa station, the highest concentration of airborne grains was recorded in 2017–2018 with 568 pg/m³; whereas in the PNDL station the maximum concentration was observed in 2022–2023 with 170 pg/m³.

Fig 4

According to the comparison of the total number of MPP days for each station and pollen type (Fig. 5A), Cupressaceae in Coyoacán station showed a median of 287 days, with a 75th percentile of 316 days and a 25th percentile of 258 days. In Cuajimalpa station, the median was 236 days, with a 75th percentile of 247 days and a 25th percentile of 185 days, whereas in the PNDL station, the median was 171 days, with a 75th percentile of 253 days and a 25th percentile of 143 days. In addition, significant differences were found between Coyoacán vs. Cuajimalpa and Coyoacán vs. PNDL ($P < 0.01$).

For *Pinus* sp. (Fig. 5B), at the Coyoacán station, the median was 262 days, with a 75th percentile of 329 days and a 25th percentile of 184 days. In Cuajimalpa station, the median was 182 days, with a 75th percentile of 212 days and a 25th percentile of 177 days, whereas in the PNDL station, the median was 175 days, with a 75th percentile of 261 days and a 25th percentile of 101 days. Significant differences were found between Coyoacán and Cuajimalpa ($P < 0.05$).

Additionally, for *Quercus* sp. (Fig. 5C), no significant differences were found among the Coyoacán, Cuajimalpa, and stations.

Fig. 5

3.2.2 Trend analysis of the annual pollen index (API)

The three pollen types from the three localities were characterized by interannual variations throughout the different study periods. The trend analysis was performed by applying the Mann-Kendall test to determine how the presence of pollen from the three tree types (*Cupressaceae*, *Pinus sp.,* and *Quercus sp.*) changes across the three different sites. Table 5 shows the test values which determine if there is a significant trend (a constant increase or decrease) in various pollen parameters over time: indicates a positive trend (increase) and indicates a negative trend (decrease).

Table 5. Mann–Kendall test ($z > 0$: positive trend; $z < 0$: negative trend) for Cupressaceae, *Pinus* sp., and *Quercus* sp. during the Main Pollen Period at three localities.

Site	Pollen season parameter	Cupressaceae		Pinus *sp.*		Quercus *sp.*	
		Z	p-value	*Z*	p-value	*Z*	p-value
Coyoacán	**Start PPP**	-2.18279	0.0290513*	-2.32875	0.0198722*	2.08357	0.0371991*
	End PPP	3.95897	0.0000753****	3.17496	0.00149868*	0.09922	0.92096
	Duration of period	1.13960	0.25445	0.84231	0.39961	-0.79636	0.42582
	Maximum concentration	-2.52694	0.0115061*	-2.42785	0.0151888*	-0.94141	0.34649
	APIN	-2.57333	0.0100725*	-2.62604	0.00863859*	-1.68256	0.09246
Cuajimalpa	**Start PPP**	-0.34286	0.73170	-0.20572	0.83701	-1.86023	0.06285
	End PPP	-0.41241	0.68004	1.30905	1.30905	0.20572	0.83701
	Duration of period	-1.98860	0.0467447*	-1.09975	0.27144	-0.13747	0.89066
	Maximum concentration	-0.89144	0.37269	-1.30288	0.19262	-0.61715	0.53713
	APIN	-1.71431	0.08647	-1.57717	0.11476	-1.30288	0.19262
PNDL	**Start PPP**	--	--	--	--	--	--
	End PPP	--	--	--	--	--	--
	Duration of period	--	--	--	--	--	--
	Maximum concentration	--	--	--	--	--	--
	APIN	--	--	--	--	--	--

*P<0.05; **P<0.01; ***P<0.001; ****P<0.0001

At Coyoacán station, the *Cupressaceae* pollen family showed several significant trends. A significant negative trend was observed at the start of the Main Pollen Period (MPP), indicating that the season has begun earlier over the years. Conversely, the end of the MPP presented a significant positive trend, suggesting that the season is ending later. Furthermore, both the maximum concentration and the Annual Pollen Index (API) registered a significant negative trend, confirming that both the peak pollen count and the total annual pollen load have been declining sharply.

In Cuajimalpa, the only significant trend observed was a shortening of the pollen duration over the years.

In summary, *Cupressaceae* pollen at the Coyoacán station reveals robust trends pointing to a lengthening of the season alongside a decrease in its concentration and total pollen load. Meanwhile, the trend in Cuajimalpa station is characterized solely by a significant shortening of the pollen duration.

For *Pinus* sp., significant trends were only found in the pollen data recorded at the Coyoacán station. A significant negative trend was observed at the beginning of the PMP, while a significant positive trend was observed at the end of the PMP. Furthermore, both the maximum concentration and the API showed a significant negative trend.

In conclusion, *Pinus* sp. pollen at this station exhibits a dual pattern of change that affects both the duration and intensity of its season. There is a clear and strong tendency for the MPP to lengthen. This is because the start of the season has moved significantly earlier, and the end has moved significantly later. This exposes the area's inhabitants to pollen levels for a more extended period each year. However, the intensity of the pollination event decreases significantly over time. Therefore, the season time for this pollen type is now longer, but less intense, and with a decreasing total pollen load.

For *Quercus* sp., the only parameter that showed a positive and statistically significant trend was the onset of the MPP, which refers to a significant delay in the flowering date.

3.3 Correlation analysis with meteorological parameters

The Spearman correlation analysis (rs) obtained from the MPP data with the main meteorological parameters for the three types of pollen (Cupressaceae, *Pinus* and *Quercus*), at the three sampled stations (TableS1, Table S2. Table S3) showed that, for Cupressaceae, correlation coefficients were significant and positive with heat-related parameters (maximum temperature and solar radiation), and negative in the post-peak period. It was also observed that correlations were significant and negative with wind parameters, relative humidity, and precipitation. It is important to highlight that, in the PNDL correlation, values were significant and negative, with the exception of maximum temperature during the pre-peak period.

Tables S1, S2, S3

For the correlations obtained with *Pinus* sp. in the three stations (Coyoacán, Cuajimalpa and Parque Nacional Desierto de los Leones) (Tables S5, Table S6) significant and positive correlations were observed mainly with temperature (maximum, mean, and minimum), relative humidity, and solar radiation. Significant negative correlations were observed with wind, humidity, and precipitation.

Tables S4, S5, S6

For the correlations obtained with *Quercus* sp. in the three stations (Coyoacán, Cuajimalpa and Parque Nacional Desierto de los Leones) (Table S7, Table S8, Table S9), the correlations obtained were positive and significant with temperature (maximum, mean, and minimum), wind, and solar radiation, while significant negative correlations were found with relative humidity and precipitation.

In addition, linear regression analysis (r) indicated a significant decrease in relative humidity throughout the study period for Cupressaceae at the Coyoacán and the PNDL stations. Moreover, a significant difference was found for minimum temperature in the PNDL with Cupressaceae (Table 6).

Table 6. Linear regression for each MPP of Cupressaceae, *Pinus* sp. and *Quercus* sp. of the annual average relative humidity and temperature (maximum, mean and minimum) in Coyoacán (2008-2023), Cuajimalpa (2010-2023) and PNDL (2016-2023).

Site	Pollen type		Max Temp	Mean Temp	Min Temp	Relative Humidity
Coyoacán	Cupressaceae	y=	-0.1222x ± 270	-0.1220x ± 270	-0.06408x ± 140.9	-0.2900 ± 643.5
		r2	0.1645	0.1718	0.03513	0.107
		p	0.1502	0.1406	0.5211	0.2537
	Pinus sp.	y=	-0.09529x ± 215.7	-0.1289 ±277.1	-0.1526 ± 319.6	-0.8797 ± 1834
		r2	0.1361	0.01681	0.01025	0.08683
		P	0.238	0.688	0.7542	0.3525
	Quercus	y=	0.1278x -233.5	0.02532x -33.36	-0.07625x ± 166.3	-1.547x ± 3182
		r2	0.1306	0.007715	0.07822	0.5059
		p	0.1856	0.7556	0.3127	0.0029**
Cuajimalpa	Cupressaceae	y=	-0.09401x ± 213	0.05949x -102.2	-0.03024x ± 72.76	-0.8259x ± 1719
		r2	0.1361	0.01681	0.01025	0.08683
		p	0.238	0.688	0.7542	0.3525
	Pinus sp.	y=	-0.05607x ± 136.4	0.1159x -215.7	0.005385x ± 166.1	-0.8033x ± 2007
		r2	0.06243	0.04066	0.0004272	0.06119
		p	0.4335	0.5297	0.9492	0.4383
	Quercus	y=	0.01370x -3.613	0.01085x ± -4.052	-0.06014x ± 133.8	-0.4618x ± 990.7
		r2	0.002256	0.002532	0.02517	0.01957
		p	0.8835	0.8766	0.6224	0.6646
PNDL	Cupressaceae	y=	-0.3654x ± 761.3	-0.03839x ± 95.15	-0.3099x ± 638.1	-6.207x ± 12590
		r2	0.7075	0.006165	0.5525	0.7554
		p	0.0359*	0.8825	0.0904	0.0246*
	Pinus sp.	y=	-0.2805x ± 589.4	-0.1265x ± 273.7	-0.1834x ± 382.2	-6.693x ± 13570
		r2	0.415	0.0225	0.1739	0.7527
		p	0.1673	0.7767	0.4108	0.0251*
	Quercus	y=	0.6448x -1278	0.1980x -380.7	0.7336x -1464	-4.126x ± 8389
		r2	0.8227	0.06689	0.587	0.5451
		p	0.0126*	0.6207	0.0756	0.0937

3.4 Hysplit Model

Table 7 presents a summary of the most relevant daily pollen concentration dates for the three pollen types at each locality.

Table 7. Dates and pollen types for particle dispersion analysis using the HYSPLIT model

Cupressaceae	Locality	Date	Pollen concentration/day	Horary
	Coyoacán (A)	26/01/2016	317 gp/m3	09:00 hrs
	Cuajimalpa (B)	11/01/2015	6270 gp/m3	00:00 hrs
	PNDL (C)	06/12/2017	2156 gp/m3	13:00 hrs
***Pinus* sp.**	Coyoacán (A)	07/04/2019	23 gp/m3	16:00 hrs
	Cuajimalpa (B)	29/04/2017	37 gp/m3	06:00 hrs
	PNDL (C)	01/04/2017	177 gp/m3	06:00 hrs
***Quercus* sp.**	Coyoacán (A)	28/03/2018	147 gp/m3	15:00 hrs
	Cuajimalpa (B)	18/03/2018	568 gp/m3	20:00 hrs
	PNDL (C)	17/03/2022	99 gp/m3	16:00 hrs

Figure 6 shows the trajectories of the three pollen types studied. The figure indicates the dispersion of particles carried by the wind 24 hours before the date of maximum pollen concentration recorded at each locality.

Fig. 6

In the Coyoacán locality, the wind originated from the southwest, passing through the Tlalpan forest in the case of Cupressaceae (Fig. 6A). For *Pinus* sp., the wind was observed to come from Los Dinamos Park (Fig. 6B), whereas for *Quercus* sp., the wind trajectory derived from the Ajusco mountain range, passing through different urban parks (Fig. 6C).In the wind trajectory for Cuajimalpa, it was observed that for Cupressaceae the direction originated from the area known as 'Barranca Becerra Tepecuache,' as well as from main avenues (Bosques de la Reforma and Paseo de los Laureles), where different types of ornamental trees can be observed along the medians (Fig. 6D). For *Pinus* sp., the airflow originated from sources near 'La Marquesa,' as well as from the urban area (Fig. 6E). For *Quercus* sp., the wind trajectory also originated from 'Barranca Becerra Tepecuache,' as well as from different areas of 'Lomas de Chapultepec,' which include ravines and several urban parks (Fig. 6F).

In Desierto de los Leones (Fig. 6G–I), the winds were observed to originate from the western part of Mexico City, corresponding to 'La Marquesa' park, and from the southwest, 'Los Dinamos,' areas where the predominant vegetation consists mainly of conifers, similar to the sampling site.

The wind trajectory distances were obtained at the monitoring stations for the three pollen types, showing significant differences ($P < 0.02$). For *Pinus* sp. at the Coyoacán station, the mean distance ($\bar{x}$) traveled by the wind was 11.72 km, whereas in Desierto de los Leones it was 3.1 km. In the case of *Quercus* sp., at the Desierto de los Leones station the mean distance was $\bar{x}$ = 10.42 km, while in Coyoacán and Cuajimalpa it was $\bar{x}$ = 2.7 km and $\bar{x}$ = 4.5 km, respectively.

4. Discussion

4.1 Pollen calendar of Cuajimalpa

The Cuajimalpa borough is characterized by a temperate sub-humid climate with summer rains and high humidity, conditions that favour primary vegetation composed mainly of Pinus sp., Abies sp., and Quercus sp. (SEDEMA, n.d.). However, secondary vegetation such as *Alnus* sp. (CONABIO, n.d.), *Fraxinus* sp. and *Salix* sp. was also identified, with pollen levels exceeding 1% of the total concentration. These species are currently used extensively in reforestation programs for wooded areas, parks, medians, and gardens (SEDEMA, 2021). A high relative abundance of Cupressaceae pollen was also recorded, which is attributed to its frequent anthropogenic and ethnobotanical use in the area (Fonseca, 2011). Under this scenario, the pollen calendar of Cuajimalpa acquires critical relevance for public and environmental health, since increasing anthropogenic pressure on the environment can lead to temporal changes in pollen emissions. Consequently, continuous aerobiological monitoring is crucial for detecting these variations and mitigating their impact on the population.

Our results indicate that pollination periods extended from October to September for Cupressaceae, Fraxinus sp., Poaceae, and Casuarina sp.; from October to June for Alnus sp.; and from January to June for Quercus sp., Pinus sp., and Urticaceae. These seasonal patterns differ from those reported in cities with temperate and Mediterranean climates in other regions of the world, where the main periods are usually concentrated between March and October (Kolek et al., 2021). However, the pollination periods observed in cities in the US and Canada show similarities to our findings, with the exception of Casuarina sp., which was not reported in those studies (Lo et al., 2019).

4.2 Interannual and seasonal variation

The Cupressaceae family, *Pinus* sp., and *Quercus* sp. predominate throughout the year due to the meteorological conditions that influence the flowering periods of plants. In addition, they have medical importance, since several studies have reported them as allergens (De la Cruz et al., 2007; Ríos et al., 2016).

In our study, the highest presence of Cupressaceae pollen occurred in both Coyoacán and Cuajimalpa, making it the most representative pollen type in Mexico City. This finding is consistent with several studies reported since the 1990s (Calderón et al., 2015; Calderón et al., 2018). This family includes the genera *Cupressus* and *Juniperus*, which are characteristic of the Valley of Mexico region (Rzedowski, 2005) and encompass a large number of ornamental species. Interestingly, this pollen has also been studied in other countries, highlighting its importance since it releases large amounts of pollen throughout the year, triggering allergies.

The Pinaceae family is characterized by its anemophilous pollination (Green et al., 2003). In the Valley of Mexico, the genus *Pinus* is represented by a high diversity of species, such as *P. patula*, *P. teocote*, *P. hartwegii*, *P. montezumae*, *P. pseudostrobus*, *P. leiophylla*, and *P. ayacahuite*, which are characteristic of mountainous areas (Rzedowski, 2005). In various regions of Spain, Italy, and the United States, *Pinus* has been reported as the most abundant taxon during spring or early summer (Frenguelli et al., 2002b; Fernández-González et al., 2021). This pattern is consistent with our observations, where this pollen type predominated during the warm–dry season (March to June).

Furthermore, we observed that the Main Pollen Period (MPP) of this pollen presents extended durations. This could be explained by its morphology, specifically the presence of **air sacs (sacculi)**, which facilitate its persistence and prolong its presence in the atmosphere (Velasco-Jiménez, 2017). Additionally, Jato et al. (2000) suggest that the duration of the MPP is associated with the participation of multiple species whose flowering periods overlap, a phenomenon that likely occurs in our study zones due to the aforementioned species richness. In this way, our results for the Cupressaceae family and the genus *Pinus* sp. show similarities with studies in other geographic regions that have evaluated various airborne pollen types, identifying trends toward earlier pollen seasons (February–May) and more prolonged durations (Gross et al., 2019; Manangan et al., 2021; Adams-Groom et al., 2022; Alcázar et al., 2024)."

In the Valley of Mexico, the Fagaceae family is represented by a single genus, Quercus sp., which comprises approximately 25 species. Among the main reported species are Q. laeta, Q. deserticola, Q. crassipes, Q. obtusata, and Q. rugosa, which are wind-pollinated trees and shrubs distributed in tropical and subtropical regions (Rzedowski, 2005). This pollination type is widely documented globally, with its Main Pollination Period (MPP) typically occurring between March and April, coinciding with spring (Jato et al., 2002; Fernández-Rodríguez et al., 2015). Similarly, our results show that the MPP is short and annual (March–May), as previously reported by Calderón-Ezquerro et al. (2018) for Mexico City. Additionally, a biennial alternation in pollen production (API) was observed, a phenomenon that has also been recorded in Mediterranean regions (Spieksma et al., 2003; Grundström et al., 2019; Alcázar et al., 2024).

On the other hand, there is a latitude-related trend, where at higher latitudes (> 35°N) the peak pyroclastic flow (PPF) is usually later and more prolonged. For example, Lo et al. (2019) reported an earlier and shorter PPF in Waco, Texas, compared to London, Ontario; in accordance with this, our results show that the PPF was restricted to the period from February to May, similar to what was reported for Texas. It is worth noting that the PPF at the Coyoacán station showed an earlier onset, which is attributed to the fact that it is a site influenced by the 'urban heat island' effect (temperature increase). However, this study had limitations regarding the length of the periods analysed for the Mann-Kendall test when evaluating current PPF trends; therefore, it is likely that some of these trends will acquire greater statistical relevance in future long-term studies.

When comparing the duration of pollen maturation time (PMT) in days across the three stations for the Cupressaceae, Pinus sp., and Quercus sp. families, the Coyoacán site differed from Cuajimalpa and the PNDSL (National Park of San Luis), while the latter two showed similar behaviour. A likely explanation for these differences lies in the role of reforestation and ornamental use in Mexico City. In Coyoacán and Cuajimalpa, Cupressaceae and Pinus sp. are present in various green areas, such as parks, medians, and gardens, which promotes a greater presence of these pollen types in the environment. In contrast, no significant differences were found between the locations for the genus Quercus sp., which is probably due to its limited ornamental use, as its presence is more restricted to natural areas such as the Pedregal Ecological Reserve or ravine areas in Chapultepec and Cuajimalpa.

4.3 Correlation analysis with meteorological parameters

According to the correlations observed between the concentrations of the three pollen types and environmental factors, our results are consistent with previous studies published for Mexico City (Calderón et al., 2015; Ríos et al., 2016). Numerous studies have investigated the relationships between daily pollen concentrations and various general meteorological parameters (Pérez-Badia et al., 2011; Simoleit et al., 2015; Borycka and Kasprzyk, 2014; Ščevková et al., 2015). For several arboreal species, significant positive correlations have been observed with solar radiation, mean temperature, and wind speed, as these factors promote anther dehiscence and the subsequent release of pollen grains. Furthermore, anther desiccation occurs effectively only when relative humidity is low.

Conversely, negative correlations have been reported with relative humidity and precipitation. This is because high relative humidity hinders pollen emission, leading to grain aggregation and deposition, whereas precipitation accelerates pollen sedimentation through atmospheric washout (Fernández-Rodríguez et al., 2015; Ščevková et al., 2015; Monroy-Colín et al., 2020).

4.4 Linear regression (Temperature and Relative Humidity)

The reproductive phenology of plants is controlled by temperature, particularly in arboreal species, and thus exerts a strong influence on daily pollen concentrations. In a review by Schramm et al. (2021), it was noted that trees are producing pollen earlier due to the effects of shorter winters caused by rising temperatures. Consequently, there is an association between elevated temperatures and an earlier onset of the MPP, along with longer durations and later terminations, evidencing an extension of the pollination period that is consistent with our findings.

This phenomenon has been well documented in Europe. In 2019, for instance, a heatwave manifested as an increase of 1.1–1.5°C in mean daily temperature between June and December in the cities of Bratislava and B. Bystrica (Menzel et al., 2006; Ščevková et al., 2024). Although temperature increases have been reported in several countries, our study found no significant increasing trend between specific monitoring sites, but rather a trend in the general temperature of the city.

Regarding *Quercus* sp., several authors have linked temperature increases (> 1.5°C) to the advancement or elongation of the MPP; therefore, this pollen type has been utilized as a bioindicator of climate change (Gómez-Casero et al., 2007; Tormo-Molina et al., 2010). As García-Mozo et al. (2002) noted, the onset of the MPP consistently begins earlier in Madrid, where temperatures are higher compared to other regions of Spain. In our analysis for *Quercus* sp., it was observed that during the dry–warm season (April–June), the temperature increase showed a positive trend, supporting the environmental association that promotes the pollination of these trees. Specifically, at the Coyoacán station, a positive temperature trend was observed, which could explain the lengthening of the MPP for this pollen type.

Furthermore, an independent linear regression analysis using temperature data from 2008–2023 (Meteoblue, 2025) yielded a correlation value of r = 0.7362 ($p < 0.05$), indicating a significant temperature increase in Mexico City. Therefore, we can state that while this increase was not significant at a local (site-specific) scale, it was significant for Mexico City as a whole."

4.5 Back trajectories

Regarding the analysis of the most relevant daily pollen concentrations for the three taxa at each locality, our results evidenced hourly variations, with nighttime, afternoon, and early morning being the most significant periods.

Nocturnal pollen peaks, such as those observed for Pinus sp., are common, particularly when temperatures increase while relative humidity and wind speed decrease. According to observations in European countries, this family releases large amounts of pollen intermittently over short periods of 3–4 weeks (Simoleit et al., 2015), with temperatures ranging between 8–17°C (Kluska et al., 2020). However, our study recorded diurnal peaks (9–13°C) and pollination periods lasting more than four weeks.

Furthermore, it has been reported that during diurnal peaks, the variability in pollen concentrations is closely related to the time of day, temperature, and air humidity (Ščevková et al., 2015; Bruffaerts et al., 2017). In our findings, both temperature and thermal radiation likely influence pollen levels, especially in Coyoacán and Cuajimalpa. These sites are classified as 'vulnerable with severe effects of the urban heat island,' where natural elements have been replaced by materials with a higher capacity to absorb, retain, and emit heat (SEDEMA, 2025). This environmental condition generates small convection currents that lift pollen grains, potentially explaining the high concentrations observed throughout the day. In other words, as temperature increases and relative humidity decreases, the resuspension of pollen grains is promoted (Zhao et al., 2014; Borycka and Kasprzyk, 2018).

It is crucial to account for these phenomena (pollen resuspension and long-distance transport), as they drive both diurnal and nocturnal peaks. Likewise, long-distance transport should not be underestimated, as anemophilous pollination is a constant process (Kolek et al., 2021; Ghasemifard et al., 2020). Based on the wind back-trajectory analysis for the three pollen types, it was evident that the wind direction originated from both local sources and neighbouring forested areas.

4.6 HYSPLIT model and source áreas

Regarding the HYSPLIT model, we analysed wind trajectories at different altitudes, revealing distinct patterns: at 30 m and 50 m, the distance travelled is shorter due to artificial barriers, whereas at 200 m, the trajectories are longer and originate primarily from forested sources. This is consistent with the results of the present study, where Coyoacán and Desierto de los Leones (PNDSL) exhibited trajectories exceeding 10 km.

In this context, Quesada et al. (2013) reported that in disturbed environments with limited green areas, the average estimated pollen dispersal distance ranges from 198 m to 300 m, suggesting that anemophilous pollen from urban parks and medians does not travel long distances. Conversely, in undisturbed areas, pollen can remain in the atmosphere for up to 24 hours and travel distances as far as 100 km (Robledo-Arnuncio, 2011; Bogawski et al., 2019), a phenomenon observed in the Desierto de los Leones forest.

Following this premise, the trees in the urban area of Cuajimalpa are mostly restricted to ravine zones. Consequently, the trajectories recorded at this sampling station correspond to the same local area, where the dominant vegetation includes oaks such as *Quercus laurina*, *Q. rugosa*, *Q. laeta*, and *Q. obtusata*, as well as pine individuals (*Pinus* sp.) (INEGI, 2001; SEDEMA, 2016). According to SEDEMA (2024), reforestation efforts in these ravines are ongoing, with *Quercus rugosa* and *Pinus patula* being among the tree species most frequently utilised for these activities.

5. Conclusion

This study demonstrates that the Main Pollen Periods (MPP) of Cupressaceae, Pinus sp., and Quercus sp. at the Coyoacán and Cuajimalpa stations exhibit significant temporal variations, characterised by advancements, delays, and an overall lengthening of the pollination seasons. These findings highlight the sensitivity of these arboreal taxa to local environmental conditions.

Regarding meteorological parameters, although a relationship between temperature increases and phenological changes was identified, it is essential to continue strengthening long-term aerobiological and environmental databases to further consolidate this association. Furthermore, the occurrence of both diurnal and nocturnal peaks in anemophilous pollen confirms that transport dynamics are not solely determined by the urban landscape, as seen in Coyoacán, but are also driven by regional atmospheric circulation—a pattern observed even in forested areas like Desierto de los Leones.

In conclusion, maintaining continuous phenological and aerobiological monitoring in Mexico City is imperative. Future research should incorporate additional species of environmental health relevance and employ multi-scale analyses—ranging from daily atmospheric circulation patterns to long-term dynamics—to better understand and mitigate the impact of pollen abundance on public health in the context of climate change."

Declarations

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Figures

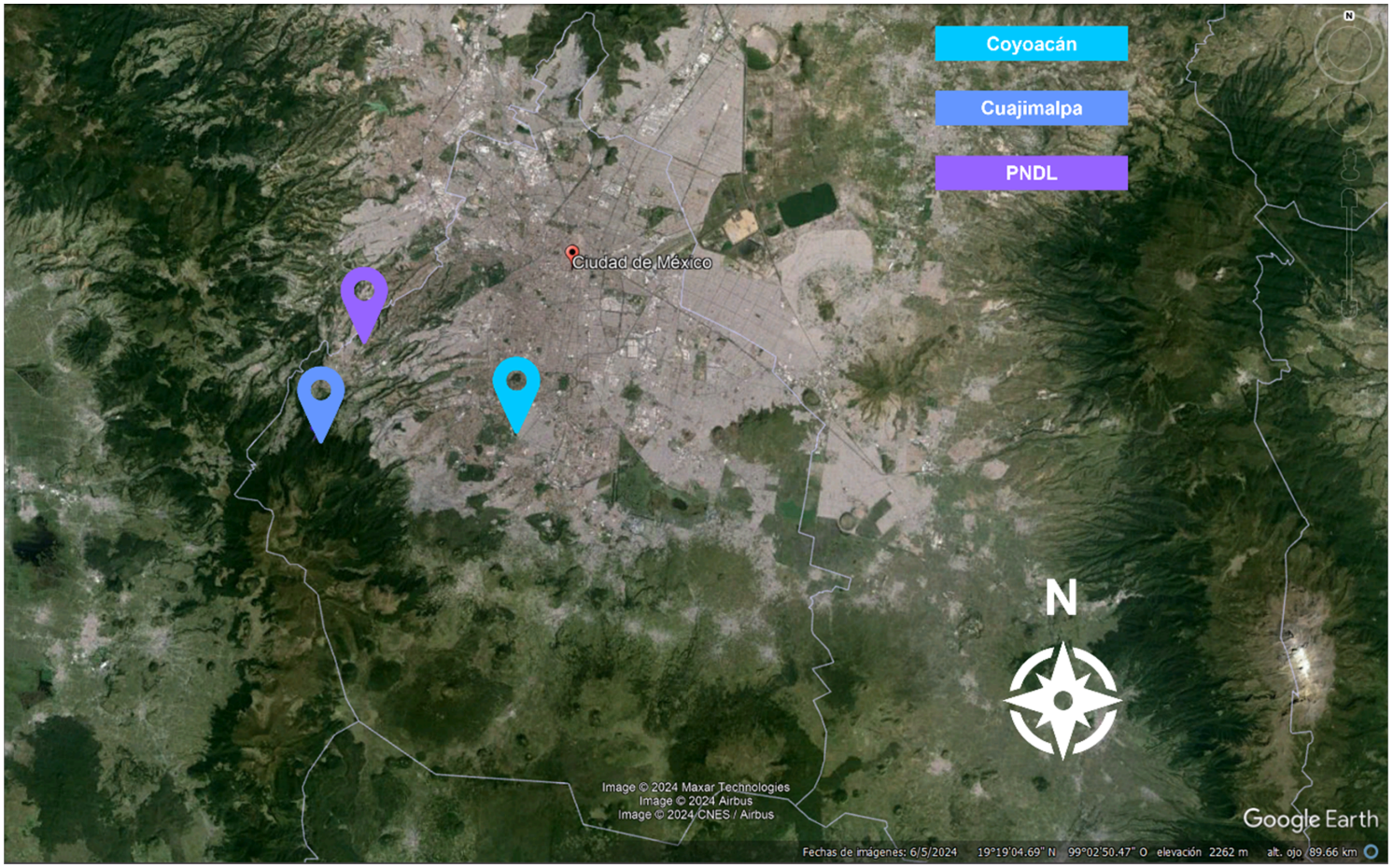

Figure 1

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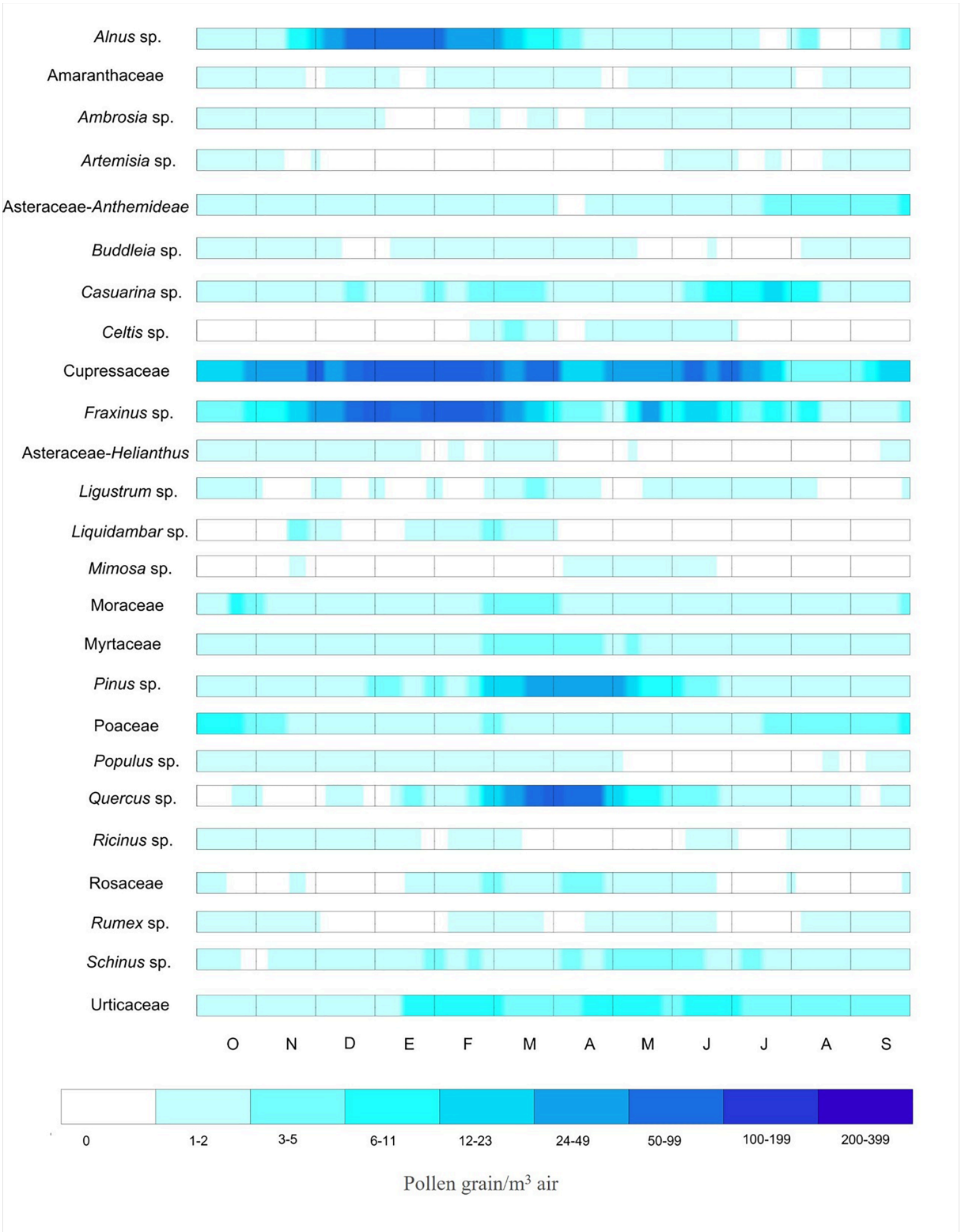

Figure 2

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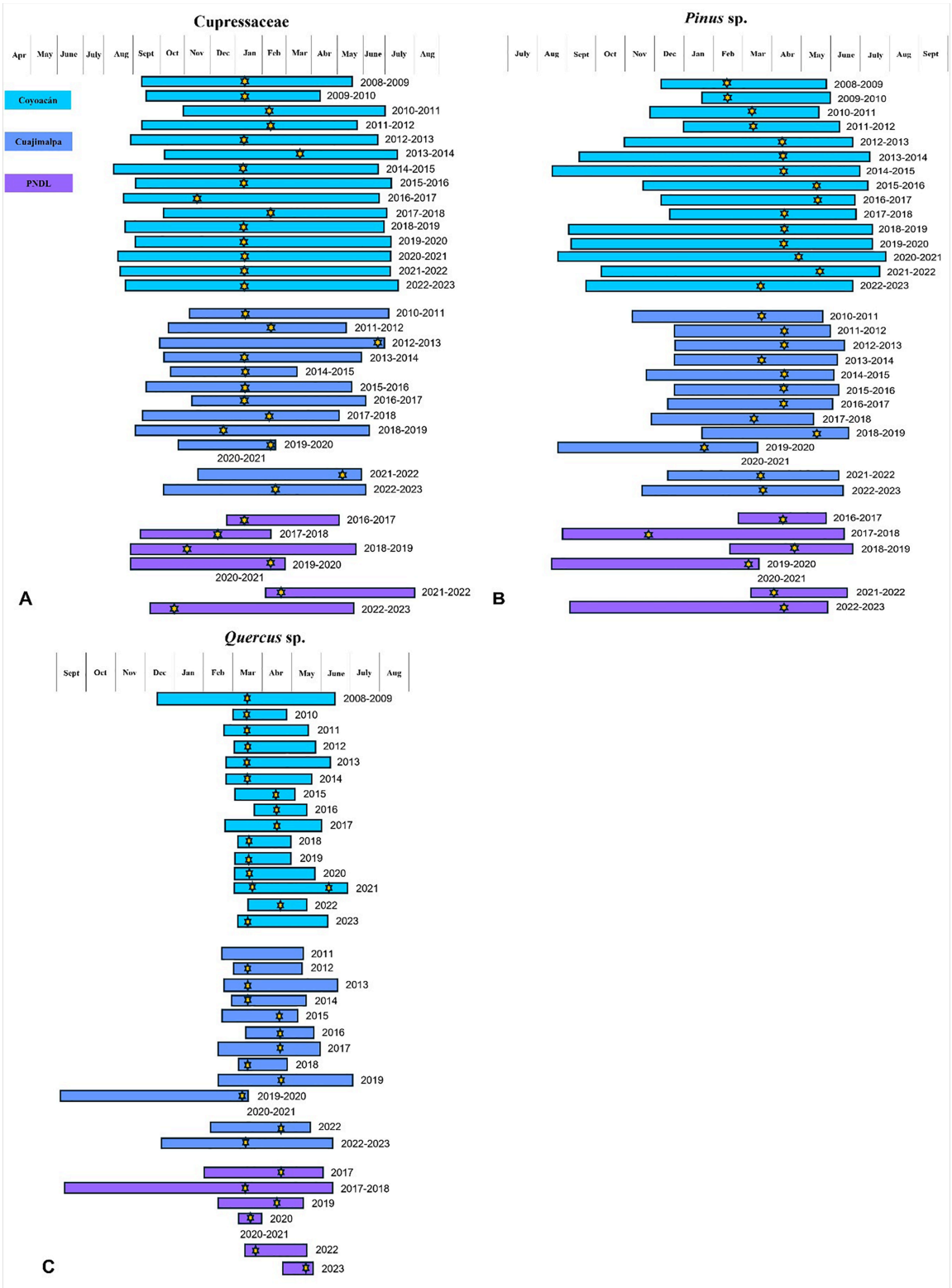

Figure 3

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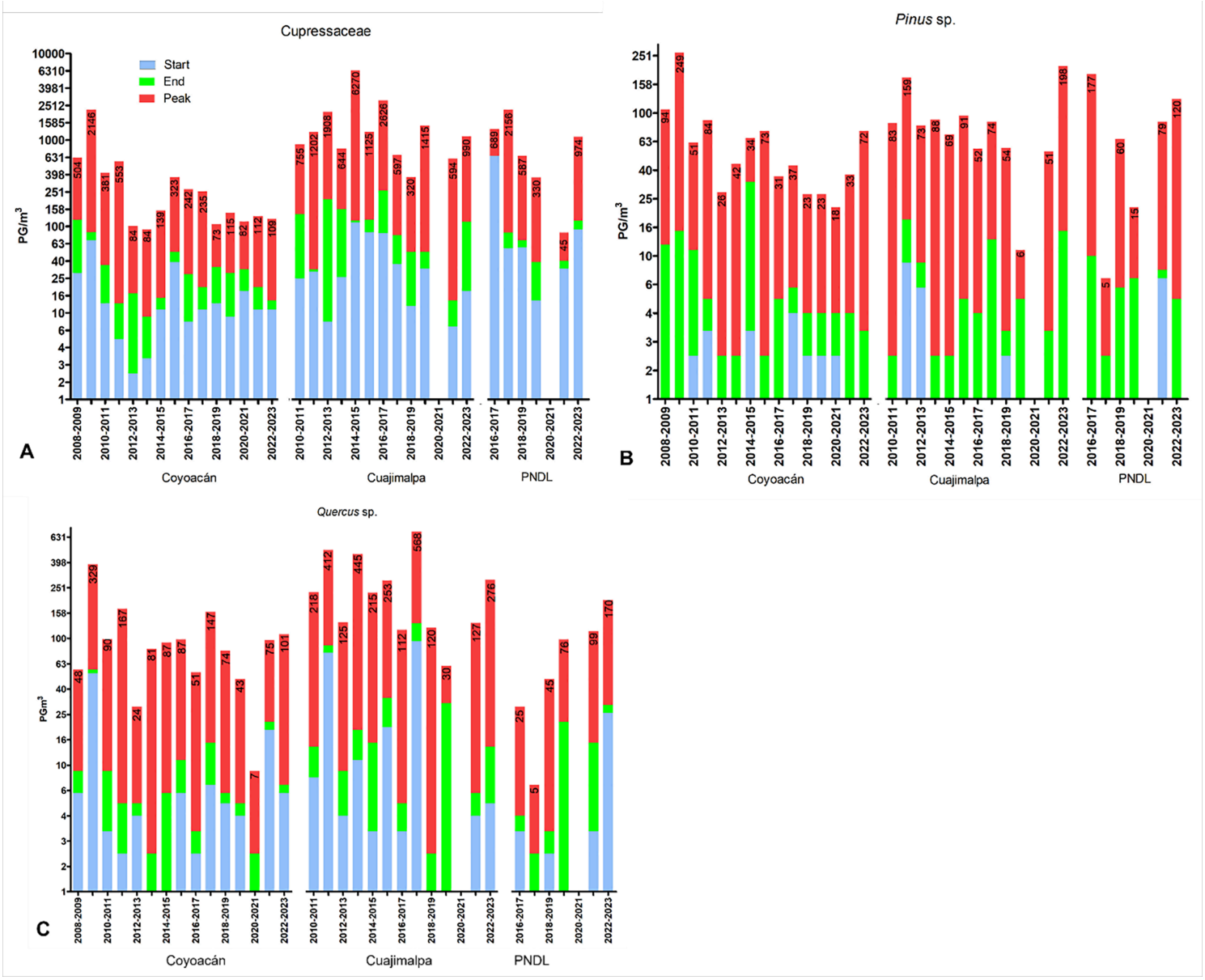

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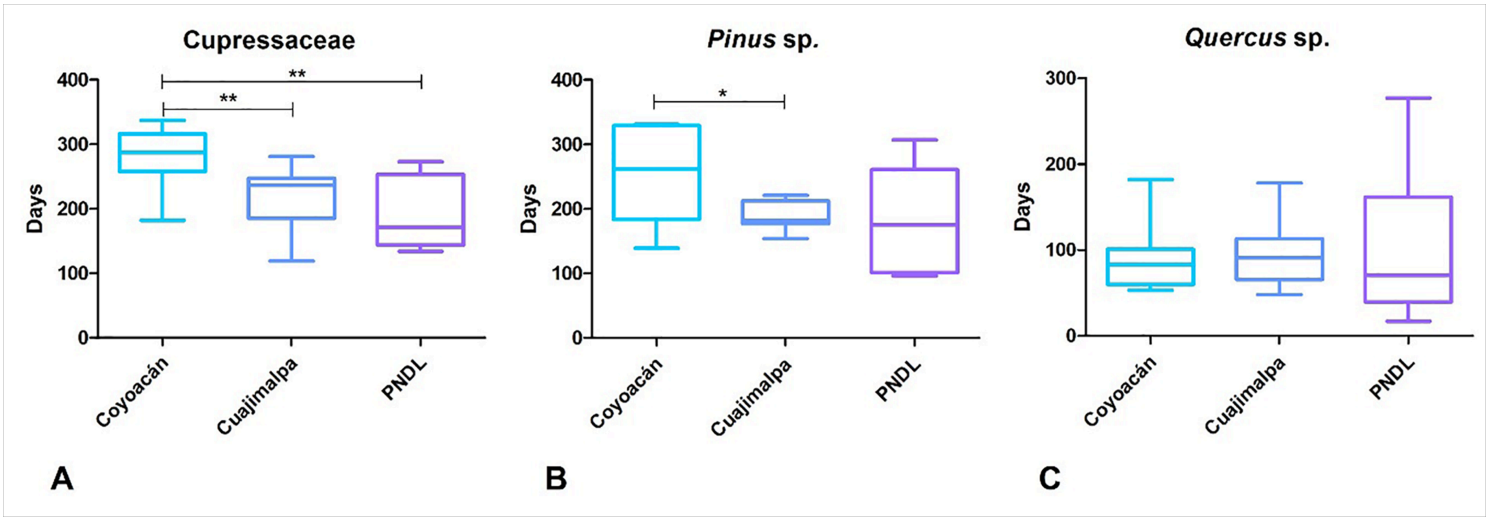

Figure 5

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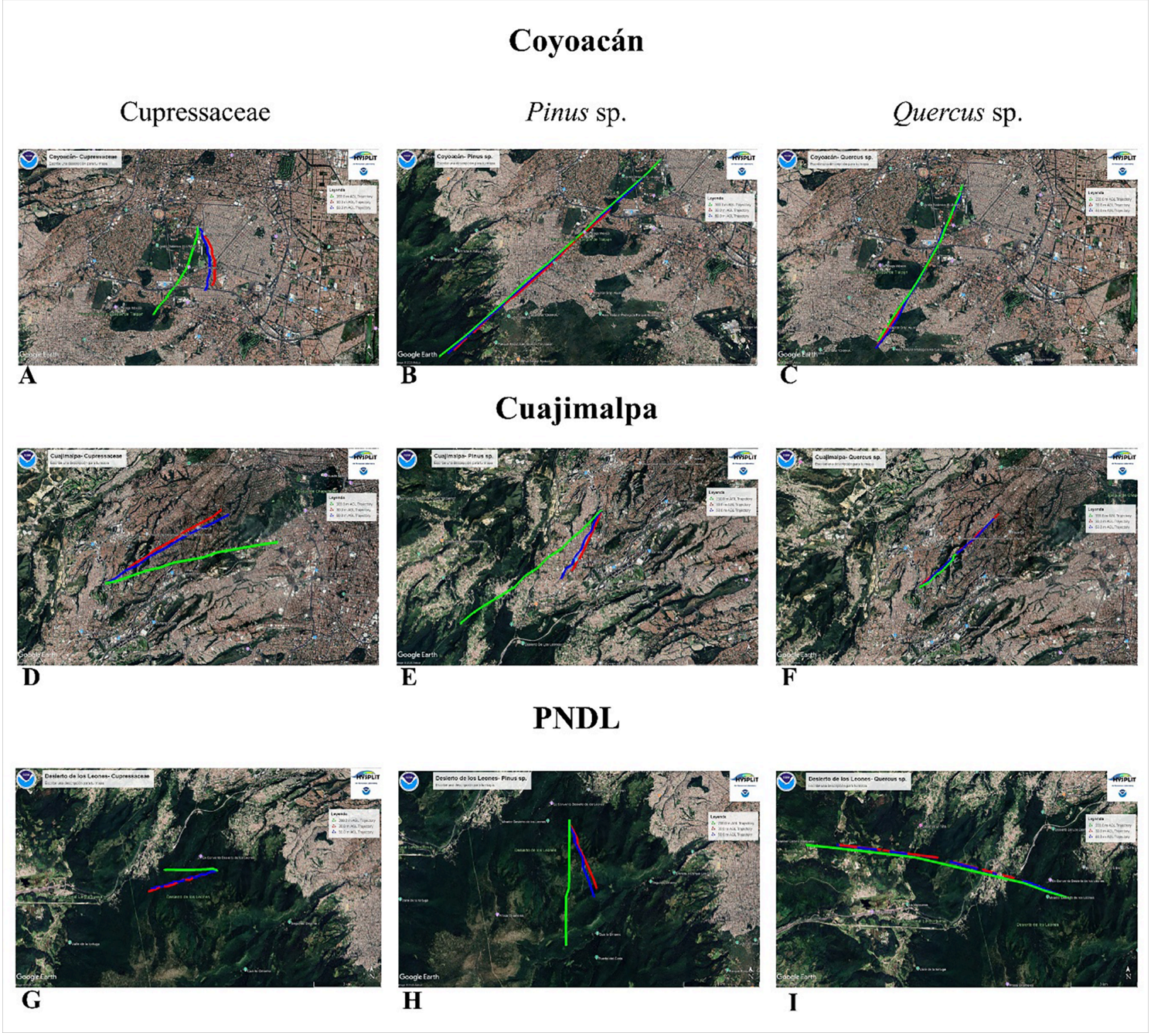

Figure 6

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