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Phenological and seismological impacts on airborne pollen types: A case study of *Olea* pollen in the Region of Murcia, Mediterranean Spanish climate

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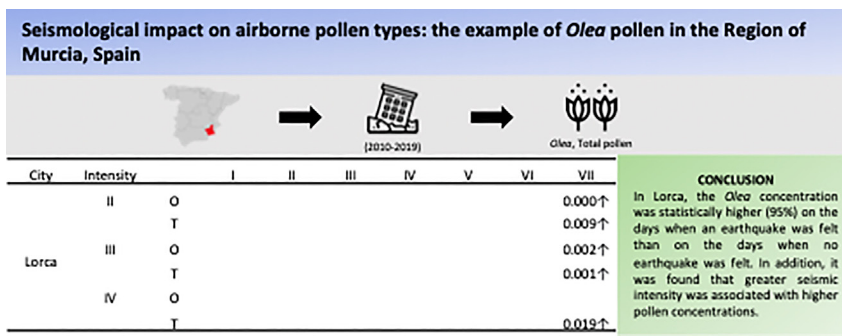
HIGHLIGHTS

- *Olea* pollen concentrations were higher on days with earthquakes in Lorca.
- The paucity of earthquakes impeded conclusions in other cities of the study.
- The higher the earthquake intensity, the higher the pollen concentration.
- Meteorology prevailed over earthquakes impacting pollen concentrations.
- African dust outbreaks were associated with reductions in pollen concentrations.

GRAPHICAL ABSTRACT



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ABSTRACT

The rationale of this paper was to investigate whether earthquakes impact airborne pollen concentrations, considering some meteorological parameters. Atmospheric pollen concentrations in the Region of Murcia Aerobiological Network (Spain) were studied in relation to the occurrence of earthquakes of moment magnitude (up to $M_w = 5.1$) and intensity (intensity up to grade VII on the European Macroseismic Scale). In this study, a decade (2010–2019) was considered across the cities of the network. Earthquakes were detected in 12 out of 1535 days in the *Olea* Main Pollen Season in Cartagena, 49 out of 1481 days in the *Olea* Main Pollen Season in Lorca, and 39 out of 1441 days in the *Olea* Main Pollen Season in Murcia. The *Olea* pollen grains in this network were attributed to the species *Olea europaea*, i.e., the olive tree, a taxon that appears widely in the Mediterranean basin, in both cultivated and wild subspecies. Differences between the *Olea* concentration on days with and without earthquakes were only found in Lorca (Kruskal-Wallis: *p*-value = 0.026). The low frequency and intensity of the earthquakes explained these results. The most catastrophic earthquake felt in Lorca on May 11th, 2011 (IVII, $M_w = 5.1$, 9 casualties) did not result in clear variations in pollen concentrations, while meteorology (e.g., African Dust Outbreak) might have conditioned these pollen concentrations. The research should be broadened to other active seismological areas to reinforce the hypothesis of seismological impact on airborne pollen concentrations.

1. Introduction

The nature of sediments, the alteration of sedimentary sequences, and the variation of pollen types near lakes have reflected changes in vegetation caused by earthquakes (Leroy et al., 2009). Airborne pollen grains deposit on surfaces, including man-altered areas. The pollen grains or palynomorphs of an abandoned synagogue in the village of Horvat Kur, Israel have been used to indicate the vegetation in the vicinity of the temple

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after the devastating earthquake of 749 CE (Neumann et al., 2014). The changes to vegetation brought about by major earthquakes are attributed to the spread of seismic waves (Li et al., 2014). Existing vegetation is destroyed by earthquakes, and opportunistic species colonize these stricken areas. These alterations have been reported in more recent events in our Contemporary Age. Such has been the case with vegetation changes in Tennessee, USA, following an earthquake in 1811, with a short-period body-wave magnitude of "m_b", $m_b > 7$; or in Río Estrella, Costa Rica, after an earthquake in 1991, with a surface-wave magnitude of "M_s", $M_s = 7.5$ (Kanamori, 1983; Mirecki, 1996; Phillips et al., 1997). Through palynology, earthquakes of great magnitudes in Tibet "M", 6.7–7.5 M, which were responsible for changes to vegetation, have been dated (Xu et al., 2020). About 24% of the trees in a beech forest (10 km from the epicenter) were destroyed after the Arthur's Pass earthquake in New Zealand in 1994, with a moment magnitude of "M_w", $M_w = 6.7$ (Allen et al., 1999; Bormann and Saul, 2020). All these examples illustrate how earthquakes can alter vegetation and, in the long term, the atmospheric pollen grains produced by new plant species.

Alterations in vegetation series brought about by agriculture are studied in the field of Phytosociology (Bazan et al., 2020). Among tree crops, olive trees, i.e., *Olea europaea*, have historically been linked to the Mediterranean basin (Diez et al., 2015). The 31 BCE earthquake along the Jericho Fault in Palestine had a local magnitude of "M_L", estimated as $M_L = 6.7$ (Kanamori, 1983; Ben-Menahem, 1991). The olive trees located there were destroyed, probably due to damage to the agricultural infrastructure rather than other civil interests (Leroy et al., 2010). Langgut et al. (2016) used the *Olea* pollen grains and the flowering period of olive trees to locate the earthquake in the central Jordan Valley in the spring of 659 CE. The magnitude of this earthquake was estimated at $M \approx 6$. In short, *Olea* was an abundant species in those areas, with an arboreal biomass capable of transmitting seismic waves to flowers, thereby causing them to release their airborne pollen. This pollen is also allergenic (Moreno-Grau et al., 2016).

Fortunately, devastating earthquakes are not as frequent as other environmental events that impact pollen grain concentrations. The importance of meteorology in pollen concentrations is undisputed due to the effects of relative humidity, hours of sunlight, precipitation, or wind speed (Alba et al., 2000; Gioulekas et al., 2004; Pérez-Badia et al., 2010; Uguz et al., 2017). On a synoptic scale, different types of air masses (i.e., Atlantic, European, African, Mediterranean, or regional) have been shown to correspond to different concentrations of airborne pollen, and maritime air masses are associated with lower concentrations (Negral et al., 2021). A recent paper has reported that African Dust Outbreaks (ADOs) can be associated with lower pollen concentrations in Spain (Rojo et al., 2021). Most ADOs occur during late spring and summer, favored by atmospheric events with a stable synoptic pattern (Escudero et al., 2006). This synoptic pattern causes the displacement of dust-laden winds from northern Africa to higher latitudes, causing African air masses to enter the atmosphere of the Iberian Peninsula (De Longueville et al., 2013). These air masses are generally warm and dry (García-Mozo et al., 2017).

However, the infrequent incidence of earthquakes makes it challenging to study the phenomenon in an aerobiological time series. Of the five measures that characterize an earthquake: epicenter, focal depth, origin time, magnitude, and intensity, the last two are scaled (Ansari Esfeh et al., 2016). Magnitude (M) evaluates the energy released after earthquakes and allows scientists to compare their effects using seismographic records. The modified Richter scale of logarithmic units is often used to avoid saturation problems at high magnitudes in the original scale (Ansfield, 2019). Intensity (I) evaluates the effects of earthquakes on the environment. Among the variety of scales used to evaluate intensity, the European Macroseismic Scale EMS-98, is comparable to the Modified Mercalli intensity scale, or MM (Wood and Neumann, 1931; Ansari Esfeh et al., 2016). It defines 12 grades of intensity from "Not felt" (I) to "Damage total" (XII). Table 1 describes the grades of the MM with effects on trees (Wood and Neumann, 1931). Although magnitude can be objectified with seismographs, intensity is, to a great extent, dealing with perceptions in the affected area. Shaking and the vulnerability of what is exposed to seismic waves are two determining variables of intensity (Wald et al., 2011). For example, earthquakes of the same magnitude could have different intensities.

Table 1
Grades of the Modified Mercalli intensity scale with effects on trees (adapted from Wood and Neumann, 1931).

Grades	Description
I	Sometimes trees may sway
II	Sometimes trees may sway
V	Trees shaken slightly
VI	Trees shaken slightly to moderately
VII	Trees shaken moderately to strongly
VIII	Trees shaken strongly – branches, trunks, broken off, especially palm trees

On another level, given the relative infrequency of earthquakes, even those of lower magnitude/intensity could increase the number of events in pollen concentrations. This, in turn, could lead to a threshold of intensity in species´ perceptions and later aerobiological detection of the pollen released. It seems likely that airborne pollen types of tree species abundant in an area will reflect the impact of these "minor" earthquakes since they will most likely reflect vibrations if they occur within their flowering period. Vibration transmission in the wood of olive trees is not unknown. Transmission to fruit is an olive harvesting strategy which, on the other hand, can cause structural stress to the trees (Formato et al., 2019). When using shaker harvesters, olive trees receive vibrations anisotropically, with more intensity in the branches and less in the trunk (Sola-Guirado et al., 2018). It might be interesting to study the impact of earthquakes on airborne pollen grains. While harvesters want to detach fruit, this paper investigates the effect of earthquakes on an amphiphilic species. For all of these reasons, the co-authors think that olive trees are appropriate to study the effect of earthquakes on pollen concentrations. Indeed, they have already been used in investigations of historical earthquakes and archaeology in the Mediterranean basin (Leroy et al., 2010; Neumann et al., 2014; Langgut et al., 2016).

To the best of our knowledge, there is no previous work studying the relationship between airborne pollen concentrations and seismic activity. This paper assesses the relationship between earthquakes and *Olea* pollen grain concentrations in one of the two most hazardous seismic areas in Spain (on the Alhama de Murcia fault), coinciding with the tenth anniversary of the catastrophic earthquake in Lorca (Alguacil et al., 2014; Instituto Geográfico Nacional, n.d.). The objectives are: 1) to determine the relationship between pollen concentrations and meteorological variables during the ten years of the aerobiological network's existence; 2) to determine whether ADOs affect pollen concentrations; and 3) to determine whether pollen concentrations are altered by low/medium magnitude/intensity earthquakes.

2. Materials and methods

The aerobiological, meteorological, and seismological variables were incorporated into the SPSS version 26 software database with which the statistical analysis was performed. The correlation between variables was evaluated with the Spearman non-parametric correlation coefficient due to the absence of normally patterned variables. The Kruskal-Wallis test was used to detect significant differences in pollen concentrations, comparing the following independent variables in every city: years, presence/lack of ADOs, and presence/lack of earthquakes. After confirming significant differences with the Kruskal-Wallis test (i.e., p-value<0.05), the post-hoc Bonferroni test was applied to investigate which pairs of years, types of ADO scenarios or grades of seismic intensity were statistically different. No combined effects were statistically assessed. The analysis for each variable is described under the following headings.

2.1. Main pollen season of Olea

The Red Aerobiológica de la Region de Murcia (REAREMUR) reports the pollen concentrations detected according to the standard EN 16868

(European Committee for Standardization, 2019) in the HIRST type (Lanzoni VPPS 2000) pollen traps, located in three Spanish cities: Cartagena, 10 m above mean sea level (m amsl), 37°36′00″N, 0°59′00″W; Lorca, 353 m amsl, 37°38′42″N, 1°39′55″W; and Murcia, 42 m amsl, 37°58′57″N, 1°07′16″W. REAREMUR is managed by our research group. Trained staff quantified the pollen grains. The pollen trap suctioned 10 L air/min. The air was conducted to a rotating drum at 2 mm/h, facing downwind. A Mellinex tape coated with adhesive silicone was mounted on the drum. The device could collect particles ranging between 1 and 100 μm for seven days. After one week, the head containing the tape was replaced. The tape was cut into 24-hour pieces in the laboratory. The pieces were placed on slides with glycerogelatin and protected with a coverslip. Every piece was analyzed with optical microscopy (Olympus BH2, equipped with plan-achromatic optics). Four transverse transects were read with an immersion 50× optical zoom lens, and the total surface analyzed was always above 10%. Pollen types were identified, and the corresponding count was made. A conversion algorithm was used to calculate daily concentrations, expressed as pollen grains/m^3 (Galán et al., 2007). The climate of all of these cities is Mediterranean, with dry, warm summers and mild winters, corresponding to the classifications BSh, BSk, and BSk, respectively, in the Köppen-Geiger climatic classification. The *Olea* main pollen season (MPS) was defined from the first day of the year when an *Olea* pollen grain was detected to the last day of the year with an *Olea* pollen grain. This definition sought to maximize the probability of earthquakes occurring within the *Olea* MPS. Some shortcomings of this decision are related to the temporal decoupling between environmental factors, e.g., ADOs and earthquakes, and the flowering periods of local specimens. This statement should also pay attention to the pollen grain resuspension risen by the environmental factors. We worked with the first decade of REAREMUR in operation in the three cities: 2010–2019. The statistical analysis assessed significant differences in the concentrations of both the *Olea* pollen type and the total amount of all pollen grains during the *Olea* MPS in every city for the years under study. The Kruskal-Wallis non-parametric test was implemented to identify differences in annual pollen concentrations and, subsequently, the post-hoc Bonferroni test was used to find the pairs of years in which differences were present.

2.2. Meteorological information

The average temperature, minimum temperature, maximum temperature, precipitation, wind speed, and maximum gust speed were provided by the Spanish Meteorological Agency (AEMET, Spain) in every city. In addition, AEMET provided the hours of sunlight and the maximum and minimum barometric pressure in Murcia. All the data in this paper were organized by days.

The data of the days with ADOs in Spain were obtained from the annual reports by the Spanish Ministry for Ecological Transition and Demographic Challenge (MITECO, 2021). These reports list the dates when airborne particulate matter elevation events occurred due to natural causes all over Spain. Regarding the days with ADOs, the methodology to identify these episodes follows the corresponding technical document by the European Commission (2011). Once the days with ADOs were listed, they were classified in the five synoptic ADO scenario charts (Escudero et al., 2005; Negral et al., 2012). Scenario classification is based on the synoptic charts at mean sea-level pressure and 700 hPa. They are: Type A) North African high, located at surface level; Type B) Atlantic depression centered over Northwestern Africa, Western Iberia, or the Southwestern Portuguese coast, with an associated high or ridge over the Mediterranean Sea; Type C) North African depression; Type D) North African high, located at upper levels; and Type E) Weak pressure gradient at surface level. The synoptic charts of days with ADOs were obtained from the Air Resources Laboratory (ARL) of the National Oceanic and Atmospheric Administration

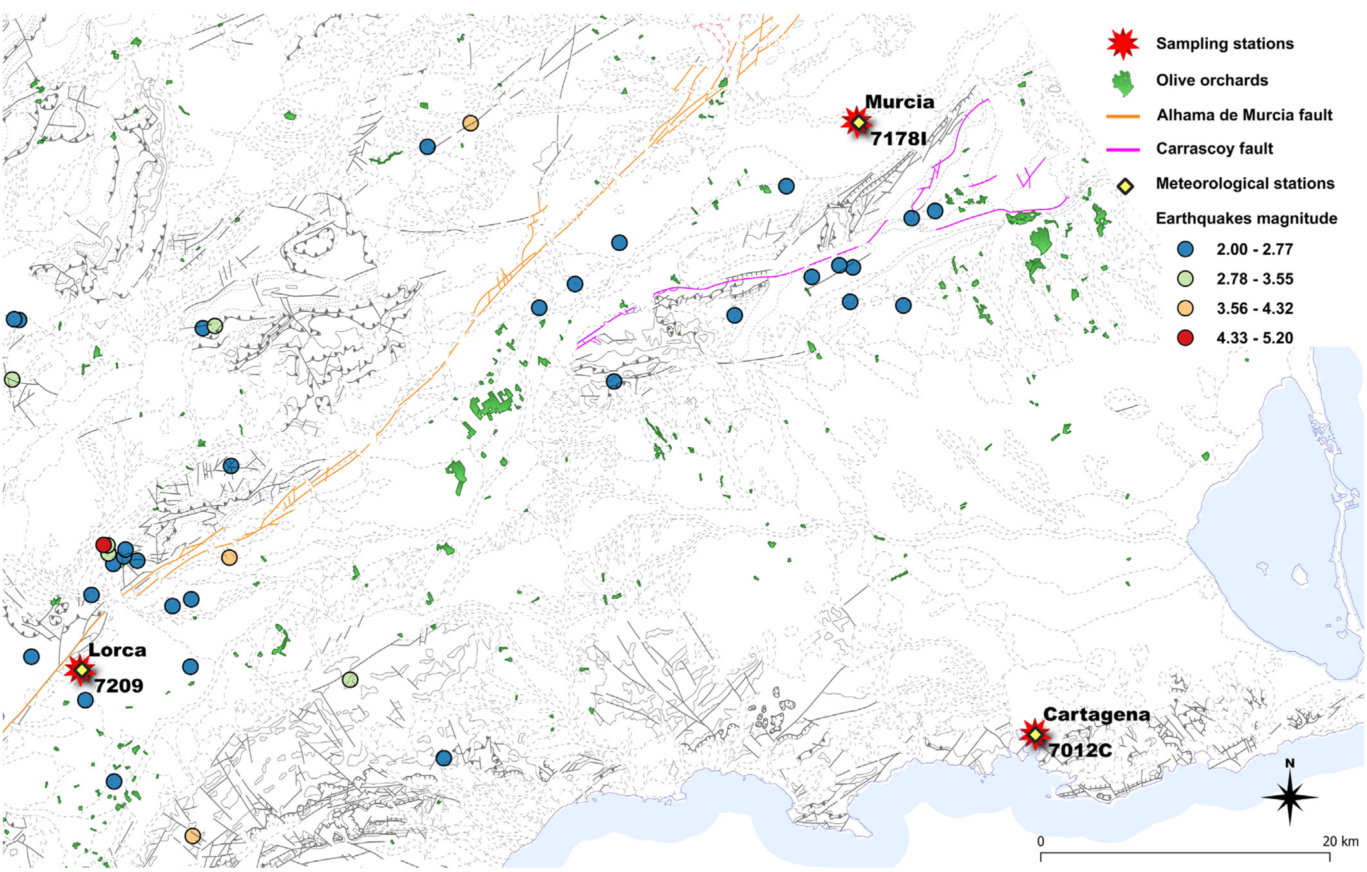

Fig. 1. Map with the distibution of olive orchards, aerobiological and meterological stations, main faults, and major earthquakes between 2010 and 2019. The numeric or alphanumeric expressions in the map are metereological station codes.

(NOAA) website (https://www.ready.noaa.gov/archives.php), using the GDAS database (Global Data Assimilation System): January 1st, 2010 to December 31st, 2019; global domain; 1 degree latitude-longitude (360 by 181); 23 levels in the vertical, with the top level at 20 hPa; 4 times a day, i.e., at 00, 06, 12, and 18 UTC (https://www.ready.noaa.gov/gdas1.php). ADOs were included in this study because they could be associated with reduced pollen concentrations (Rojo et al., 2021). The statistical analysis evaluated significant correlations between the meteorological variables. Pollen concentrations of *Olea* and those of the other pollen types in the *Olea* MPS were evaluated with the Spearman correlation coefficient. Significant differences in *Olea* pollen concentrations and total pollen types in the *Olea* MPS with and without ADOs (i.e., Kruskal-Wallis test) and pollen concentration differences depending on ADO scenario types were investigated with the post-hoc Bonferroni test.

2.3. Seismological information

Seismological information was provided by the National Geographic Institute (Instituto Geográfico Instituto Geográfico Nacional, n.d.). We worked with all earthquakes experienced in the territories of Cartagena, Lorca, and Murcia between 2010 and 2019. L_g-wave magnitude (m_{bLg}) values were used, except for major earthquakes in which it was possible to calculate the moment and provide the M_w. The intensity was expressed using the EMS-98 grades. In cases of more than one earthquake per day, the most intense one was selected. With more than one earthquake on the same day and with the same grade of intensity, the earthquake with the largest magnitude was selected. If intensity and magnitude were equal, the shallowest earthquake was selected. In the Supplementary material, Table S1 shows the meteorological records on days with earthquakes, with their characterizations. To assess the impact of earthquakes on daily pollen concentrations, the concentration on the day of the earthquake was compared with those of up to two days before and two days after the event with the Kruskal-Wallis non-parametric test. The statistical analysis examined significant differences in *Olea* pollen concentrations and total pollen grains during the *Olea* MPS between days with and without earthquakes using the Kruskal-Wallis non-parametric test. Finally, we evaluated whether there were significant differences according to grades of intensity with the Kruskal-Wallis non-parametric test and, subsequently, the post-hoc Bonferroni test was conducted to find the pairs of intensities with differences. Fig. 1 shows a map with the distribution of olive orchards near Cartagena, Lorca, and Murcia and major earthquakes between 2010 and 2019.

3. Results and discussion

3.1. Main pollen season of Olea

Table 2 presents the onset and end dates of the *Olea* MPS, the peak day, the duration of the *Olea* MPS, the *Olea* pollen concentration on the peak day, the sum of *Olea* pollen grains in the MPS, and the sum of all the pollen types during the *Olea* MPS for the three cities annually. Pollen concentrations were found in decreasing order in Lorca, Murcia, and Cartagena. Other pollen types are listed in the Supplementary material (Table S2). In the decade covered, we worked with 1535, 1481, and 1441 days of *Olea* MPS in Cartagena, Lorca, and Murcia, respectively. As a result of the Kruskal-Wallis test, significant differences were found in the concentrations per year. The Bonferroni test was applied to pairs of years. It allowed us to obtain the significant differences expressed in Table 3. In all the cities, 2016 was the year with the lowest concentrations. In contrast, 2019 was the year with the highest concentrations.

The definition of the *Olea* MPS from the first day of the year that an *Olea* pollen grain appeared to the last day of the year with *Olea* pollen resulted in a prolonged MPS, compared to the definition in which the beginning and end of the flowering days are eliminated (Andersen, 1991). The definition

Table 2
Olea pollen concentrations in Cartagena, Lorca, and Murcia (2010–2019).

City	Year	Start day mm/dd	Final day mm/dd	Peak day mm/dd	MPS days	*Olea* peak grains/m^3	*Olea* MPS grains/m^3	Total MPS grains/m^3
Cartagena	2010	04/02	09/07	05/26	159	390	3853	13,233
	2011	03/29	07/29	05/08	123	648	2197	8699
	2012	04/10	08/21	05/19	134	168	2121	9975
	2013	04/06	07/30	05/12	116	206	3176	8514
	2014	03/19	07/28	05/13	132	86	999	5937
	2015	04/07	08/23	05/05	139	276	1902	7390
	2016	03/31	11/22	06/04	237	116	1393	7238
	2017	03/21	07/31	05/10	133	249	2407	8507
	2018	03/29	10/29	06/04	215	236	2694	10,895
	2019	03/22	09/12	05/08	175	358	4447	18,484
Lorca	2010	03/17	09/08	05/26	176	786	8669	22,354
	2011	03/23	07/26	05/08	126	1707	7137	19,144
	2012	04/07	08/29	05/19	145	515	5718	16,849
	2013	04/05	07/31	05/11	118	622	5864	11,722
	2014	03/19	07/22	05/08	126	138	1767	8410
	2015	03/19	08/23	05/15	158	540	4360	13,961
	2016	04/02	11/24	06/15	237	46	953	3354
	2017	03/21	08/09	05/10	142	694	5822	13,473
	2018	03/27	10/06	06/10	194	225	4553	14,444
	2019	03/22	09/10	05/11	173	644	7836	25,199
Murcia	2010	04/02	09/30	05/26	182	378	3299	14,463
	2011	04/09	07/26	05/08	109	909	3324	11,678
	2012	04/03	08/19	05/27	139	159	2555	13,613
	2013	04/07	07/22	06/19	107	123	1568	5001
	2014	03/30	07/31	05/13	124	192	1576	8892
	2015	03/31	08/01	05/05	124	300	2505	10,649
	2016	03/28	09/26	05/25	183	115	1410	7351
	2017	03/22	08/11	04/26	143	233	2174	9555
	2018	03/29	10/29	06/04	215	236	2440	10,731
	2019	03/16	08/28	05/08	166	641	4623	21,096

Start day mm/dd = month/day of the first *Olea* pollen grain; Final day mm/dd = month/day of the last *Olea* pollen grain; Peak day mm/dd = month/day of the highest *Olea* pollen concentrations; MPS days = *Olea* main pollen season duration in days; *Olea* peak grains/m^3 = *Olea* pollen concentrations on the peak day; *Olea* MPS grains/m^3 = *Olea* pollen grains in the *Olea* main pollen season; Total MPS grains/m^3 = total pollen grains from all pollen types in the *Olea* main pollen season, grains/m^3.

Table 3
Statistical differences in pollen concentrations: Bonferroni test *p*-values (<0.05) between paired years.

City	Year		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Cartagena	2010	O		0.000↓		0.000↑	0.041↓			0.000↓		0.002↑
		T							0.000↓			
	2011	O						0.004↓	0.000↓		0.017↓	
		T						0.000↓	0.000↓			
	2012	O							0.000↓			
		T							0.000↓			
	2013	O						0.000↓	0.000↓		0.002↓	
		T						0.017↓	0.000↓			
	2014	O							0.000↓			
		T								0.000↑		
	2015	O								0.004↑		0.042↑
		T										0.000↑
	2016	O								0.000↑	0.004↑	0.000↑
		T								0.000↑	0.000↑	0.000↑
	2017	O									0.018↓	
		T										
Lorca	2010	O		0.000↑	0.014↓	0.000↓	0.016↓			0.000↓		0.000↓
		T		0.047↑					0.000↓			
	2011	O							0.000↓			
		T				0.022↓	0.009↓	0.000↓	0.000↓	0.028↓	0.032↓	
	2012	O							0.000↓			
		T							0.000↓			
	2013	O						0.000↓	0.000↓		0.041↓	
		T							0.000↓			
	2014	O							0.000↓			
		T							0.000↓			
	2015	O								0.020↑		0.041↑
		T							0.000↓			0.000↑
	2016	O								0.000↑	0.000↑	0.000↑
		T								0.000↑	0.000↑	0.000↑
Murcia	2010	O		0.000↑	0.001↑	0.000↓	0.000↓			0.000↓		0.000↑
		T		0.001↑					0.287↓			
	2011	O						0.021↓	0.000↓			
		T				0.000↓	0.657↓	0.285↓	0.000↓	0.038↓		
	2012	O							0.026↓			
		T							0.000↓			
	2013	O							0.000↓		0.000↓	
		T										
	2014	O							0.000↓			
		T							0.003↓			
	2015	O										
		T							0.012↓			0.196↑
	2016	O								0.001↑		0.000↑
		T								0.043↑		0.000↑

O = *Olea* pollen concentrations, T = Total pollen grains from all pollen types in the *Olea* main pollen season. The arrow ↑ indicates that the concentrations are higher in the year of the column. The arrow ↓ indicates that the concentrations are lower in the year of the column.

of the *Olea* MPS previously mentioned in this work increases the probability of observing the impact of earthquakes on pollen concentrations and is endorsed by Jato et al. (2006), who conclude that "The limits of the pollen season should be set in accordance with the aims of each survey." The extension of the *Olea* MPS was achieved by not removing the tails (Andersen, 1991). This resulted in a platykurtic distribution in which the *Olea* MPS comprised more than half the days of the year for the three cities in 2016 and 2018. In Cartagena, it went from 72 days with the tails discarded in 2016 to 237 days without discarding them (Galera et al., 2018). In addition, peak day concentrations were low in 2016, an order of magnitude lower than the other years in Lorca. These assessments are in line with the significantly lower concentrations of 2016, and this was also reflected in the total pollen types during the *Olea* MPS. Furthermore, 2019 was the year with the highest concentrations of both *Olea* and all the pollen types during the *Olea* MPS in Cartagena and Murcia. In Lorca, 2010 was the year with the highest *Olea* pollen concentrations, and 2019 was the year with the highest concentrations of all the pollen types during the *Olea* MPS. However, there were no significant differences between 2010 and 2019 for the total pollen types during the *Olea* MPS. This highlighted the relevance of *Olea* in the pollen concentrations of the REAREMUR, which reflected the importance of olive-growing areas in Spain (Martínez-Bracero et al., 2015; Rojo and Pérez-Badia, 2015; Fernández-Rodríguez et al., 2020). The higher concentrations in Lorca compared to Cartagena and Murcia are justified by the greater agricultural character of the former (Elvira-Rendueles et al., 2019). However, the simultaneity of the *Olea* peak days in 2010 and 2011 is worth noting in the other years, except in 2016. *Olea* pollen peaked on May 8th, 2011 in the three cities. In Lorca, this peak (1707 grains/m^3) comprised 24% of the total *Olea* grains in the *Olea* MPS. This *Olea* pollen concentration was 37 times the *Olea* concentration on the peak day of the year with the lowest concentration. Regional synchronization can be explained based on phenology (Günter et al., 2008; Dahl et al., 2013). The different routes of the air masses that reached each city or their trajectories over the sea could explain variations in pollen concentrations and the consequent loss of complete simultaneity in the other years of the study (Negral et al., 2021).

3.2. *Olea* pollen concentrations and meteorology

Considering the ten years as a whole, Table 4 presents the significant Spearman correlation coefficients, calculated between the meteorological variables, *Olea* concentrations, and the total pollen types in the *Olea* MPS up to the peak day and after the peak day.

Table S3 (Supplementary material) presents the number of days with ADOs in the *Olea* MPS, the number of earthquakes in the *Olea* MPS, the maximum magnitudes and intensities and the dates they occurred, the maximum intensity in the *Olea* MPS and its date, and the *Olea* concentrations a

Table 4
Spearman correlation coefficients between pollen concentrations and meteorological variables in Cartagena, Lorca, and Murcia.

City			Total	AvT	MinT	MaxT	Rain	AvSpeed	Gust	Sunlight	MaxPre	MinPre
Cartagena	Up to the peak day	*Olea*	0.467**	0.582**	0.572**	0.492**	−0.100*					
		Total		0.305**	0.276**	0.283**	−0.172**	0.157**	0.142**			
		AvT			0.894**	0.914**	−0.160**	−0.103*	−0.196**			
		MinT				0.646**						
		MaxT					−0.222**	−0.215**	−0.294**			
		Rain							0.116*			
		AvSpeed							0.747**			
	After the peak day	*Olea*	0.777**	−0.484**	−0.478**	−0.440**		0.229**	0.231**			
		Total		−0.484**	−0.517**	−0.404**		0.165**	0.150**			
		AvT			−0.933**	0.954**	−0.130**	−0.062*	−0.164**			
		MinT				0.792**	−0.084**		−0.067*			
		MaxT					−0.161**	−0.119**	−0.239**			
		Rain							0.096**			
		AvSpeed							0.674**			
Lorca	Up to the peak day	*Olea*	0.547**	0.529**	0.464**	0.487**	−0.119**					
		Total		0.286**	0.206**	0.281**	−0.154**					
		AvT			0.851**	0.939**	−0.254**					
		MinT				0.632**		−0.086*				
		MaxT					−0.351**					
		Rain						−0.087*				
		AvSpeed							0.587**			
	After the peak day	*Olea*	0.846**	−0.363**	−0.414**	−0.298**		0.243**	0.179**			
		Total		−0.361**	−0.383**	−0.307**		0.206**	0.106**			
		AvT			0.909**	0.947**	−0.160**	0.102**	0.115**			
		MinT				0.739**		0.079*	0.070*			
		MaxT					−0.212**	0.102**	0.129**			
		Rain						−0.142**				
		AvSpeed							0.482**			

City			Total	AvT	MinT	MaxT	Rain	AvSpeed	Gust	Sunlight	MaxPre	MinPre
Murcia	Up to the peak day	*Olea*	0.347**	0.591**	0.562**	0.512**	−0.100*		0.094*	0.255**	−0.111*	
		Total		0.169**		0.201**	−0.175**					
		AvT			0.850**	0.930**	−0.277**			0.367**		
		MinT				0.611**		0.131**			−0.111*	
		MaxT					−0.369**			0.500**		
		Rain						−0.131**		−0.531**	−0.333**	−0.340**
		AvSpeed							0.543**	0.158**		
		Gust									−0.155**	−0.204**
		Sunlight									0.263**	0.308**
		MaxPre										0.933**
	After the peak day	*Olea*	0.777**	−0.402**	−0.476**	−0.295**		0.142**	0.171**	0.184**		
		Total		−0484**	−0.554**	−0.362**		0.069*	0.066*	0.107**		
		AvT			0.896**	0.933**	−0.236**	0.083**	0.083*	0.162**	−0.289**	−0.285**
		MinT				0.691**	−0.127**	0.159**	0.117**		−0.256**	−0.231**
		MaxT					−0.289**			0.319**	−0.264**	−0.273**
		Rain						−0.169**		−0.412**	−0.080*	−0.095**
		AvSpeed							0.602**	0.161**	0.075*	0.098**
		Gust								0.092**	−0.099**	−0.114**
		Sunlight									0.092**	0.102**
		MaxPre									0.918**	

Olea = *Olea* pollen concentrations, Total = Total pollen concentrations from all pollen types in the *Olea* main pollen season. * = p-value <0.05. ** p-value <0.01. AvT = Average temperature, °C. MinT = Minimum temperature, °C. MaxT = Maximum temperature, °C. Rain = precipitation, mm. AvSpeed = Average wind speed, m/s. Gust = Maximum gust speed, m/s. Sunlight = Sun hours. MaxPre = Maximum barometric pressure, mbar. MinPre = Minimum barometric pressure, mbar.

day before an earthquake, the day an earthquake occurred, and a day after the earthquake for the three cities on an annual basis. The number of days with ADOs is the same for the three cities due to the synoptic scale of these phenomena.

The Kruskal-Wallis test pointed to statistical differences in the *Olea* concentrations and total pollen between days with and without ADOs (p-value<0.01 in the three cities).

Table 5 presents the significant differences observed in pollen concentrations according to ADO scenario types. All these significant differences pointed to low pollen concentrations under ADO scenario types D and E.

Olea is a spring-flowering species (Aguilera et al., 2015). Therefore, the significant and positive correlation between its pollen concentrations and the hours of sunlight observed in Murcia was expected. However, an accentuated effect of the prolonged *Olea* MPS was the appearance of negative and statistically significant Spearman correlation coefficients for *Olea* concentrations with the mean, minimum, and maximum temperatures. In some cases, the *Olea* MPS lasted until November, although always in low concentrations, despite it being a spring-flowering species. This could be attributed to the resuspension of grains deposited on surfaces (López-Orozco et al., 2020). After the peak days, which are usually in spring, days with higher temperatures, typically in summer, were expected to have decreasing concentrations. To address this anomaly, the *Olea* MPS was separated into periods up to the peak day and after the peak day. This strategy of separating up to the peak day has been employed in other works with olive trees (Recio et al., 1997). Apart from the periods up to the peak day, the *Olea* correlation was positive, and this was significant for the Spearman correlation coefficient with the temperatures in the three cities up to the peak day. After the peak day, the correlation remained statistically significant and negative with temperature, for the reason previously explained. In terms of precipitation, the well-known atmospheric washing effect of rain was reflected in negative correlation coefficients with the *Olea* correlation (Bonofiglio et al., 2008).

Table 5
Statistical differences in pollen concentrations: Bonferroni test *p*-values (<0.05) between paired types of ADO scenarios.

City	Scenarios		A	B	C	D	E
Cartagena	B	O					
		T				0.001↓	
	C	O					
		T				0.003↓	
	D	O					
		T					0.000↓
Lorca	A	O					
		T				0.015↓	
	B	O					
		T				0.006↓	
	C	O					
		T				0.030↓	
	D	O					
		T					0.000↓
Murcia	B	O				0.038↓	
		T				0.000↓	0.001↓
	C	O					
		T				0.005↓	
	D	O					
		T					0.000↓

O = *Olea* pollen concentrations, T = Total pollen grains from all pollen types in the *Olea* main pollen season. The arrow ↓ indicates that the concentrations are lower in the scenario of the column.

Two aspects of wind speed and maximum gust speed should be considered. These two variables correlated positively and significantly with *Olea* concentrations in the three cities after the peak day. Pollen transport time is known to be a function of distance and wind speed (Šaulienė and Veriankaitė, 2012). Thus, greater kinetic energy would cause the transport of pollen grains and higher pollen concentrations released at points far from the pollen trap to be detected. In the Iberian Peninsula, it has been shown that the olive-growing areas close to pollen traps may not be responsible for pollen concentrations. However, other, more distant areas could be responsible for these concentrations with the concurrency of different wind patterns (Rojo and Pérez-Badia, 2015). The positive correlation with *Olea* pollen concentrations up to the peak day only existed with the maximum gust speed in Murcia. This city has the least agricultural influence, so it would require greater kinetic energy, exemplified by the maximum streak, for pollen grains to reach it.

Barometric pressure showed a significant negative correlation with *Olea* pollen concentration. The pressure variables had a negative and significant correlation at 99% with the maximum gust speed. This could be explained by the consequences of atmospheric instability, as wind dynamics have been shown to affect the pollen grains of tree species (Galveias et al., 2021).

The fact that the total pollen types in the *Olea* MPS replicated many of the weather patterns with *Olea* can be explained by the great importance olive trees have in the aerobiology of the REAREMUR. This was demonstrated by the Spearman correlation coefficients between *Olea* and the total pollen types in the *Olea* MPS for the three cities, which were statistically significant at 99% (Spearman correlation coefficient up to the peak = 0.347–0.547 and after the peak = 0.777–0.846).

Finally, in terms of atmospheric phenomena, it is necessary to highlight the decrease of concentrations that occurred both for *Olea* and all the pollen types in the *Olea* MPS for the three cities when ADOs occurred. Rojo et al. (2021) have observed that ADOs coincide with decreases in pollen concentrations in the Iberian Peninsula. With respect to the scenario types that caused the ADOs, Murcia showed the greatest differences. The Type D scenario was that of the lowest pollen concentrations. This situation also occurred in Cartagena. Due to atmospheric dynamics, the synoptic configuration of the Type D scenario is more frequent in summer (Negral Álvarez, 2010). Independently of the ADOs, the REAREMUR pollen calendar reflects the lowest pollen concentrations in summer (Elvira-Rendueles et al., 2019). Therefore, a causal relationship between lower concentrations and the Type D scenario cannot be established. In Lorca, the scenario with the lowest concentrations was Type A. The most frequent scenario in autumn/winter is Type A, when Lorca's pollen calendar also presents low total concentrations (Negral Álvarez, 2010; Elvira-Rendueles et al., 2019). García-Mozo et al. (2017) pointed out the limited impact of African intrusions on *Olea* pollen concentrations in Malaga, Córdoba, and other southern cities on the Iberian Peninsula.

3.3. *Olea* pollen concentrations and seismological activity

The Kruskal-Wallis test pointed to statistical differences in the *Olea* pollen concentrations between days with and without earthquakes only in Lorca (p-value<0.05).

Table 6 presents the significant differences observed between the five-day concentrations (centered on the day an earthquake occurred), according to earthquake intensities. Where significant differences were shown, the higher the earthquake intensity, the higher the pollen concentrations.

Fig. 2 shows three examples of *Olea* pollen concentrations and the concentrations of all pollen types during the *Olea* MPS. The selected years and cities correspond to: Lorca 2011, coinciding with the most intense earthquake in the decade; Lorca 2018, when pollen grain concentrations seemed to peak with earthquakes; and finally, Murcia 2016, when the earthquakes also seemed to influence pollen concentrations. No figure is presented for Cartagena as this city registered the lowest number of earthquakes, and the annual pollen index is the lowest of the cities. These figures exemplify the difficulty in observing variations in pollen concentrations, even in years with relatively high numbers of earthquakes and with intensities up to grade VII.

The number of days with at least one earthquake during the *Olea* MPS was 12 in Cartagena, 49 in Lorca, and 39 in Murcia. This low number of events limits conclusions. The co-authors want to state this shortcoming as earthquakes are independent of the main pollen season, so the simultaneity between earthquakes and the *Olea* MPS is random. A strategy to minimize this problem is to compare pollen concentrations on days near the day earthquakes take place. No significant differences were detected in any of the three cities between the pollen concentrations on the day of an earthquake and those of one and two days before and after an earthquake. This could be explained by the preponderance of phenology in pollen concentrations. However, it was possible to detect higher *Olea* concentrations on the days of earthquakes than on the days without earthquakes in Lorca. A priori, this could be expected. The fact that there were no significant differences in the concentrations of the total pollen types in the *Olea* MPS reinforces the decision to carry out the study of earthquakes on olive trees. This is despite the aforementioned correlation between *Olea* and all the pollen types in the *Olea* MPS during the study period. The abrupt pollen releases after vibration transmission could be behind the increase in pollinosis observed in Japan after the Great Eastern Japanese Earthquake in 2011, with $M_w = 9.0$ (Siringoringo et al., 2014; Suda et al., 2019). The greatest earthquake in our study occurred on May 11th, 2011, with $M_w = 5.1$, I = VII, causing nine victims in Lorca (García-Ayllón and Tomás, 2014). There was a precursory earthquake with $M_w = 4.5$ and

Table 6
Statistical differences in pollen concentrations: Bonferroni test *p*-values (<0.05) between paired types of earthquake intensity (grades I to VII).

City	Intensity		I	II	III	IV	V	VI	VII
Cartagena	II	O				0.001↑			
		T			0.000↑	0.000↑			
Lorca	II	O							0.000↑
		T							0.009↑
	III	O							0.002↑
		T							0.001↑
	IV	O							
		T							0.019↑
Murcia	III	O					0.044↑		
		T							

O = *Olea* pollen concentrations, T = Total pollen grains from all pollen types in the *Olea* main pollen season. The arrow ↑ indicates that the concentrations are higher in the earthquake intensity of the column.

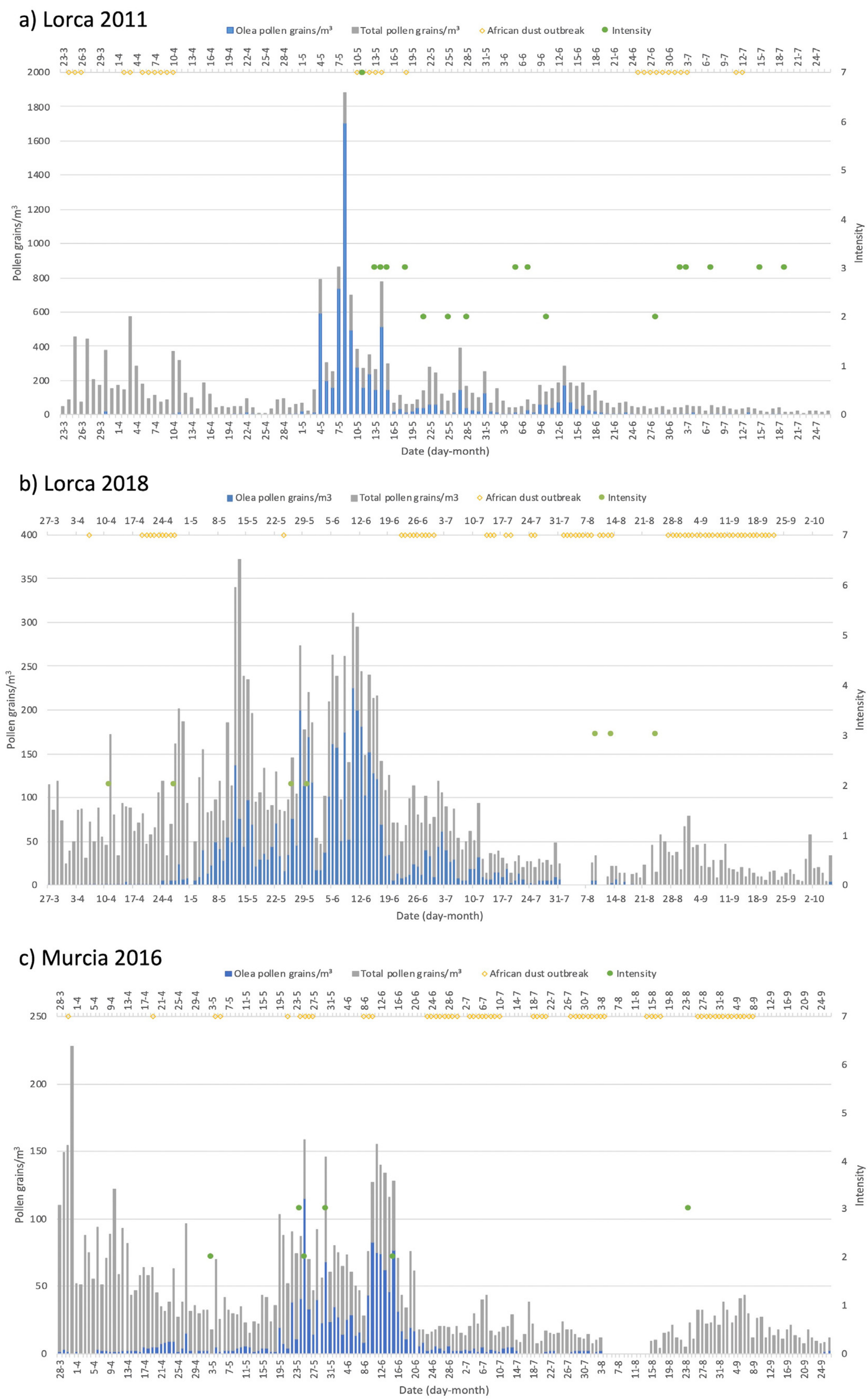

Fig. 2. *Olea* and total grain concentrations during the *Olea* MPS with indication of African Dust Outbreaks (yellow dots) and earthquake intensity (green dots) in a) Lorca in 2011, b) Lorca in 2018, and c) Murcia in 2016. Upper and lower panels are for date (day-month). Right axis is for intensity in the European Macroseismic Scale -EMS- (“1” corresponds to grade I and “7” corresponds to grade VII). Yellow dots should be read in the upper/lower panel.

another aftershock earthquake with M_w = 3.9 (Aguilar-Meléndez et al., 2019). López Comino et al. (2012) alluded to the shallowness of the focal depth, 4.6 km deep, and the fact that the epicenter was only 5.5 km from the center of the city, as two of the reasons for its devastation. Martínez-Díaz et al. (2012) indicated the pine forest of Sierra de la Peña Rubia as the most seriously affected area. However, *Pinus* pollen concentrations were not of much use as the taxon was outside the flowering period. After the earthquake of May 11th, 2011 (162 *Olea* grains/m^3), aftershocks were recorded for several days, although Hamdache et al. (2013) reported that most of the energy was released in the mainshock. One day after the earthquake, May 12th, 2011, the concentration rose to 176 *Olea* grains/m^3. Earthquakes occurred on May 13th, 2011 (145 *Olea* grains/m^3); May 14th, 2011 (512 *Olea* grains/m^3); and May 15th, 2011 (147 *Olea* grains/m^3), with all of them reaching I = III. Regarding the concentrations of *Olea*, the peak day was May 8th, 2011 (1707 *Olea* grains/m^3), three days before the earthquake of I = VII. There are several reasons why a clear impact on pollen concentrations cannot be observed. First, we can see that the peak day before the earthquake had the highest concentration in the whole series. Second, there was a drop in concentration (116 *Olea* grains/m^3) between the day before the earthquake (May 10th, 2011) and the day of the earthquake. And, third, the day before the earthquake began, there was an ADO that lasted for five days. As already mentioned, ADOs are associated with reductions in pollen concentrations (Rojo et al., 2021). Therefore, the rise of 76 *Olea* grains/m^3 the day after the earthquake was less obvious due to the temporary context in which it occurred. However, previously, a situation of high concentrations after aftershocks lasted for several days, despite the ADO, and this could be responsible for the fall of an order of magnitude in *Olea* concentrations after the three days of aftershocks between May 13th and 15th, 2011.

In Fig. 2b, examples of pollen concentration elevations coinciding with earthquakes can be seen for Lorca. Concentrations on May 29th, 2018 (114 *Olea* grains/m^3), prior to the earthquake on May 30th, 2018 with I = II (170 *Olea* grains/m^3), returned to similar concentrations on the day after the earthquake, May 31st, 2018 (117 *Olea* grains/m^3). In the case of Murcia, this evolution during and after seismic movements can be seen in Fig. 2c. May 23rd, 2016 (11 *Olea* grains/m^3) was prior to the earthquake I = III occurring in Murcia on May 24th, 2016 (41 *Olea* grains/m^3). On May 25th, 2016, a new earthquake I = II was felt, reaching 115 *Olea* grains/m^3. On May 26th, 2016, the concentrations dropped to 33 *Olea* grains/m^3. In this sequence, the presence of ADOs from the day of the IIII earthquake did not prevent the variation of an order of magnitude between days with and without earthquakes.

However, comparing the concentrations on earthquake days with the concentrations two days before, one day before, one day after, and two days after, no significant differences were detected in any of the three cities. As seen in the case of the greatest earthquake in Lorca, this is explained by phenological influences. Therefore, days before earthquakes did not show statistically different concentrations than days when earthquakes occurred. Seismic disturbance was difficult to observe in the context of the pollen series. When considering the periods of five days, centering on the day of an earthquake, the context and influence of the phenology of each day were incorporated. With this strategy, it was possible to detect significant increases by comparing the context of earthquakes by intensity. Again, cautiously, necessary due to the limited number of events, this allowed us to observe *Olea* and the total pollen types during the days of the *Olea* MPS with higher concentrations during days with greater seismic intensity.

4. Conclusions

We studied the concentrations of *Olea* and all of the pollen types during the *Olea* Main Pollen Season in the three cities of the Region of Murcia Aerobiological Network, in the Southeastern Iberian Peninsula: Cartagena, Lorca, and Murcia. The statistical analysis of pollen concentrations and meteorological and seismological variables allowed us to underline the preponderance of phenology over seismic movements in terms of airborne pollen concentrations. In addition, the presence of African Dust Outbreaks was clearly associated with lower pollen concentrations both for *Olea* and for all the pollen types in the *Olea* Main Pollen Season in the three cities.

During the decade under study, 2010–2019, there were 100 out of the 4457 days of the *Olea* Main Pollen Season in the three cities when at least one earthquake was felt. The maximum intensity was grade VII in the European Macroseismic Scale-98, corresponding to the earthquake in Lorca on May 11th, 2011, which caused nine fatalities. With this earthquake, there was no immediate impact on the city's pollen concentrations, possibly due to simultaneity with an African Dust Outbreak. However, in Lorca, *Olea* concentrations were statistically higher (95%) on the days when an earthquake occurred than on days when no earthquake was felt. In addition, it was found that greater seismic intensity was associated with higher pollen concentrations. The limitation of the time series and the relative scarcity of seismic events calls for these findings to be taken with caution. They should be ratified by expanding the time series and studying other places with seismic activity.

CRediT authorship contribution statement

L. Negral: Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing, Supervision. **F. Aznar:** Conceptualization, Methodology, Software, Investigation, Supervision. **M.D. Galera:** Methodology, Software, Formal analysis, Writing – original draft, Supervision. **I. Costa-Gómez:** Formal analysis, Investigation, Supervision. **S. Moreno-Grau:** Validation, Investigation, Supervision, Project administration. **J.M. Moreno:** Conceptualization, Validation, Data curation, Writing – review & editing, Project administration, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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