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Abstract

The olive tree (*Olea europaea*) is a native evergreen tree in the Mediterranean region, being one of the most important causes of seasonal respiratory allergies in Mediterranean countries. This work aims to relate flowering phenology, source tree distribution, meteorology, and airborne pollen records for this species and to analyse the possible arrival of air masses from distant areas during days when differences between the phenological and pollen peaks. Aerobiological sampling was carried out in Badajoz (SW Spain) for 4 years (2016-2019) using a Hirst volumetric sampler. Trees were geolocalized in the city and surrounding areas. The pollination phenology of 15 specimens was studied for four years (2016-2019) during the months from April to June. The daily data for the whole period and the hourly data for the four years, including pollen records and meteorology, were analysed. The comparison between the pollen records and sources distribution was assessed. The main pollen season (thereafter, MPS) lasted an average of 34.5 (29-40) days. Phenological observations indicate that pollination occurred for 26.5 days and was mostly within the period of recorded airborne pollen; however, were days with airborne pollen recorded outside the pollination period. In 2017 the peak day was recorded when the flowering period has reached only the 10%, in other seasons this value reached the maximum peak of pollen concentration was found only a few days after the maximum of flowering. The hourly analysis showed that the maximum pollen concentrations were reached just after noon. The analysis of pollen sources and pollen records showed a close relationship with the predominant winds and tree distributions. The observed discrepancies between phenological and aerobiological data (in 2017 and 2018) were explained by the movement of air masses and long-distance transport.

Keywords: Aerobiology, Botany, Phenology, HYSPLIT, Urban maps, Olea pollen

1. Introduction

The monitoring of airborne olive tree pollen is very important from the points of view of agriculture, ecology (Rallo & Cuevas, 2001; Pérez-Badia, 2015a) and medicine (D´Amato *et al.* 2007; Salamanca *et al.,* 2010; Vara *et al.* 2016) due to the close relationship between fruit production, high allergenic potential, high pollen production by the tree and extensive cultivation (SEAIC, 2005; Rojo *et al.*, 2016). Although aerobiological studies have traditionally been applied to allergy research, their usefulness for crop prognosis is currently being demonstrated, and they are highly desirable from an economic standpoint, for harvesting and for planning olive oil marketing and global commercial distribution (Llerena & Garrido, 2010; Galán *et al.,* 2004).

The olive tree is an entomophilous species that has evolved towards anemophily with many flowers, and an adult olive tree can produce large quantities of pollen grains (Rojo *et al*., 2016; Ferrara *et al*., 2007). The genus *Olea* includes approximately 35 species worldwide; 98% of olive groves are concentrated in the Mediterranean area and 24% are in Spain, mostly present in Andalucía (62%), Castilla-La Mancha (15%) and Extremadura (11%), and consist of *Olea europaea* subsp. *europaea* var. *europaea* (Vargas & Talavera, 2012) as the most cultivated taxon and an important oil-producing crop (Sefc *et al.*, 2001; Rojo 2014). In Extremadura, five varieties dominate those planted (e.g., Manzanilla de Sevilla, Manzanilla Cacereña, Cornicabra, Verdial de Badajoz, and Morisca), being the first that was present in the study area (Llerena & Garrido, 2010).

Moreover, olive tree pollen is considered to be one of the main pollen types responsible for allergic diseases that occur in the Mediterranean region (D´Amato *et al.,* 2007). An elevated proportion of Mediterranean patients show poli-sensitizations that reach a rate of 80% within the group of *Olea* allergy sufferers (Moreno-Grau *et al.* 2016). In some regions of southern Spain, olive tree pollen is the main cause of allergic sensitization and is the cause of sensitization in more than 40-45% of sensitized individuals (Moreno-Grau *et al.* 2016; Salamanca *et al.*, 2010).

Furthermore, despite this fact, in recent years, there has been much planting of this species in urban green spaces that produces large amounts of pollen (Staffolani *et al.,* 2011; Galán *et al.,* 2016; Charalampopoulus *et al.,* 2018). Allergic problems in urban environments should be considered in the design of the public environments (Velasco-Jiménez *et al.,* 2014), being olive trees frequently used as ornamentals in urban environments that have allergenic properties (Cariñanos & Casares-Porcel, 2011; Cariñanos *et al.*, 2014).

Allergenic properties are relevant to visitor behaviour and the characteristics of green spaces in Spain (Adinolfi *et al.,* 2014; Mohammad & Pooryousef, 2011; Fernández-Rodríguez *et al.* 2018; Maya-Manzano *et al.,* 2017a).

Phenological studies are an important and complementary part of aerobiological monitoring (Monroy-Colín *et al.* 2018), since they allow connecting emission sources with the airborne pollen records and enable better interpretation of the aerobiological results (Fernández-Rodríguez *et al.* 2014a; Tormo *et al.,* 2011); in addition to allowing the population with allergenic problems to be alerted to the increase in pollen in the air (Bruns *et al.* 2013; Carter *et al.* 2017; Monroy-Colín *et al.* 2018). Furthermore, the information about the flowering periods helps to differentiate species within the same pollen type by their pollen curves at a specific time (Monroy-Colín *et al.* 2018; Zerboni, 1998).

The olive tree blooms during the spring and flower production is conditioned by important physiological regulations that depend directly on the environmental conditions from the previous year (Rojo, 2014; Galán, *et al.*, 2001a). In addition, there are genetic conditions that are specific to each variety (Rosati *et al.,* 2012; Rojo, 2014; Rojo & Pérez-Badia, 2015a) and the timing and intensity of the pollen curves are strongly influenced by meteorological parameters (Hernández-Ceballos *et al.,* 2012). Olive tree flowering shows an annual cycle, including bud formation during the previous summer, dormancy during the cold period, budburst in late winter, and flower structure development from budburst to flowering in the spring (Aguilera *et al.* 2015a; Zhu, *et al.*; 2012). Temperature is one of the main factors affecting the flowering of olive trees, and a low-temperature period prior to bud development is essential to interrupt dormancy (Aguilera *et al.* 2015a; Galán, *et al.*, 2001a). Light affects the induction of floral buds in olive trees, but its impact on the floral phenology of olive trees is much smaller than that of temperature, and these depend on olive tree cultivars and geographical locations (Zhu, *et al.*; 2012; Galán, *et al.*, 2001a). Several studies have reported that the weather-related variable that is most influential for olive tree flowering is the temperatures during the months prior to anthesis (Galán, *et al.* 2001a; Galán, *et al.*, 2001b; Rojo & Pérez-Badia, 2015a). The floral phenological behaviours of olive trees are very consistent in response to similar meteorological conditions and are independent of latitude variations (Orlandi, 2005). *Olea* pollen in the air is influenced by several factors, such as time of day, season, weather conditions, geographical locations of sources (Fernández-Rodríguez *et al.* 2016) and the vegetation type that dominates one area (Charalampopoulus *et al.,* 2018).

It is for this reason that detailed mapping of the vegetation must be available, from which the pollen sources can be identified (Skjøth *et al.*, 2013; Maya-Manzano *et al.,* 2017b). Airborne pollen counts in areas with different levels of urbanization reveal differences in the number of pollen types recorded (Fernández-Rodríguez *et al.* 2014b; Skjøth *et al.*, 2013). Therefore, to know the distributions of ornamental plants with potentially allergenic pollen and its phenology allows to create urban risk maps (Pecero-Casimiro *et al.* 2019) and to take preventive measures that allows better preparation by hospital emergency services, which are often saturated during periods of high pollen levels (Galán, *et al.*, 2001a; Charalampopoulus *et al.,* 2018). Also to reduce the pollen exposure and to initiate treatment at the appropriate times (Monroy-Colín *et al.* 2018; Tedeschini *et al.,* 2006). The pollen distributions within cities depend on various factors such as microclimates, the spatial locations of trees, the predominant wind directions as related to source locations and the building heights (Maya-Manzano *et al.,* 2017b; Charalampopoulus *et al.,* 2018; Fernández-Rodríguez *et al.*, 2018). Geostatistical techniques and geographic information systems have been used recently for modelling olive tree flowering. These tools provide reliable interpretations of aerobiological data and the factors involved in airborne pollen dispersal (Rojo & Pérez-Badia, 2015). Recently, there has been an increase in the mapping of these trees in urban environments (Maya-Manzano *et al*., 2017a) and in regional areas to model pollen intensities (Rojo *et al.,* 2016; Aguilera *et al*., 2015b).

Based on previous aerobiological analyses in the study area (Fernández-Rodríguez *et al.*, 2014a) and in nearby locations (Hernández-Ceballos *et al.*, 2011a; Hernández-Ceballos *et al.,* 2014b; Hernandez-Ceballos *et al.*, 2012), long-distance transport episodes should be considered in the study of the temporal cycles of pollen concentrations and their attribution to local sources (Skjøth *et al.*, 2012). Furthermore, regional scale transport of olive tree pollen can result in increased nightly concentrations of this important aeroallergen (Fernández-Rodríguez *et al.*, 2014a). A number of studies have examined the long-distance transport episodes (LDT) of airborne pollen grains and have attempted to identify their sources, e.g., the pollen types from trees such as *Betula* spp. (Skjøth *et al.*, 2014; Skjøth *et al.*, 2009; Skjøth *et al.*, 2007); *Quercus* spp. (Hernández-Ceballos *et al.*, 2011b; Hernández-Ceballos *et al.*, 2014a; Maya-Manzano *et al.,* 2016) and *Olea* spp. (Fernández-Rodríguez *et al.*, 2014a; Hernández-Ceballos *et al.,* 2011a; Hernández-Ceballos *et al.,* 2012; Hernández-Ceballos *et* *al.,* 2014b). In this sense, this mapping, combined with dispersion models as Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT), (Draxler & Hess, 1998) can be helpful for achieving a full understanding of some of the discrepancies between pollen content and phenology. In this work, the backward dispersion calculation for particles was used, and it provided information for the characteristics of air-mass movements over a region, in terms of their origin, horizontal pathways and altitudes. This information also provides detailed information on the paths followed by air masses until its arrival over the study area and is therefore a useful tool for a range of scientific applications that are related to air-quality analysis (Borge *et al.* 2007; Hernández-Ceballos *et al.* 2011b).

The aim of this study is to evaluate the relationships of airborne *Olea europaea* pollen recorded by the pollen trap and the arrangements of olive trees within the city of Badajoz (Spain), and to relate the influence of vegetation through the study of phenology to the presence of pollen in the air. Additionally, some LDT were analysed to determine the possible arrival of air masses from distant places during these divergences between the phenological and pollen peaks.

2. Material and methods

2.1. Study area

This study was conducted in Badajoz, a city in the SW of Spain with 150 543 inhabitants (NSI, 2018). The city is 184 m above sea level and is crossed by the Guadiana River with the Gévora River as a tributary.

Daily meteorological data were provided by the National Meteorology Agency (AEMET) from a meteorological station located at 38° 53' 00'' N, 6° 48' 50'' W, which was 3.7 km from the aerobiological sampler. This station provided data of Mean, maximum and Minimum temperature (ºC), rain (l/m^2), wind direction (km/h) and wind direction (degrees). Moreover, for hourly data, a portable weather station (WS-GP1 Delta-T) was located 2 metres from the pollen trap (Fig. 1A) to achieve more similar results to the pollen sampling point. The portable meteorological station data were recorded every 10 minutes, and included temperature (ºC), rain (mm), relative humidity (%), wind speed (m s^{-1}) and wind direction (grades) and provided data for the four years of the study. To process the wind direction data, 10-minute values were transformed into 30º sections (12 values) and the modes of the hourly data were calculated; for the remaining meteorological parameters, average values were used except for rain, for which the sums were calculated.

2.2. *Olea* trees mapping

Olea europaea trees in the city were examined during the period of this study (2016 to 2019) and were counted and geo-referenced on a map (Fig. 1B) and included ornamental or urban green areas and the city outskirts. Also, the mapping for those specimens whose phenology was studied have been included (Fig. 1B). Major olive tree pollen sources were identified using the Corine Land Cover (CLC) 2006 v. 17 datasets for the studied area (EC, 2013). The inventory maps were gridded using the CLC 2012 projection by aggregating the grid cells to 20 km x 20 km using procedures similar to Sadyś *et al.,* (2014) and Skjøth *et al.,* (2012). This procedure enables easy comparisons of habitat densities at regional and national scales. Olive trees appear as agricultural areas with permanent crops and are denoted as olive tree groves (code 223). Furthermore, layers of the elevation data of the Iberian Peninsula were used (Fig. 2).

2.3. Pollen sampling

Olea pollen grains were collected using a Burkard seven-day pollen trap (Hirst, 1952). The trap was located on a 6 m high terrace and was placed in the Agricultural Engineering School, in Badajoz at SW Iberian Peninsula (38°53' N, 6°58' W) (Fig. 1). Standardized data management procedures for capturing and counting airborne pollen were used, according to the Spanish Aerobiology Network (REA) (Galán *et al.,* 2007). Pollen records were expressed as the numbers of pollen grains per cubic metre of air (pollen grains /m^3). The method used to calculate the MPS was the proposed by Nilsson & Persson (1981), which considers the 90% for the whole annual pollen amount (Fig.3).

2.4. Phenological analysis

The phenological phases studied were recorded according to the BBCH code (Biologische Bundesanstalt, Bundessortenamt, Chemische Industrie) (Meier, 1997). This is an internationally recognized standard in the agricultural sector and classifies plant growth phases according to a standardized system (Meire, 2001). From 15 specimens, but only on sunny days and with calm winds at noon, pollen shedding was mechanically tested from 10 branches at 1.5-2 m height that were touched or shaken, during four years (2016-2019) from April to July. Five specimens were 4 km from the pollen station; five specimens were 3.6 km distant; and five specimens were 3 km distant, while an average sampling frequency of 3-4 days was used. Specimens close to the pollen trap are shown in Fig. 1B. The plots for the MPS and the phenological analysis is shown In Fig. 4.

The percentages of pollen shedding were recorded from beginning of flowering with 10% open flowers (BF, BBCH 61) up to full flowering (FF, BBCH 65, general flowering or full blossom) when at least approximately 50% of the flowers were open. This methodology has also been previously used in other works (Monroy-Colín *et al.,* 2018).

2.5.HYSPLIT analysis

The air mass transport patterns above Badajoz were examined using daily 24-hours backward dispersion analysis, following the methodology explained in previous works (De Weger et al., 2015). According to the hourly analysis (Fig. 5), the maximum peaks for 2017 and 2018 were observed from 13-15 hours (Fig. 5B and 5C), and it was the time set up for the arrival of air masses. These plumes were calculated with the HYSPLIT model (Draxler & Hess, 1998; Draxler & Rolph, 2014; Rolph, 2014). The Global Data Analysis System (GDAS) data with 0.5 x 0.5-degree resolution were downloaded from the NOAA ARL (National Oceanic and Atmospheric Administration Air Resources Laboratory) FTP server. The position for the particles in the layers of the atmosphere was studied, from 0 to 4 000 meters height (AGL), and the starting time of 15 hours for two consecutive days before each episode were calculated to trace the path that the air masses followed. They were during the mismatches between the MPS period and the phenological phenophases from 2016 to 2019. The results are displayed in Fig. 7.

2.6. Statistical analysis

After checking the normality by using the Kolmogorov-Smirnov test and due to the negative results, that were obtained, non-parametric statistics was applied. The Spearman´s rank coefficient test was used to analyse the associations between pollen concentrations and meteorological parameters (temperature, rain, relative humidity, wind frequency and wind speed). To determine what temperature recorded the most pollen, a graphical analysis was performed that summed the daily pollen concentrations for each average temperature. The statistical analysis was performed with the package R (R Core Team, 2018) . The calculations for the MPS and other parameters for the MPS were carried out by the package AeRobiology (Rojo *et al*., 2019).

3. Results

In the entire city of Badajoz and the immediate surroundings, a total of 2,217 *Olea europaea* trees were counted (Fig. 1B). Most of the olive tree crops in the Iberian Peninsula are located below 765 m in elevation and are concentrated mainly in the south (Fig. 2). Olive tree flowering in Badajoz started the last week in April and finished the second week in June, with a maximum in the second week of May (Table 1 and Fig. 4). The flowering started two weeks earlier in 2017 (Table 1 and Fig. 3). The average temperature in the two months before the flowers opened was higher in 2017 and 2019 (Table 1). 2017 and 2019 presented high pollen concentrations (Table 2 and Fig. 3). In 2016, the phenological period ranged from 06/05-03/06, with a maximum on 20/05 (Table 1); pollen recorded outside this period represented the 19.83% of the total pollen. Maximum pollen concentrations were reached only one day after relative to the maximum pollination phenophase (Fig. 4A). For 2017, the Phenological period ranged from 21/04-19/05 (Table 1), with a maximum on 12/05; pollen records outside this period represented the 14.54% of the total pollen. Maximum pollen concentrations were reached nine days before the maximum pollination phenophase (Fig. 4B). By contrast, in 2018 the Phenological period ranged from 11/05-01/06, with a maximum on 18/05 (Table 1); pollen records outside this period represented the 36.71% of the total pollen. The maximum pollen concentrations were reached five days later relative to the maximum pollination phenophase (Fig. 4C). In 2019, the Phenological period ranged from 22/04-21/05 (Table 1), with a maximum on 13/05; pollen records outside this period represented the 14.83% of the total pollen. Maximum pollen concentrations were reached two days later relative to the maximum pollination phenophase (Fig. 4D).

The phenological observations of *Olea europaea* (Table 1) indicate that pollination occurred for 26.5 days as the 4-year-average and was mostly within the period of the airborne pollen records (Fig. 4). The pollen record dates outside the phenological observations represented 19.29%. 4.35% of pollen was detected before the pollen season and 3.89% of pollen was detected after the pollen season. In 2016 and 2019, the maximum pollen concentrations coincided with the maximum of the phenology periods, however, in 2017 and 2018 they did not. In 2017, the maximum concentration of pollen occurred nine days before the maximum of the phenology period, while in 2018, it occurred five days later than the phenological maximum (Table 1 and Fig. 4).

In 2016, the SPIn (Seasonal Pollen Integral, Galán *et al.,* 2017) for the period studied was 2 606 pollen*day/m^3 (Table 2). The daily peak was reached on 21/05 (451 pollen grains/m^3 (Fig. 4A), 18 days later than in 2017 (03/05), when a concentration of 1 994 pollen grains/m^3 was reached (Table 2 and Fig. 4B). In 2017, the SPIn was 14 015 pollen*day/m^3, while in 2018 it was 7 894 pollen*day/m^3 (Table 2) and the daily peak value for pollen concentration reached 794 pollen grains/m^3 (23/05) (Fig. 4C). 2019 was the year with the highest SPIn, (considering the first semester data) with a total of 14 823 pollen*day/m^3 (Table 2), and the daily peak reached 1 558 pollen grains/m^3 (15/05) (Fig. 4D).

Table 2 show the SPIn for the studied period and the Spearman´s correlations for meteorology and daily concentrations regarding the MPS. Fig. 5 shows the hourly concentration patterns for 2016 (Fig. 5A), 2017 (Fig. 5B), 2018 (Fig. 5C) and 2019 (Fig. 5D). During the four study years, the highest concentrations were found after noon, and we found a direct correlation with temperature increases and humidity decreases in the atmosphere. In addition, the statistical analysis indicates a positive correlation with wind speed and negative with wind frequency (Table 3). Fig. 6 shows the frequency of wind directions, and the highest concentrations appeared when the winds were predominantly W and SW.

The pollen season of 2016 and 2019 were explained well because of local flowering conditions (Fig. 4A and 4D), but not for 2017 and 2018 (Fig. 4 B and 4C). For these years, the years with the greatest difference between the maximum pollen concentrations and the maximum phenological status, the backward dispersion calculation are displayed in Fig. 7. They were the most likely to be due to LDT episodes. Thus, we can understand the effects of long-distance transport that arrived from the SE zone of Andalusia (Fig. 7A and 7B), which coincides with the region of greater *Olea* crop concentrations within the Iberian Peninsula (Fig. 2). Moreover, we can observe that even for the episode occurred on 3rd May 2017, some particles are coming from Portugal contained in air masses travelling for higher layers (>2 000 m AGL). For 2016, the difference between the maximum pollen concentration and the maximum phenology was one day (Tables 1 and 2). For 2018, the difference between the maximum pollen concentration and the maximum phenology was five days (Tables 1 and 2). The air masses came mostly from the SW (Fig. 6C), but for the episodes of higher concentrations out of the flowering season (they produced high peaks when the flowering was decreasing), was found that the air masses were coming from distant places in Portugal

(7C, 7D, 7E and 7F). Finally, for 2019, at the time of the maximum pollen concentration, the dominant wind direction was from the SW, the place where the most of trees are dispersed within the city (Fig. 1 and 6D).

4. Discussion

The pollen season parameters were measured in the current work were similar to those reported by Aguilera *et al.* (2015b), Rojo & Pérez-Badia, (2015b) and Rodríguez-De la Cruz *et al.* (2010), who reported maximum pollen peaks in the third week of May, but with lower values than reported in this work. However, the start date coincides with the reports for some Mediterranean cities in Tunisia and southern Spain in the hottest years (2017 and 2019) (Table 1), and these cities were those with average temperatures very similar to those found in Badajoz in those years. The dates for the beginning of the season during the coldest years were coincident with the reported by Aguilera *et al.* (2015b) in some Italian cities with continental climate. Latitude-induced microclimatic conditions determine the physiological responses of olive trees. In particular, the peak pollen emission date, which corresponds to the day on which most of the tree canopy flowers are open, is influenced strongly by this factor (Aguilera *et al.* 2015b). The current findings confirmed that the air pollen counts were determined by the flowering succession (Rojo & Pérez-Badia, 2015b). *Olea* pollen was detected in the atmosphere of Badajoz from April to July. The flowering dates of the olive trees in the city of Badajoz coincided with that reported by Fornaciari *et al.* (2000), González & Candau (1997) and Trigo *et al.*, (2008) who reported that the flowering period in the Mediterranean area for the genus *Olea* generally occurred between April and June. Moreover, other authors in Spain have also reported that flowering took place at the end of May and in the beginning of June (Rojo & Pérez-Badia, 2015a; Galán, *et al.* 2001a; González & Candau, 1997).

From a phenological point of view, come early the onset of the flowering period can be interpreted as a defence mechanism or an adaptive phenomenon of the olive tree physiology to the higher temperatures expected in the future and, above all, to the increases projected for the spring temperatures (Aguilera *et al.* 2015a). It has been observed that olive trees with constant maintenance and irrigation initiate flowering earlier and have longer flowering periods (Aguilera *et al,.* 2013). Aguilera & Ruiz (2009) indicated that the accumulated temperature and precipitation during the months prior to the flowering period greatly favour the phenological development of the olive tree, and significantly affect the processes of flower formation and the release of pollen grains into the atmosphere. Otherwise, precipitation washes the atmosphere and causes a decrease and discontinuity in the presence of pollen in the atmosphere.

It has been evidenced, using partial least-squares regression, that the reproductive phenology of olive trees in the Mediterranean area is regulated by meteorological parameters that are related to the previous autumn and to both the winter and spring seasons, and, above all, by the temperatures (Aguilera *et al.,* 2015a). Moreover, an increase in temperature before the beginning and advance of flowering play a relevant role in the biological cycle (Bonofiglio *et al.,* 2008), and studies show that in the coldest years, the flowering period is shorter (Tedeschini, *et al.,* 2006), while in the warmer years, the buds break earlier and in this manner, flowering commences. González & Candau (1997) in a study in Sevilla, indicated that the beginning of the main pollination period was related to the mean temperature of the two preceding months and that pollination occurred when the average temperature in both months was above 14°C. In contrast, pollination was delayed when the average temperature was lower. This agrees with the results of this study (Table 1), with the opening of flowers occurring earlier in the hottest two years and with temperatures above 14°C (2017 and 2019). In addition to the release of pollen occurring gradually, this phenomenon could explain the differences in the beginning dates and durations of flowering in 2017 and 2019 (Rojo & Pérez-Badia, 2015a; García-Mozo *et al.* 2008; Tedeschini, *et al.,* 2006). Excessive temperatures negatively influenced several reproductive parameters, including flower development, pollen-tube growth, pollen viability, and the pollination process and, consequently, subsequent fertilization and productive yields (Aguilera *et al.* 2013). Other meteorological factors considered in relation to the phenology were humidity, cumulative rainfall and cumulative solar radiation (Aguilera & Ruiz-Valenzuela, 2009). High relative humidity sometimes can delay or even inhibit anther opening and pollen release (Yates & Sparks, 1993; Lisci *et al.,* 1994). This could be another explanation for the observed discrepancies, as shown in Fig. 4, in which it is possible to see the influence of rainfall. The associated increase in the relative humidity provoked by rain during months with high temperatures can provoke that pollen remains more time in the anthers, and brief showers can also precipitate the abrupt deposition of pollen into the ground.

The values for the cumulative annual pollen mentioned in this study are only lower than those for Córdoba, Jaen and Granada, as reported for Spanish cities that present amounts above 22,000 pollen*day/m^3 (Rojo *et al.* 2016). The *Olea* concentration values on the peak days ranged from 414 pollen grains/m^3 in 2016 to 1,994 pollen grains/m^3 in 2017, and the interannual variability in the different variables that define the pollen season is remarkable. Regarding the concentrations of *Olea* grains found on both the peak days and during the pollen season, it should be noted that the olive tree is recognized as a species with alternation in flowering (Galera *et al.* 2018), which depends on vegetative and reproductive processes, and occurs throughout a biennial cycle (Rallo & Cuevas, 2001); hence a part of the interannual fluctuations is associated with this phenomenon (Galera *et al.* 2018). *Olea* pollen concentrations on both the peak days and in the pollen seasons (Table 2) show important interannual variations, and those years with low concentrations (2016 and 2018) are followed by years with high concentrations (2017 and 2019). This effect seems to be due to the alternate bearing years of pollen production by this species (Rojo *et al.* 2015c) and coincides with that reported by Galera *et al.* (2018) for the city of Cartagena, where the same effect was seen.

Considering some mismatches between phenology and pollen (Fig. 4) and for the backward dispersion calculation analyses (Fig. 7), we suggest that for 2017 and 2018, the pollen outside the flowering season originated from distant sources (Fernández-Rodríguez *et al.* 2014a). Specifically, for 2017 the peak for pollen was produced quite before the flowering peak (9 days earlier), that could be due to pollen contributions from the SE of Badajoz, and for 2018 the episodes showed air masses arriving from Portugal. Pollen transport from remote sources is particularly relevant for species with small pollen size, such as the olive tree (Hernandez-Ceballos *et al.* 2011). Other authors (Estrella *et al.,* 2016) have also argued that the discrepancy between pollen and phenology is due to LDT episodes. The pollen quantities that were recorded in 2017 before the flowering of olive trees in the area must have been transported by winds from south and southeast of Spain, where the olive trees flowered sooner due to higher temperatures and where earlier-flowering varieties are more widely grown (García-Mozo *et al.* 2008). Specifically, winds from the south (May 3, 2017) could have carried pollen from the olive tree groves in the Andalusian provinces of Jaen and Granada which, along with Cordoba, have the largest olive tree growing areas in Spain.

Additionally, another pollen source in the west part of the territory could correspond to the Alentejo region, which hosts nearly half of the olive tree groves of Portugal (Fernández-Rodríguez *et al.* 2014). It could be the reason for the episodes shown in Fig. 7 regarding 2018. Our results are consistent with the findings of Silva-Palacios *et al.* (2000) and Fernández-Rodríguez *et al.* (2014), who demonstrated that, in Badajoz, there were significant correlations between the daily pollen concentrations of *Olea* and the amounts of wind hours each day from the southeast, southwest and northwest quadrants. In this study, the HYSPLIT model has been proven to be an adequate tool to estimate the directions taken by air masses and to identify the sources of pollen originating from long distances outside the pollen season in the same region than for the current study (Maya-Manzano *et al.* 2016). Finally, we cannot discard the occurrence of some contribution from resuspension phenomena, especially in 2018. This fact has been proven to be important, above all in favourable conditions of high temperature and absence of rain (Jato *et al.*, 2006). In addition to the importance of temperature, this study highlights the importance of wind, whether for long-distance transportation or for nearby areas for those moments in that flowering peaks and pollen peaks are not coincident. This is probably related to the fact that the prevailing winds are from the west (Fig. 5), where there are sources of olive tree pollen and that some of the highest densities of olive tree groves in the Iberian Peninsula are found in the southeast (Fig. 3).

5. Conclusions

This type of studies facilitate better planning for the management of olive tree crops in the region because they are useful to establish future predictions of the start of olive tree flowering. LDT phenomena and delays in the flowering caused by environmental conditions may lead to a non-exact match between the phenological and aerobiological peaks. At the aerobiological level, LDT can be recognized by sudden appearances or increases (peaks) that are sometimes coincident in different locations or by changes in the trends of atmospheric pollen dynamics, and LDT can be demonstrated using atmospheric models of air mass dynamics. Backward dispersion calculations need to be combined with knowledge of the geographical distributions and phenological characteristics of the pollen sources, as well as with pollen concentration data of high temporal resolution, to clearly identify the origins of pollen measured at a monitoring site. This information is extremely useful for predicting the amounts of airborne *Olea* pollen in the city of Badajoz and for other cities with similar conditions.

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Tables and figures

Table 1. Pollination phenology of *Olea europaea* (2016-2019). The onset, finish and maximum dates are related to the flowering period.

	Onset Date	Finish Date	Maximum	Length (days)	Tmean°C (two months before the flowers opened)
2016	06-May	01-Jun	20-May	26	12.8
2017	21-Apr	24-May	12-May	33	15.3
2018	11-May	08-Jun	18-May	28	13.1
2019	22-Apr	21-May	13-May	30	14.2

Table 2. SPIn (Seasonal Pollen Integral) values, mean pollen season characteristics and Spearman´s rank correlation coefficients for daily values daily values of *Olea europaea* 2016-2019 with rain (mm), Minimum (T_{min}), Maximum (T_{max}) and mean temperature (T_{mean}), in ºC, and Wind Speed ($m\ s^{-1}$).

* significance at the 95% level. ** significance at the 99% level.

	Seasonal Pollen Integral (**SPIn**)						Mean Pollen Season (MPS)	
	pollen*day m^{-3}	Spearman´s rank coefficient rank					Length	Maximum pollen concentration
		Rain	T_{min}	T_{max}	T_{mean}	Wind speed		
2016	2,606	0.11	-0.04	-0.19	-0.12	-0.11	14/05 to 22/06 (40 days)	21/05 (451 pollen grains/m^3)
2017	14,015	-0.22	0.01	0.09	0.1	-0.01	27/04 to 25/05 (29 days)	03/05 (1,994 pollen grains/m^3)
2018	7,894	-0.04	-0.15	0.08	0.01	-0.09	17/05 to 23/06 (38 days)	23/05 (794 pollen grains/m^3)
2019	14,823	0.12	-0.07	-0.22	-0.2	-0.28	02/05 to 01/06 (31 days)	15/05 (1,558 pollen grains/m^3)

Table 3. Spearman´s rank correlation coefficients between hourly values of *Olea europaea* 2016-2019 during their MPS and hourly meteorological parameters.

* significance at the 95% level. ** significance at the 99% level.

	Hourly values with the highest pollen concentration	**Hourly values with the lowest pollen concentration**	**Statistically significant correlation**			
			Relative humidity	Wind speed	Temperature	Wind frecuency
2016	10:00-15:00	22:00-09:00	-0.64**	-0.74**	0.59**	-0.64**
2017	11:00-18:00	23:00-07:00	-0.73**	0.89**	0.73**	-0.76**
2018	13:00-18:00	22:00-09:00	-0.84	0.42*	0.86*	-0.84**
2019	10:00-17:00	23:00-08:00	-0.82**	0.27	0.43*	-0.59**

Fig. 1 **A**. Pollen trap and portable weather station (WS-GP1 Delta-T). **B**. Geolocation of *Olea* trees. Spore trap (red dot). Olive trees (blue dots). Specimens whose phenology was studied (yellow dots)

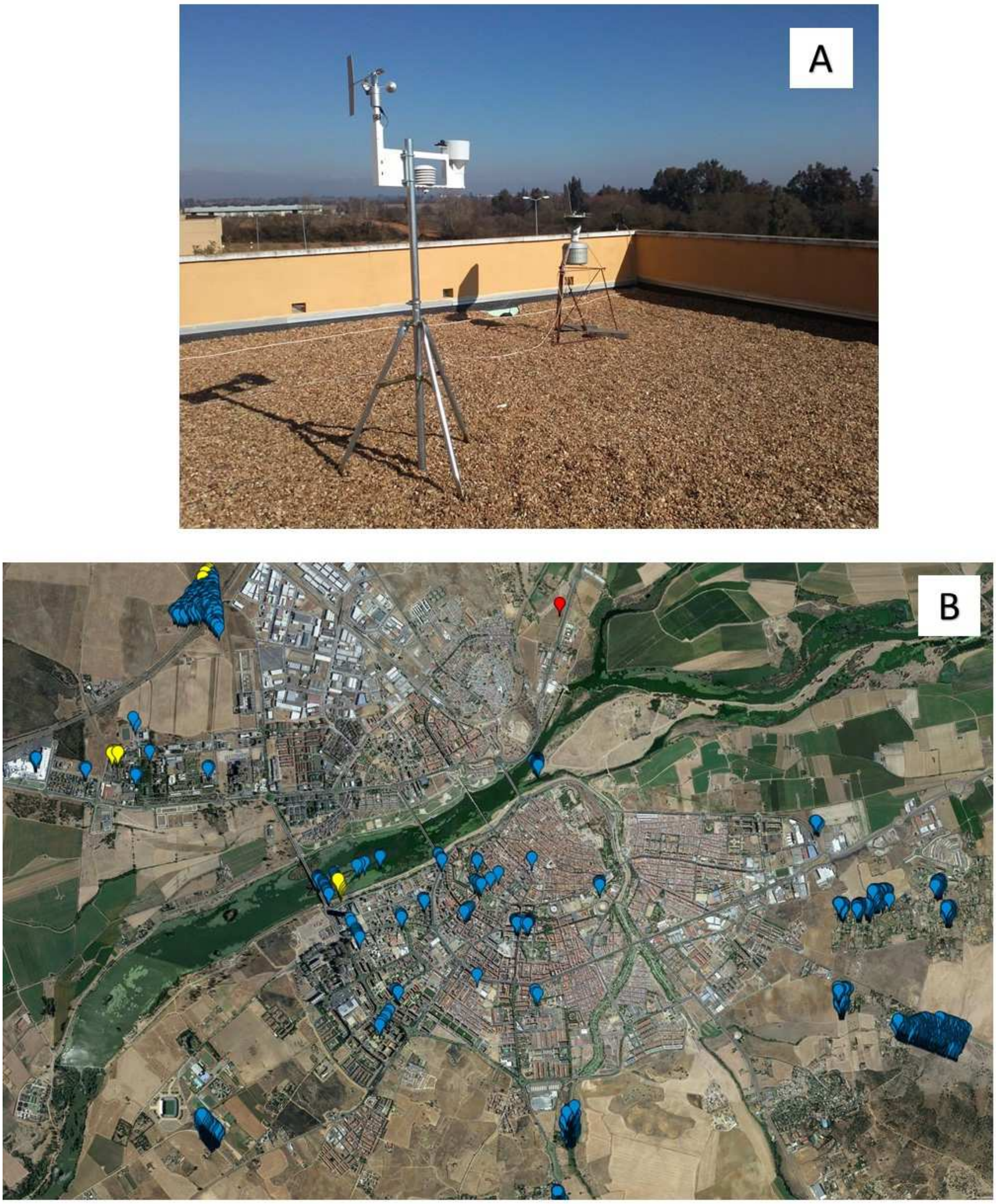


Fig. 2. Mapping sources of olive pollen of the Iberian Peninsula with olive groves (black colour) from CLC and elevation data in Badajoz (BA).

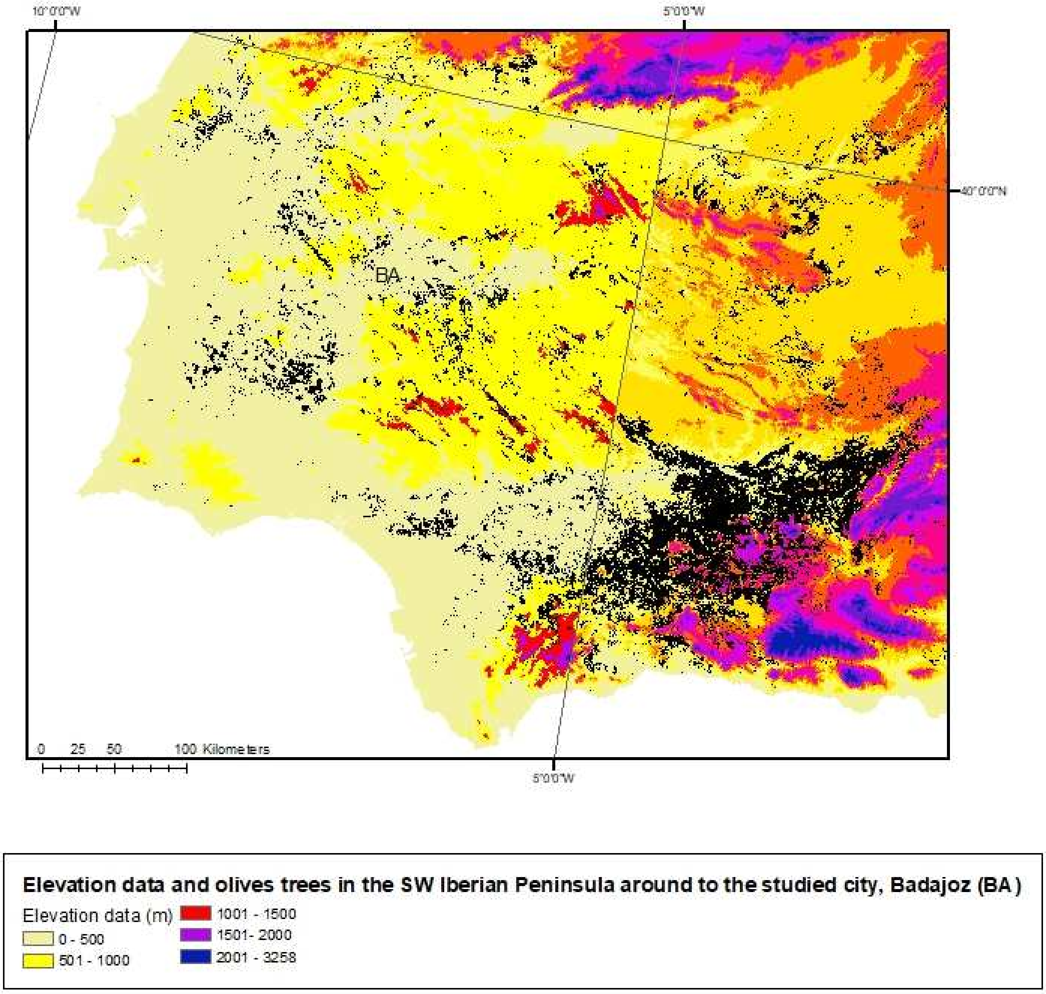


Fig. 3. Pollen Season of *Olea europaea* 2016-2019.

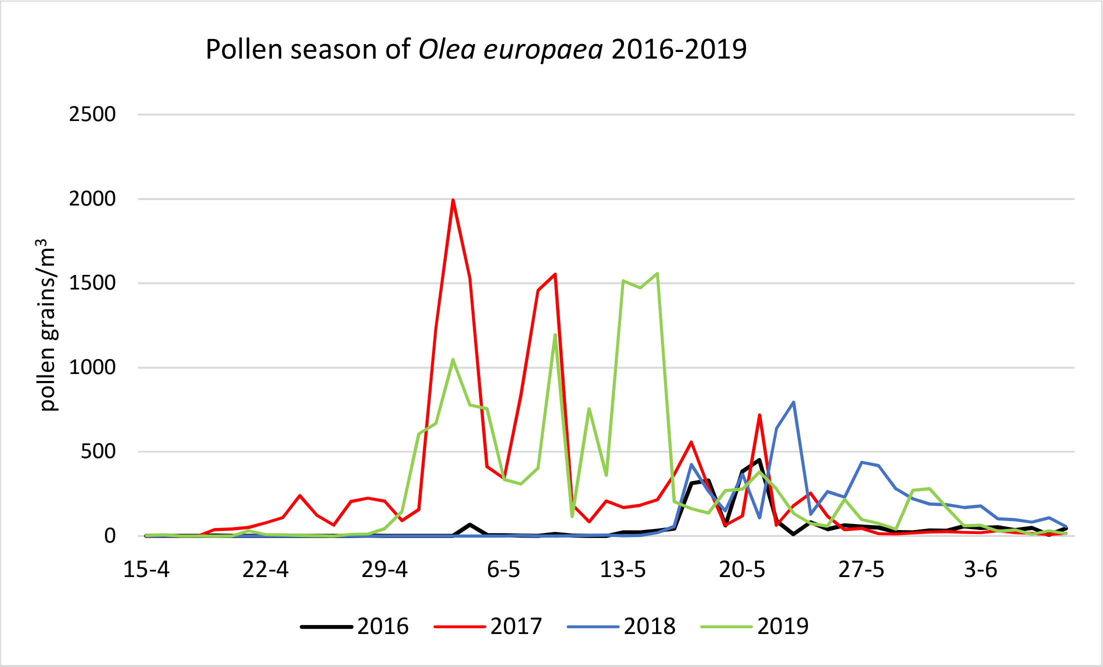


Fig. 4. Daily airborne olive pollen concentration (blue lines), mean temperature (orange lines), rain (black bars), MPS dates for start and end (blue bars) and phenology (red dots). 2016 (A), 2017 (B), 2018 (C) and 2019 (D).

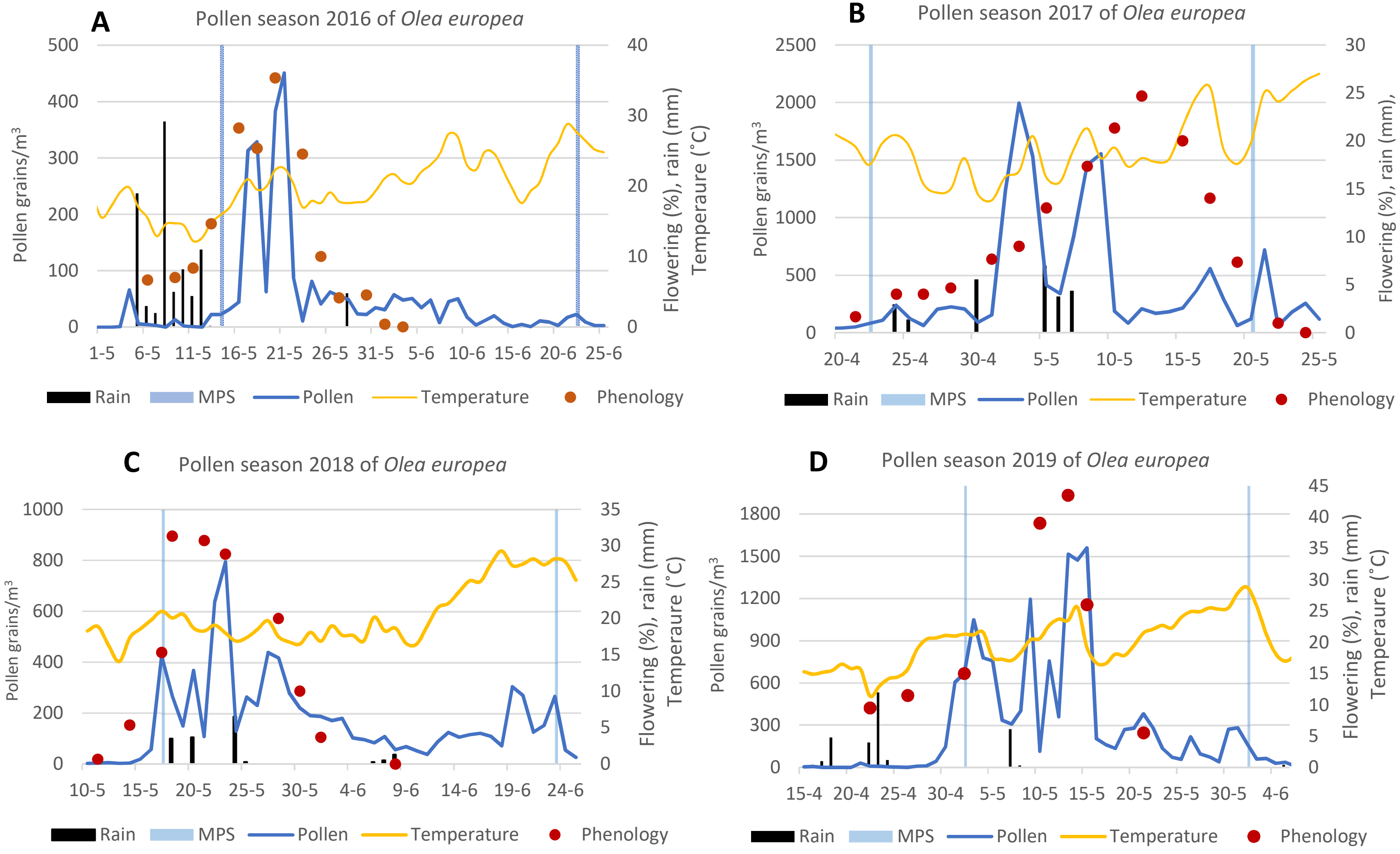


Fig. 5. Hourly data for *Olea* pollen concentrations in 2016 (A), 2017 (B), 2018 (C) and 2019 (D), including error bars and average for relative humidity and mean temperature.

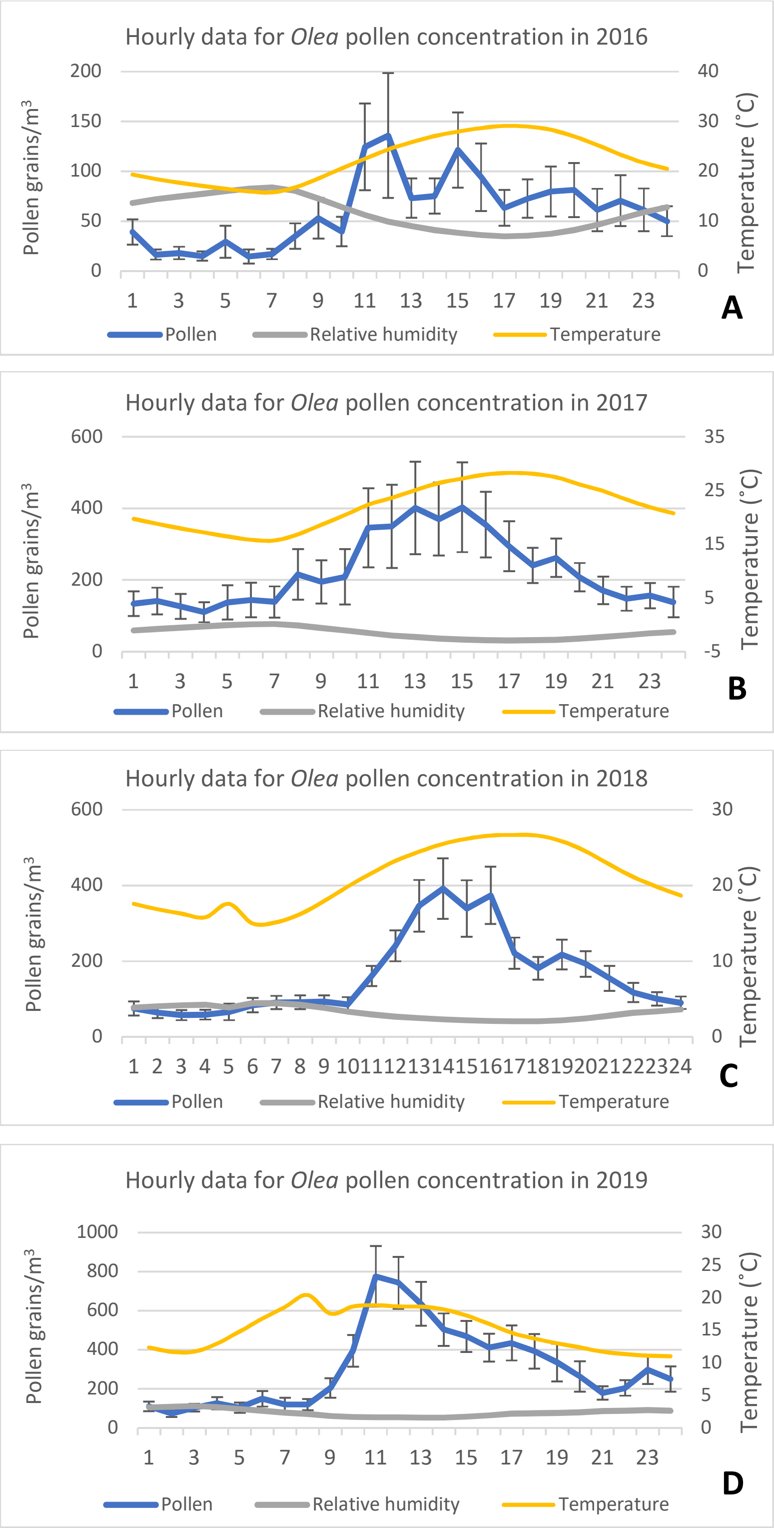


Fig. 6. Wind direction frequency during pollen season of *Olea europaea* in 2016 (A), 2017 (B), 2018 (C) and 2019 (D).

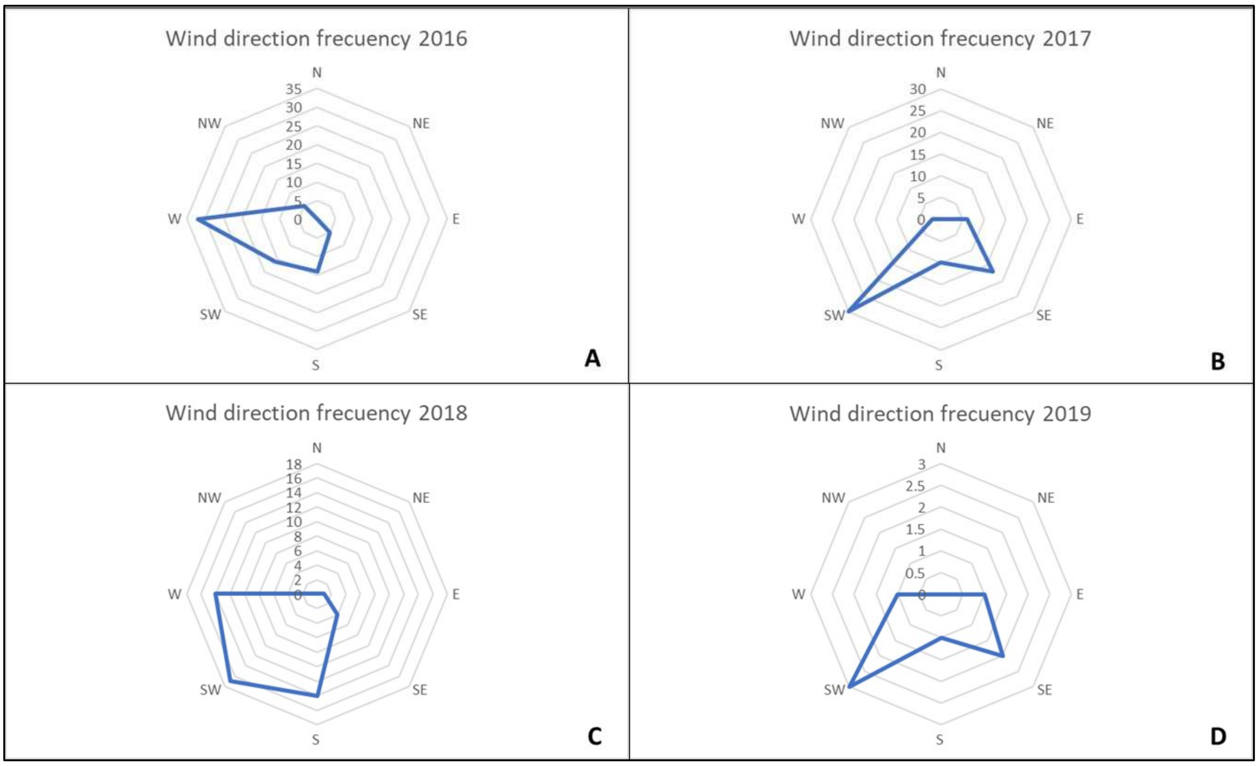
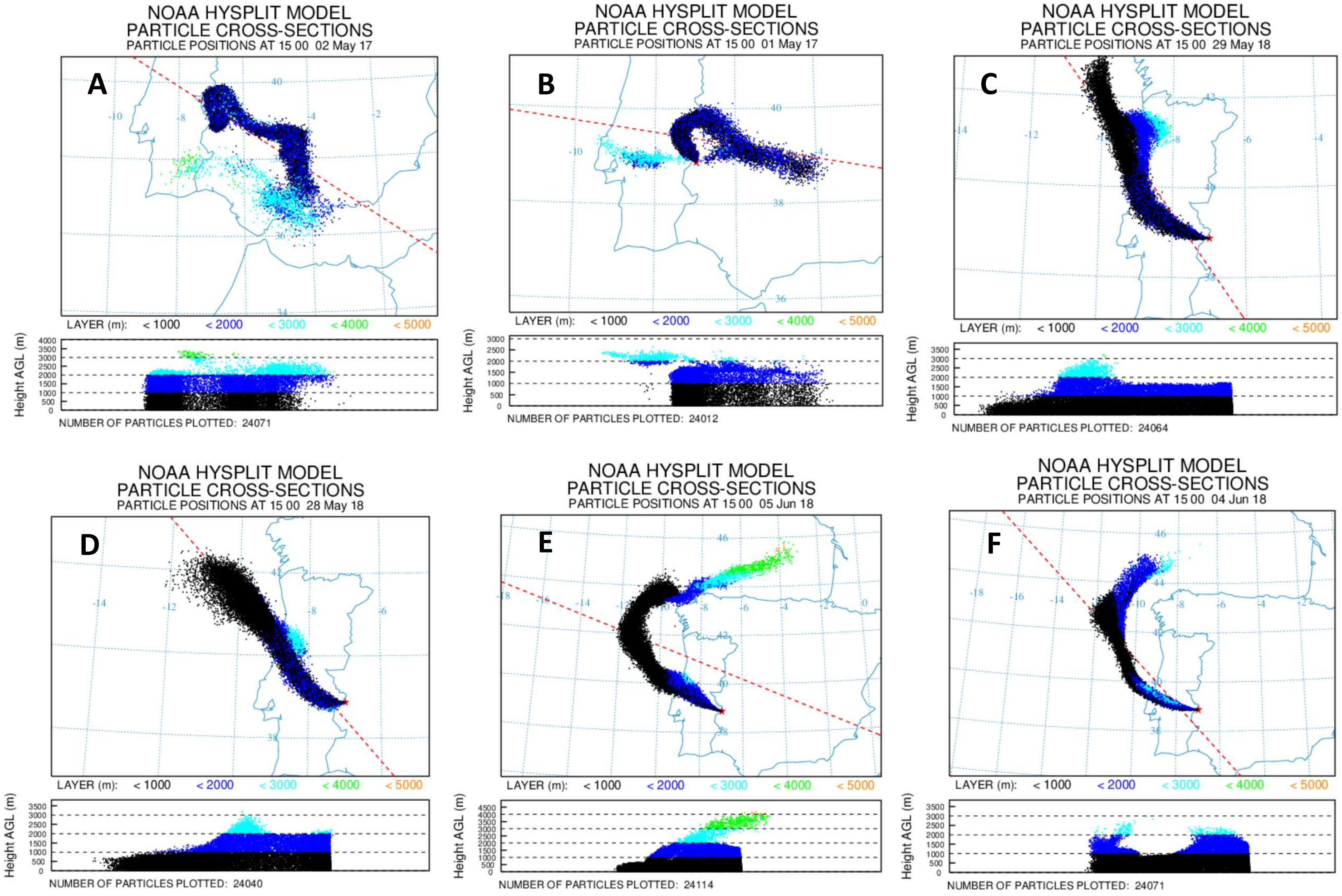
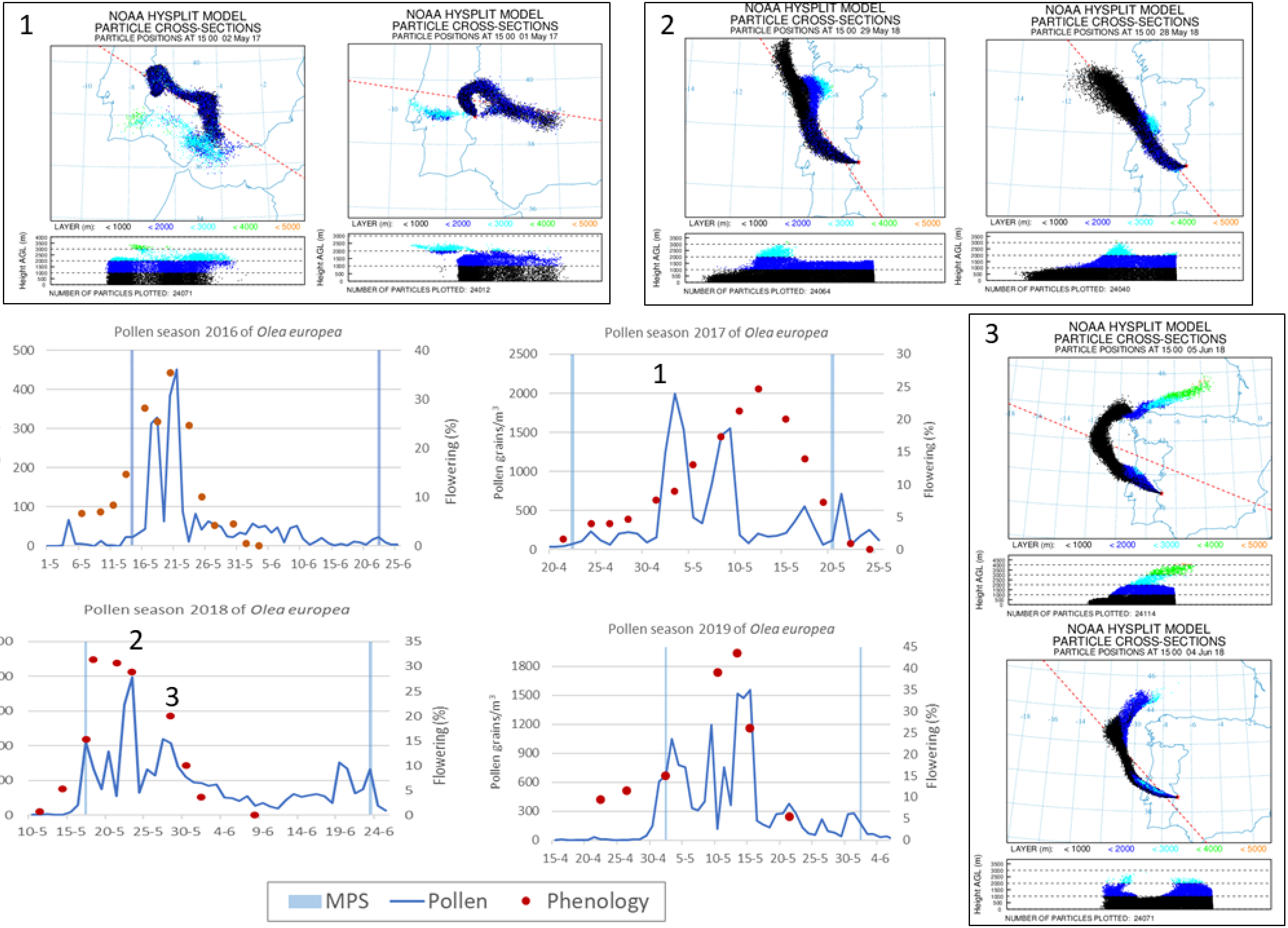


Fig. 7. HYSPLIT model calculation for the 24-hours back-distribution of particles released in Badajoz for the mismatches between pollen peaks and flowering peaks in 2017 (May 3rd A and B) and 2018 (May 30th C and D, and June 6th E and F).





1
NOAA HYSPLIT MODEL
PARTICLE CROSS-SECTIONS
PARTICLE POSITIONS AT 15 00 02 May 17
NUMBER OF PARTICLES PLOTTED: 24071
NOAA HYSPLIT MODEL
PARTICLE CROSS-SECTIONS
PARTICLE POSITIONS AT 15 00 01 May 17
NUMBER OF PARTICLES PLOTTED: 24012
2
NOAA HYSPLIT MODEL
PARTICLE CROSS-SECTIONS
PARTICLE POSITIONS AT 15 00 29 May 18
NUMBER OF PARTICLES PLOTTED: 24064
NOAA HYSPLIT MODEL
PARTICLE CROSS-SECTIONS
PARTICLE POSITIONS AT 15 00 28 May 18
NUMBER OF PARTICLES PLOTTED: 24040
LAYER (m): < 1000 < 2000 < 3000 < 4000 < 5000
Height AGL (m)
Pollen season 2016 of *Olea europea*
Pollen grains/m³
Flowering (%)
1-5 6-5 11-5 16-5 21-5 26-5 31-5 5-6 10-6 15-6 20-6 25-6
Pollen season 2017 of *Olea europea*
1
20-4 25-4 30-4 5-5 10-5 15-5 20-5 25-5
Pollen season 2018 of *Olea europea*
2
3
10-5 15-5 20-5 25-5 30-5 4-6 9-6 14-6 19-6 24-6
Pollen season 2019 of *Olea europea*
15-4 20-4 25-4 30-4 5-5 10-5 15-5 20-5 25-5 30-5 4-6
3
NOAA HYSPLIT MODEL
PARTICLE CROSS-SECTIONS
PARTICLE POSITIONS AT 15 00 05 Jun 18
NUMBER OF PARTICLES PLOTTED: 24114
NOAA HYSPLIT MODEL
PARTICLE CROSS-SECTIONS
PARTICLE POSITIONS AT 15 00 04 Jun 18
NUMBER OF PARTICLES PLOTTED: 24071
MPS
Pollen
Phenology