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Identification of potential sources of airborne *Olea* pollen in the Southwest Iberian Peninsula

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Abstract This study aims to determine the potential origin of *Olea* pollen recorded in Badajoz in the Southwest of the Iberian Peninsula during 2009–2011. This was achieved using a combination of daily average and diurnal (hourly) airborne *Olea* pollen counts recorded at Badajoz (south-western Spain) and Évora (south-eastern Portugal), an inventory of olive groves in the studied area and air mass trajectory calculations computed using the HYSPLIT model. Examining olive pollen episodes at Badajoz that had distinctly different diurnal cycles in olive pollen in relation to the mean, allowed us to identify three different scenarios where olive pollen can be transported to the city from either distant or nearby sources during conditions with slow air mass movements. Back trajectory analysis showed that olive pollen can be transported to Badajoz from the West on prevailing winds, either directly or on slow moving air masses, and from high densities of olive groves situated to the Southeast (e.g. Andalucía). Regional scale transport of olive pollen can result in increased nighttime concentrations of this important aeroallergen. This could be particularly important in Mediterranean countries where people can be outdoors during this time due to climate and lifestyle. Such studies that examine sources and the atmospheric transport of pollen are valuable for allergy sufferers and health care professionals because the information can be incorporated into forecasts, the outputs of which are used for avoiding exposure to aeroallergens and planning medication. The results of studies of this nature can also be used for examining gene flow in this important agricultural crop.

Keywords Olive · Aerobiology · Back-trajectory · Synoptic conditions · HYSPLIT model · Spain · Portugal

Introduction

The cultivation of olives (*Olea europaea*) is one of the major economic activities in the Mediterranean Basin (Galán et al. 2005) with > 5 Mha of olive orchards in the European Union (De Melo-Abreu et al. 2004). *Olea europaea* is an anemophilous (wind pollinated) species (Galán et al. 2008) that has evolved to produce large amounts of pollen, ~9.4×10^4 pollen grains per anther (Tormo-Molina et al. 1996), which are small

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to medium sized (14-)22(-31)×(10-)19(-31) μm (Nilsson 1988) and suitable for atmospheric dispersion (Hernández-Ceballos et al. 2011a). In the Iberian Peninsula, olive crops occupy ~2.5 Mha (AAO 2011) and episodes of regional scale transport of olive pollen grains have been identified (Hernández-Ceballos et al. 2011a).

IgE-associated allergic diseases are a global health problem that is increasing in prevalence and severity (Bousquet et al. 2011). Sensitisation occurs at the site of allergen exposure such as the airways (Traidl-Hoffmann et al. 2009), and is associated with two closely related allergic diseases—allergic rhinitis (hay fever) and asthma (Demoly and Bousquet 2006; Ziska et al. 2011)—that significantly reduce quality of life and have a significant economic impact on society (Bousquet et al. 2001). Olive pollen allergens are considered to be one of the most important causes of respiratory allergic disease in the Mediterranean region (D'Amato et al. 2007), including Greece (Gioulekas et al. 2004), Israel (Geller-Bernstein et al. 1996), Italy (Liccardi et al. 1994; Filon et al. 1998), Portugal (Sánchez-Mesa et al. 2005), Spain (Fernández-Florido et al. 1999; De Linares et al. 2007) and Turkey (Kirmaz et al. 2005).

It is usually not known whether the airborne olive pollen grains that have been sampled are from nearby or more remote sources. Information about sources and possible atmospheric transport of air pollutants and aeroallergens can be very valuable in population-based clinical exposure studies as well as in the daily recommendation to hay fever patients. Back-trajectory analysis is a tool that allows us to study the origin of airborne biological particles registered at a sampling station. In recent years, a number of scientific articles have combined trajectory calculations and pollen count data (Cecchi et al. 2006, 2007; Stach et al. 2007; Smith et al. 2008; Šikoparija et al. 2009; Hernández-Ceballos et al. 2011a, 2011b). Such studies have provided information on the possible local, regional or long distance transport of different pollen types in Europe, e.g.: *Ambrosía* in Poland (Stach et al. 2007; Smith et al. 2008; Kasprzyk et al. 2011), Italy (Cecchi et al. 2006, 2007) and the Balkans (Šikoparija et al. 2009); *Betula* in the UK (Skjøth et al. 2009) and Denmark (Mahura et al. 2007; Skjøth et al. 2007); *Fagus* in Spain (Belmonte et al. 2008); *Quercus* in Spain (Hernández-Ceballos et al. 2011b); *Olea* in Spain (Hernández-Ceballos et al. 2011a); Poaceae in the UK (Smith et al. 2005). When used in combination with detailed land cover information (EC 2005) such studies can be used to locate sources of allergenic pollen (Skjøth et al. 2008b, 2009).

Orlanski (1975) separated atmospheric transport on the meso-scale into the following: meso-gamma (2–20 km); meso-beta (20–200 km); meso-alfa (200–2,000 km). Each of the scales is suited to be studied by a certain type of atmospheric model. When identifying episodes of regional or long-distance scale transport, beyond the meso-gamma scale (Orlanski 1975), it is important to have an understanding of the flowering phenology of the plant being studied and the diurnal cycle of pollen counts that can be attributed to local sources (Stach et al. 2007; Smith et al. 2008; Šikoparija et al. 2009; Hernández-Ceballos et al. 2011a). Córdoba is situated in Andalusia (Southwest Spain)—the world's leading olive-oil-producing region (Galán et al. 2008)—and airborne pollen recorded in the city can be attributed to source areas over Córdoba province (Hernández-Ceballos et al. 2011a). Galán et al. (1991) showed that diurnal olive pollen concentrations recorded in Córdoba peaked during the middle of the day (1200–1800 hours) and minimum concentrations were witnessed at night and early in the morning (2000–1000 hours).

This study aims to determine the potential origin of *Olea* pollen recorded in Badajoz in the Southwest of the Iberian Peninsula during 2009–2011. This was achieved using a combination of daily average and diurnal airborne *Olea* pollen counts recorded at Badajoz (south-western Spain), daily average and diurnal airborne *Olea* pollen counts in a potential source area (Évora, south-eastern Portugal), an inventory of olive groves in the studied area, analysed weather maps of the overall synoptic situation and air mass trajectory calculations computed using the HYSPLIT model (Draxler and Hess 1998; Draxler et al. 2009) from selected days.

Material and methods

Sites and inventory of potential olive pollen sources

The pollen-monitoring site in Badajoz is situated at 16 m above ground level (38° 53′87″N, 7° 00′87″W) in the Faculty of Science in the University of Extremadura. Badajoz is located at 184 m above sea level (m a.s.l.) (Fig. 1a). Badajoz has a population of 150,376 (NSI 2011) and is the largest city in the Extremadura region, which is a rural agricultural province. Around the city of Badajoz there are irrigated crops (e.g. fruits, corn, tomato), olive trees, more distant holm-oak trees and extensive grazing. In Extremadura, olive plantations cover ~2.5×10^5 ha, which is ~10 % of the total area occupied by olive crops in Spain (AAO 2011).

Évora is 84 km to the West of Badajoz. The pollen-monitoring site in Évora is located at the meteorological station of the Geophysical Center of the University of Évora, 12 m above ground level (m a.g.l.; 38° 34′ N; 7° 54′ W) mean altitude 300 m a.s.l. (Fig. 1a). Évora is a small city with a population of around 60,000 habitants located in the Alentejo region, which is an essentially rural area in the south-eastern part of Portugal. Farming, predominantly holm-oak plantations, vineyards and olive trees are the core of the local economy. In Portugal, olive plantations occupy about 11 % of the total agricultural area (~3.4×10^5 ha) with a large proportion (~1.6×10^5 ha = 49 %) found in the Alentejo region (NSI 2009).

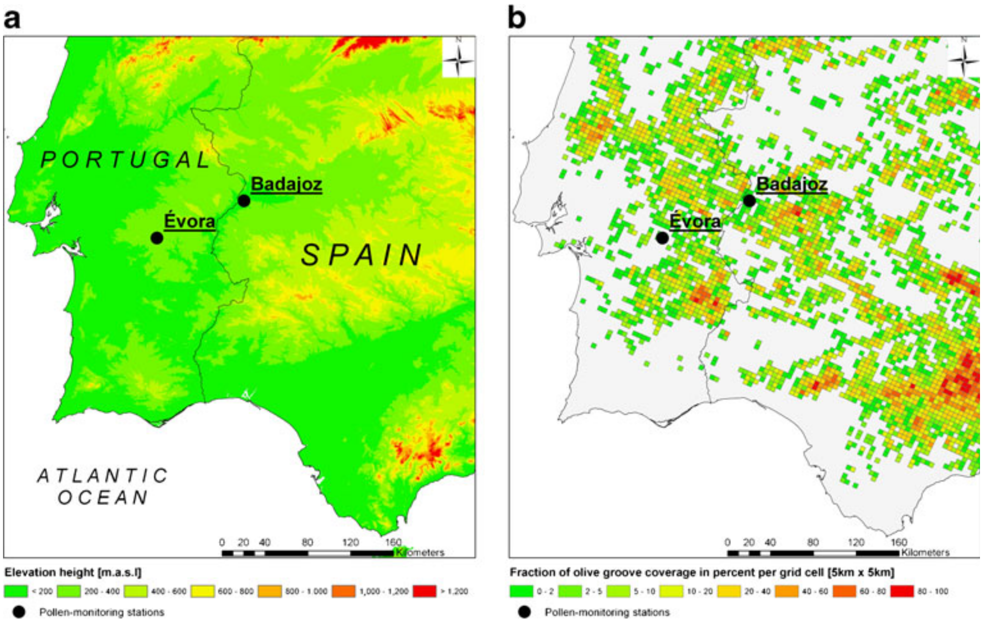


Fig. 1 Site map including the location of Badajoz and Évora showing **a** elevation, **b** olive grove density

In Badajoz and Évora, the main *Olea* pollen season is from April to June, with the most olive pollen grains are present in the air during May (Silva et al. 1996; Caeiro et al. 2007). Olive pollen groves in the studied area have been identified in the CLC2000 dataset (EC 2005) and gridded to a tenth of the EMEP50 grid (http://www.emep.int/grid/griddescr.html) which is a 50 km×50 km resolution model grid by using ArcGIS from ESRI (Fig. 1b). The EMEP grid is commonly used for inventories in European air quality studies such as the EMEP (Fagerli et al. 2004; Fagerli and Aas 2008), the EMEP4UK (Vieno et al. 2010) and DEHM (Skjøth et al. 2011) CTM models. This grid procedure allows for easy comparison of olive grove density throughout the region and analysis in relation to atmospheric transport.

Climate and meteorological data

Badajoz and Évora both have a Mediterranean climate with some influence from the Atlantic Ocean. The orography of the region is flat (Fig 1a); there are no high altitude mountains between the two cities so that prevailing winds are from the West (Silva-Palacios et al. 2007). Badajoz has a typical Mediterranean climate, with autumn and winter maximum precipitation and a dry period in summer when the highest temperatures are recorded (Tormo-Molina et al. 2010). On average, annual rainfall is 463 mm and annual temperature is 16.6 °C (1971–2000 mean). The Atlantic Ocean has a stronger influence on the climate of Évora, as is shown by the fact that precipitation is higher. The average annual precipitation in Évora is 609.4 mm and average annual temperature is 15.9 °C (1971–2000 mean).

For this study, daily meteorological data for Badajoz were provided by the meteorological station located in the botany area experimental garden of the Faculty of Science in the University of Extremadura (38° 53′N, 7° 00′W), situated 16 m from the pollen-monitoring site. Climate data for Badajoz (1971–2000 mean) were taken from Badajoz Airport (38° 53′ N, 6° 49′ W) (AEMET 2011). Daily meteorological data and climate data (1971–2000 mean) for Évora were provided by the Geophysical Center of the University of Évora (38° 34′N, 7° 54′W), instruments situated on the same platform as the Hirst (1952) type trap (3 m distance). The meteorological parameters examined during the investigated episodes were: daily average temperature (°C); maximum daily temperature (°C); daily precipitation (mm). The overall synoptic weather situation was investigated using analysed weather maps from the UK Met Office, and reanalysed meteorological data obtained from the National Centres for Environmental Prediction (NCEP). The analysed weather maps from the UK Met Office and NCEP meteorological fields represent the synoptic situation at 0000 UTC each day.

Olive pollen data

Daily average and diurnal (hourly) olive pollen counts from 2009 to 2011 were obtained using volumetric spore traps of the Hirst design (Hirst 1952). Air is sucked into the trap at a rate of 10 l/min through a 2 mm×14 mm orifice. Behind the orifice the air flows over a rotating drum (or microscope slide) that moves past the inlet at 2 mm/h and is covered with an adhesive coated, transparent plastic tape. Particles in the air impact on the tape to give a time-related sample (Emberlin 2000). The samplers used in this study were located on open terraces with the intake at 1.5 m from the floor. Standardised data management procedures were used, similar to those described by the Spanish Aerobiology Network (REA)

(Galán et al. 2007). Slides were examined along either four (Évora) or two (Badajoz) longitudinal transects. Daily average (0000–2400 hours) *Olea* pollen counts and diurnal variations (hourly counts) are expressed as grains/m^3.

The olive pollen seasons were defined using the 90 % method, whereby the season starts when 5 % of the total catch is achieved and ends when 95 % is reached (Nilsson and Persson 1981). The characteristics of the *Olea* pollen season for each city are described by the start and end dates of the olive pollen season, the duration (in days), the date of the maximum daily average *Olea* pollen concentration, the maximum daily average *Olea* pollen concentration and the sum of daily *Olea* pollen recorded in the season [the seasonal pollen index (SPI)]. The mean diurnal (hourly) variation of all days with a daily average olive pollen count >100 grains/m^3 recorded during the season were examined at both Badajoz and Évora. The threshold of 100 grains/m^3 was simply an arbitrary figure selected for removing days with low daily average pollen counts, whilst still allowing enough days for analysis. Olive pollen episodes at Badajoz that showed diurnal patterns that were distinctly different to the mean daily cycle were investigated further using back trajectory analysis (Skjøth et al. 2009). Badajoz was selected as the focus of the study because this station is more or less surrounded by potential sources of olive pollen and less affected by coastal influences. As the prevailing winds are from the West (Silva-Palacios et al. 2007) air masses must sometimes pass areas near Évora before arriving at Badajoz, which will provide additional information when identifying possible sources.

Back-trajectory analysis

Back trajectories were computed using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model, developed by NOAA's Air Resources Laboratory (ARL) (Draxler and Hess 1998; Draxler et al. 2009). Kinematic back trajectories (3D) were considered the best option for representing air-mass pathways, since they enabled use of the vertical wind data included in the GDAS (Global Data Analysis System) meteorological files (Hernández-Ceballos et al. 2011b). The weather data used for the computation of trajectories came from the GDAS archives maintained by ARL, with a temporal resolution of 3 h and spatial resolution of 1°× 1°. Air mass trajectories were calculated at Badajoz and Évora during the identified episodes. Air mass trajectories were plotted 48 h back in time with 2 h steps. Back trajectories were also calculated at both 200 m a.g.l. and 500 m a.g.l. to account for uncertainty in air mass transport with respect to height above the surface. In the three selected episodes, uncertainty was low and the inclusion of low level trajectories (200 m a.g.l) did not affect the results. It was therefore decided to only present trajectories at 500 m a.g.l. following the method described by Stach et al. (2007).

Results

Inventory of potential olive pollen sources

The inventory of potential olive pollen sources depicts the gridded density of olive groves in the Southwest of the Iberian Peninsula (Fig. 1b). The inventory shows that olive groves are found in many parts of the studied area. The highest densities of olive groves in the area are found around the Guadalquivir Valley in Andalucía, which is about 250 km to the Southeast of Badajoz. Within 30–80 km distance of Badajoz, local hot spots are mainly found to the Southeast, Southwest, West and Northwest. Limited sources are found to the Northeast of Badajoz as well as along the coastal of Portugal to the South and West of Évora.

Temporal variations in Olea pollen counts

The following statistics refer only to the years covered in this study (2009–2011). The timing and the amount of *Olea* pollen recorded in Badajoz and Évora varied from year to year (Table 1). The lowest and highest SPI of *Olea* pollen were recorded in Badajoz. These were 6,305 and 9,852 olive pollen grains recorded in 2010 and 2011, respectively. The highest daily average olive pollen count was also recorded in Badajoz, which was 1,616 olive pollen grains/m^3 on the 11 May 2011. The timing of the olive pollen season also varied annually. The earliest (28 April 2011) and latest (17 May 2010) start dates of the olive pollen season were the same at both sites. The duration of the olive pollen season ranged between 18 and 29 days (Badajoz) and between 22 and 27 days (Évora). The olive pollen season usually ended in late May or early June at both sites. The mean diurnal (hourly) variation of all days with

Table 1 Characteristics of *Olea* pollen seasons calculated using the 90 % method in Badajoz and Évora (2009–2011). *SPI* Seasonal pollen index

Characteristic	City	2009	2010	2011
Start date	Badajoz	3 May	17 May	28 April
	Évora	4 May	17 May	28 April
End date	Badajoz	31 May	3 June	22 May
	Évora	30 May	7 June	21 May
Duration (days)	Badajoz	29	18	25
	Évora	27	22	24
Peak date	Badajoz	6 May	22 May	11 May
	Évora	9 May	20 May	15 May
Daily maximum (pollen grains/m^3)	Badajoz	583	1,175	1,616
	Évora	1,176	1,252	941
SPI (pollen grains)[a]	Badajoz	8,003	6,305	9,852
	Évora	8,649	6,498	9,288

[a] Calculated as the sum of daily average pollen counts recorded in the pollen season

a daily average olive pollen count >100 grains/m^3 recorded during the season (n=58 in Badajoz and n=55 in Évora) were examined (Fig. 2). Analysis showed that there was usually a peak between 1000 and 1800 hours at both Badajoz and Évora, and that mean hourly counts were higher at Évora than Badajoz.

Back trajectories

Three olive pollen episodes at Badajoz that had distinctly different diurnal cycles in olive pollen in relation to the mean were selected for investigation using back trajectory analysis following the method described by Skjøth et al. (2009). These were: (1) 7–8 May 2009; (2) 5–6 May 2011; (3) 13–14 May 2011.

Episode 1: 7–8 May 2009

Daily average *Olea* pollen counts for 7 and 8 May 2009 in Badajoz were 441 and 406 grains/m^3 and in Évora were 442 and 624 grains/m^3, respectively. Hourly *Olea* pollen counts at Évora peaked at 1300 hours on 7 May (1,050 grains/m^3) and 1100 hours on 8 May (1,737 grains/m^3). Interestingly, hourly *Olea* pollen counts at Badajoz peaked between 6 and 8 h later than Évora on both 7 and 8 May, at 1900 hours on 7 May (1,102 grains/m^3) and 1700 hours on 8 May (1,426 grains/m^3). After the peak at 1900 hours on 7 May, hourly olive pollen counts at Badajoz remained >300 grains/m^3 until 0200 hours (Fig. 3a). During the period 7–8 May 2009, a low-pressure system (1,014–1,017 hPa) developed over the Iberian Peninsula and corresponding high pressure (1,025–1,029 hPa) was situated to the West in the Atlantic Ocean. Back-trajectory analysis shows that this caused air masses to approach Badajoz from either a north-westerly or westerly direction after passing areas with olive groves either between Évora and Badajoz or to the Northwest of Badajoz. According to the trajectories, the air masses spent up to 10 h over areas with high densities of olive groves, and transport time from the area near Évora to Badajoz was ~7–8 h during the day (Fig. 3b, c). Back-trajectories also show that air masses arriving at Évora came from the West/Northwest and passed areas with limited amounts of olive groves that are only a few hours of atmospheric transport time from the city (Fig. 3b, c). Average wind speeds of the air masses were 3.8 m/s and 4.2 m/s during the 10 h before arriving at Évora and Badajoz, respectively. Daily average temperatures were between 23.3 °C and 18.6 °C, with maximum daily temperatures reaching 32 °C on the 7 May in Badajoz. No precipitation was recorded during the episode.

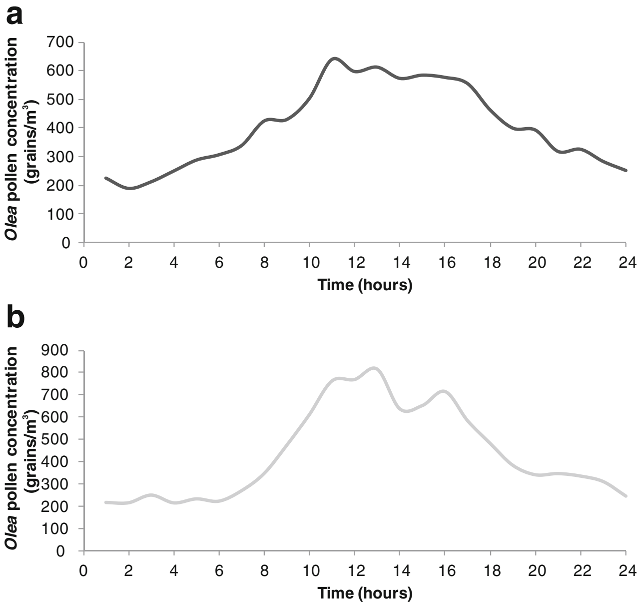
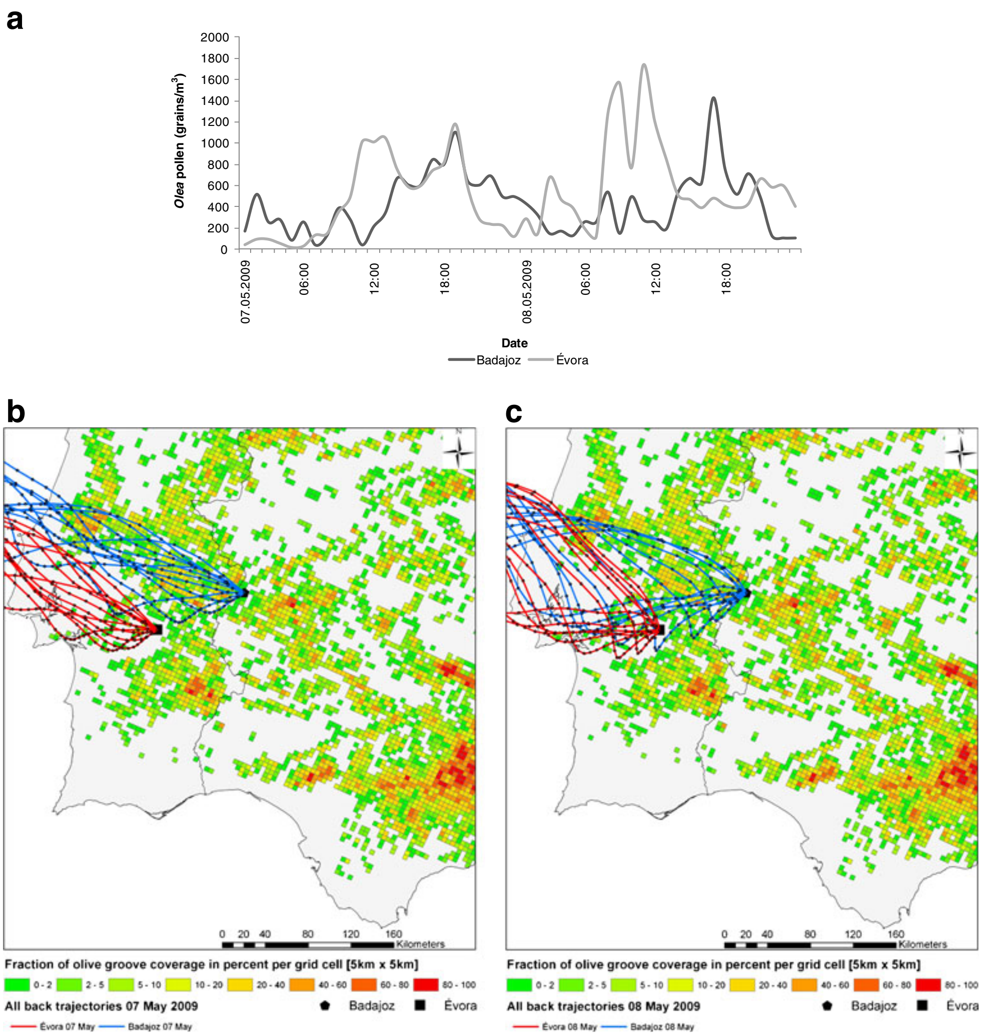


Fig. 2 Mean hourly *Olea* pollen concentrations (2009–2011) for all days ≥100 grains/m^3 recorded in **a** Badajoz and **b** Évora

Episode 2: 5–6 May 2011

Daily average *Olea* pollen counts on the 5 and 6 May 2011 were 518 and 680 grains/m^3 in Badajoz and 244 and 610 grains/m^3 in Évora, respectively. Hourly *Olea* pollen counts at Évora peaked at 1600 hours on 5 May (700 grains/m^3) and 1300 hours on 6 May (1,957 grains/m^3). Hourly olive pollen counts in Badajoz peaked around the middle of the day on both the 5 and 6 May; 1,513 olive pollen grains/m^3 were recorded at 1400 hours on 6 May and 2,853 grains/m^3 were recorded at 1000 hours on 6 May. However, there was also a nighttime peak in diurnal olive pollen counts recorded at Badajoz between 2100 hours on 5 May and 0500 hours on 6 May, with hourly olive pollen concentrations > 1,300 grains/m^3 recorded at 0100 hours and 0200 hours on 6 May (Fig. 4a). Synoptic charts show that during the period 5–6 May 2011 a low-pressure system (991–992 hPa) was located over the Atlantic Ocean near to the Southwest Approaches of the British Isles and extended southward towards the Bay of Biscay. High pressure in the range of 1,019–1,021 hPa was centred over the Mediterranean but this deepened to 1,014 hPa over the Iberian Peninsula on 6 May. Back-trajectory analysis show that air masses approached Badajoz from a either a north-westerly or a westerly direction throughout 5 May. During night and early morning these air masses were slow moving, taking 12–18 h to travel from southern Portugal after passage over areas with large amounts of olive groves. Conversely, back-trajectory analysis shows air masses approached Évora from either a north-westerly direction or a westerly direction after passing areas with limited amount of olive groves most of the day. The path taken by the air masses backed to a more southerly direction early on 6 May (Fig. 4b, c). Average wind speeds of the air masses during the 10 h before arriving at Évora or Badajoz were 3.6 m/s and 3.7 m/s, respectively. Daily average temperatures were between 19.1 °C

Fig. 3 **a** Diurnal (hourly) variation in olive pollen counts recorded at Badajoz and Évora 7–8 May 2009 (grains/m^3). **b**, **c** Back-trajectories arriving at the pollen trap in Badajoz on 7 (**b**) and 8 (**c**) May



and 16.3 °C, with maximum daily temperatures reaching 25.8 °C on 5 May in Badajoz. No precipitation was recorded.

Episode 3: 13–14 May 2011

Daily average *Olea* pollen counts recorded on the 13 and 14 May 2011 in Badajoz were 706 and 515 grains/m^3 and in Évora were 523 and 569 grains/m^3, respectively. Hourly olive pollen counts recorded at Badajoz peak sharply (>1,000 grains/m^3) between 0800 and 0900 hours on both 13 and 14 May and tended to remain high during the day. There was also a peak during the evening with hourly olive pollen counts in excess of 1,000 grains/m^3 recorded at 1900 and 2200 hours. Hourly olive pollen counts at Badajoz decreased below 100 grains/m^3 during the evening of 14 May. Hourly olive pollen counts at Évora tended to be lower than Badajoz on 13 May, but a similar peak occurred in the evening at 2200 (985 grains/m^3) and 2300 hours (1,931 grains/m^3). The similarities with the counts at Badajoz continued on 14 May, with a sharp peak at 0800 hours (1,672 grains/m^3) followed by high hourly olive pollen counts during the day until they began to decrease in the evening (Fig. 5a). The period 13–14 May 2011 was characterised by high pressure over the Mediterranean (1,018–1,021 hPa) and low pressure over the Iberian Peninsula (1,014–1,015 hPa) that pushed air masses in a north-westerly direction towards Badajoz and Évora from areas of high olive grove densities around Andalucía. According to the trajectories, the air masses took 1–2 days to travel from Andalucía to Badajoz and Évora. Air masses continued to veer northward throughout the episode until they eventually arrived at Badajoz and Évora from the North on the evening of 14 May (Fig. 5b, c). Average wind speeds of the air masses were 3.0 m/s during the 10 h before reaching both Évora and Badajoz. Daily average temperatures were between 24.8 °C and 23.1 °C, with maximum daily temperatures reaching 33.1 °C°C on 13 May in Badajoz. No precipitation was recorded.

Discussion

The importance of olive trees in agriculture and as a source of aeroallergens has resulted in their being the focus of a large

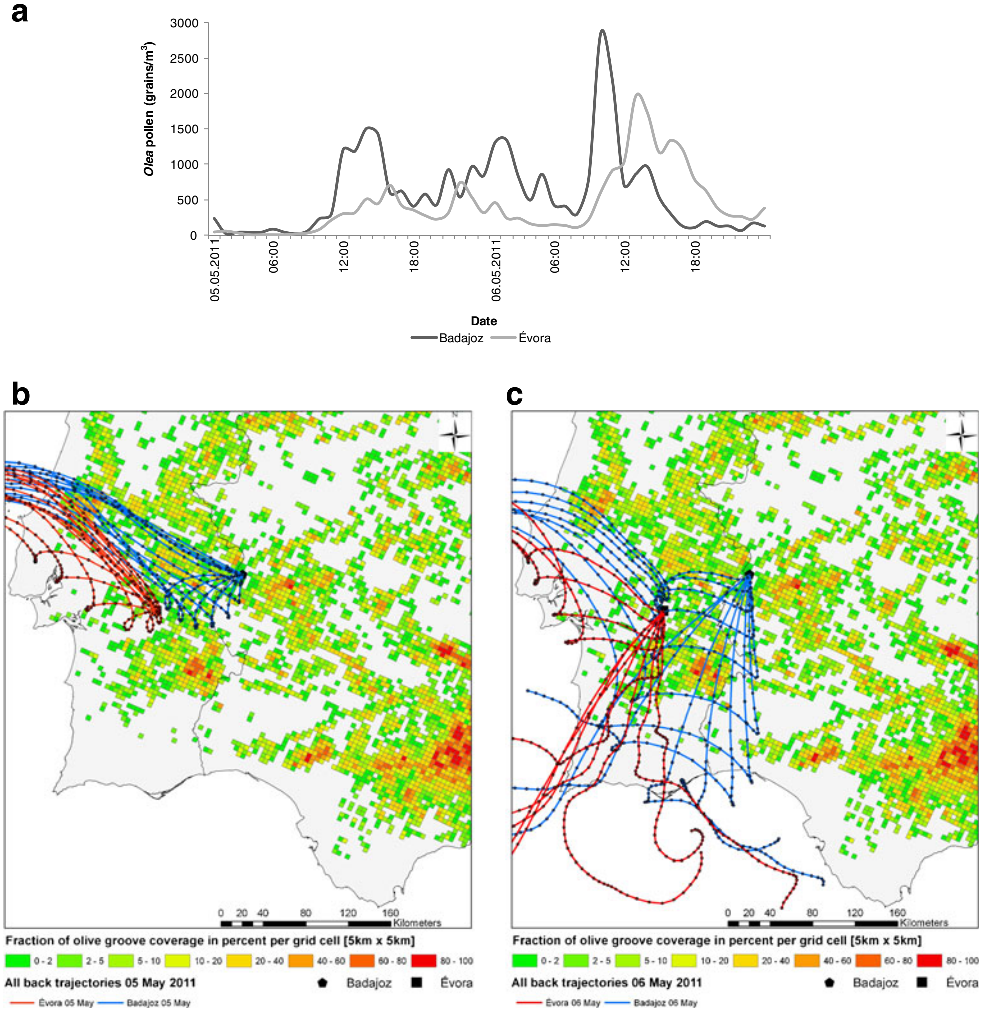


Fig. 4 **a** Diurnal (hourly) variation in olive pollen counts recorded at Badajoz and Évora 5–6 May 2011 (grains/m^3). **b**, **c** Back-trajectories arriving at the pollen trap in Badajoz on 5 (**b**) and 6 (**c**) May

number of aerobiological and phenological studies in different Mediterranean countries (Gioulekas et al. 1991; González-Minero and Fernández-Mensaque 1996; Fornaciari et al. 1998; Galán et al. 2001; Hidalgo et al. 2002; De Melo-Abreu et al. 2004; Orlandi et al. 2005a, 2005b; Ribeiro et al. 2007). Many such studies have attempted to quantify the conditions required for the start of olive flowering (González-Minero and Fernández-Mensaque 1996; De Melo-Abreu et al. 2004; Orlandi et al. 2004, 2005b) and the effect of daily meteorological parameters on daily average olive pollen counts once the season has commenced (Díaz de la Guardia et al. 2003; Vázquez et al. 2003; Aznarte-M et al. 2007). It is generally agreed that temperature is an important influence on olive flowering, whereas rainfall and humidity cause atmospheric concentrations to decrease (Díaz de la Guardia et al. 2003). Fewer studies have focussed on other factors such as wind direction that can have an impact on the amount of olive pollen recorded at a site (Damialis et al. 2005). However, air masses do not flow in straight lines, which is why transport models are used to study air mass transport. This study focuses on measured olive pollen concentrations in relation to actual air mass transport using the HYSPLIT model and a potential source map in the study region.

In southern Europe, *Olea* is present in both rural and urban areas as a crop in olive groves (De Melo-Abreu et al. 2004), as well as forest trees (Skjøth et al. 2008a) and ornamentals (Konijnendijk et al. 2005). Based on this type of information, Alba et al. (2006) produced an airborne pollen map for *Olea* in Andalucía that was based upon pollen data and geostatistics (GIS). In contrast, the source map presented in this study shows the density of olive groves in the studied area (Fig. 1b) but does not take into account variations in airborne pollen. We have also omitted factors such as the fraction of olive trees in forests or olive trees ornamentally planted in urban areas as statistical information about these sources are scarce. In the case of the CLC2000 data set (EC 2005) areas of olive groves have been identified specifically with high accuracy.

Olive groves can be considered to be the main source to *Olea* pollen on the Iberian Peninsula as ordinary forests in this region are mainly oaks (*Quercus* sp.), pines (*Pinus* sp.) and, to a smaller degree, beech (*Fagus* sp.) in the north (Skjøth et al. 2008a), and wild olive trees that generally appear as sporadic

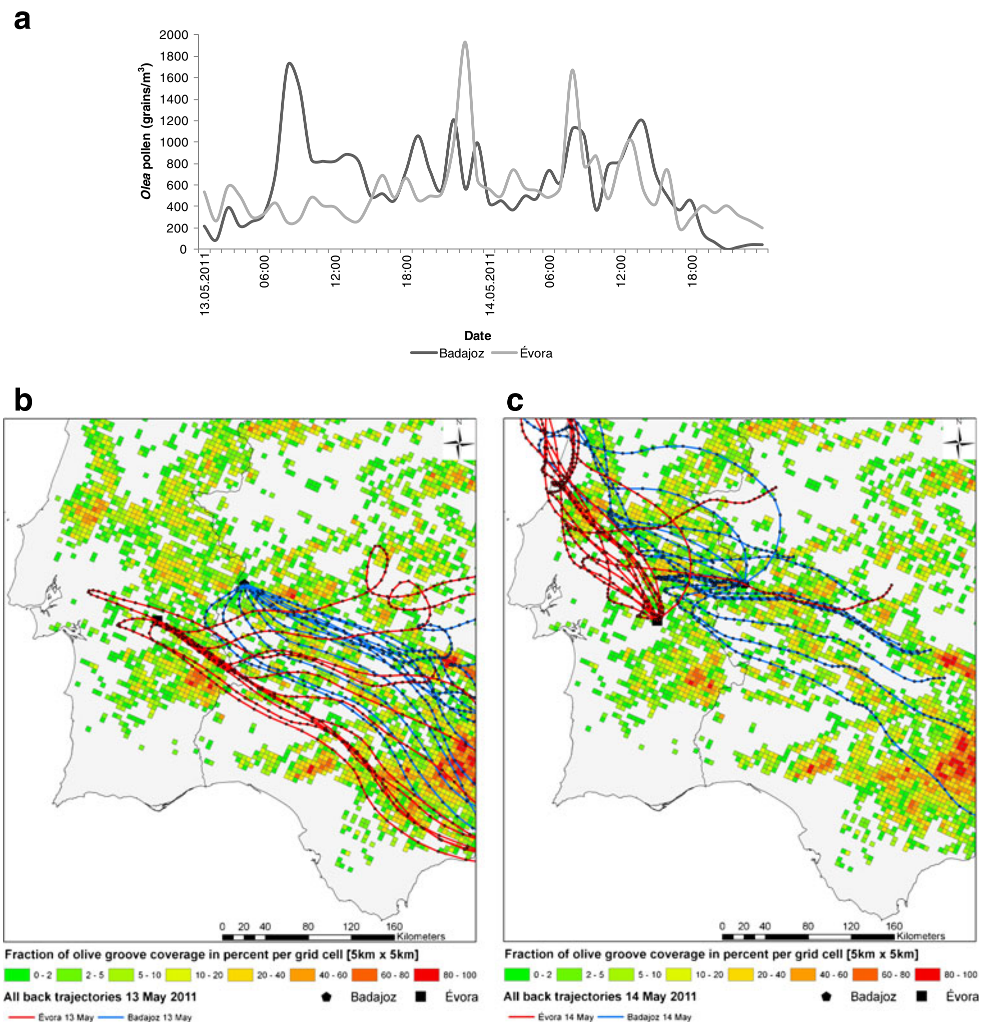


Fig. 5 **a** Diurnal (hourly) variation in olive pollen counts recorded at Badajoz and Évora 13–14 May 2011 (grains/m^3). **b**, **c** Back-trajectories arriving at the pollen trap in Badajoz on 13 (**b**) and 14 (**c**) May

elements except in some areas to the south, east and the Balearic Islands (Rodríguez-Ariza and Montes 2005). As a result, the inclusion of forest trees and ornamentals could introduce an error into the calculation of the source map, which is not justified by the limited impact from these sources. It was therefore decided to focus on known sources and omit these uncertain sources from the analysis. In addition, it should be noted that the map presented here does not take into account the density of olive trees within olive groves. As planting densities of olive trees can range from less than 100 trees/ha (traditional rain fed systems) to more than 300 trees/ha (intensive drip-irrigated systems) (De Melo-Abreu et al. 2004), which may affect to local pollen load as pollen production can be expected to scale linearly with the amount of sources locally (Pidek et al. 2010; Skjøth et al. 2010). Consequently, combining land use data with spatial variations in olive pollen data (Skjøth et al. 2010) could be used to improve the source inventory.

The distribution of the major *Olea* sources found in olive groves is relatively well known, but understanding of the atmospheric transport of pollen from these sources has been much less investigated. In addition, local and regional scale atmospheric transport can be severely affected by topography or land-sea interactions, which modifies synoptic scale air mass transport by creating meso-scale patterns that are tightly linked to local topography and land-sea distribution. Such issues make source receptor relations far from trivial. A well established method for this type of investigation is to include atmospheric models that take these effects into account (Hernández-Ceballos et al. 2011a, 2011b).

Mean hourly pollen concentrations recorded at Badajoz and Évora were used to aid understanding of what could be considered the normal diurnal variations from local sources. This is based on the assumption that the time of day that pollen is recorded will depend on the transport time (a product of distance and wind speed) from the source to the trap (Stach et al. 2007). The results of this study are similar to those presented by Galán et al. (1991), who showed that olive pollen concentrations recorded in Córdoba peaked during the middle of the day (1200–1800 hours). Of course, it is impossible to definitively state that pollen recorded during the day originates from purely local sources because transported pollen from more distant areas may arrive at any time to either enhance the contributions from more local sources during the day or result in high nighttime concentrations (Skjøth et al. 2009). For instance, phenological observations recorded at Badajoz by Tormo et al. (2011) show that the episode in May 2009 occurred during the period of full flowering of local olive trees, but the combination of diurnal pollen data and air mass trajectories presented in this paper suggests that olive pollen potentially arrived from distant areas to augment pollen recorded from local sources.

Examining olive pollen episodes at Badajoz that had distinctly different diurnal cycles in olive pollen in relation to the mean, allowed us to identify three different scenarios where olive pollen can be transported to the city from more distant sources. Episode 1 (7–8 May 2009) showed how prevailing winds from the west could result in high nighttime concentrations of olive pollen in Badajoz. Furthermore, the combination of back-trajectories and diurnal olive pollen concentrations from Badajoz and Évora showed that evening peaks in hourly olive pollen counts in Badajoz could be related to sources a few hours of air mass transport away, while simultaneously measured lower concentrations at Évora are related to the fact that the air masses that arrived at Évora passed limited sources found in the area between Évora and the Atlantic Ocean. Episode 2 (5–6 May 2011) identified the presence of slow moving air masses passing either dense olive grove areas (Badajoz) or areas with limited olive groves (Évora) that resulted in nighttime peaks in hourly olive pollen counts particularly at Badajoz; a phenomenon previously reported for birch (Skjøth et al. 2009). Episode 3 (13–14 May 2011) was an example of contrasting conditions where high pressure over the Mediterranean and low pressure over the Iberian Peninsula resulted in air masses approaching Badajoz and Évora from the Southeast where there are high densities of olive groves. This episode resulted in high nighttime concentrations of olive pollen at both sites. Incidentally, analysis also showed that olive pollen concentrations decreased noticeably when air masses veered to the North where there are areas with lower densities of olive groves.

The use of air mass trajectory calculations are known to be associated with uncertainty that increases with the travel distance. Previous results with the FLEXPART model and the ETEX experiment suggest a mean error of individual trajectories of about 20 % of the distance travelled (Stohl et al. 1998). Trajectory calculations are known to be very dependent on the quality of the meteorological input and results have shown that improving the meteorological input alone significantly improves model results in relation to dispersion and transformation of air pollutants (Skjøth et al. 2002). The latest version of the HYSPLIT model and the GDAS archive is based on the most up-to-date method for reanalysed global weather data and can therefore be expected to have at least the same accuracy as described by Stohl et al. (1998). The air mass transport in the selected episodes and possible source areas are within 6–48 h of transport (Figs. 3–5) with a transport distance of about 75 km to 400 km. Note, that this extended distance of 400 km is because the trajectories are not moving along a straight line. This suggests a mean error of the shown trajectories to be within 15 km to 80 km. Air mass trajectories calculated at Badajoz and Évora during all identified episodes were plotted 48 h back in time with 2 h steps. The use of 2 h time steps allows for a match to pollen count data and also allows for an assessment of uncertainty in air mass movements due to hourly variations in wind directions. This uncertainty is rather large, but does not affect the conclusions with respect to overall directions of air masses and possible source areas such as the large area to the Southeast of Badajoz. Back trajectories were also calculated at both 200 m and 500 m a.g.l. to account for uncertainty in air mass transport with respect to height above the surface. In the three selected episodes, uncertainty was low and the inclusion of low level trajectories (200 m a.g.l) did not affect the results. Therefore, despite the known limitations, uncertainty with respect to trajectory calculations is not expected to affect the overall conclusions.

These results are consistent with the findings of Silva-Palacios et al. (2000), who showed that, in Badajoz, there were significant correlations between daily *Olea* pollen concentrations and the number of hours of wind each day from southeast, southwest, and northwest quadrants. This is probably related to the fact that the prevailing winds are from the west, where there are sources of olive pollen and that some of the highest densities of olive groves on the Iberian Peninsula are in the Southeast. The study by Silva-Palacios et al. (2000) relates well to the source map (Fig. 1b), as the southeast, southwest, and northwest quadrants are areas with olive groves, whilst the last quadrant (Northeast) has limited olive grove densities. Air mass trajectories have been described as being rather limited (Veriankaitė et al. 2010) particularly in mountainous areas (Pérez-Landa et al. 2007a, 2007b). In this study, the HYSPLIT model has proved to be an adequate tool for estimating the direction taken by air masses over the flat terrain (Fig. 1a). The effectiveness of the approach is improved by the combination of daily and diurnal pollen count data and source maps.

Conclusions

In this study, daily average and diurnal *Olea* pollen counts were combined with a source inventory and back-trajectory calculations to show that olive pollen grains arriving in Badajoz are from regional scale sources; either 30–80 km or about 200–300 km away. In this study, we see that olive pollen recorded at Badajoz during the examined episodes were generally brought on prevailing winds from the west by meso-alfa scale atmospheric transport processes (Orlanski 1975), either directly or on slow-moving air masses, as well as from high densities of olive groves situated to the southeast (e.g. Andalucía). Episodes of pollen transport have been shown to be intermittent and related to the occurrence of certain conditions, but can result in high bi-hourly and daily average pollen concentrations (Skjøth et al. 2009). This study has shown that the regional scale transport of olive pollen can result in increased nighttime concentrations of this important aeroallergen. This could be particularly important in Mediterranean countries where people can be outdoors during this time due to climate and lifestyle. Such studies that examine sources and the atmospheric transport of pollen are valuable for allergy sufferers and health care professionals because the information can be incorporated into forecasts, the outputs of which are used for avoiding exposure to aeroallergens and planning medication. The results of studies of this nature can also be used for examining gene flow in this important agricultural crop that, as in the case for aeroallergens, can improve research and information to end users by using high quality source maps of pollen. However, olive groves vary in pollen production per area and land cover types other than olive groves contain olive trees. Further work in this area will therefore focus on improving the source map by combining land use and pollen data and extending the area covered by the map so that it covers the entire Iberian Peninsula.

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