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First phenological and aerobiological assessment of olive orchards at the Northern limit of the Mediterranean bioclimatic area

Alejandro Garrido · María Fernández-González · Sabela Álvarez-López · Estefanía González-Fernández · F. Javier Rodríguez-Rajo

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Abstract An increase in the cultivation of olive trees was prompted in the Northwestern Spain during recent years favored by the agricultural politics in the region. The aim of this study is to know the phenological and aerobiological behavior of the olive trees at the northern limit of the Mediterranean bioclimatic area in order to determine their thermal requirements for the development of predictive agro-phenological models for two varieties (Arbequina and Frantoio) of the new olive cultivated areas. The BBCH scale was used for the phenological observations. Chill accumulation during dormancy and heat requirements to overcome the successive phenological stages were calculated following different methods. To complete the phenology predictive models, the Mitscherlich's monomolecular equation was applied. The monitoring of the atmospheric pollen content was conducted by means a volumetric pollen Hirst trap placed in the middle of the plot. The period of chilling accumulation was completed during the first fortnight of January with an average of 654 chilling hours and a base temperature of 7.5 °C. Considering the duration of the vegetative olive cycle around 2390°GDD (growing degree days) was necessary to overcome the ripening of berries. The proposed model for the prediction of the successive ecological events showed a deviation between 1.5 and 3.5 days on the phenological scale. The presence of *Olea* pollen grains in the atmosphere of the olive grove was registered during stage 5 and stage 6 (flowering). The Hybrid Single Particle Lagrangian Integrated Trajectory Models confirmed that pollen peaks during the previous days to the flowering stage came from the extensive olive groves of the Northern Portugal which flowers some days in advance.

Keywords Aerobiology · Dormancy · Olive · Phenology · Pollen

1 Introduction

Olive (*Olea europaea* L.) ecosystems represent one of the major economic resources in the Mediterranean region (Galán et al. 2005). The Southern Spain areas produce the 41.9% of the world's total olive oil production followed by Italy, Greece and Tunisia (FAO 2012). During the last years, an increase in the cultivation of olive trees was prompted in the Northwestern Spain areas, with both ornamental and industrial uses, favored by the agricultural politics in

A. Garrido · M. Fernández-González (✉) · S. Álvarez-López · E. González-Fernández · F. J. Rodríguez-Rajo
CITACA, Agri-Food Research and Transfer Cluster, University of Vigo, 32002 Ourense, Spain
e-mail: mfgonzalez@uvigo.es

M. Fernández-González
Pole of the Faculty of Sciences, Earth Sciences Institute (ICT), University of Porto, Porto, Portugal

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the region. Currently, there are planted a 300-ha extension of olive trees distributed throughout the South Galicia zones at the limit of the Mediterranean bioclimatical area. The most part of the new cultivated plantations belong to the Arbequina variety. However, a recent study carried out between 2012 and 2018 by the Superior Council of Scientific Investigations (CSIC) discovered the existence of 13 autochthonous Galician varieties, as the olive cultivation was highly extended in this region during the sixteenth century. The main autochthonous varieties are the Galician "Brava" and the Galician "Mansa" (Gago et al. 2019).

Climatic conditions of the Northern Spain area at the limit of the Mediterranean bioclimatical area are very suitable for the olive cultivation. Temperature is one of the most determining environmental factors (Rojo and Pérez-Badía 2014b) since is the meteorological variable that most influences certain phases of the phenological olive cycle, such as foliation, flowering or fruit ripening (García-Mozo et al. 2010; Gordo et al. 2010). Higher temperatures recorded during the previous flowering months cause advances of this phenological stage start date (Rojo and Pérez-Badia 2014a). The effect of this weather variable has been also widely studied by many authors during the flowering period (Galán et al. 2005; Martínez-Bracero et al. 2019). Temperature was involved in the photosynthetic processes of the olive tree since unfavorable conditions cause the reduction of the metabolic rate as well as a delay in the development of reproductive tissues (Kozlowski and Pallardy 1997; Rojo and Pérez-Badia 2014a). In addition, other meteorological variables prompted important effects in the olive's phenological response such as precipitation or humidity (Rojo and Pérez-Badía 2014b).

Phenology of olive flowering is characterized by bud formation in summer, dormancy in autumn, budburst in late winter (around February) and flowering in late spring (between May and June) (Fernández-Escobar et al. 1992; Galán et al. 2005). The release of floral bud dormancy occurs when the olive trees have been exposed to chilling temperatures for an enough period (Fernández-Escobar et al. 1992; Pinney and Polito 1990; Rallo and Martin 1991). After bud break, a certain amount of biothermic units was required for the development of the inflorescences (Chuine et al. 1998). The determination of the start date for the olive heat accumulation has proven difficult, partly because the climate of different geographical areas can be conditioned by different base temperatures (Aguilera et al. 2014). Changes in temperature requirements could affect negatively the development of flower buds and the timing of flowering, with the consequent changes on the olive pollen season (Aguilera et al. 2014). So flowering phenology characteristics and timing can be considered as an important indicator of climatic change in the Mediterranean region (Rojo and Pérez-Badia 2014a). An early accomplishment of chilling requirements during dormancy was associated with earlier budburst and increased production (Rojo et al. 2015). Many authors have used the aerobiological and phenological pollen production data to analyze the *Olea* flowering stage (Galán et al. 2008; Jato et al. 2002; Orlandi et al. 2005a; Orlandi et al. 2010). The production rate varies among different varieties (Rojo and Pérez-Badía 2014b). Geographical factors constitute another source of variability in olive pollen production (Damialis et al. 2011) as consequence of climatic conditions, mainly the combination of temperature and water availability (Aguilera and Ruiz-Valenzuela 2012; Damialis et al. 2011). Knowledge about the influence of both factors should be extended with new studies to give more accurate understanding (Rojo and Pérez-Badía 2014b).

A great relationship between temperature and plant phenology was observed (Galán et al. 2005; Hunter and Lechowicz 1992; Rodríguez-Rajo et al. 2003). Several studies proposed bioclimatic models to forecast the flowering timing in tree species in order to predict the responses of plant phenology to climate changes (Chuine and Cour 1999; García-Mozo et al. 2008; Orlandini et al. 2004; Rojo and Pérez-Badía 2014b). Many models are based on the relationship between temperature, photoperiod and olive floral phenology (García-Mozo et al. 2008; Orlandi et al. 2010). Nevertheless, many other modeling studies have considered temperature, accumulated rainfall and bioclimatic indices as predictor variables (Aguilera et al. 2015).

The aim of this study is to know the phenological and aerobiological behavior of the olive trees in the Northwestern Spain in order to determine their thermal requirements for the development of predictive agrophenological models in two varieties (Arbequina and Frantoio) of new olive cultivated areas.

2 Materials and methods

The study was conducted in an olive grove located in Verín (41° 56′ N, 7° 26′ W), Northwestern Spain, at an altitude of 400 m (Fig. 1). This zone is categorized by an oceanic climate with Mediterranean and Continental influence (Orriols et al. 2006) characterized by temperate and rainy winters, dry and hot summers, with variated autumns and springs regarding temperatures and rainfall (Castellano et al. 2009). An amount of 10 trees of each variety (Arbequina and Frantoio) was selected for the phenological survey. The study was conducted from April to the harvest date during the 2016 and 2017 years. The great summer fires during the year 2018 that wholly burned the studied olive grove stopped our investigation. A weekly visit to the plot was conducted, except during the flowering stage, in which the number of visits was increased twice a week. The BBCH scale based on grow states codification of Zadoks et al. (1974), developed by Meier (2001) and described in the olive tree by Sanz-Cortés et al. (2002) was used for the phenological observations. The beginning of each phenological stage was considered when the half of the studied trees reached a given stage.

To estimate the chill accumulation during dormancy, the model proposed by Aron (1983) was applied to estimate the number of chilling hours (C.H.) below 7.2 °C, considering maximum and minimum daily temperatures:

$$N = 801 + 0.2523B + 7.57B^2 \cdot 10^{-4} - 6.51B^4 \cdot 10^{-10} - 11.44T_{\min} - 3.32\,T_{\max}$$

N = number of chilling hours, B = 24D, D = length of the period in days, $T_{\max}$ and $T_{\min}$ = mean maximum and minimum temperatures of the period D

To obtain the chilling accumulation expressed as "chilling hours," we established the start date as the moment when the mean temperature descends below the considered base temperature. Furthermore, the vegetative activity method (V.A.) developed by Jato et al. (2002) was also applied, which consider the Aron model and only selects the days in which meteorological conditions impeded any physiologic activity. In order to stablish the optimum base temperature for the chilling period in the studied area, a range of possible base temperatures was tested. The threshold temperature with the lowest coefficient of variation and standard deviation was selected. The moment when mean temperatures register their minimum values and a temperature trend change was detected it has been considered as the end of the chill accumulation period (Fernández-González 2011).

In order to calculate heat requirements, the Ring et al. (1983) method was applied. The °GDD was obtained daily during the olive tree developmental

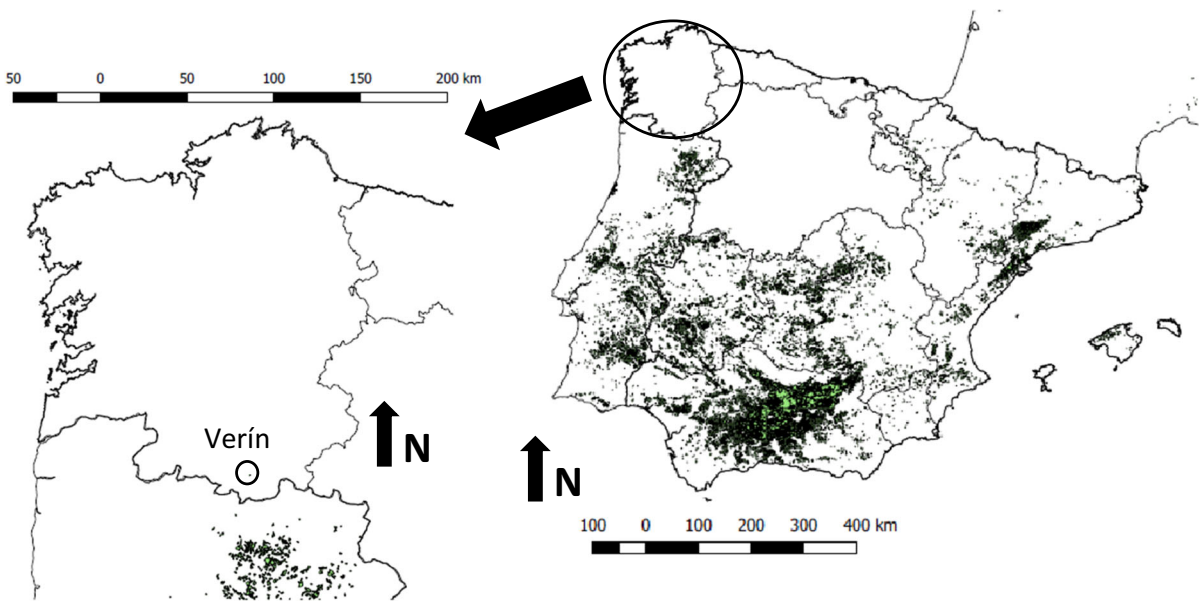


Fig. 1 Location of the olive grove

period to calculate the total °GDD for each phenological or pollen season stages:

$$^{\circ}\mathrm{GDD} = \sum (T_{\mathrm{med}} - T_{\mathrm{b}})$$

T_{med} is daily mean temperature, and T_{b} is base temperature.

Several base temperatures from 0 to 10 °C in steps of 0.5 °C were tested. The threshold temperature with the lowest coefficient of variation and standard deviation was selected. The starting date for heat unit accumulation as well as the base temperature is critical variables for the quality of this kind of statistical models (Wielgolaski 1999). In both studied years, the following day after the chilling accumulation is completed has been considered as the first day of heat accumulation.

To complete the phenology predictive models, the Mitscherlich's monomolecular equation was used:

$$Y = A - A \times \mathrm{e}^{-kt}$$

X = Growing degree days (GDD), Y = phenological scale (PS), A = equation parameter (maximum theoretical value possible to reach), K = equation parameter, e = base of natural logarithm.

By means this equation it is assumed that the growth is continuous and therefore there is no inflection point (Thornley and Jonson 1990). The Eichhorn and Lorenz (1977) phenological scale modified by Coombe (1995) was related to the GDD in each phenology stage. The Coombe (1995) scale assigns a number (determined by direct observation) to each phenological stage. The scale numeration allows us to elaborate mathematical models, where phenological events are incorporated as a numeric variable.

The monitoring of the atmospheric pollen content was carried out by means a volumetric spore Hirst trap, model Lanzoni VPPS-2010, which was placed at height of 2.5 m in the middle of the olive grove. The pollen sampling was conducted during the olive flowering season (stage 6) and the previous and posterior phenological phases, following the model proposed by the Spanish Aerobiology Network (REA) based on four longitudinal transects along the slides (Galán et al. 2007). The results obtained were expressed as seasonal pollen integral (SPIn) (pollen grains) and daily mean values (pollen grains/m^3). The main pollen season (MPS) is considered as the period in which the 95% of the total annual pollen is recorded (Galán et al. 2017).

Meteorological variables were obtained from a Hobo Micro Station data logger placed in the olive grove. The measured parameters were maximum, minimum and average temperatures, relative humidity and dew point. Rainfall and wind speed were obtained from the closest MeteoGalicia Verín-Vilamaior station.

With the aim to analyze the association degree between the studied variables, a Spearman correlation test was applied (calculating the significance for $p \leq 0.01$ and $p \leq 0.05$). In order to test the variability degree of the prediction models, a SEE (standard error of the estimates) was applied between the estimated and observed values of the Mitscherlich's monomolecular equation (Ortega-Farías et al. 2002). Finally, a principal component analysis (PCA) was conducted in order to complement the analysis of the aerobiological variables considering the weather variables influence of all variables as a whole.

The Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) developed by the National Oceanic and Atmospheric Administration (NOAA) was applied in order to evaluate the origin of air masses during the episodes of the main pollen concentrations in the atmosphere of the olive grove. Hourly back-trajectories in 3D (latitude, longitude and elevation) were calculated from meteorological data. The isentropic back-trajectories of air masses arriving to the plot of the study were calculated during the following peak pollen episodes: June 3, 2016, June 7, 2016, June 14, 2016, May 4, 2017, May 9, 2017, May 15, 2017, and May 24, 2017. The trajectories showing 24-h HYSPLIT backward trajectories were considered at a final height of 300, 500 and 750 m.

3 Results

The olive cycle duration from inflorescence emerge to harvest lasted from 221 days in 2016 to 194 days in 2017 (Table 1, Fig. 2). The stage 5 of inflorescence emergence took place in 2016 from the last 10 days of April to the first 10 days of June and advanced from the first day of April to the second 10 days of May in 2017. The variety with the longer stage 5 duration was Arbequina in 2017 with 53 days (Table 1, Fig. 2). The stage 6 (flowering), the most important of the

Table 1 Dates of the start, end and length (days) of the main BBCH phenological stages for the two studied varieties, stage 5: inflorescence emergence, stage 6: flowering, stage 7: fruit development and stage 8: maturity of fruit

	Stage 5	Stage 6	Stage 7	Stage 8	Total length (days)
2016					
Arbequina					
Start	27 April	9 June	20 July	31 October	216
End	8 June	19 July	30 October	28 November	
Length	43	41	103	29	
Frantoio					
Start	21 April	10 June	10 July	2 November	221
End	9 June	9 July	1 November	28 November	
Length	50	30	115	26	
2017					
Arbequina					
Start	1 April	24 May	25 June	1 September	195
End	23 May	24 June	30 August	15 October	
Length	53	31	67	44	
Frantoio					
Start	1 April	17 May	26 June	27 August	194
End	16 May	25 June	26 August	15 October	
Length	46	39	61	48	

biological cycle for a successful harvest, was the shortest in the study area, with a mean duration of 41 and 31 days in 2016 and 2017, respectively, for the Arbequina variety, and of 30 days in 2016 and 39 days in 2017 for the Frantoio variety. A difference between varieties was not detected for the beginning of this stage, starting 1 day earlier in the Arbequina variety in the year 2016 and 5 days in the Frantoio variety during 2017. Nevertheless, a year-a-year difference was detected, starting and ending the flowering stage later in 2016 (first fortnight of June) than in 2017 (when commenced several weeks earlier during mid-May) (Table 1, Fig. 2). The stage 7 of fruit development started in the last fortnight of June and finished in November. This stage occurred earlier in 2017 (from the end of June to the end of August) than in the year 2016 (from first fortnight of July to first day of November). This was the longest phenological stage of the biological olive cycle with a duration around 103 days for Arbequina and 115 for Frantoio in 2016 (Table 1, Fig. 2). Finally, stage 8 (maturity of fruit) occurred more than 1 month earlier in 2017.

The woody plants of temperate regions have evolved mechanisms during the periods of adverse meteorological conditions in order to preserve their cells from risk of frost. The strategy involves a requirement for winter chilling followed by another of warm temperatures, to break a physiologic state of inactivity denominated dormancy. The growing degree days method was applied in order to determine the heat requirements. A thermal time model was used in order to quantify the chill requirement. These conditions generally take place during November, and the period of chilling accumulation continues until the first fortnight of January with an average of 654 C.H. and a base temperature of 7.5 °C following the V.A. method. The Aron method showed higher variation coefficients, and this fact indicates this method is not adequate for this study area (Table 2).

Once chilling requirements are completed, heat accumulation begins until the fruit maturation ends. The base temperature of 7 °C was the most accurate for heat accumulation (Fig. 3), and a total amount of around 2300–2500°GDD was necessary for both varieties to reach the end of the maturity of fruit stage in the years 2016 and 2017, respectively (Table 3). In general, not differences regarding the heat accumulation were observed between varieties. Nevertheless, variations between years were detected as a greater accumulation of °GDD was required to overcome the succession of the different stages during the year 2016. A mean of 542 and 509°GDD is to trigger the Arbequina and Frantoio stage 6 (flowering) in 2016 and 2017, respectively. An amount of 1033 and

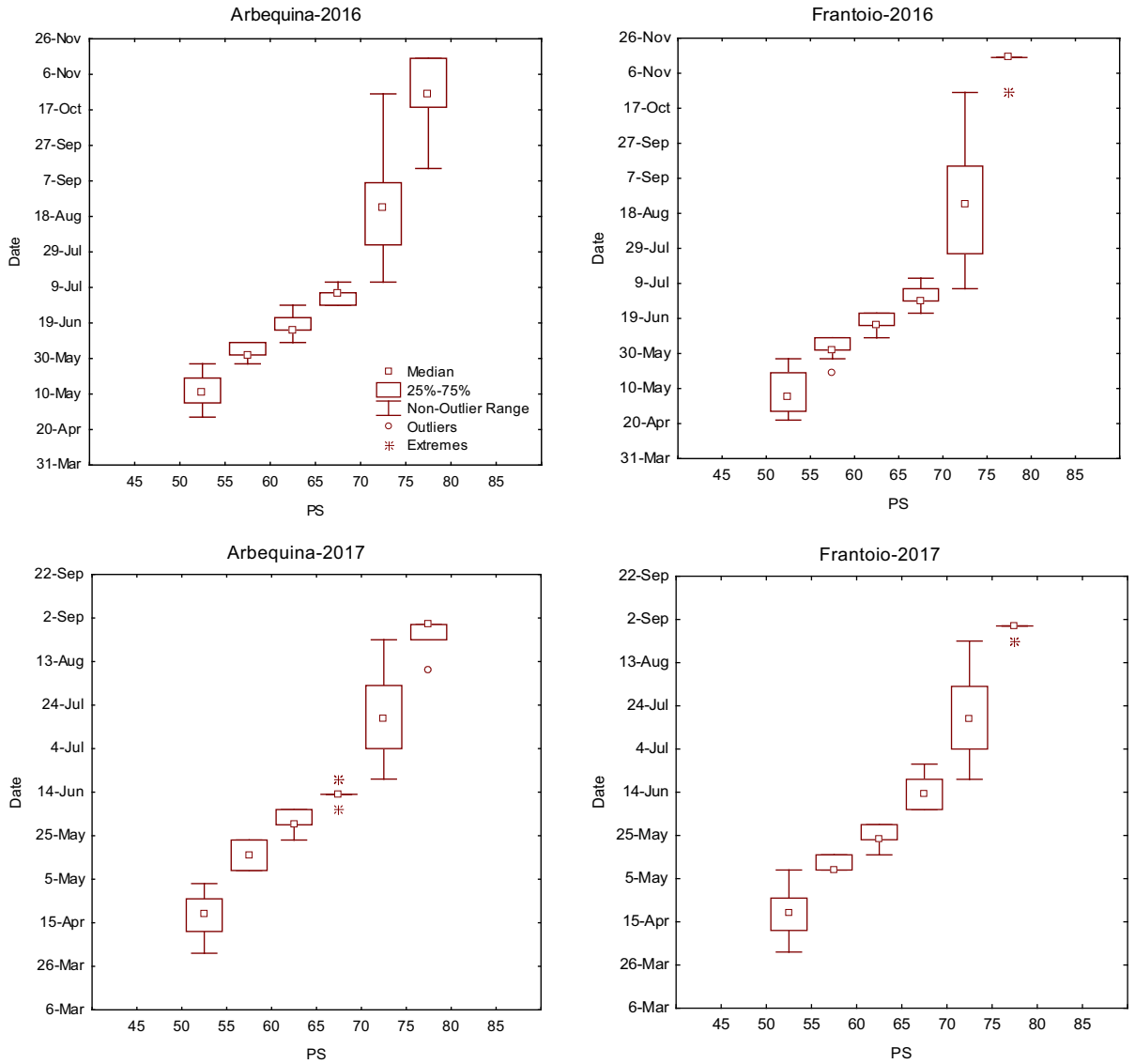


Fig. 2 Variations of the dates of each phenological stages (PS) following the BBCH standardized scale in the two varieties of olive crop (Arbequina and Frantoio varieties) during the 2 years of study

966°GDD was necessary to reach stage 7 (fruit development) in 2016 and 2017. Finally, a mean of 2399 and 2380°GDD was required to the end of the stage 8 (fruit maturation) in 2016 and 2017, respectively (Table 3).

To determine the association degree between the timing of the phenological stages and the °GDD accumulation (base temperature 7 °C), the Mitscherlich's monomolecular equation was applied to predict the timing of the different stages (Fig. 3). Standard error of estimates (SEE) between observed and estimated values was calculated in order to determine the variability degree and the accuracy of the proposed models. The higher deviation was registered in the year 2016 (SEE = 3.500) for the Arbequina variety, whereas the lowest in 2017 (SEE = 1.560) for the same variety. The high association degree between estimated and observed phenology data was shown in Fig. 3. Our results indicate that the proposed models have a prediction variability around 1 phenological scale for Arbequina 2017, 2 phenological scales for Frantoio 2016 and 2017 and 3 phenological scales for

Table 2 Chilling requirements (chilling hours) obtained by means the Aron (1983) and the V.A. (Jato et al. 2002) methods

Threshold (°C)	2016	2017	Mean	SD	CV (%)
ARON					
3	365	792	578	302	52.3
3.5	699	933	816	165	20.3
4	750	1095	922	244	26.5
4.5	707	1169	938	326	34.8
5	695	988	842	207	24.6
5.5	772	334	553	310	56.1
V.A.					
4.5	353	702	527	247	46.9
5	564	687	625	87	13.9
5.5	663	670	667	5	0.7
6	701	655	678	33	4.9
6.5	691	651	671	28	4.2
7	676	650	663	19	2.9
7.5	**657**	**651**	**654**	**4**	**0.6**
8	635	647	641	8	1.2
8.5	616	648	632	22	3.6
9	610	640	625	21	3.4
9.5	607	642	625	24	3.9
10	598	638	618	28	4.5

In bold: method selected in the study

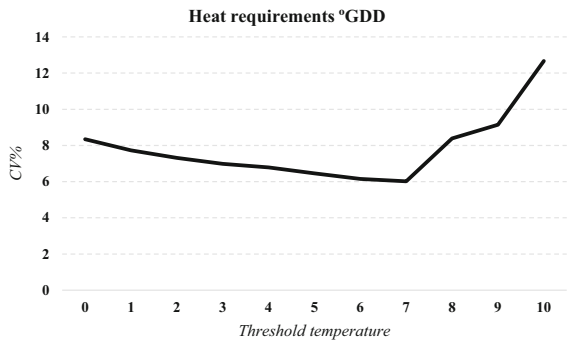


Fig. 3 Values of the coefficient of standard variation in percentage (CV%) for heat requirements (°GDD) considering several base temperatures

Arbequina 2016 (Fig. 4). The best association between the estimated and the observed data was obtained during the year 2017. On the other hand, considering separately each phenological stage, the best association between real and estimated data was observed in the stage 7 (fruit development), whereas the higher differences were observed in stage 5 (inflorescence development) (Fig. 4).

The *Olea* pollen grains presence in the atmosphere of the olive grove was registered during the end of the stage 5 (inflorescence emergence) and along the stage 6 (flowering) (Table 4, Fig. 5). The main pollen season (MPS) started during the closing inflorescence development period (June 1, 2016, and April 28, 2017). The end of the MPS took place during the flowering (stage 6), the July 12, 2016, and June 22, 2017 (Table 4, Fig. 5). The *Olea* annual pollen integral (APIn) during the study years was 1978 and 5157 pollen in 2016 and 2017, respectively. The higher pollen concentration was registered during the flowering stage with a pollen peak concentration of 264 pollen/m^3 on June 14, 2016, and 938 pollen/m^3 on May 24, 2017. In the case of 2016 this main peak took place under moderate temperatures and presence of rainfall as consequence of a storm, while in 2017 the peak coincides with high temperatures and absence of rainfall (Fig. 5). The Spearman correlation test and the PCA analysis showed positive significant correlation with the average, maximum, minimum temperature and the dew point (Table 5, Fig. 6).

Several important pollen concentrations were detected in the atmosphere of the studied olive orchard during the previous days to the beginning of the flowering stage. Moreover, the most important pollen peaks were detected during the phenophase 60 of first flowers opening and not during the phenophase 65 full flowering (Fig. 5). Back-trajectory analysis showed that the pollen registered in the atmosphere before the Arbequina and Frantoio flowering is coincident with southern air masses (Fig. 7). In general, the most important contributions of pollen in the orchard atmosphere were coincident with air masses passing through potential sources areas from the important olive groves located in the Northeastern Portugal areas (Fig. 1).

4 Discussion

The timing of the phenological stages may change between regions by means two conditions, either because of the different types of soil or because of the different types of climate. Under high-temperature conditions, the vegetative growth tends to be higher and therefore the olive cycle becomes shorter (Pedro

Table 3 Heat requirements (°GDD) for the different phenological stages calculated with the 7 °C threshold temperature

	2016	2017	Mean	SD	CV%
ARBEQUINA heat requirements (GDD)					
5 (Inflorescence development)	170	170	170	0.1	0.1
6 (Flowering)	487	597	542	77.7	14.3
7 (Fruit development)	1018	1049	1033	21.8	2.1
8 (Fruit maturation)	2253	2004	2129	176.0	8.3
Harvest	2309	2488	2399	126.7	5.3
FRANTOIO heat requirements (GDD)					
5 (Inflorescence development)	140	170	155	21.3	13.8
6 (Flowering)	497	520	509	16.7	3.3
7 (Fruit development)	871	1062	966	134.9	14.0
8 (Fruit maturation)	2265	1949	2107	223.4	10.6
Harvest	2284	2476	2380	136.1	5.7

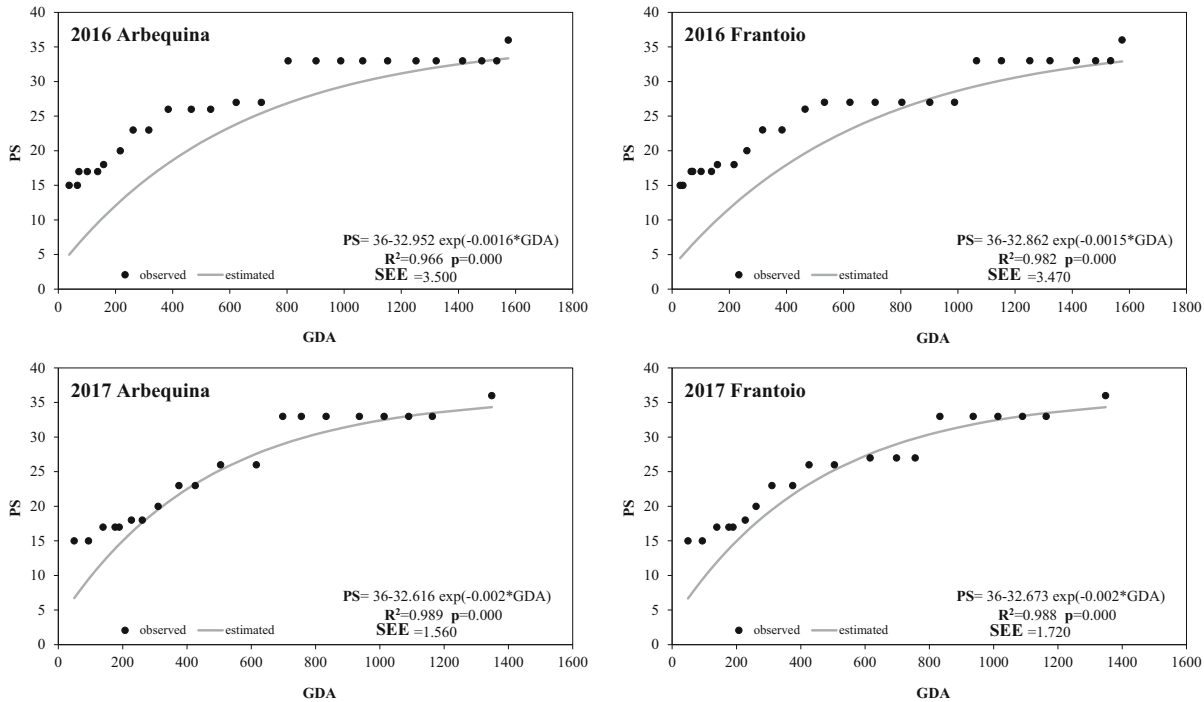


Fig. 4 Observed and estimated values of the phenological scale (PS) of olive crop for Arbequina and Frantoio varieties in 2016 and 2017 years. Statistical analysis (R^2 and p values), predictive model of phenology according to growing degree days' accumulation (GDA) and standard error of the estimates (SEE) for each cultivar and years studied. Relationship BBCH and Coombe phenological scales (stage 5: inflorescence emergence—15 to 18, stage 6: flowering—20 to 26, and stage 7: fruit development—27 to 36)

Júnior and Sentelhas 2003). The most important variable for the timing of the ecological events is the weather parameters, and the diversity in the climatic conditions of the different locations would explain the unequal phenological behavior (Fernández-González et al. 2007). Some authors indicated that the temperature has been recognized as the factor that most affects flowering (Osborne et al. 2000; Orlandi et al. 2002; Galán et al. 2001). Furthermore, according to several studies, temperature affects the dormancy induction and the flowering time (Achmakh et al. 2015; Galán et al. 2005). Therefore, the olive trees of

Table 4 Duration of the atmospheric *Olea* pollen season, seasonal pollen integral, peak day, concentration in the peak day and total heat requirements (°GDD) at the start and end date of the pollen season

	2016	2017
MPS		
Start	01-June	28-April
End	12-July	22-June
APIn	1978	5157
Peak day	14-June	24-May
Pollen peak day	264	938
°GDD		
Start	158.2	177.1
End	532.8	647.6

the northern regions will need lower temperatures than those in the southern regions for blooming (Edwards et al. 2006; Foley et al. 2009; Ramos et al. 2005). In addition, several studies noted that the annual changes at the beginning of the pollen season may be due to the North Atlantic Oscillation (NAO) being this dependence stronger in northern than in southern Europe (D'Odorico et al. 2002; Galán et al. 2005).

The knowledge of the chilling requirements in an olive cultivation is transcendental to ascertain when dormancy is completed and the bud initiation begins. In our study, the month of January was identified as the start of the chilling accumulation period. The V.A. method (Jato et al. 2002) showed lower standard variation coefficients of 0.6% considering the base temperature of 7.5 °C and a chilling requirement of 654 CH. Studies conducted in the Mediterranean area revealed higher base temperatures than in our area. In central Italy a base is between 9.5 and 12.5 °C (Orlandi et al. 2002) and 12 °C in Córdoba (Orlandi et al. 2004). Chilling and heat requirements geographically differ (Wielgolaski 1999; Orlandi et al. 2005b; Galán et al. 2005; Bonofiglio et al. 2008, 2009; Aguilera and Ruiz-Valenzuela 2012). Therefore, the observed differences could be explained as the location of an olive crop within a specific bioclimatic step might be the main cause for both variations, in the base temperatures and in the thermal accumulation.

Moreover, the heat requirements (GDD) accumulation will determine the advance of the successive phenological stages. Heat requirements were exceeded 1 month in advance during 2017 mainly as consequence of the high temperatures recorded during the last year of study during the summer and fall. Base temperature is the mainly factor to determine the GDD required in each phenological stage. This base change between geographical areas has been closely linked with latitude and altitude, decreasing the base temperature values as the latitude/altitude increased (Aguilera et al. 2014; Črepinšek et al. 2006; Galán et al. 2005). In addition, base temperature could differ between species or even between cultivars (De Melo-Abreu et al. 2004; Martins et al. 2012; Ruml et al. 2010). Our study showed a base temperature of 7 °C, a lower value than the pointed by several authors in different areas: 9–9.7°GDD in Portugal (Ribeiro et al. 2006), 10–13°GDD in California (Hackett and Hartmann 1967), 12.5°GDD in Cordoba (Galán et al. 2001) and 10°GDD in Malaga (Galán et al. 2005). A mean of 509–542°GDD was required to reach flowering in the 2 years and for the two varieties Arbequina and Frantoio, higher value than the noted in Jaén (346°GDD), Priego (380°GDD), Málaga (180°GDD) and Córdoba (211°GDD) (Galán et al. 2005).

Base temperature is an important factor, closely linked to the different phenological and pollen season events. Chilling base temperatures between 3 and 5.5 °C and heat base temperatures from 4.5 to 10 °C in 0.5 °C ranges have been considered as the optimum base temperatures (Rodríguez-Rajo et al. 2003). The chilling base temperature of 3.5 °C and the 7 °C heat base temperature registered the lowest standard deviation coefficient in our study.

The Mitscherlich's monomolecular equation demonstrates the close association between the timing of the phenological stages and the heat accumulation (°GDD). Our data indicate a variability around 2 phenological scales for Frantoio variety and 1 or 3 phenological scales for Arbequina variety depending on the year (data observed for stage 7 fruit development which showed the best fitting). Similar results were pointed out in the Mediterranean basin using a model based on artificial neural networks (ANN) for six cultivars: Carolea, Coratina, Frantoio, Leccino, Pendolino and Picholine (Mancuso et al. 2002). The Mitscherlich's monomolecular equation has been applied in other crops like vine. Different authors pointed values between 1 and 2 phenological scales for Treixadura and Godello cultivars in Spain (Fernández-González et al. 2013) or the Cabernet Sauvignon and

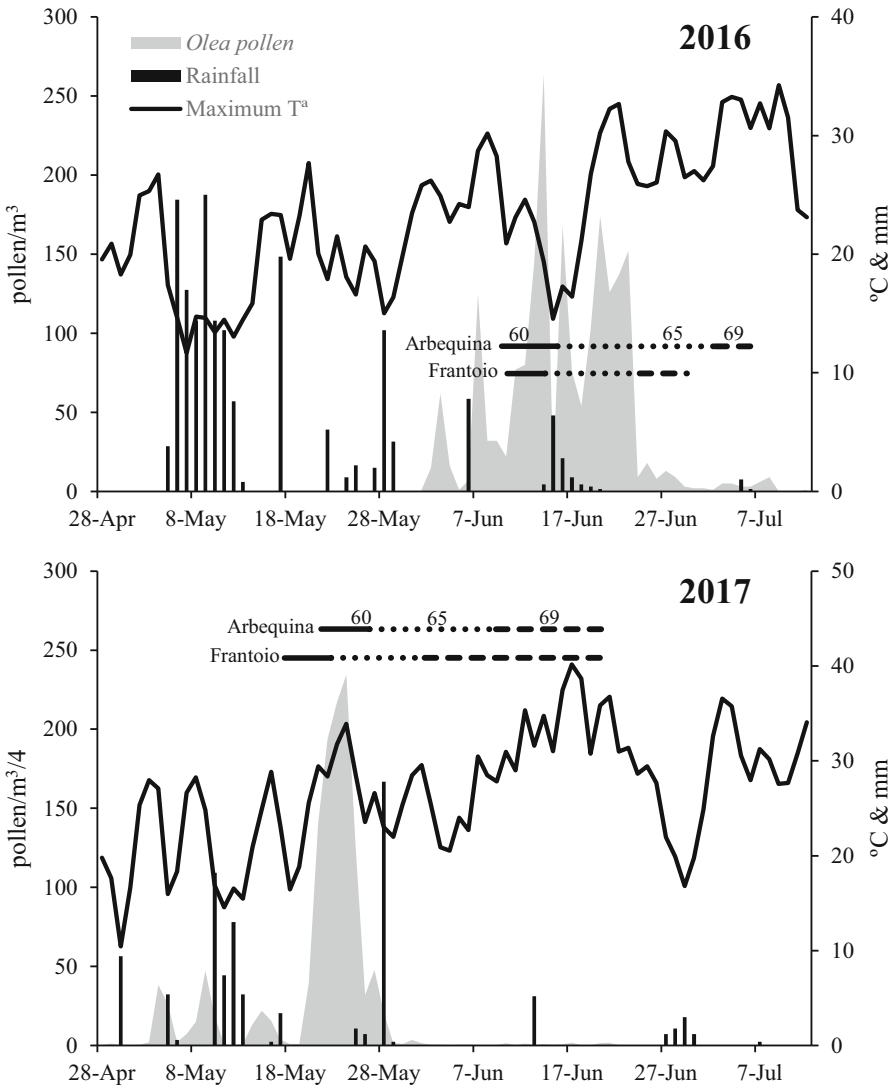


Fig. 5 Evolution of the *Olea europaea* L. airborne pollen concentration (in areas) and daily meteorological parameters (maximum temperature in line and rainfall in bars). In lines the length of the stage 6 (flowering) and its different phenophases (60 first flowers opening, 65 full flowering at least 50% of flowers are open and 69 end of flowering, fruit set and fall of unfertilized ovaries) for the two varieties, Arbequina and Frantoio

Chardonnay cultivars in Chile (Ortega-Farías et al. 2002), and around 2 phenological scales for Thompson Seedless, Crimson Seedless, Red Globe and Superior Seedless in Chile (Verdugo-Vásquez et al. 2017). The proposed models in the present study accurately predict phenological events by using temperature data and could be used for simulation of phenological evolutions stages under the different climate change scenarios (Jorquera-Fontena and Orrego-Verdugo, 2010).

The starting date of the *Olea* pollen season depends on the temperature in the previous precedent months, because the forcing spring temperature can greatly limit the winter temperature effects linked to flower induction or dormancy phenomena (Orlandi et al. 2010). Great variations in the beginning of the *Olea* main pollen season between the studied years were detected, June 1, 2016, and April 28, 2017, with a mean length of 48 days. Similar results were registered in Jaen with a MPS start average date on May 7th and an average length around 35 days (Aguilera and Ruiz-Valenzuela 2009). Other authors reported earlier start dates of the MPS, in different places of Southern Spain at the beginning of April (Galán et al. 2005; Elvira-Rendueles et al. 2019) or in Morocco at the end of March with a mean duration of 89 days (Achmakh et al. 2015). These fluctuations are consequence of the biogeographical and climatic differences between the

Table 5 Correlation between daily *Olea* pollen concentration and the main meteorological variables

	Spearman R		Spearman R
Pollen		Relative humidity	− 0.101
Pollen_1	0.903**	RH_1	− 0.116
Pollen_2	0.817**	RH_2	− 0.051
Pollen_3	0.761**	RH_3	0.015
Average temperature	0.243**	Dew point	0.229**
Avg.T_1	0.191*	Dp_1	0.154
Avg.T_2	0.107	Dp_2	0.080
Avg.T_3	0.034	Dp_3	0.025
Maximum temperature	0.216**	Rainfall	− 0.079
Max.T_1	0.189*	Rainfall_1	− 0.099
Max.T_2	0.114	Rainfall_2	− 0.080
Max.T_3	0.034	Rainfall_3	− 0.035
Minimum temperature	0.230**	Wind speed	− 0.159
Min.T_1	0.145	Ws_1	− 0.181
Min.T _2	0.048	Ws_2	− 0.138
Min.T _3	0.001	Ws_3	− 0.043

The correlations with the pollen and meteorological variables registered the previous 1, 2 or 3 days were also showed ($p < 0.01$**, $p < 0.05$*)

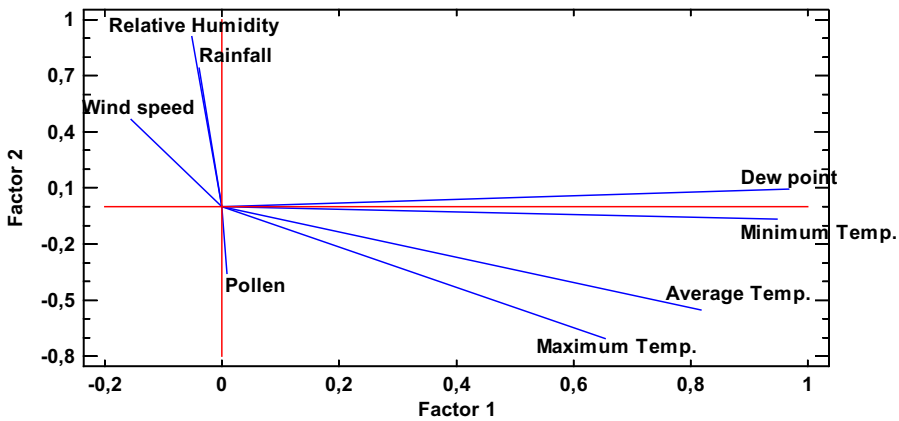


Fig. 6 Principal components and factor analysis (PCFA). Rotation varimax. Extraction principal components for daily values for *Olea* pollen and main meteorological variables during the study 2 years

areas, mainly related to altitude, and temperature or rainfall in the preceding months (Achmakh et al. 2015; Aguilera and Ruiz-Valenzuela 2012; Galán et al. 2005). During the studied years the annual pollen integral (APIn) varied between 1978 and 5157 pollen grains. Some authors noted that when a short olive pollen season length occurs, the number of days with high pollen concentrations in the atmosphere increases (Díaz de la Guardia et al. 2003). Studies carried out in Jaen, Southern Spain, noted higher annual pollen integral (APIn) average of 44,024 pollen and a peak pollen average of 4795 pollen/m^3 with a main pollen season average of 35 days. These greater values are consequence to the importance of the area dedicated to olive crop, with more than 570.000 ha of olive groves throughout the province of Jaén covering the 41.5% of its total surface area (Aguilera and Ruiz-Valenzuela 2012; Barranco et al. 2008). In addition, these variations may be due to the different meteorological conditions, being the rainy periods favorable to a decrease in the total amount of pollen and being the periods with higher mean temperature followed by a rise of the pollen concentration (Fernández-González et al. 2013). Important year-to-year variations in the APIn were detected. In 2016 an APIn of 1978 pollen was observed, but during 2017 a higher amount of 5157 pollen grains was detected. This may be due to the fact that during 2016 important rains accompanied by a temperature decrease were registered during the main pollen season, which led to a lower pollen

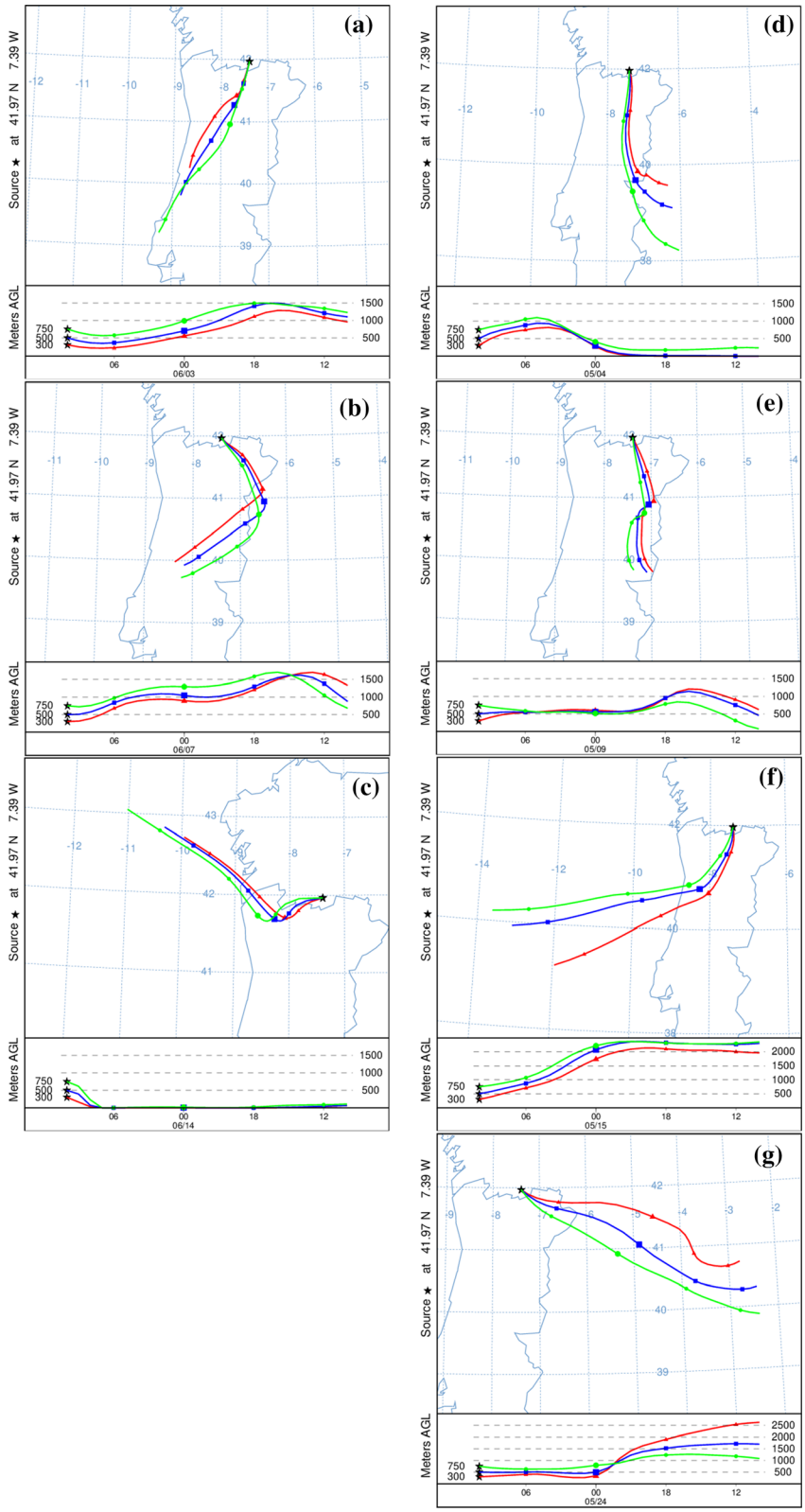


Fig. 7 Maps showing 24-h HYSPLIT backward trajectories at a final height of 300, 500 and 750 m agl at considered episodes: **a** June 3, 2016; **b** June 7, 2016; **c** June 14, 2016; **d** May 4, 2017; **e** May 9, 2017; **f** May 15, 2017; and **g** May 24, 2017

concentration in the atmosphere than during 2017. Alternate bearing is a built-in character of olive trees, condition that results when the olive tree takes an "off year" (Lavee 2007; Moreno-Grau et al. 2016; Recio et al., 1996). Production alternance phenomenon makes years with high energy expenditure to form vegetative structures (stems, branches, leaves) and few sexual reproductive structures (few flowers) and other years with more energy expenditure to form sexual reproductive structures, many flowers. Moreover, the flowering pattern of the year 2016 also presents several contrasts as a delay in the flowering season was detected related to a delay of the pollen liberation season. Therefore, the maximum pollen peak in the atmosphere occurred the June 14th when the Arbequina variety was in 60 first flowers opening phase and the Frantoio variety in 65 full flowering phase. By contrast, the main pollen season started on April 28, 2017, with a regular pollen emission until the maximum peak of 938 grains/m^3 on May 24th as it is stated for several studies conducted in the Mediterranean area (Achmakh et al. 2015; Galán et al. 2005; Bonofiglio et al. 2009). In addition, studies conducted in the Ourense city at 70 km from the study area noted atmospheric pollen concentrations particularly remarkable (Moreno-Grau et al. 2016).

The Spearman correlation analysis between pollen and main meteorological parameters showed positive association for mean and maximum temperature and negative for rainfall and relative humidity. This may be because during 2016 nearly two times precipitation has been registered that in 2017 (190.6 mm and 107.2 mm, respectively). In addition, the average relative humidity has been higher 73.57% and 66.53% in 2016 and 2017 years, respectively. These data are according to other several researches (Achmakh et al. 2015; Aguilera and Ruiz-Valenzuela 2009, 2012; Fernández-Rodríguez et al. 2016; Recio et al., 1996).

During the years of the study an important amount of olive pollen grains was detected in the atmosphere of the plot during the previous week to the phenological flowering stage. Moreover, the atmospheric olive pollen season showed two peaks. The first was the more important occurring during the stage 60 first flowers open. The second took place during the stage 65 full flowering. This fact could be associated with a long-range transport processes from the extensive olive groves of the Northern Portugal which flowers some days in advance (Moreno-Grau et al. 2016). The HYSPLIT models obtained in our study confirmed that air masses during the previous days to the flowering of the Verin olive orchard came from the Northeastern Portugal. Transporting pollen from remote sources is particularly relevant in species with small pollen size as the olive tree (Hernández-Ceballos et al. 2016). Several researchers noted that the amounts of pollen recorded are governed not only by local sources of pollen emission but also by other factors relating to the airborne dispersal and large-range transport of particles (Hernández-Ceballos et al. 2016; Rojo and Pérez-Badia 2015).

5 Conclusions

The olive flowering phenological stage occurs during the first fortnight of April in the Northern Spain area. Considering the duration of the vegetative olive cycle from stage 5 (inflorescence development) to the end of stage 7 (fruit development) an amount of around 2390°GDD was necessary to overcome the stage 8 (fruit maturation) and the consequent olive harvest. A higher degree of association was obtained between the heat accumulation and the timing of the different phenological stages. The model proposed in this research showed a great accuracy with a low SEE between observed and estimated data. The developed model is a useful tool for the prediction of the successive ecological events in this area.

The presence of *Olea* pollen grains in the atmosphere of the olive grove was registered during stage 5 (inflorescence development) and stage 6 (flowering). The HYSPLIT models obtained in our study confirmed that pollen peaks during the previous days to the flowering stage came from the extensive olive groves of the Northern Portugal (which flowers some days in advance) by means long-range transport. The presence of pollen in these stages, in particular, benefits the success of the fertilization process. The airborne *Olea* pollen concentrations are highly influenced by meteorological conditions such as temperature and dew point. The days with higher presence of airborne *Olea* pollen in the flowering stage coincide with higher values of maximum temperature and low values of rainfall.

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