

Models for forecasting the flowering of Cornicabra olive groves

Jesús Rojo · Rosa Pérez-Badía

Received: 1 May 2014 / Revised: 5 January 2015 / Accepted: 8 January 2015 / Published online: 6 February 2015
© ISB 2015

Abstract This study examined the impact of weather-related variables on flowering phenology in the Cornicabra olive tree and constructed models based on linear and Poisson regression to forecast the onset and length of the pre-flowering and flowering phenophases. Spain is the world's leading olive oil producer, and the Cornicabra variety is the second largest Spanish variety in terms of surface area. However, there has been little phenological research into this variety. Phenological observations were made over a 5-year period (2009–2013) at four sampling sites in the province of Toledo (central Spain). Results showed that the onset of the pre-flowering phase is governed largely by temperature, which displayed a positive correlation with the temperature in the start of dormancy (November) and a negative correlation during the months prior to budburst (January, February and March). A similar relationship was recorded for the onset of flowering. Other weather-related variables, including solar radiation and rainfall, also influenced the succession of olive flowering phenophases. Linear models proved the most suitable for forecasting the onset and length of the pre-flowering period and the onset of flowering. The onset and length of pre-flowering can be predicted up to 1 or 2 months prior to budburst, whilst the onset of flowering can be forecast up to 3 months beforehand. By contrast, a nonlinear model using Poisson regression was best suited to predict the length of the flowering period.

Keywords Phenology · Olive tree · Meteorological variables · Generalized linear models

J. Rojo · R. Pérez-Badía (✉)
Area of Botany, Institute of Environmental Sciences, University of
Castilla-La Mancha, E-45071 Toledo, Spain
e-mail: rosa.perez@uclm.es

J. Rojo
e-mail: jesus.rojo@uclm.es

Introduction

The plant life cycle is closely linked to local weather conditions (García-Mozo et al. 2009), and plant reproductive patterns—like other processes related to vegetative growth—reflect the degree of adaptation to the local climate (Chuine et al. 2000). Moreover, meteorological gradients associated with geographical features of the terrain give rise to variations in plant phenology (Oteros et al. 2013; Rojo and Pérez-Badía 2014). Phenological monitoring can thus help to assess the biological changes taking place as a response to climate variations (Chung et al. 2011; Kramer et al. 1996; Menzel et al. 2006).

Analysis of the relationship between weather-related variables and flowering phenology enables the construction of models to predict the onset and length of various phases of the plant life cycle (Orlandi et al. 2010). So-called thermal models are based solely on temperature variations (Chuine et al. 1998, 1999), whilst other models take into account a wider range of variables, including rainfall, relative humidity and photoperiod (Fornaciari et al. 1998; Galán et al. 2001a; Peñuelas et al. 2004).

To understand the dynamics of the floral phenology of the olive is important since the olive (*Olea europaea* L.) is a species of considerable agricultural and economic interest, particularly in terms of olive oil production. The Mediterranean area accounts for 98 % of the world's olive groves. Spain is the world's largest olive oil producer, and the Spanish region of Castilla-La Mancha has the second largest surface area of olive groves in Spain after Andalusia. The most widely grown variety in this region is “Cornicabra”, which is endemic to the central Iberian Peninsula and it is the second largest Spanish variety in terms of surface area after “Picual”, grown mainly in Andalusia. Cornicabra olive trees, grown on 270,000 ha, yield a much sought-after oil rich olive (Barranco and Rallo 2000).

Knowledge of flowering phenology in key crops with agricultural importance such as the olive, and of the influence of weather-related variables on the succession of phenophases, is of great value for good crop management, enabling producers to optimise irrigation, fertilisation, pruning and pest control, amongst other things (Chmielewski 2003; Chung et al. 2011; García-Mozo 2011). Recent research, moreover, has focused on olive phenology in terms of the allergenic capacity of this crop (Bonofiglio et al. 2013), whose pollen is a major cause of allergy in the Mediterranean area (Subiza et al. 2007).

A number of studies have reported that the weather-related variable most influencing olive flowering is temperature during the months prior to anthesis (Bonofiglio et al. 2008; Orlandi et al. 2010; Osborne et al. 2000), and olive flowering phenology has been modelled by various authors (De Melo-Abreu et al. 2004; Galán et al. 2001a; García-Mozo et al. 2009; Orlandi et al. 2009, 2010), taking into account the relationship between meteorological variables and successive phases of the olive life cycle (Crepinsek et al. 2006; Ruml et al. 2011).

A key consideration when constructing olive phenology models is that such models can rarely be extrapolated beyond the area for which they were constructed, since weather-related variables affect different varieties differently (Ayerza and Sibbett 2001; Orlandi et al. 2002), and thus phenological behaviour differs depending on the olive cultivar (Alcalá and Barranco 1992; Barranco et al. 2008). In most growing areas, including central Spain, few studies of Cornicabra olive phenology have investigated the relationship between weather variables and either phenological

observations in the field (Sáenz-Lain et al. 2003) or aerobiological data (García-Mozo et al. 2008).

This study sought to analyse the influence of weather-related variables on Cornicabra olive phenology and to construct models based on linear and Poisson regression to predict the onset and length of the pre-flowering and flowering phenophases.

Materials and methods

Study area and phenological sampling

The study was carried out in the province of Toledo (Castilla-La Mancha, central Spain). The area has a continental Mediterranean climate, characterised by marked seasonal contrasts: winters are cold, and summers are hot and dry; annual rainfall is between 350 and 600 mm. In Toledo City, situated in the centre of the study area (Fig. 1), the annual mean temperature is 15.4 °C; January is the coldest month (mean 6.4 °C), and July the warmest, with a mean temperature of 26.0 °C (INM 2008).

Phenological sampling was conducted at four sampling sites in Cornicabra olive groves, in La Puebla de Montalbán, Toledo, Olías del Rey and Mascaraque (Table 1). The selected sites are in the same area of Toledo, and they have the same biogeographical characteristics and covered a range of altitudes from 440 to 750 m (Fig. 1). Sampling was carried from 2009 to 2013, except in La Puebla de Montalbán and Olías del Rey, where sampling started in 2010.

Fig. 1 Sampling sites in the province of Toledo (Spain)

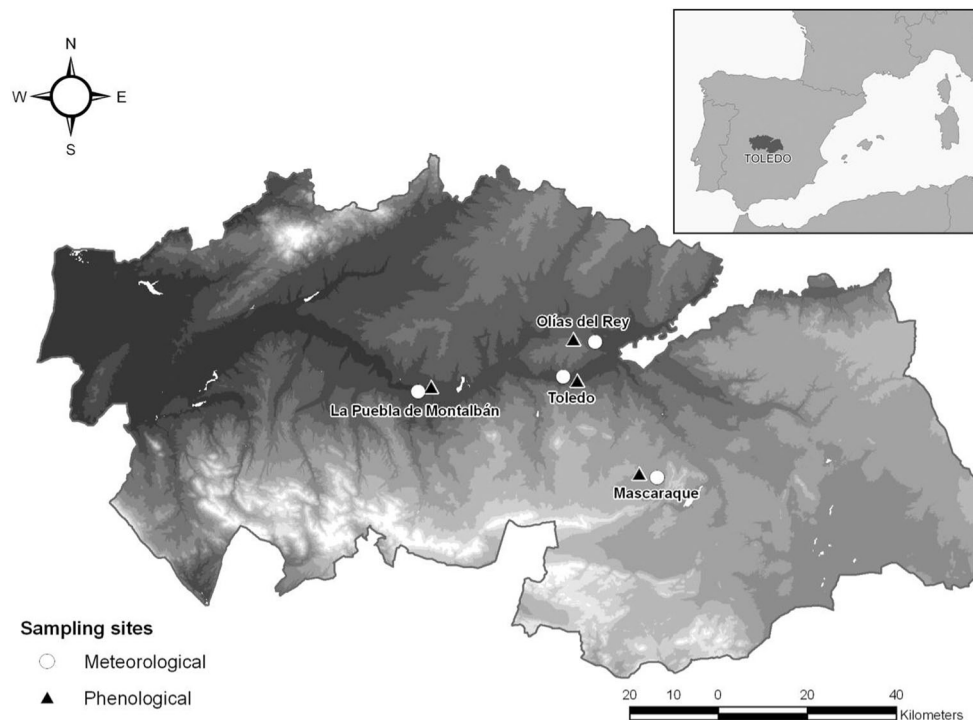


Table 1 Phenological sites in the study area. Sampling sites and geographical characteristics

Site (code)	Elevation (m.a.s.l.)	Coordinates	Studied period
La Puebla de Montalbán (LPue)	440	39° 50' N, 4° 22' W	2010–2013
Toledo (To)	470	39° 51' N, 3° 59' W	2009–2013
Oliás del Rey (Oli)	590	39° 56' N, 3° 59' W	2010–2013
Mascaraque (Mas)	748	39° 40' N, 3° 49' W	2009–2013

At each sampling site, flowering phenology was monitored over the whole canopy of a total of 10 trees. Observations were made weekly from the beginning of March to the end of June, and every 3 days during the flowering phase.

The phenophases used in the BBCH (Biologische Bundesantalt, Bundessortenamt und Chemische Industrie) scale for olive (Meier 2001) were adapted to a scale from 0 to 8 from dormancy to the start of fruiting, which marks the end of flowering. Phenophases were grouped into the following periods: dormancy: winter bud status (0/BBCH 50); pre-flowering: swelling buds (1/BBCH 51), flower cluster development (2/BBCH 54), petals just visible (3/BBCH 55) and petals whitening (4/BBCH 59); flowering: appearance of stamens (5/BBCH 60), full flowering (6/BBCH 65) and end of flowering (7/BBCH 68); and fruiting: non-fertilised flowers fallen and fruit set (8/BBCH 69).

Phenological data were processed using the Weighted Plant Development (WPD) method, which yields a phenological mean for the canopy as a whole and for all the individuals in each population, taking into account the percentage of buds or flowers on each tree during each phenophase, since at any given moment, up to four different phenophases may simultaneously coincide on a single tree. Following this method, the phenological development is calculated by linear interpolation between the values of two consecutive dates (Cornelius et al. 2011). This data enables constant monitoring of the progress of olive flower phenology (Rojo and Pérez-Badía 2014); the start dates of each phenological period were defined as the dates midway between phases (Cornelius et al. 2011) (Fig. 2). Using the 0–8 scale indicated earlier, the onset of pre-flowering was established as the date when 40–50 % of buds were swollen (threshold 0.5); the onset of flowering was considered when 15–35 % of flowers were fully open (threshold 4.5) and at this point pre-flowering finished; and the end of flowering was established as the date by which only the last 5–10 % of flowers were open, whilst 30–40 % had wilted and the rest were fruiting (threshold 7.5). The results are comparable to those reported by other authors, since phenophases were established using similar criteria (Maillard 1975).

Weather data

Meteorological data were obtained from weather stations close to phenological sampling sites (Fig. 1) belonging to the Castilla-La Mancha Air Control and Monitoring Network (<http://pagina.jccm.es/medioambiente/rvca/calidadaire.htm>) and the Integrated Irrigation Advice Network (SIAR, <http://crea.uclm.es/siar/>). The following weather-related variables were analysed: maximum temperature (Tmax), minimum temperature (Tmin), mean temperature (Tm), solar radiation (SR), relative humidity (RH) and accumulated rainfall (R). These variables were calculated for months, seasons (DJF December–January–February winter, MAM March–April–May spring) and the periods from November and January to the onset of both pre-flowering and flowering (Nov-PRE, Jan-PRE, Nov-FLO, Jan-FLO), as well as during the pre-flowering (PRE) and flowering periods (FLO).

Statistical analysis

Pearson and Spearman tests were used to test for correlations between phenological data and weather variables, depending the normality of the correlated variables (Zar 2010). This preliminary analysis enabled identification of weather variables displaying some correlation with reproductive phases in the olive life cycle (Orlandi et al. 2010).

Linear regression models were constructed to predict the onset and length of the pre-flowering and flowering phases, by means of stepwise selection of weather variables. Data for these variables fitted a normal distribution, thus enabling application of the linear model. Regression models were constructed using data for the years 2010 to 2013. Poisson regression models were also constructed to predict the length of pre-flowering and flowering phases (LengthPRE, LengthFLO), since these variables were expressed as count data (number of days) (Cameron and Trivedi 2013) and fitted a Poisson distribution (checked using the Kolmogorov-Smirnov test).

The validity of the models constructed was estimated using the Akaike information criterion (AIC) based on null models without independent variables which are used only to assess the resulting models from the initial AIC values. Models with the lowest AIC value were selected to obtaining models displaying the greatest accuracy and simplicity (Akaike 1974). Finally, models were validated using data for 2009, and calculating differences between predicted and observed data. Models were constructed using R software (R Development Core Team 2008).

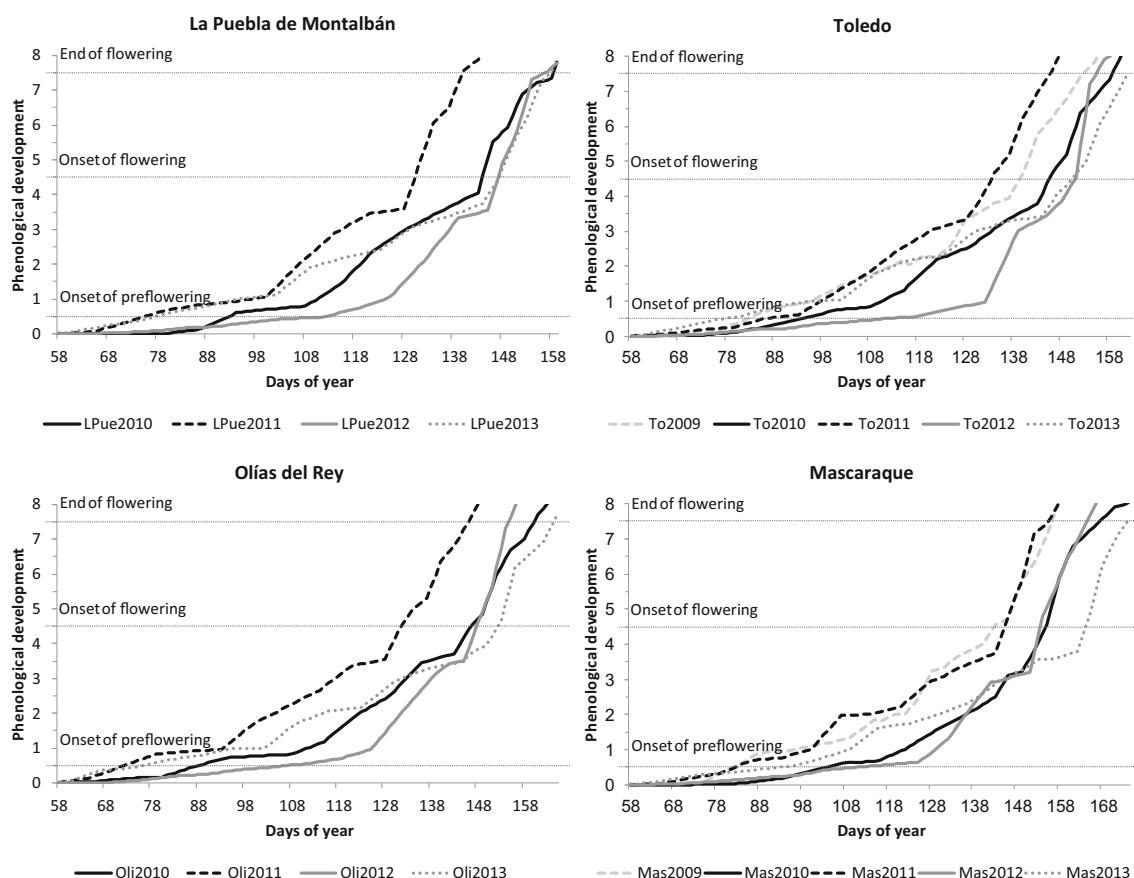


Fig. 2 Phenological development. The onset and end of the phenological phases were marked by the following thresholds: 0.5 onset of pre-flowering; 4.5 end of pre-flowering and onset of flowering; 7.5 end of flowering

Results

Phenological analysis

The onset of the pre-flowering period, marked by budburst, was recorded between the second week in March and the third week in April (72–109 Julian days (JD), Table 2). In 2009, 2011 and 2013, pre-flowering started earlier than in 2010, whilst in 2012, it started later. This pattern was recorded for all sampling sites (Fig. 2). Considerable year-to-year variation was observed in the onset of pre-flowering.

Flowering started between the second week in May and the second week in June (131–165 JD, Table 2); the mean length of the flowering period was just 11 ± 2 days (Table 2). Flowering started earliest in 2009 and 2011.

The length of the olive pre-flowering and flowering phases was similar in all years and at all sampling sites (Fig. 2). Phenological development during the pre-flowering phase was a long process, lasting a mean 57 ± 13 days (40–78 days, Table 2), but accelerating rapidly over the days prior to the onset of flowering (Fig. 2). Pre-flowering started early in 2013, and thus lasted longest (mean 75 ± 6 days).

Correlations between phenology and weather-related variables

Temperature was the weather variable that most significantly influenced the start date and length of the phenophases studied (Table 3). A positive correlation was observed between the onset of the pre-flowering phase and maximum temperature from the previous November to the onset of pre-flowering ($T_{\max Nov-PRE}$), i.e. for the dormancy phase. This indicates that an increase in maximum temperature during dormancy prompts delayed budburst in the olive. By contrast, a negative correlation was observed between minimum and mean temperatures in January, February and March ($T_{\min Jan}$, $T_{\min Mar}$, $T_{\min Feb}$) and the onset of the pre-flowering phase. An inverse correlation was recorded between temperatures during the pre-flowering phase ($T_{\max PRE}$, $T_{\min PRE}$, $T_{\min PRE}$) and phenophase length (Table 3).

On the other hand, the onset of pre-flowering correlated positively with solar radiation during dormancy ($SR_{Nov-PRE}$) and negatively with relative humidity ($RH_{Nov-PRE}$) (Table 3).

A negative correlation was observed between the flowering onset and maximum and mean temperatures in February ($T_{\max Feb}$, $T_{\min Feb}$), and also between flowering onset and

Table 2 Onset data (day of year, DOY±standard deviation, SD) and length (days±SD) of the pre-flowering (OnsetPRE, LengthPRE) and flowering (OnsetFLO, LengthFLO) phases for the study area

Data	OnsetPRE (DOY±SD)	LengthPRE (days±SD)	OnsetFLO (DOY±SD)	LengthFLO (days±SD)
LPue2010	4 April (94±5)	50±5	24 May (144±1)	14±1
LPue2011	16 March (75±5)	56±4	11 May (131±1)	10±1
LPue2012	17 April (108±7)	40±7	28 May (149±1)	10±2
LPue2013	18 March (77±6)	71±4	28 May (148±2)	11±1
To2009	24 March (83±5)	55±4	20 May (140±2)	14±2
To2010	3 April (93±6)	54±5	27 May (147±3)	12±1
To2011	27 March (86±7)	49±5	15 May (135±3)	11±2
To2012	18 April (109±8)	43±7	31 May (152±2)	6±2
To2013	18 March (77±5)	74±2	31 May (151±4)	12±2
Oli2010	29 March (88±4)	60±3	28 May (148±3)	13±2
Oli2011	13 March (72±3)	62±3	14 May (134±4)	12±2
Oli2012	14 April (105±7)	45±6	29 May (150±1)	8±1
Oli2013	16 March (75±7)	78±5	2 June (153±2)	12±1
Mas2009	23 March (82±3)	60±3	25 May (145±3)	12±2
Mas2010	13 April (103±8)	52±8	4 June (155±1)	13±1
Mas2011	23 March (82±4)	64±4	26 May (146±1)	9±1
Mas2012	18 April (109±7)	46±6	3 June (155±1)	11±1
LPue La Puebla de Montalbán, To Toledo, Oli Olías del Rey, Mas Mascarque	Mas2013	30 March (89±9)	14 June (165±1)	11±1
	Average	31 March (90±14)	27 May (147±8)	11±2

spring temperatures (TmaxMAM, TminMAM, TmMAM). This indicates that a drop in February–May temperatures prompts a delay in olive flowering. A negative correlation was recorded between the length of the flowering period and maximum temperatures from January to flowering onset (TmaxJan–FLO) (Table 3). Flowering period length also correlated negatively with solar radiation in winter (SRDJF), but positively with relative humidity in February (HRFeb).

Statistical models

Regression analysis (Table 4) revealed that the best linear model for pre-flowering onset (L1, Table 4) accounted for 92 % of variance. The variables that influence this model were mean temperature in January and February (TmJan, TmFeb) with a coefficient of −5.1 and −3.8, respectively, maximum temperature in November (TmaxNov) with a positive effect on pre-flowering onset (coefficient of 3.3) and solar radiation in January with a positive effect too (0.22SRJan).

A positive linear correlation was observed between pre-flowering length and mean January temperature (TmJan), whilst the correlation with maximum temperature from November to pre-flowering onset (TmaxNov–PRE) was negative. This linear model accounted for 77 % of variance in the length of the pre-flowering period (L2, Table 4). The Poisson regression model for this variable (P2, Table 4) highlights the positive nonlinear relationship between minimum March temperature (TminMar) and the length of the pre-flowering period.

The model obtained for flowering onset accounted for 87 % of variance (L3, Table 4). The variables included in the equation were maximum temperature in February (−4.4TmaxFeb) and accumulated rainfall in November, which had a positive influence (0.1RNov).

In the linear regression model, the length of the flowering period was negatively influenced by solar radiation in February, which accounted for 63 % of variance in duration (L4, Table 4). By contrast, the Poisson model (P4, Table 4) indicated a positive nonlinear correlation between the flowering period length and relative humidity in February (RHFeb).

Validation of models

In terms of the Akaike information criterion (Table 4), all the models obtained proved statistically valid; however, not all models guaranteed that the forecast would be accurate within an acceptable range of error. Forecasts were validated using data obtained in 2009 for Toledo (To2009) and Mascarque (Mas2009) (Fig. 3), which had not been used in constructing the models.

The model for forecasting the onset of pre-flowering (L1, Fig. 3) displayed a mean prediction error of 2.9 days. Since the independent variables involved were linked to weather conditions in November, January and February, this model would enable the onset of pre-flowering to be accurately forecast in March, i.e. 1 to 2 months prior to the actual start date. The best model for forecasting the length of the pre-flowering period

Table 3 Results of Pearson correlation test between phenological variables and meteorological variables with a significance level of $p < 0.01$ and those included in the regression equations ($p < 0.05$)

	OnsetPRE	LengthPRE	OnsetFLO	LengthFLO
TmaxNov	0.51*			
TmaxJan				−0.59**
TmaxFeb			−0.82***	
TmaxMar		−0.69**		
TmaxApr			−0.78***	
TmaxMay		−0.64**		
TmaxMAM		−0.59**	−0.82***	
TmaxNov-PRE	0.68**	−0.70**		
TmaxJan-PRE		−0.67**		
TmaxPRE		−0.91***		
TmaxJan-FLO				−0.60**
TminJan	−0.73**	0.62**		
TminFeb				0.67**
TminMar	−0.77***	0.73**		
TminDJF	−0.68**			
TminMAM			−0.66**	
TminPRE		−0.63**		
TmJan	−0.61**	0.66**		
TmFeb	−0.81***		−0.65**	
TmApr			−0.73**	
TmMay		−0.65**		
TmDJF	−0.72**			
TmMAM			−0.87***	
TmPRE		−0.84***		
RNov			0.51*	−0.53*
RPRE		0.73**		
SRJan	0.53*			−0.58*
SRFeb				−0.67**
SRMar	0.65**	−0.71**		
SRDJF				−0.63**
SRNov-PRE	0.72**	−0.69**		
SRJan-PRE	0.77***	−0.70**		
RHFeb				0.65**
RHMar	−0.67**	0.79***		
RHNov-PRE	−0.72**	0.69**		
RHJan-PRE		0.68**		

For the variables TmaxMay, TmaxJan-PRE, TminFeb, RHFeb and RHJan-PRE, the Spearman test was used due to the non-normality of the data. Number of cases=18

Tmax maximum temperature, *Tmin* minimum temperature, *Tm* mean temperature, *R* rainfall, *SR* solar radiation, *RH* relative humidity, *Nov* November, *Dec* December, *Jan* January, *Feb* February, *Mar* March, *Apr* April, *May* May, *DJF* December–January–February, *MAM* March–April–May, *PRE* pre-flowering phase, *FLO* flowering phase

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

was the linear model (L2, Fig. 3), which yielded a mean error of 2.7 days.

The model constructed to forecast flowering onset displayed a mean error of 1.4 days. Moreover, on validation the predicted value for Mascaraque in 2009 coincided with the observed value (−0.1 days' difference), suggesting that this forecasting model was very accurate (L3, Fig. 3). Since the variables influencing the forecast were linked to weather conditions in February and November, this model would enable the onset of flowering to be forecast in March, i.e. 2 to 3 months beforehand.

Finally, the best model for forecasting the length of the flowering period, obtained by Poisson regression (P4, Fig. 3), displayed a mean error of 1.7 days with respect to observed data for 2009.

Discussion and conclusions

The average date of budburst, i.e. the onset of pre-flowering, in Cornicabra olive groves coincided with the average date reported for Picual groves (Aguilera and Ruiz 2009), and also with the dates observed for the Italian varieties “Ascolana” and “Giarrappa” (Orlandi et al. 2002, 2004). All varieties display considerable year-to-year variations in the timing of pre-flowering onset depending on weather conditions. The flowering period in the Mediterranean area generally starts between April and June (Fornaciari et al. 2000; Orlandi et al. 2010); Cornicabra olives, a late cycle variety (Barranco et al. 2008) flower in late May and early June in Toledo province.

Budburst, marking the onset of the pre-flowering phase, is governed largely by temperatures during autumn and winter, when the chilling requirements ensuring bud induction are reached (García-Mozo et al. 2010; Orlandi et al. 2010). At the start of dormancy, low temperatures are needed for floral bud development (Denney et al. 1985; Rallo and Martín 1991), because after exposure to low winter temperatures, a variation of endogenous inhibitors and promoters such as gibberellins, abscisic acid and other substances leads to the differentiation of floral buds (Badr et al. 1970; Baktir et al. 2004; Hartmann et al. 1967). In this period of dormancy, prior to differentiation of flower buds, variations in the content of the starch of the buds are also produced (De la Rosa et al. 2000).

Temperature plays an important role in the transition from vegetative meristem to floral meristem. Plants must ensure that the winter is over to bloom. In the months prior to budburst, increased temperatures are required to bring buds out of dormancy; an increase in temperature produces a greater photosynthetic and metabolic activity leading to the activation of the flower buds (Cesaraccio et al. 2004). Another variable that affects the regulation of the processes that lead to the initiation of the pre-flowering is the relative humidity. This variable has a negative effect on the maximum temperature (Dessens and Bücher 1995). Higher humidity during winter implies lower maximum temperatures that will allow the

Table 4 Models for forecasting phenological parameters (start dates and length)

	Code	Model	AIC	R^2
Onset of pre-flowering	L1	(Null model: OnsetPRE=89.69)	131.30	0.92
		OnsetPRE=68.65–5.18TmJan–3.75TmFeb+3.27TmaxNov+0.22SRJan	99.73	
Length of pre-flowering	L2	(Null model: LengthPRE=57.44)	128.39	0.77
		LengthPRE=100.79+7.47TmJan–6.41TmaxNov–PRE	108.61	
	P2	(Null model: Log(LengthPRE)=4.05)	134.33	
		Log(LengthPRE)=3.59+0.12TminMar	114.07	
Onset of flowering	L3	(Null model: OnsetFLO=147.00)	117.78	0.87
		OnsetFLO=196.82–4.36TmaxFeb+0.13RNov	89.54	
Length of flowering	L4	(Null model: LengthFLO=10.94)	70.80	0.63
		LengthFLO=20.44–0.07SRFeb	56.94	
	P4	(Null model: Log(LengthFLO)=2.39)	75.63	
		Log (LengthFLO)=1.39+0.01RHFeb	74.10	

Null models are regression models without independent variables, which are shown for the purpose of comparing the Akaike information criterion with that of the models obtained

L linear model, *P* Poisson regression model

chilling requirements necessary for the subsequent differentiation of flower buds.

Regarding the onset of flowering, the weather-related factor most influencing was temperature over the months prior to flowering. Similar findings have been reported by other authors (e.g. Bonofiglio et al. 2008; García-Mozo et al. 2010; Orlandi et al. 2010). Specifically, the results indicate that a drop in temperature between February and the onset of flowering was found to prompt a delay in flowering onset. This effect, as mentioned previously, is due to the need of heat accumulation for the olive tree to break latency (Alba and de la Díaz Guardia 1998; Bonofiglio et al. 2008; Galán et al. 2001b). Also, once the development of the flower buds starts, photosynthetic rate generally increases with increasing temperature (Pallardy 2008). Therefore, an increased in the metabolic activity causes faster development of olive floral structures.

Although temperature was the weather-related variable most influencing the onset and duration of olive pre-flowering and flowering, as reported by other authors (Orlandi et al. 2004, 2010), solar radiation also exerted some effect: increased solar radiation during dormancy contributed to a delay in pre-flowering onset. Solar radiation influences the rate of photosynthesis and the distribution of nutrients within the tree, thus affecting reproductive phenology (Atwell et al. 1999; Privé et al. 1993) and, in this case, budburst. Sunlight also has an indirect effect on temperature, which may explain why an increase during dormancy prompts a delay in budburst.

Our results show that rainfall at the start of dormancy produces a delay on flowering onset; the same has been

documented by Aguilera et al. (2014). Connor and Fereres (2005) demonstrated that, in olive groves located in South America where there is no vernalisation, water stress that occurs during dormancy seems to have a similar effect to that produced by low temperatures in the Mediterranean area. Therefore, the lack of rainfall, the same as the accumulation of low temperatures, would advance the onset of flowering and the opposite conditions the delay.

Data obtained here for the length of the pre-flowering and flowering periods were similar to those reported for Picual olives (Aguilera and Ruiz 2009), confirming that these two varieties share similar phenological behaviour despite differences in the timing of flowering onset.

In selecting models for forecasting the timing of the various olive phenophases, the Akaike information criterion was used to identify the most statistically suitable model (Akaike 1974). Given the continuous nature of the variables of pre-flowering and flowering onset, the best models were based on linear regression, which also yielded the most accurate model for predicting the length of the pre-flowering period, as confirmed by validation using independent data. However, the most accurate forecast of flowering period length was provided by the Poisson model since this variable was expressed as count data (number of days) and covers a small number of values (Cameron and Trivedi 2013; Hardin and Hilbe 2007).

Two key considerations when applying and assessing predictive models are the accuracy achieved and how far in advance they allow a given event to be forecast (Ruml et al. 2011). Models performing well in these respects are of enormous value in improving olive crop

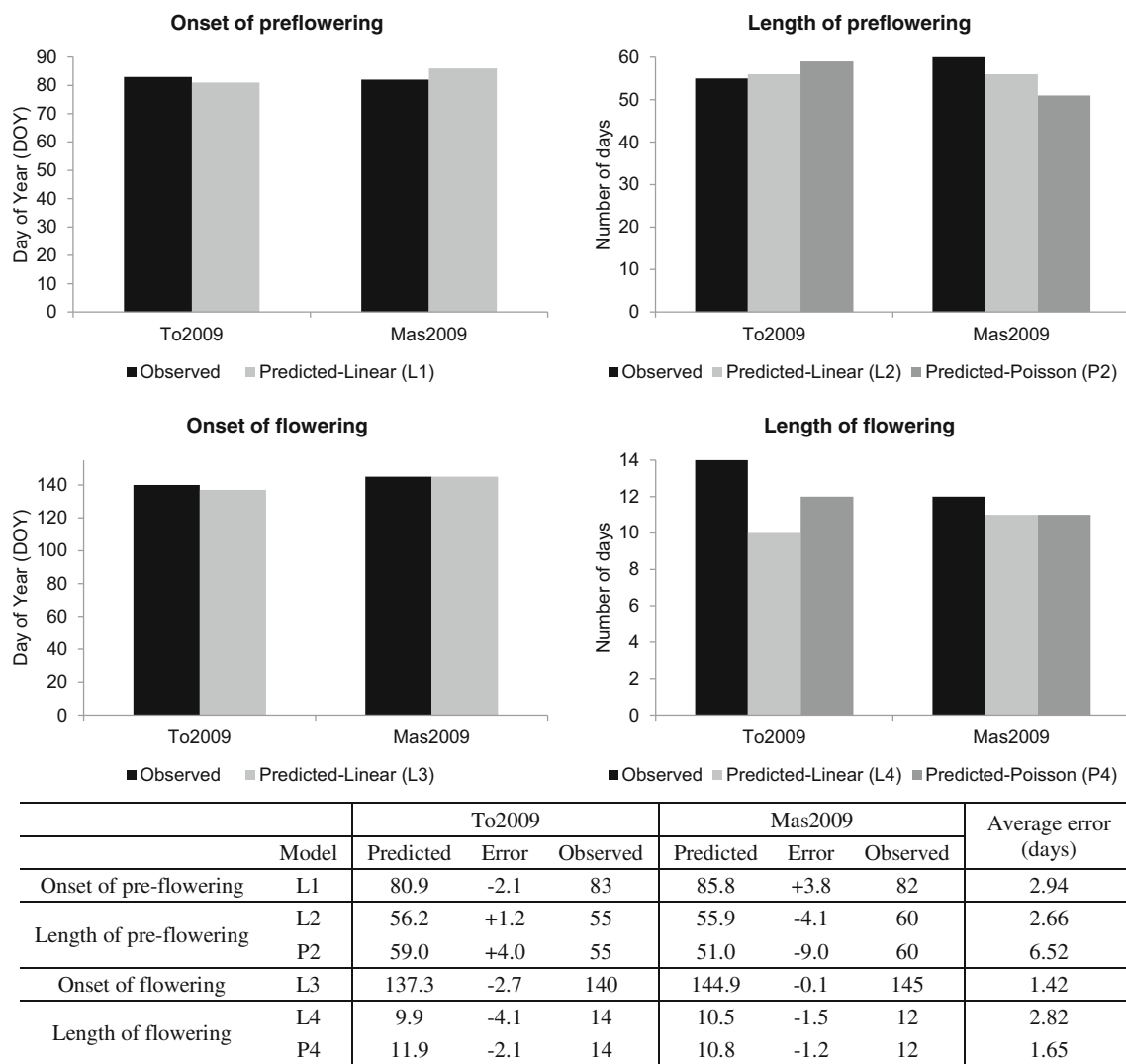


Fig. 3 Observed and predicted values for start dates (day of year, DOY) and length (days) of pre-flowering and flowering phases for independent study data (To2009 Toledo year 2009; Mas2009 Mascaraque year 2009). The average error is calculated with the absolute value of the errors in both cases

management in major production areas. The findings of the present study have a number of highly practical direct applications, in that they indicate—several months before the event—the optimum timing of certain agricultural operations (Chmielewski 2003) such as pruning, pest control and fertilisation, thus enhancing the efficacy of treatments and optimising resource use.

The model obtained here for forecasting the date of pre-flowering onset allows this event to be predicted accurately between 1 and 2 months beforehand, and is thus of great value for decision-making. In some cases, the addition of essential nutrients to support the pre-flowering is necessary, and these nutrients must be incorporated in a given date (Delgado et al. 1994; Fernández-Escobar et al. 2004; Guerrero 2002). This period can be forecast accurately using the pre-flowering time model, in order to optimise treatment.

On the other hand, the ability to forecast olive flowering onset 2–3 months prior to the event is particularly useful for planning pruning operations (Gucci and Cantini 2000) and for improving the efficacy of treatments aimed at controlling the pests that attack floral tissues which are synchronised with the olive biological cycle. For instance, in the case of the olive moth (*Prays oleae*) (Civantos 1998; Kumral et al. 2005), the optimum time for treatment is during the first few days of flowering, when larvae are at their most vulnerable.

In addition to these crop management applications, the findings of this study are of value in forecasting events of allergy, given that olive pollen is considered highly allergenic (Subiza et al. 2007). Using the models obtained here, the periods of greatest risk to allergy sufferers in central Spain can be identified 2–3 months in advance.

References

- Aguilera F, Ruiz L (2009) Study of the floral phenology of *Olea europaea* L. in Jaén province (SE Spain) and its relation with pollen emission. *Aerobiologia* 25(4):217–225
- Aguilera F, Fornaciari M, Ruiz-Valenzuela L, Galán C, Msallem M, Ben Dhiab A, de la Díaz Guardia C, Trigo MM, Bonofiglio T, Orlandi F (2014) Phenological models to predict the main flowering phases of olive (*Olea europaea* L.) along a latitudinal and longitudinal gradient across the Mediterranean region. *Int J Biometeorol*. doi:10.1007/s00484-014-0876-7
- Akaike H (1974) A new look at the statistical model identification. *IEEE Trans Autom Control* 19(6):716–723
- Alba F, de la Díaz Guardia C (1998) The effect of air temperature on the starting dates of the *Ulmus*, *Platanus* and *Olea* pollen seasons in the SE Iberian Peninsula. *Aerobiologia* 14:191–194
- Alcalá AR, Barranco D (1992) Prediction of flowering time in olive for the Córdoba olive collection. *Hortic Sci* 27(11):1205–1207
- Atwell BJ, Kriedemann PE, Turnbull CGN (1999) Plants in action: adaptation in nature, performance in cultivation. Macmillan Education AU, Australia
- Ayerza R, Sibbett GS (2001) Thermal adaptability of olive (*Olea europaea* L.) to the Arid Chaco of Argentina. *Agric Ecosyst Environ* 84:277–285
- Badr SA, Hartmann HT, Martin GC (1970) Endogenous gibberellins and inhibitors in relation to flower induction and inflorescence development in the olive. *Plant Physiol* 46:674–679
- Baktir I, Ulger S, Kaynak L, Himelrick DG (2004) Relationship of seasonal changes in endogenous plant hormones and alternate bearing of olive trees. *Hortic Sci* 39(5):987–990
- Barranco D, Rallo L (2000) Olive cultivars in Spain. *Hortic Technol* 10:107–110
- Barranco D, Fernández-Escobar R, Rallo L (2008) El cultivo del olivo, 6th edn. Junta de Andalucía y Ediciones Mundi-Prensa, Madrid, España
- Bonofiglio T, Orlandi F, Sgromo C, Romano B, Fornaciari M (2008) Influence of temperature and rainfall on timing of olive (*Olea europaea*) flowering in southern Italy. *New Zeal J Crop Hortic* 36:59–69
- Bonofiglio T, Orlandi F, Ruga L, Romano B, Fornaciari M (2013) Climate change impact on the olive pollen season in Mediterranean areas of Italy: air quality in late spring from an allergenic point of view. *Environ Monit Assess* 185:877–890
- Cameron AC, Trivedi PK (2013) Regression analysis of count data, 2nd edn. Cambridge University Press, New York, USA
- Cesaraccio C, Spano D, Snyder RL, Duce P (2004) Chilling and forcing model to predict bud-burst of crop and forest species. *Agric Meteorol* 126:1–13
- Chmielewski FM (2003) Phenology and agriculture. In: Schwartz MD (ed) Phenology: an integrative environmental science. Kluwer Academic Publ, Dordrecht, Netherlands, pp 505–522
- Chuine I, Cour P, Rousseau DD (1998) Fitting models predicting dates of flowering of temperate-zone trees using simulated annealing. *Plant Cell Environ* 21:455–466
- Chuine I, Cour P, Rousseau DD (1999) Selecting models to predict the timing of flowering of temperate trees: implications for tree phenology modelling. *Plant Cell Environ* 22:1–13
- Chuine I, Cambon G, Comtois P (2000) Scaling phenology from the local to the regional level: advances from species-specific phenological models. *Glob Chang Biol* 6:943–952
- Chung U, Mack L, Yun JI, Kim SH (2011) Predicting the timing of cherry blossoms in Washington, DC and Mid-Atlantic States in response to Climate Change. *PLoS One* 6(11):e27439. doi:10.1371/journal.pone.0027439
- Civantos M (1998) Sanidad del olivar. *Vida rural* 40:50–52
- Connor DJ, Fereres E (2005) The physiology of adaptation and yield expression in olive. *Hortic Rev* 31:155–229
- Cornelius C, Petermeier H, Estrella N, Menzel A (2011) A comparison of methods to estimate seasonal phenological development from BBCH scale recording. *Int J Biometeorol* 55:867–877
- Crepinsek Z, Kajfez-Bogataj L, Bergant K (2006) Modelling of weather variability effect on fitophenology. *Ecol Model* 194:256–265
- De la Rosa R, Rallo L, Rapoport HF (2000) Olive floral bud growth and starch content during winter rest and spring budbreak. *Hortic Sci* 35(7):1223–1227
- De Melo-Abreu JP, Barranco D, Cordiro AM, Tous J, Rogado BM, Villalobos FJ (2004) Modelling olive flowering date using chilling for dormancy release and thermal time. *Agric Meteorol* 125:117–127
- Delgado A, Benlloch M, Fernández-Escobar R (1994) Mobilization of boron in olive trees during flowering and fruit development. *Hortic Sci* 29(6):616–618
- Denney JO, McEachern GR, Griffiths JF (1985) Modeling the thermal adaptability of the olive (*Olea europaea* L.) in Texas. *Agric Meteorol* 35:309–327
- Dessens J, Bicher A (1995) Changes in minimum and maximum temperatures at the Pic du Midi in relation with humidity and cloudiness, 1882–1984. *Atmos Res* 37:147–162
- Fernández-Escobar R, Moreno R, Sánchez-Zamora MA (2004) Nitrogen dynamics in the olive bearing shoot. *Hortic Sci* 39(6):1406–1411
- Fornaciari M, Pieroni L, Ciuchi P, Romano B (1998) A regression model for the start of the pollen season in *Olea europaea*. *Granada* 37:110–113
- Fornaciari M, Galán C, Mediavilla A, Domínguez E, Romano B (2000) Aeropalynological and phenological study in two different Mediterranean olive areas: Cordoba (Spain) and Perugia (Italy). *Plant Biosyst* 134(2):199–204
- Galán C, Cariñanos P, García-Mozo H, Alcazar P, Domínguez-Vilches E (2001a) Model for forecasting *Olea europaea* L. airborne pollen in South-West Andalusia, Spain. *Int J Biometeorol* 45:59–63
- Galán C, García-Mozo H, Cariñanos P, Alcázar P, Domínguez-Vilches E (2001b) The role of temperature in the onset of the *Olea europaea* L. pollen season in southwestern Spain. *Int J Biometeorol* 45:8–12
- García-Mozo H (2011) The use of aerobiological data on agronomical studies. *Ann Agric Environ Med* 18:159–164
- García-Mozo H, Pérez-Badía R, Galán C (2008) Aerobiological and meteorological factors' influence on olive (*Olea europaea* L.) crop yield in Castilla-La Mancha (Central Spain). *Aerobiologia* 24:13–18
- García-Mozo H, Orlandi F, Galán C, Fornaciari M, Romano B, Ruiz L, Díaz de la Guardia C, Trigo MM, Chuine I (2009) Olive flowering phenology variation between different cultivars in Spain and Italy: modeling analysis. *Theor Appl Climatol* 95:385–395
- García-Mozo H, Mestre A, Galán C (2010) Phenological trends in southern Spain: a response to climate change. *Agric Meteorol* 150:575–580
- Gucci R, Cantini C (2000) Pruning and training systems for modern olive growing. Csiro Publishing, Collingwood VIC, Australia
- Guerrero A (2002) Nueva olivicultura, 5th edn. Ediciones Mundi-Prensa, Madrid, Spain
- Hardin JW, Hilbe JM (2007) Generalized linear models and extensions, 2nd edn. Stata Press, Texas
- Hartmann HT, Fadl MS, Hackett WP (1967) Initiation of flowering and changes in endogenous inhibitors and promoters in olive buds as a result of chilling. *Physiol Plant* 20(3):746–759
- INM Instituto Nacional de Meteorología (2008) Guía resumida del clima en España 1971–2000. Ministerio de Medio Ambiente, Madrid, Spain
- Kramer K, Friend A, Leinonen I (1996) Modelling comparison to evaluate the importance of phenology and spring frost damage for the effects of climate change on growth of mixed temperate-zone deciduous forests. *Climate Res* 7:31–41

- Kumral NA, Kovanci B, Akbudak B (2005) Pheromone trap catches of the olive moth, *Prays oleae* (Bern.) (*Lep., Plutellidae*) in relation to olive phenology and degree-day models. *J Appl Entomol* 129(7): 375–381
- Maillard R (1975) *L'olivier*. Invuflec, Paris, France
- Meier U (2001) Growth stages of mono- and dicotyledonous plants. BBCH Monograph. 2nd Edition. Federal Biological Research Centre for Agriculture and Forestry
- Menzel A, Sparks TH, Estrella N, Koch E, Aasa A, Ahas R, Alm-Kübler K, Bissolli P, Braslavski O, Briede A, Chmielewski FM, Crepinsek Z, Curnel Y, Dahl A°, Defila C, Donnelly A, Filella Y, Jateczak K, Ma°ge F, Mestre A, Nordli O, Peñuelas J, Pirinen P, Remis°ova° V, Scheifinger HM, Striz A, Susnik A, Van Vliet JH, Wielgolaski FE, Züst ASZ (2006) European phenological response to climate change matches the warming pattern. *Glob Chang Biol* 12(10):1969–1976
- Orlandi F, Fornaciari M, Romano B (2002) The use of phenological data to calculate chilling units in *Olea europaea* L. in relation to the onset of reproduction. *Int J Biometeorol* 46:2–8
- Orlandi F, García-Mozo H, Vazquez Ezquerro L, Romano B, Dominguez E, Galán C, Fornaciari M (2004) Phenological olive chilling requirements in Umbria (Italy) and Andalusia (Spain). *Plants Biosyst* 138(2):111–116
- Orlandi F, Sgromo C, Bonofiglio T, Ruga L, Romano B, Fornaciari M (2009) A comparison among olive flowering trends in different Mediterranean areas (south-central Italy) in relation to meteorological variations. *Theor Appl Climatol* 97:339–347
- Orlandi F, García-Mozo H, Galán C, Romano B, de la Díaz Guardia C, Ruiz L, Trigo MM, Dominguez-Vilches E, Fornaciari M (2010) Olive flowering trends in a large Mediterranean area (Italy and Spain). *Int J Biometeorol* 54:151–163
- Osborne CP, Chuine I, Viner D, Woodward FI (2000) Olive phenology as a sensitive indicator of future climatic warming in the Mediterranean. *Plant Cell Environ* 23:701–710
- Oteros J, García-Mozo H, Vázquez L, Mestre A, Domínguez-Vilches E, Galán C (2013) Modelling olive phenological response to weather and topography. *Agric Ecosyst Environ* 179:62–68
- Pallardy SG (2008) *Physiology of woody plants*, 3rd edn. Academic Press, San Diego, California, USA
- Peñuelas J, Filella I, Zhang X, Llorens L, Ogaya R, Lloret F, Comas P, Estiarte M, Terradas J (2004) Complex spatiotemporal phenological shifts as a response to rainfall changes. *New Phytol* 161:837–846
- Privé JP, Sullivan JA, Proctor JTA, Allen OB (1993) Climate influences vegetative and reproductive components of primocane-fruiting red raspberry cultivars. *J Amer Soc Hortic Sci* 118(3):393–399
- R Development Core Team (2008) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL: <http://www.R-project.org>
- Rallo L, Martín GC (1991) The role of chilling in releasing olive floral buds from dormancy. *J Amer Soc Hortic Sci* 116(6):1058–1062
- Rojo J, Pérez-Badía R (2014) Effects of topography and crown exposure on olive-tree phenology. *Trees* 28:449–459
- Ruml M, Milatovic D, Vulic T, Vukovic A (2011) Predicting apricot phenology using meteorological data. *Int J Biometeorol* 55:723–732
- Sáenz-Lain C, Gutiérrez-Bustillo M, Alcolado V (2003) Fenología, aerobiología y producción del olivar en Almodóvar del Campo (Castilla-La Mancha). *Anales Jard Bot Madrid* 60(1):73–81
- Subiza FJ, Pola J, Feo F, Moral AJ (2007) Pólenes de interés en alergología en nuestro medio. In: Peláez A, Dávila IJ (eds) *Tratado de alergología*. Ergón, Madrid, Spain, pp 425–446
- Zar JH (2010) *Biostatistical analysis*. 5th Ed. Prentice-Hall, Upper Saddle River, New Jersey, Englewood, USA