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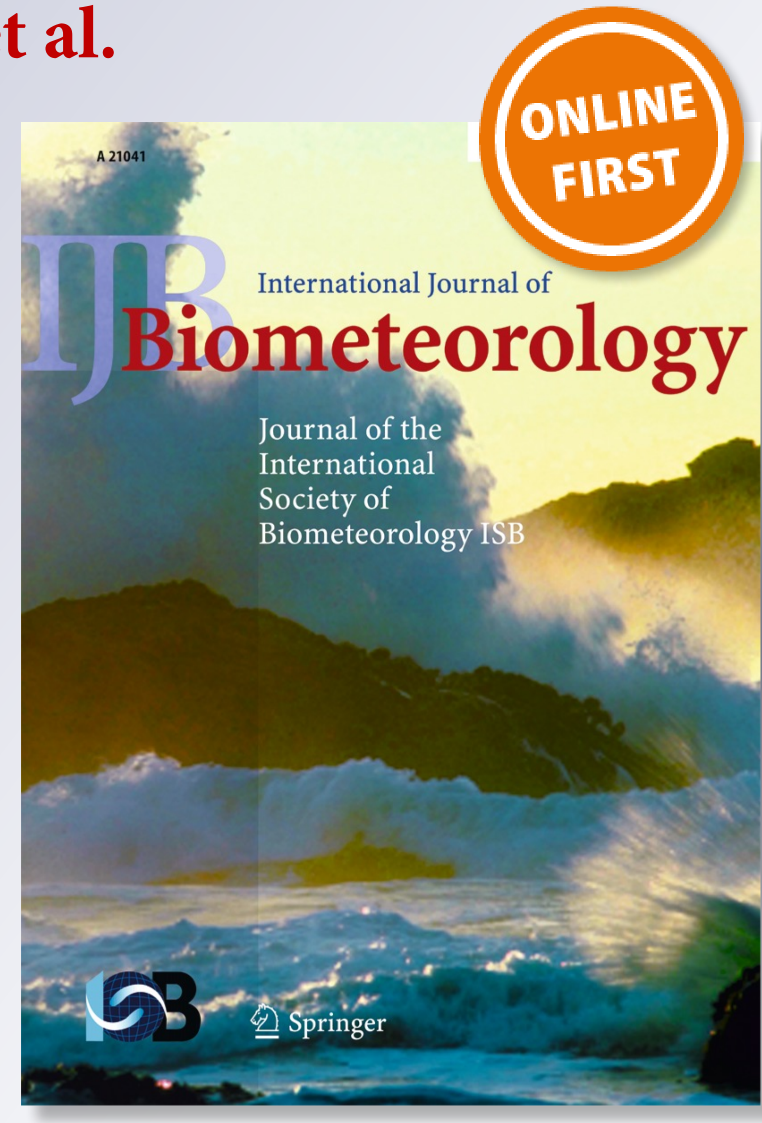
International Journal of Biometeorology

ISSN 0020-7128

Int J Biometeorol
DOI 10.1007/s00484-014-0876-7



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ORIGINAL PAPER

Phenological models to predict the main flowering phases of olive (*Olea europaea* L.) along a latitudinal and longitudinal gradient across the Mediterranean region

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Received: 21 March 2014 / Revised: 28 May 2014 / Accepted: 12 July 2014

Abstract The aim of the present study was to develop pheno-meteorological models to explain and forecast the main olive flowering phenological phases within the Mediterranean basin, across a latitudinal and longitudinal gradient that includes Tunisia, Spain, and Italy. To analyze the aerobiological sampling points, study periods from 13 years (1999–2011) to 19 years (1993–2011) were used. The forecasting models were constructed using partial least-squares regression, considering both the flowering start and full-flowering dates as dependent variables. The percentages of variance explained by the full-flowering models (mean 84 %) were greater than those explained by the flowering start models (mean 77 %). Moreover, given the time lag from the North African areas to the central Mediterranean areas in the main olive flowering dates, the regional full-flowering predictive models are proposed as the most useful to improve the knowledge of the influence of climate on the olive tree floral phenology. The meteorological parameters related to the previous autumn and both the winter and the spring seasons, and above all the temperatures, regulate the reproductive phenology of olive trees in the Mediterranean area. The mean anticipation of flowering start and full flowering for the future period from 2081 to 2100 was estimated at 10 and 12 days, respectively. One question can be raised: Will the olive trees located in the warmest areas be northward displaced or will they be able to adapt their physiology in response to the higher temperatures? The present study can be considered as an approach to design more detailed future bioclimate research.

Keywords Climate change · Flowering phenology · Least-squares regression · Modeling · Olive · Pollen

Introduction

In the Mediterranean basin, olive trees (*Olea europaea* L.) are one of the most widespread tree crop species. These are adapted to the mild climate, as olive fruit and oil are among the oldest and most important products in this area (Barranco et al. 2008). Spain is the largest olive oil-producing country, followed by Italy, Greece, and Tunisia. Together, these four countries produce about 2,178,000 tonnes of olive oil, which represents 78 % of the total world olive oil production (International Olive Council 2012).

Of all of the biological phases, flowering is the most critical for every fructiferous plant, and it can be highly influenced by weather conditions (Barranco et al. 2008; Bonofiglio et al. 2008; Osborne et al. 2000). Prior to flowering, meteorological factors influence the plant growth and development, such as

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Published online: 25 July 2014

the accumulated values of temperature since the start of the pre-flowering period and the water availability (Aguilera and Ruiz-Valenzuela 2009; Galán et al. 2005; Rallo and Martin 1991; Ribeiro et al. 2007). In addition, it has been demonstrated that low temperatures and high precipitation during the pre-flowering months are weather conditions that promote the formation of flowers and contribute positively to increased pollen production (Aguilera and Ruiz-Valenzuela 2012a). During the flowering period, other factors, such as cumulative rainfall or cumulative sunshine, can influence both the length of the flowering period and the pollen release (Aguilera and Ruiz-Valenzuela 2012b; Oteros et al. 2012; Recio et al. 1996).

Future warming trends and spatial variability in rainfall regimes will potentially cause a serious imbalance between the physiological and biological rhythms of natural and cultivated plant species (Alcamo et al. 2007; Giorgi and Lionello 2008; Osborne et al. 2000). The Mediterranean region has been identified as one of the most prominent "hot spots" in the world, and it is considered a particularly vulnerable area to the effects of climate change (Capra et al. 2013; Giorgi and Lionello 2008). Thus, the roles of the meteorological parameters related to the olive flowering period under projected climate change scenarios need further evaluation.

Models that predict the timing of flowering in tree species are used widely to predict the responses of plant phenology to global warming (Chuine et al. 1999; García-Mozo et al. 2008; Orlandi et al. 2014). Many of these studies have highlighted strong relationships between temperature and plant phenology, mainly for woody plants. Several models that predict phenological phases in different Mediterranean species have been described in the literature (Chuine et al. 1999; Galán et al. 2005; Hunter and Lechowicz 1992; Rodríguez-Rajo et al. 2003). However, the availability of long-time series of phenological data for the same location that can be used to construct reliable statistical models is very rare. For this reason, among the different types of phenological datasets that can be distinguished, the measurements of pollen emissions into the atmosphere are generally the most used (Chuine et al. 1999). Many studies have thus used aerobiological information to analyze the flowering phases in anemophilous species, with airborne pollen data widely used as a well-proven tool for indirect evaluation of the flowering period (Aguilera and Ruiz-Valenzuela 2009; Galán et al. 2008; García-Mozo et al. 2008, 2009; Jato et al. 2002; Orlandi et al. 2010). Moreover, a combination of aerobiological and phenological information can be used efficiently to track the impact of global climate change on plants (Chuine et al. 1999; García-Mozo et al. 2008; Orlandi et al. 2010).

Several models based in the relationships between temperature, photoperiod, and olive floral phenology have been constructed previously on local and regional scales, and using data from various Spanish and Italian sites (García-Mozo et al. 2008; Orlandi et al. 2010). However, there have been few studies on modeling analysis that have considered temperature, accumulated rainfall, and bioclimatic indices across a wide Mediterranean area. For this reason, the present study was aimed at the development of pheno-meteorological models to explain and forecast the main olive flowering phenophases within the Mediterranean basin, across a large latitudinal and longitudinal gradient that includes Tunisia, Spain, and Italy. On this basis, and given the great socio-economic importance of this cultivated species in the Mediterranean region, future projections for olive flowering have been elaborated and evaluated for each study site, and these are also discussed in terms of the possible impact of climate change on olive tree flowering phenology.

Materials and methods

Study area

The studied area stretches across the Mediterranean basin and includes three of the main olive oil production countries in the world: Spain, Italy, and Tunisia (International Olive Council 2012). In these countries, the main olive-growing areas have been considered. The latitudinal and longitudinal gradients through the Mediterranean basin cover a geographical area that extends from 43° 06′ N of Perugia, Italy, to 33° 35′ N of Zarzis, Tunisia, and from 16° 10′ E of Cosenza, Italy, to 04° 45′ W of Cordoba, Spain (Fig. 1). The altitude ranges from 5 m a.s.l. in Malaga to 685 m a.s.l. in Granada, both located in Spain. The main geographical characteristics and aerobiological sampling periods for each of the study sites are given in Table 1. The study period comprises from 13 years (1999–2011) to 19 years (1993–2011), depending on the year of onset of the aerobiological monitoring at each site.

Forecasting models

Different variables were taken into account in this study, including aerobiological, meteorological, and bioclimatic parameters.

Phenological and aerobiological data

The anthesis phenophase in olive was recorded using aerobiological monitoring for the detection of the airborne pollen (International Association for Aerobiology 2011). The sampling was carried out using the volumetric method, which is based on capturing the pollen and other biological particles present in the air in the olive-growing areas around a monitoring station. The amount of pollen captured reflects the process of flower opening. On this basis, the monitoring traps were located inside or near to olive groves, for the detection of the pollen from a wide olive-growing area. Moreover, this

Fig. 1 Location of the study sites. *1–4*, Spain: *1*=Cordoba; *2*=Jaen; *3*=Granada; *4*=Malaga. *5–10*, Italy: *5*=Perugia; *6*=Foggia; *7*=Avellino; *8*=Cosenza; *9*=Messina; *10*=Trapani. *11–15*, Tunisia: *11*=Mornag; *12*=Jemmel; *13*=Menzel; *14*=Chaal; *15*=Zarzis

kind of sampling reduces the subjectivity in the interpretation of the flowering period using field observations and monitors the behavior of the tree population as a whole (Orlandi et al. 2010; Osborne et al. 2000).

The data collected were used to calculate the daily pollen concentrations in the air, and subsequently, to construct a complete emission spectrum for the pollen (Fornaciari et al. 2000). The determination of the daily pollen concentrations allowed the definition of the pollination curve; i.e., the graphical representation of the flowering trend for each year for the study area (Aguilera and Ruiz-Valenzuela 2012b; Fornaciari et al. 2002). Two phenological variables were calculated: (1) the flowering start, which was defined as the day when 2.5 % of the total pollen counts during the entire flowering season was reached (modification of the criterion described by Galán et al. 2001) and (2) the full-flowering date, which corresponds to the day with the maximum daily pollen count, i.e., the peak pollination date. This value was chosen because it corresponds to the moment when the majority of the olive trees are involved in the full-flowering phenomenon, which thus indirectly represents the full-flowering periods for the different study sites. All of the flowering dates were calculated on the basis of the number of days from January 1 (the Julian days).

Table 1 Main features of each of the study areas

Study area	Country	Coordinates	Altitude (m a.s.l.)	Sampling period
Cordoba	Spain	37° 50′ N, 04° 45′ W	123	1993–2011
Jaen	Spain	37° 48′ N, 03° 48′ W	568	1993–2011
Granada	Spain	37° 11′ N, 03° 35′ W	685	1993–2011
Malaga	Spain	36° 47′ N, 04° 19′ W	5	1993–2011
Perugia	Italy	43° 06′ N, 12° 23′ E	450	1999–2011
Foggia	Italy	41° 25′ N, 15° 33′ E	70	1999–2011
Avellino	Italy	41° 10′ N, 15° 00′ E	29	1999–2011
Cosenza	Italy	39° 43′ N, 16° 10′ E	150	1999–2011
Messina	Italy	38° 06′ N, 14° 75′ E	200	1999–2011
Trapani	Italy	37° 40′ N, 12° 46′ E	160	1999–2011
Mornag	Tunisia	36° 39′ N, 10° 16′ E	40	1993–2011
Jemmel	Tunisia	35° 38′ N, 10° 41′ E	30	1993–2011
Menzel	Tunisia	35° 25′ N, 09° 50′ E	160	1993–2011
Chaal	Tunisia	34° 34′ N, 10° 19′ E	97	1993–2011
Zarzis	Tunisia	33° 35′ N, 11° 01′ E	17	1993–2011

Meteorological and bioclimatic data

The meteorological variables considered in the present study were arranged into two groups, as monthly or three-monthly (i.e., seasonal). These provided the mean maximum temperatures (*T*max, °C), the mean minimum temperatures (*T*min, °C), and the cumulative precipitation (*P*acp, mm). For the seasonal analysis, the meteorological variables were grouped as follows: June, July, and August (JJA; summer season); September, October, and November (SON; autumn season); and December, January, and February (DJF; winter season). It is important to consider that the olive tree is a plant with a 2-year reproductive cycle. Thus, the statistical analyses were between the flowering dates and meteorological parameters recorded from the summer of the previous year (June, *t*-1) to the late-spring of the flowering year (April, *t*).

The bioclimatic indices can be used to study the influence of climate on the distribution and biological development of plant species (Rivas-Martínez and Loidi 1999; Rivas-Martínez and Rivas-Sáenz 2008). In the present study, the seasonal ombrothermic indices (Io_x) were calculated as follows:

$$\mathrm{Io}_x = (\mathrm{Pp}_x/\mathrm{Tp}_x), \tag{1}$$

where Pp_x is the accumulated precipitation in season x (mm) and Tp_x is 10-fold the sum of the positive monthly mean temperatures of season x (°C) (Io_1, for the winter season; Io_3, for the summer season; Io_4, for the autumn season).

The meteorological data were obtained from the weather stations nearest to the study monitoring units, i.e., the Spanish Meteorological Agency (AEMET) for the Spanish sites, the Italian National Meteorological and Climatological Center (CNMCA) for the Italian sites, and the National Institute of Meteorology (NIM) for the Tunisian sites.

Statistical regression models

The forecasting models were constructed using partial least-squares regression, taking the dates of flowering (flowering start date, full-flowering date) as the dependent variables, and the meteorological and bioclimatic parameters as the independent variables. Partial least-squares regression is an appropriate statistical technique in this study, given the high number of parameters that can affect the date of olive flowering. The modeling was based on linear transformation of the original descriptors to a small number of orthogonal factors (latent variables), to maximize the covariance between the descriptors and the dependent variables; this procedure provides the optimal linear model in terms of the forecasting. In the present study, each latent variable represented a key factor for the start/peak olive flowering dates.

Eight regression models were built: four to predict flowering start and four to predict full flowering. The models were constructed based on different area ranges: an overall global model for the Mediterranean region that included the data from all of the 15 sampling sites and 3 national or regional models using the data for the Spanish sites (the Spain model), the Italian sites (the Italy model), and the Tunisian sites (the Tunisia model).

It can be noted that as the different study sites were analyzed together for the construction of both the global and the national models, all of the variables were standardized. The standardization of the variables prevents any particular phenological sampling points having more weight in the statistical interpretation than any of the others. To avoid these potential errors, the following standardization formula was applied:

$$Z_i = (X_i - X_m)/\sigma, \tag{2}$$

where X_i is an analyzed case of the variable X, Z_i is the typified value of X_i, X_m is the mean value of the variable X, and σ is the standard deviation of variable X.

All of the models were validated following the full cross-validation method. The Unscrambler 9.7 software was used.

Flowering date projections

Once the eight statistical models were built and validated, the mean flowering dates of each macro-area (global area or regional area) for both the past and the future periods were estimated. First, there was an evaluation of the past climate using meteorological data collected from the weather stations nearest to the monitoring units. Secondly, the future climate characterization of each study macro-area was constructed, based on the future climate change projections over the Mediterranean region obtained by Giorgi and Lionello (2008) under the A1B emission scenario for the period 2081 to 2100. The period from 1961 to 1980 was used as the reference past period. According to the Intergovernmental Panel on Climate Change (IPCC 2007), the A1B emission scenario balances the use of fossil and non-fossil energy sources, and can be considered an intermediate future scenario in terms of greenhouse gas emissions.

For a more accurate analysis, Giorgi and Lionello (2008) divided the Mediterranean area into a number of sub-regions. The projections obtained for the western Mediterranean sub-region (28° N–44° N, 9.5° W–10.5° E) were used to characterize the future climate of the Spanish and the Tunisian sites, while the projections obtained for the central Mediterranean sub-region (28° N–46° N, 10.5° E–20.5° E) were used to characterize the future climate of the Italian sites (see Giorgi and Lionello 2008). This information was useful to obtain an approximation of the hypothetical future climate under the A1B emission scenario for the study area.

Afterwards, and using the statistical models, both the flowering start and full-flowering dates for the past (1961–1980) and the future (2081–2100) periods were estimated. Finally, the past and the future olive flowering simulations (predicted data) were compared to the present flowering dates (observed data).

Results

Flowering start models

The statistical parameters for the flowering start prediction models across the different study sites are given in Table 2. The determination coefficients of the national models (R^2) were generally high, ranging from 0.66 to 0.81. The best result was obtained for the Mediterranean model, with R^2=0.84. The models offer acceptable predictions given that the determination coefficients of the full cross-validation (Q^2) were all higher than 0.60, reaching the maximum value of 0.81 for the Mediterranean model.

The more important predictive variables involved in the regression output to forecast the flowering start were generally similar in all of the models. The mean minimum temperature during the winter and the mean maximum temperature during March were included in the four statistical models with negative and generally high coefficient values (Fig. 2). The accumulated precipitation during March had a high and positive influence on the olive flowering start date. This variable was included in three of the four statistical models, i.e., in the Spanish, Italian, and Mediterranean models. The parameters related to the autumn season were particularly important. In general, high temperatures during this period had a negative effect on the flowering start, while a positive influence was observed with regard to the cumulative rainfall. The mean maximum temperature of the summer period had a negative influence on the flowering start of the olives in the Tunisian study sites.

Table 2 Summary of the partial least-squares regression parameters for the flowering start model

Study area	Flowering start model parameters						
	n	*X*	SD	R^2	Q^2	RMSE (R^2)	RMSE (Q^2)
Spain	4	115	±6.61	0.75	0.70	3.268	3.561
Italy	6	137	±4.57	0.81	0.67	1.956	2.737
Tunisia	5	108	±7.08	0.66	0.61	3.627	5.537
Mediterranean	15	120	±3.11	0.84	0.81	5.045	5.592

n number of sites in each model, *X* mean of the dependent variable, *SD* standard deviation of the dependent variable, R^2 determination coefficient of the model, Q^2 determination coefficient of the full cross-validation, *RMSE* root mean square error

The incorporation of the ombrothermic indices into the statistical models predicting the flowering start date did not promote any significant changes. In the Spanish model, the inclusion of Io_3 (summer period) increased the determination coefficient (R^2) by 0.02 and the determination coefficient of the full cross-validation (Q^2) by 0.01. On the other hand, the replacement of Io_4 (autumn period) for both the mean maximum temperature and the cumulative precipitation of the same season increased the determination coefficient (R^2) of the Italian model by 0.06 and the determination coefficient of the full cross-validation (Q^2) by 0.11. The same was observed with regard to the Tunisian flowering start model. In this case, the replacement of Io_4 (autumn period) for both the mean minimum temperature and the cumulative precipitation in the autumn increased the determination coefficient (R^2) by 0.05 and the determination coefficient of the full cross-validation (Q^2) by 0.09. Finally, the inclusion of Io_3 (summer period) in the Mediterranean statistical model only increased the determination coefficient (R^2) by 0.02 and the determination coefficient of the full cross-validation (Q^2) by 0.01. The regression coefficients of the ombrothermic indices were positives in all cases.

Full-flowering models

The statistical parameters involved in the models for the full-flowering date forecast across the different study sites are given in Table 3. The determination coefficients of the national models (R^2) were between 0.80 and 0.84, while for the Mediterranean model, this was 0.87. In addition, the determination coefficients of the full cross-validation (Q^2) ranged from 0.67 for the Italian model to 0.83 for the Mediterranean model. These coefficient values were higher than those reported for the flowering start models, which suggests that the full-flowering models are more accurate.

The predictive variables that were revealed by the regression output as those that are more important for olive full flowering are shown in Fig. 3. The mean maximum temperature of March and April was included in the four statistical models, usually with high negative coefficients. The accumulated precipitation during March had significant and positive coefficients in all of the models, with the exception of the Tunisian model. The mean minimum temperature during autumn, which had a negative coefficient, was obtained as an important variable in three of the four statistical models; i.e., in the Italian, Tunisian, and Mediterranean models. The mean minimum temperature of the winter period had a negative effect on the full-flowering date in both the Spanish and the Italian models. Again, the mean maximum temperature of the summer period was included in the Tunisian model, with a negative coefficient.

The date of full flowering was not significantly influenced by the seasonal ombrothermic indices. The inclusion of Io_3

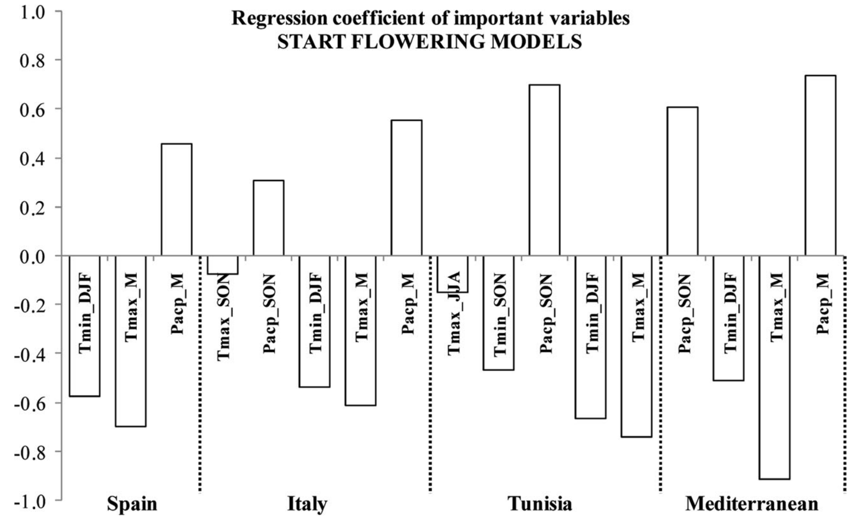


Fig. 2 Regression coefficient of the important variables included in the flowering start models. *Tmax_JJA* average maximum temperature in summer, *Tmax_SON* average maximum temperature in autumn, *Tmin_SON* average minimum temperature in autumn *Tmin_DJF* average minimum temperature in winter, *Pacp_SON* cumulative precipitation in autumn, *Tmax_M* average maximum temperature in March, *Pacp_M* cumulative precipitation in March

(summer period) in the Spanish model increased the determination coefficient (R^2) by 0.02 and the determination coefficient of the full cross-validation (Q^2) by 0.01. Moreover, the replacement of Io_4 (autumn) with the mean minimum temperature of the same season increased the determination coefficient (R^2) of the Italian model by 0.19 and the determination coefficient of the full cross-validation (Q^2) by 0.08. With regard to the Tunisian full-flowering model, the replacement of Io_4 (autumn period) for both the mean minimum temperature and the cumulative precipitation in the autumn increased the determination coefficient (R^2) by 0.05 and the determination coefficient of the full cross-validation (Q^2) by 0.02. Finally, the inclusion of Io_3 (summer) in the Mediterranean statistical model increased the determination coefficient (R^2) and the determination coefficient of the full cross-validation (Q^2) by 0.01, for both. Similar to the flowering start models, the regression coefficients of the ombrothermic indices were always positive.

The observed and expected values predicted by the eight statistical models that were validated using the full cross-validation method are shown in Fig. 4. The deviation between observed and expected values ranged from 1 to 7 % for the predictions for the flowering start dates, and between 1 and 5 % for the predictions for the full-flowering dates in the different national and global areas.

Given that the meteorological parameters related to the temperature were those more relevant to predict flowering dates, a more detailed study was carried out. The regression results showed that the combination of the mean minimum temperature during the winter with the mean maximum temperature during March significantly increased the percentage of explained variance (start of flowering) by 11 % for Spain and 29 % for Italy. However, this combination was not significant in the Tunisian area (Table 4). Regarding the full-flowering date, the incorporation of the mean minimum temperature during the winter did not show any additive and significant effects in the percentage of explained variance, with the spring temperatures being those needed for reaching full bloom.

Table 3 Summary of the partial least-squares regression parameters for the full-flowering model

Study area	Full-flowering model parameters						
	n	*X*	SD	R^2	Q^2	RMSE (R^2)	RMSE (Q^2)
Spain	4	135	±7.08	0.83	0.72	2.847	3.921
Italy	6	143	±5.44	0.84	0.67	2.158	3.432
Tunisia	5	120	±6.58	0.80	0.69	2.630	3.446
Mediterranean	15	133	±4.17	0.87	0.83	4.558	5.002

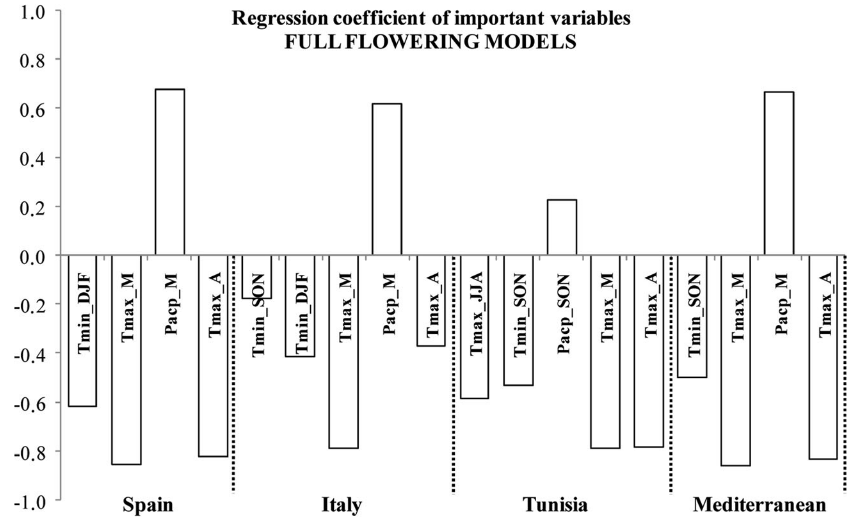
n number of sites in each model, *X* mean of the dependent variable, *SD* standard deviation of the dependent variable, R^2 determination coefficient of the model, Q^2 determination coefficient of the full cross-validation, *RMSE* root mean square error

Flowering date projections

At present, in the Spanish study sites, overall, the flowering start date is April 25 (Julian day 115). According to the statistical model, this flowering start date might be around April 16 (Julian day 106) in the future period from 2081 to 2100, and thus, it would be anticipated by 9 days with regard to the present period and by 17 days with regard to the flowering start estimated for the past period (May 3; Julian day 123) (Fig. 5a). On the other hand, at present, the mean full-flowering date is May 15 (Julian day 135). Anticipation of this by 12 days would be expected in the future (May 3; Julian day 123), which is 24 days with regard to the mean flowering start date estimated for the past period (May 27; Julian day 147) (Fig. 5b).

At present, for the Italian study sites, the average start date of the flowering period is May 17 (Julian day 137). According

Fig. 3 Regression coefficient of the important variables included in the full-flowering models. *Tmax_JJA* average maximum temperature in summer, *Tmin_SON* average minimum temperature in autumn, *Tmin_DJF* average minimum temperature in winter, *Pacp_SON* cumulative precipitation in autumn, *Tmax_M* average maximum temperature in March, *Tmax_A* average maximum temperature in April, *Pacp_M* cumulative precipitation in March



to the statistical model, for the future period, this date would be around May 8 (Julian day 128), so anticipated by 9 days with regard to the present period and by 15 days with regard to the flowering start date estimated for the past period (May 23; Julian day 143) (Fig. 5a). The mean peak of the full-flowering date is currently May 23 (Julian day 143). Anticipation by 10 days would be expected in the future (May 13; Julian day 133). In addition, a full-flowering date of June 1 (Julian day 152) was estimated for the past period for these study sites (Fig. 5b).

In the Tunisia study sites, the mean flowering start is currently April 18 (Julian day 108). According to the statistical model, in the future period, this flowering start date might be around April 7 (Julian day 97), which is anticipated by 11 days with regard to the present period and by 18 days for the flowering start estimated for the past period (April 25; Julian day 115) (Fig. 5a). At present, the mean peak of flowering date is April 30 (Julian day 120) and anticipation by 13 days would be expected in the future (April 17; Julian day 107), and by 23 days with regard to the past (May 10; Julian day 130) (Fig. 5b).

At present in the Mediterranean study area, the mean flowering start is April 30 (Julian day 120). According to the global statistical model, for the future period, this flowering start date might be around April 19 (Julian day 109), which is anticipated by 11 days with regard to the present period and by 20 days with regard to the past period (May 9; Julian day 129) (Fig. 5a). In this macro-area, the mean peak of flowering date is currently May 13 (Julian day 133) and anticipation by 12 days would be expected in the future (May 1; Julian day 121). At the same time, May 24 (Julian day 144) was estimated as the full-flowering date for the past period (Fig. 5b).

As can be seen in Fig. 5a, the flowering start date occurs in the Tunisian sites first, followed by the Spanish sites, and finally by the Italian sites. The chronological delay in this start date of the olive flowering period between these areas would tend to be similar in the future. However, an increase of 2–3 days for the anticipated full-flowering dates in the Spanish versus Italian sites over the successive time periods was observed, which is mainly due to the particular anticipation of the full flowering in Spain (Fig. 5b).

The numbers of days between both the flowering start and the full-flowering dates were also analyzed. This period is shorter over the successive time study periods, although these data did not reach significance. In the past, the number of days since the start of the flowering period to the full-flowering date ranged from 9 to 24 days, with a mean of 16±8 days. At present, this period lasts from between 6 and 20 days, with a mean of 13±7 days, which might be 11±6 days in the future (ranging between 5 and 17 days).

Discussion

The pheno-meteorological models elaborated for the explanation and forecasting of the main olive flowering phenophases across a wide latitudinal gradient throughout the Mediterranean region were successful. In general, the present dates of flowering start and full flowering were accurately predicted by all of the models, and the full cross-validation provided acceptable data.

Comparisons of the accuracies of the models indicated two particular points. On the one hand, the percentages of variance explained by the full-flowering models were greater than those explained by the flowering start models. According to previous studies and to the data obtained in the present study, the full-flowering date, which corresponds to the moment when the majority of the olive trees are in full flower, more accurately reflects the flowering period process of any particular area (García-Mozo et al. 2008; Orlandi et al. 2010). The flowering start was seen to be more variable, which appears to be due to pollen grains coming from remote olive-growing

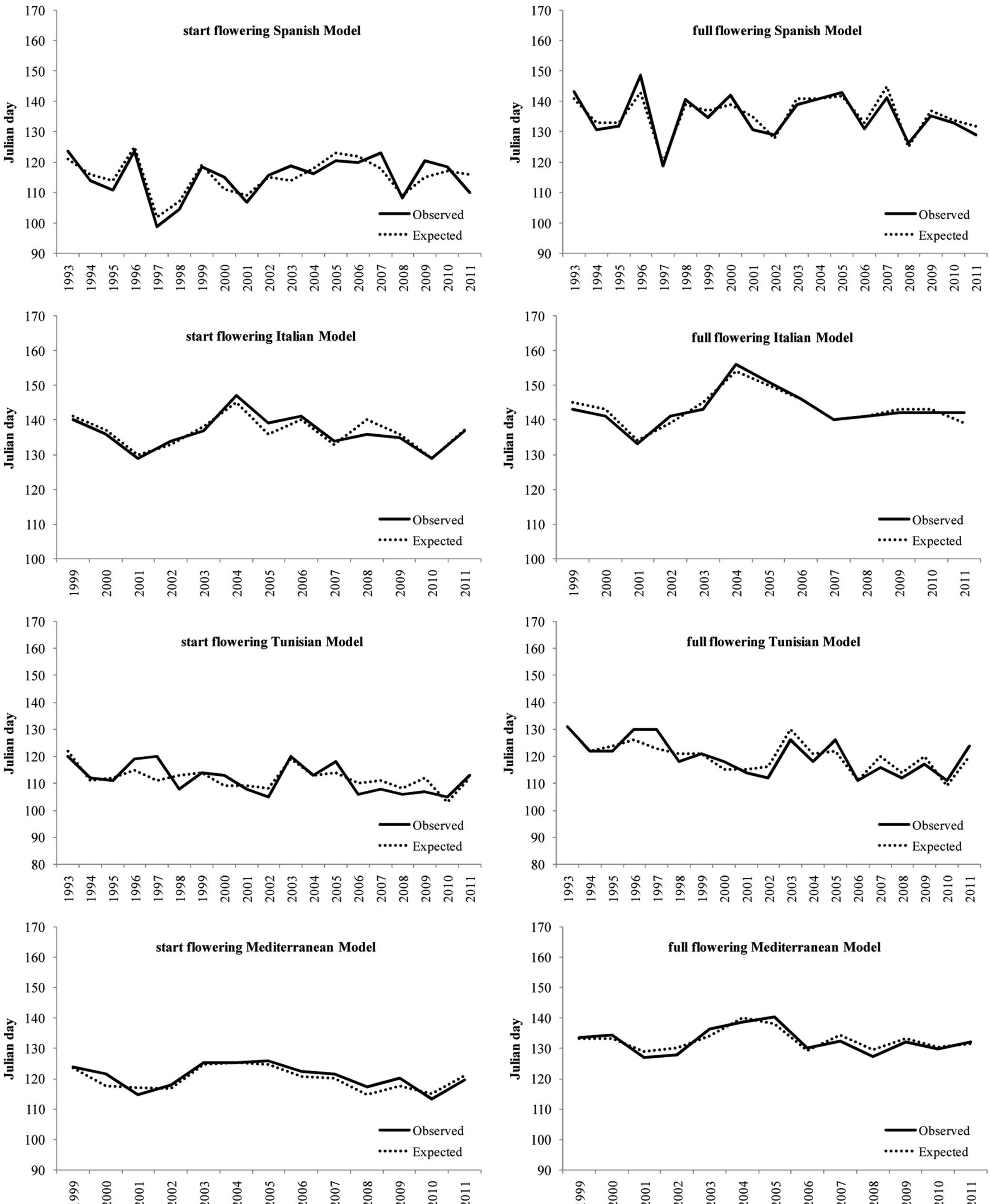


Fig. 4 Observed and expected values of the start and the full-flowering dates according to the different statistical models

areas with anticipated flowering that might introduce redundancy into the predictive models. Moreover, the full-flowering dates were accurately predicted by all of the statistical models, which explained about 84 % of the variance of the external

Table 4 Temperature effects on the start flowering date (regression results)

Parameter	Start flowering					
	Spain		Italy		Tunisia	
	R^2	β	R^2	β	R^2	β
*T*max_M	0.54	−0.75*	0.26	−0.51*	0.22	−0.49*
*T*min_DJF	0.21	−0.51*	0.32	−0.61*	0.18	−0.47*
*T*max_M, *T*min_DJF	0.65	−0.67*, −0.36*	0.55	−0.51*, −0.56*	0.31	−0.38, −0.37

Tmax_M average maximum temperature of March, *Tmin_DJF* average minimum temperature of the winter, R^2 determination coefficient, β regression coefficient value

*$p<0.05$

data. For these reasons, the full-flowering predictive models can be considered as the most useful to improve the knowledge of the influence of the climate on olive tree floral phenology.

On the other hand, large differences were not found in the significance of the determination coefficients between the regional and global models. In general, the local models are more precise than those produced on a large spatial scale, given the geographical and micro-climate variability (Capra et al. 2013; Chuine et al. 1999; García-Mozo et al. 2008). However, the data obtained in the present study indicate that the Mediterranean model is sufficiently accurate to predict the olive flowering dates as means for the global area under study. The similarities shown by the climate parameters involved in the floral phenology of the olive trees in each part of the study area might justify the good adjustment obtained with the global model, although another more feasible reason is compensation for the overestimation with the underestimation between the areas, which will result in higher coefficients.

Although the Mediterranean model is sufficiently accurate, the regional models are more effective for estimation of the olive tree flowering dates in each part of the study area. This conclusion is supported by the chronological delay detected in the actual flowering dates between these areas. A time lag from the North African sites to the central Mediterranean sites in the main olive flowering dates was clearly observed. These data are in agreement with previous aerobiological and phenological studies that have been carried out at both large and local spatial scales, which have revealed a chronology in the onset of the flowering period regarding altitude and/or latitude (Aguilera and Ruiz-Valenzuela 2012b; Aguilera et al. 2014; Díaz-de la Guardia et al. 2003; Fornaciari et al. 2000; Galán et al. 2005; Orlandi et al. 2014). Furthermore, the incorporation of similar meteorological parameters into the three regional models offers scientifically acceptable descriptions about the processes involved in the reproductive cycle of the olive tree species.

The olive flowering period is mainly affected by temperature. Numerous studies have demonstrated clear biological responses of different spring tree species to temperature, such as *Quercus* (García-Mozo et al. 2008), *Betula* (Rodríguez-Rajo et al. 2003), and *Olea* (Aguilera and Ruiz-Valenzuela 2009, 2012b; Bonofiglio et al. 2008; Fornaciari et al. 2000; Galán et al. 2008; Orlandi et al. 2009). The physiological behavior of temperate-zone tree species is regulated by different bioclimatic parameters, where temperature is a factor that has a particularly important role in several phenological phases, such as in inflorescence maturation and pollen release. The maximum temperature in March showed a strong negative influence on both the flowering start and the full-flowering dates, while the maximum temperature in April negatively affected the full-flowering date across all of the study area. These data are in agreement with those reported by Orlandi et al. (2009) for southern-central Italy. Similar negative effects were observed with respect to the autumn and winter temperatures, mainly with regard to the mean minimum temperatures of both of these seasons. According to Vergni and Todisco (2011), a general increase in minimum temperatures has been detected recently in central Mediterranean areas, which is occurring at a faster rate than for the maximum temperatures. Several studies have reported that olive trees need low temperatures to break the dormancy in the previously initiated buds, as occurs in other tree fruit species (Fernández-Escobar et al. 1992; Rallo and Martin 1991). High temperatures during these autumn and winter months might result in incomplete chilling and, consequently, a delay in the release of the floral bud dormancy, with detrimental effects on the subsequent flowering (Barranco et al. 2008; Martin et al. 1994). A previous study carried out in several localities along the Mediterranean basin demonstrated that at present, the chilling requirements for successive flower development can be considered as adequately fulfilled, even if differences were detected between the coldest and warmest areas. However, under a warmer future scenario, the chilling levels might not be sufficient to regulate olive dormancy (Aguilera et al. 2014).

In general, the winter and spring temperatures collectively affect the flowering start. The additive effect of winter temperatures was highly significant on the level of explanation of the flowering start variability, mainly in the Spanish and the Italian area. However, once the flowering has initiated, no additive effects were detected. This leads to the conclusion that from breaking bloom, only forcing temperatures are required to reaching the full-flowering stage.

Water is another main factor in the regulation of olive tree floral phenology. In general, the precipitation accumulated during both the autumn of the previous year and early spring (March) showed a high positive influence on the flowering start and full-flowering dates. Studies carried out on the southern Iberian Peninsula have shown that cumulative rainfall

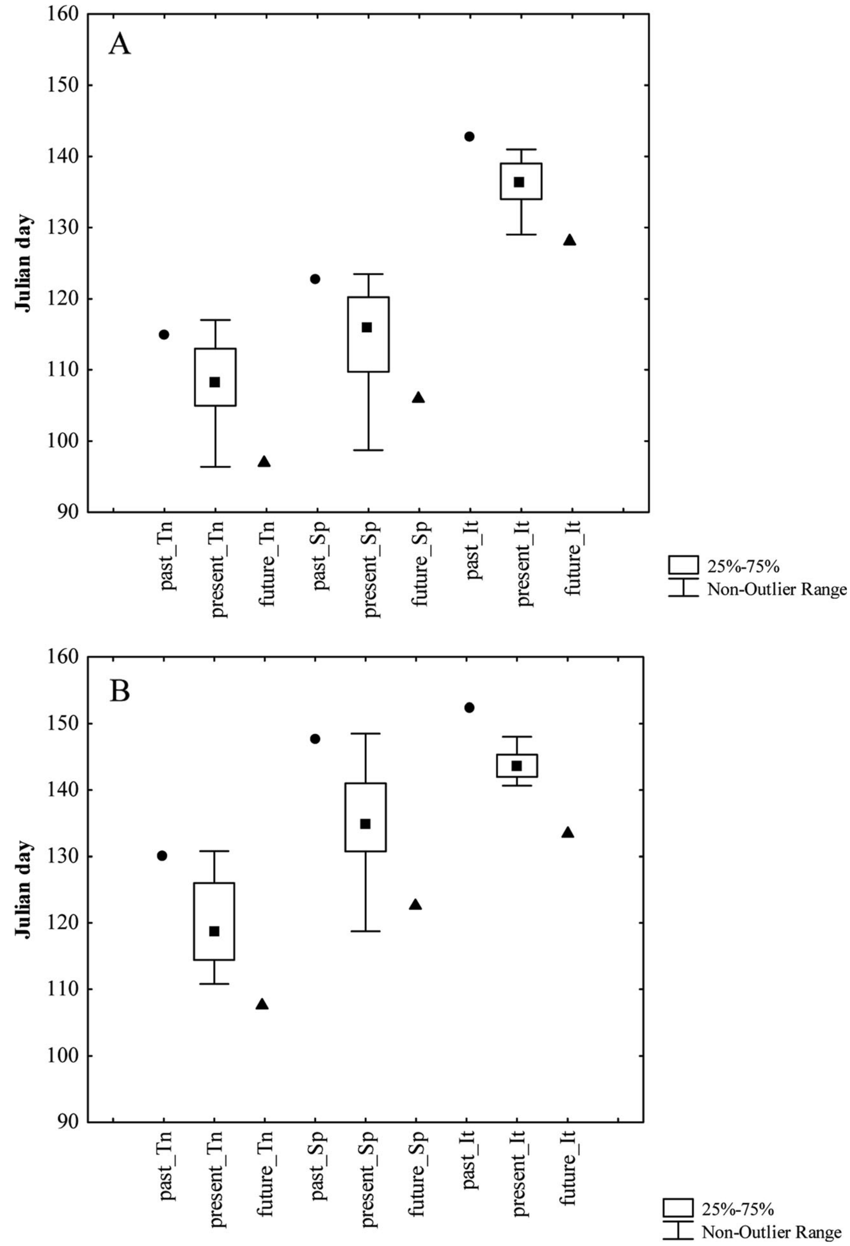


Fig. 5 Predictions of the average flowering start and full-flowering dates for both the past and the future periods. *Tn* Tunisia, *Sp* Spain, *It* Italy. **a** Flowering start date. **b** Full-flowering date

during the pre-flowering months delays the onset of the olive flowering period and increases the airborne pollen (Aguilera and Ruiz-Valenzuela 2009). When water deficit occurs during inflorescence development, many different flowering parameters can be reduced, such as inflorescence number, flower number, perfect flower number, and pollen production (Aguilera and Ruiz-Valenzuela 2009; Cuevas and Polito 2004; Gómez-Casero et al. 2004; Ogaya and Peñuelas 2007; Oteros et al. 2012; Rapoport et al. 2012). On the other hand, fruit maturation depends on the autumn rainfall pattern, as previously reported for typical Mediterranean species (Lavee 1994; Galán et al. 2008; Ogaya and Peñuelas 2007). Therefore, a lower rainfall regime during these phenological periods would seriously affect fruit production, and this is an important aspect given the socio-economical importance of olives and their products for the countries of the Mediterranean region (Oteros et al. 2013).

During the summer, the weather does not appear to affect the floral timing. Only in the warmest Mediterranean sites, such as in Tunisia, does the mean maximum temperature in the summer have negative effects on both the flowering start and full-flowering dates. This might be related to the floral-induction process. Floral induction in the olive occurs in early July, or about 6 weeks after full bloom, and environmental factors such as the temperature interact with the tree physiology to start this phenological phase (Martin et al. 1994). The extreme summer temperatures recorded in Tunisia might lead to the anticipation of floral induction and, subsequently, initiation, with an early spring flowering start being more likely. On the other hand, it is known that, under extreme temperature conditions, olive plants can reduce excessive water loss by closing their stoma, which leads to reduced photosynthetic activity and transpiration rates during dry seasons (Nogues and Baker 2000). As a consequence, tree carbohydrate levels can be drastically reduced, which negatively affects the reproductive parameters, such as flower number, ovary and ovule starch content, and the fruit-setting process (Rapoport et al. 2012).

The use of the ombroclimatic indices to construct the statistical models did not have any significant effects on the dependent variable. In general, the replacement of the seasonal ombroclimatic indices by simple variables, such as the temperature or precipitation recorded during the same season, increased the determination coefficients. This might arise because these indices use complex variables, which might not help when considering moderate improvements to the interpretation of a model; instead, the simplest plausible, or "parsimonious," regression models with the fewest possible numbers of variables can be created.

Significant warming in southern and central Europe is expected in the future, according to the different greenhouse gas emission scenarios, with decreasing trends in rainfall pattern detected, which relate mainly to the wet periods (Capra and Pavanelli 2010; Giorgi and Lionello 2008; Ulbrich et al. 2006; Vergni and Todisco 2011). However, the effects of climate change on the Mediterranean olive-growing areas might depend on how the changes in the temperature and rainfall patterns take place. The data from the present study show that a seasonal meteorological analysis is needed to establish the relationships between the Mediterranean climate and the olive tree floral development. Given that the reproductive phenology of the olive tree in the Mediterranean area is regulated by the meteorological parameters related to the previous autumn, winter, and spring seasons, the olive can be considered as a sensitive indicator of the biological impact of future climate change. In this sense, the present study adds further support to other studies that have indicated that olive phenology is a good and useful bio-indicator of future climate change, mainly through its dependence on temperature and through its geographical distribution over one of the most high-risk warming areas on the Earth (Galán et al. 2005; García-Mozo et al. 2008; Giorgi and Lionello 2008; Moriondo et al. 2008; Orlandi et al. 2014; Osborne et al. 2000; Vergni and Todisco 2011).

Over the last few decades, climate change has already modified the phenology of numerous plant species across Europe (Menzel et al. 2006). According to Menzel et al. (2006), flowering and other spring phases show stronger responses to temperature in warmer areas, where earlier mean flowering start dates have been observed. The use of the macro-areas considered in the present study for future meteorological characterization has allowed the estimation of the expected anticipation of the flowering phenology of the olive tree in the most productive olive-growing areas across the Mediterranean region. The mean anticipation for the flowering start date was here estimated at 10 days for the future period of 2081 to 2100, while a mean anticipation of 12 days would be expected for the full-flowering date. Previous studies carried out in southern Spain have suggested that the general anticipation of the pollen season start by 1 to 3 weeks can be expected by the end of this century (Galán et al. 2005). Furthermore, Orlandi et al. (2009) reported that over the last few decades, the temperature increase has corresponded to the anticipation of olive-pollen emission, with the estimation of a mean anticipation of 6.7 days/°C. Also, in large parts of southern France and Algeria, and in isolated sites in Morocco, anticipation of flowering by 6.9 days/°C was detected, with the estimated full-flowering dates from the 1990s to the 2030s occurring some 3 to 23 days earlier (Osborne et al. 2000).

From a phenological point of view, the anticipation of the flowering period can be interpreted as a defense mechanism or an adaptive phenomenon of the olive tree physiology to the higher temperatures expected in the future and, above all, to the particular increases projected for the spring temperatures (Fernández-González et al. 2005; Giorgi and Lionello 2008). This hypothesis finds support in terms that both the metabolic and photosynthetic activities of the olive are limited at temperatures higher than 30 °C (Barranco et al. 2008; Cuevas et al. 1994; Krueger 1994; Martin et al. 1994). Excessive temperatures expected in the future would negatively influence several reproductive parameters, including flower development, pollen-tube growth, pollen viability, and the pollination process, and, consequently, the subsequent fertilization and productive yield.

Along these lines, a recent study discussed how some typical areas of olive cultivation can be particularly sensitive to projected climate change, particularly in southern Mediterranean areas, which might become unsuitable for olive cultivation (Moriondo et al. 2013). One hypothesis was proposed: olive trees situated in the warmest areas can be displaced northwards or their physiology can adapt in response to the higher temperatures. Although long-time series of biological data would be necessary for this further monitoring, the present study can be considered as a first approach to design more detailed future bioclimatic studies.

Conclusions

The models defined in the present study are useful for explaining and forecasting the main olive flowering phenophases. These models are accurate, and the percentages of variance explained are considerably high. The meteorological parameters related to the previous autumn, winter, and spring regulate the reproductive phenology of the olive tree, above all in terms of the temperatures. However, the seasonal bioclimatic indices do not provide any great further significance to these models.

A general anticipation of the flowering season of the olive tree by 1 to 2 weeks could be expected by the end of the twenty-first century, which might be an adaptive phenomenon of the olive tree physiology to global warming. Although further studies would be necessary, the forecasting models proposed in the present study improve the knowledge of the influence of climate on the floral phenology of this Mediterranean tree species.

Acknowledgments F. Aguilera is grateful to the *Fundación Ramón Areces* (Madrid, Spain) for a Postdoctoral Grant. The authors are grateful to the Spanish Meteorological Agency (AEMET), the Italian National Meteorological and Climatological Center (CNMCA), and the National Institute of Meteorology of Tunisia (NIM) for providing the meteorological data. Moreover, the authors wish to thank the suggestions provided by Herminia García-Mozo and Rosa Pérez-Badia.

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