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# Modelling olive phenological response to weather and topography

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ABSTRACT

A detailed analysis was made of the response of olive floral phenology to climate and topography in southern Spain. Field phenological, topographical and meteorological data collected at 12 sampling sites in the province of Córdoba over a 17-year period (1996–2012) were statistically analyzed and used to model local olive phenological behaviour.

The study sought to determine: (1) the optimal frequency of phenological sampling during the reproductive period; (2) the major topographical parameters governing local olive reproductive phenology; and (3) the most influential meteorological variables. Findings for the Sign test indicated that weekly sampling yielded accurate results. Correlation and multiple linear regression analysis revealed that altitude and percentage eastward slope were the most influential topographical factors; a positive correlation was detected between delays in phenophases onset and increased altitude and eastward orientation. Correlation and partial least square regression analysis identified air temperature, rainfall, crop evapotranspiration and solar radiation as the major weather factors influencing local olive phenology.

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## 1. Introduction

Phenology was initially defined as “the study of the timing of recurring events, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species” (Lieth, 1974). More recent definitions, however, stress the important influence of the environment; Schwartz (1999), for example, notes that “phenology includes the study of periodic events as influenced by the environment, especially temperature changes driven by weather and climate”.

Plant reproductive phenology is heavily dependent on environmental conditions. Close examination of phenological behaviour, and of the bioclimatic factors influencing it, is of particular value in areas that are theoretically affected by climate warming, such as the Mediterranean region. This is especially true for major crops such as the olive, *Olea europaea* L., which is grown today not only over much of the Mediterranean basin, but also in south-western Asia and in the Americas, including California, Chile and Argentina (Barranco et al., 2008). The olive is clearly a key crop in agricultural, socioeconomic and environmental terms (Lavee, 1996). It is also important for health reasons the consumption of olive oil is seems to be regarded as beneficial (Tuck and Hayball, 2002), while olive pollen is associated with widespread allergic reactions (D'Amato et al., 2007; Barber et al., 2008). Andalusia region (southern Spain) is the world's largest olive-producing area, accounting for 61% of the total planted to olives in Spain; olive groves are concentrated mainly in provinces such as Jaen and Córdoba (Andalusia Statistical Yearbook, 2011).

Annual olive vegetative and reproductive cycles – and therefore annual fruit yield, which is directly related to flowering intensity (Fornaciari et al., 2005; Galán et al., 2008; García-Mozo et al., 2008; Orlandi et al., 2010a) – seems to be strongly influenced by environmental conditions. The complex phenological response to milder winter temperatures provides a reliable bio-indicator of the impact of climate change in a number of plant species (Osborne et al., 2000; Lambs et al., 2006; Menzel et al., 2006; García-Mozo et al., 2010; Gunderson et al., 2010; Xiao et al., 2013). The present study sought to examine the response of olive crops in the province of Córdoba to weather-related and topographical variables, using field phenological, topographical and meteorological data collected over a 17-year period from 1996 to 2012. Bud break in this area starts in around March, and the main flowering period is usually recorded in May, although changing weather conditions often prompt variations in timing, which have become particularly apparent over recent decades (Galán et al., 2005; Bonofiglio et al., 2008; García-Mozo et al., 2010; Orlandi et al., 2013a).

Although a combination of photoperiod and temperature determines the olive flowering period, it has been shown that temperature largely controls the reproductive development of the olive

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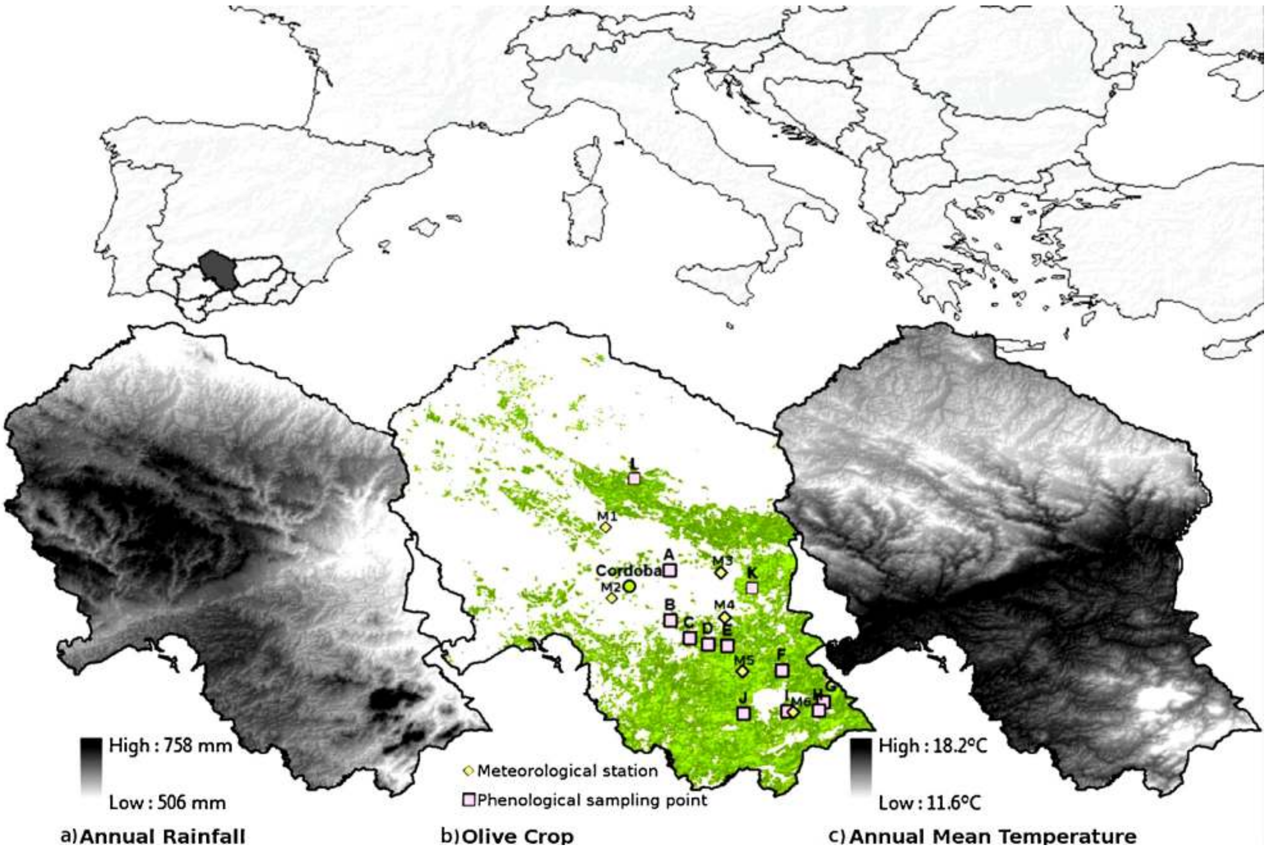

**Fig. 1.** Location of Córdoba province. (a) Annual rainfall distribution in Córdoba province. (b) Olive crop distribution, location of sampling sites (A–L) and weather stations (M1–M6). (c) Annual mean temperature distribution.

tree, especially during pre-flowering and anthesis (Galán et al., 2001, 2005; Melo-Abreu et al., 2004; García-Mozo et al., 2009; Sicard et al., 2012). Floral induction takes place during the previous summer, and a chilling period is required in order for buds to break winter dormancy (Rallo and Martin, 1991; Orlandi et al., 2006; Andreini et al., 2008). Subsequently, a warm period is required in order for the plant to accumulate sufficient forcing units physiological heat to enable flower development (Galán et al., 2005; Orlandi et al., 2010b). Logically, topography also plays an important role in phenological development, which varies as a function of different photoperiods and weather conditions (García-Mozo et al., 2006; Aguilera and Ruíz-Valenzuela, 2009).

The phenological characteristics of any area are dependent on local climate, which is in turn governed both by macroclimatic conditions, defined by variables such as latitude, and by determinants of microclimatic conditions such as topography. Within a reduced study area, knowledge of microclimatic conditions is essential for a full understanding of differences in reproductive phenology. In order to identify the variables responsible for variations in phenotypic expression in the province of Córdoba, an analysis was made of the correlations between several topographical and weather-related variables and the specific phenological features of various sampling sites.

The main goal of the study was to model olive floral phenological behaviour, taking into account variations in the main factors influencing that behaviour at different sites in the province of Córdoba (Spain) over the last 17 years. Specifically, the study sought to determine: (1) the optimal frequency of phenological sampling during the reproductive period; (2) the major topographical variables governing local olive reproductive phenology; and (3) the most influential weather-related variables.

## 2. Materials and methods

### 2.1. Area of study and weather data

The study was carried out in the province of Córdoba, Andalusia (southern Spain) (Fig. 1). The province is located in the Mediterranean region. Local vegetation and crops are adapted to drought periods that last between two and nine months every year. Córdoba city is located in the valley of the Guadalquivir river. The annual mean temperature is 17.8 °C and the annual average rainfall is 621 mm; weather conditions vary greatly year-on-year. Moreover, the continental effect is reflected in particular thermal and rainfall regimes: low rainfall, low relative humidity, and wide daily and annual temperature ranges, are characteristic of the study area (Domínguez-Bascón, 2002). Torrential rains usually occur. Peak daily temperatures are recorded in the afternoon and minimum temperatures at dawn.

The study area, the olive crop distribution, and the location of sampling sites and weather stations, are shown in Fig. 1. This figure also shows variations in annual mean temperature and rainfall within the province. The characteristics of sampling sites are shown in Table 1. The main olive cultivar in the Cordoba province is “Hojiblanca”, except for some minor areas in the south of the province, with moreover “Hojiblanca”, “Picudo” cultivar is also present and in which are located some of our sampling points (namely Cabra, Carcabuey, Priego and Fuente Tójar).

Four topographical variables were analyzed for each site: altitude (m), maximum slope inclination (%) and maximum slope orientation (%) from South to North and from East to West. Slope orientation ranged from 0% to 100%; values close to 100% indicated maximum South and East orientation, while values close to 0% indicated North and West orientation.

**Table 1**
Characteristics of sampling sites.

| Sites | Code | Years | Altitude (m) | Coordinates |
|---|---|---|---|---|
| Alcolea | A | 2002–2012 | 160 | 37°55′ N, 4°40′ W |
| Torres Cabrera | B | 2003–2012 | 157 | 37°45′ N, 4°40′ W |
| Santa Cruz | C | 1996–2012 | 165 | 37°42′ N, 4°36′ W |
| Espejo | D | 2003–2012 | 360 | 37°40′ N, 4°32′ W |
| Castro del Río | E | 1996–2012 | 261 | 37°40′ N, 4°28′ W |
| Baena | F | 1996–2012 | 450 | 37°35′ N, 4°18′ W |
| Fuente Tójar | G | 2003–2012 | 567 | 37°29′ N, 4°10′ W |
| Priego de Córdoba | H | 2003–2012 | 535 | 37°28′ N, 4°11′ W |
| Carcabuey | I | 2003–2012 | 563 | 37°28′ N, 4°17′ W |
| Cabra | J | 2003–2012 | 482 | 37°27′ N, 4°25′ W |
| Bujalance | K | 1996–2012 | 222 | 37°54′ N, 4°23′ W |
| Pozoblanco | L | 1996–2012 | 649 | 38°23′ N, 4°51′ W |

Data were obtained from the weather stations nearest to sampling sites, designated M1–M6 (Fig. 1). All weather stations belong to the Andalusian Phytosanitary Information Alert Network (RAIF; www.juntadeandalucia.es) and the Spanish Meteorological Agency (AEMET; www.aemet.es). Geo-meteorological data were supplied by Worldclim database (Hijmans et al., 2005; www.worldclim.org). The following weather-related parameters were included in the analysis: average maximum and minimum temperature, cumulative rainfall, Chilling Units (CU), Growing Degree Days (GDD), Potential Evapotranspiration for the olive crop (ETc), cumulated rainfall minus ETc (Rf-ETc), and net Radiation (Rn) from January to June, because this time cover all the flowering development period. Bi-monthly, monthly, fortnightly and 10-day data were used, with a total of 288 variables. Chilling Units were calculated following the Utah method (Richardson et al., 1974). In view of local weather conditions, the chilling period was considered as the period from 1 November to 31 January, as is the date in which change the yearly thermal trend (Orlandi et al., 2004; Aguilera et al., 2013).

Heat requirements were calculated as “Growing Degree Days” (GDD°). In the light of earlier findings for this study area, 12.5 °C was used as threshold temperature calculated in previous studies as start limit for heat accumulation (Alcalá and Barranco, 1992; Galán et al., 2001). The sine wave method was used to calculate GDD° (Snyder, 1985). The first day for starting heat accumulation is considered 1 February, when the chilling accumulation period is finished.

Evapotranspiration for the olive crop was calculated using the Penman-Monteith formula, as corrected by the FAO (Allen et al., 1998). This formula includes the following daily parameters: maximum and minimum air temperature, mean air temperature, solar radiation, wind speed, maximum and minimum humidity. The recommended FAO crop rates were used (Pastor and Orgaz, 1994).

## 2.2. Phenological data

We also analyzed field phenology at 12 different sites: Alcolea at 160 m a.s.l., Torres Cabrera at 157 m a.s.l., Santa Cruz at 165 m a.s.l., Espejo at 360 m a.s.l., Castro del Río at 261 m a.s.l., Baena at 450 m a.s.l., Fuente Tójar at 567 m a.s.l., Priego de Córdoba at 535 m a.s.l., Carcabuey at 563 m a.s.l., Cabra at 482 m a.s.l., Bujalance at 222 m a.s.l. and Pozoblanco at 649 m a.s.l. (Table 1 and Fig. 1). Ten olive trees were periodically observed in all sites, from dormancy to the start of fruit development. The standardized BBCH scale was used to monitor phenological growth (Zadoks et al., 1974; Sanz-Cortés et al., 2002). The onset of each phenophase was designated by the relevant Julian day number, and the number of days was indicated in cases of phenological amplitude.

The following 10 phenophases were analyzed:

50: Inflorescence buds in leaf axils completely closed.
51: Inflorescence buds starting to swell on stem.
52: Inflorescence buds open.
54: Flower clusters growing.
57: The corolla, green-coloured, is longer than the calyx.
61: Beginning of flowering: 10% of flowers open.
65: Full flowering: at least 50% of flowers open.
67: First petals falling.
68: Majority of petals fallen or faded.
69: End of flowering, fruit set, non-fertilized ovaries fallen.

Three intervals of phenological amplitude were also analyzed:

Pre-flowering amplitude (51–61).
Flowering amplitude (61–67).
Post-flowering amplitude (67–68).

## 2.3. Statistical analysis

### 2.3.1. Optimal frequency of phenological sampling

The optimal frequency of field sampling was determined by statistical comparison of actual daily phenology data with daily estimates based on from weekly, twice-weekly and fortnightly data at the Alcolea site in 2002, the pilot sampling point. Linear interpolation was used to calculate estimated data. Differences between estimated and real data were checked using the Sign test, due to non-normal data distribution (Hodges, 1955). The SPSS 8.0 software package was used.

### 2.3.2. Phenology and topography

Relationship between phenological features and topographical factors at each site was analyzed. The study period between 2003 and 2012 was used for this purpose, as it is the longest time series covering all study sites (Table 1). The average onset of each phenophase was taken as the overall phenological feature for each site. For statistical analysis, every site has been considered separately. The correlation between topographical variables and phenophases was analyzed using two different approaches: (1) Spearman correlation analysis and (2) multiple linear regression (MLR) analysis. The SPSS 8.0 software package was used for this purpose.

### 2.3.3. Phenology and weather-related variables

For these statistical analyses, values for weather variables in each year and at each site were considered separately. The study period between 1996 and 2012 was used for this purpose. The influence of weather variables on phenological development was analyzed by (1) Spearman correlation analysis as a univariate approach; (2) partial least squares regression (PLSR) analysis as a multivariate approach. PLSR analysis was considered more appropriate than MLR in these kinds of studies, given the large number of predictor variables (288) (Carrascal et al., 2009). The SPSS 8.0 software package was used for correlation analysis and the Unscrambler 9.7 package for PLSR analysis.

Although biological and weather features varied among sites, for PLSR analysis all sites were analyzed together for obtaining more robust results, although this fact can reduce the adjustment of the models. For this purpose, all variables were typified to prevent some sampling sites having more weight than others in the statistical interpretation. The following formula was applied:

$$Z_i = \left(\frac{X_i - \bar{X}}{\sigma}\right) \tag{1}$$

where $X_i$ is an analyzed case of variable $X$; $Z_i$ is the typified value for $X_i$; $\bar{X}$ is the average value of variable $X$; $\sigma$ is the standard deviation of variable $X$.

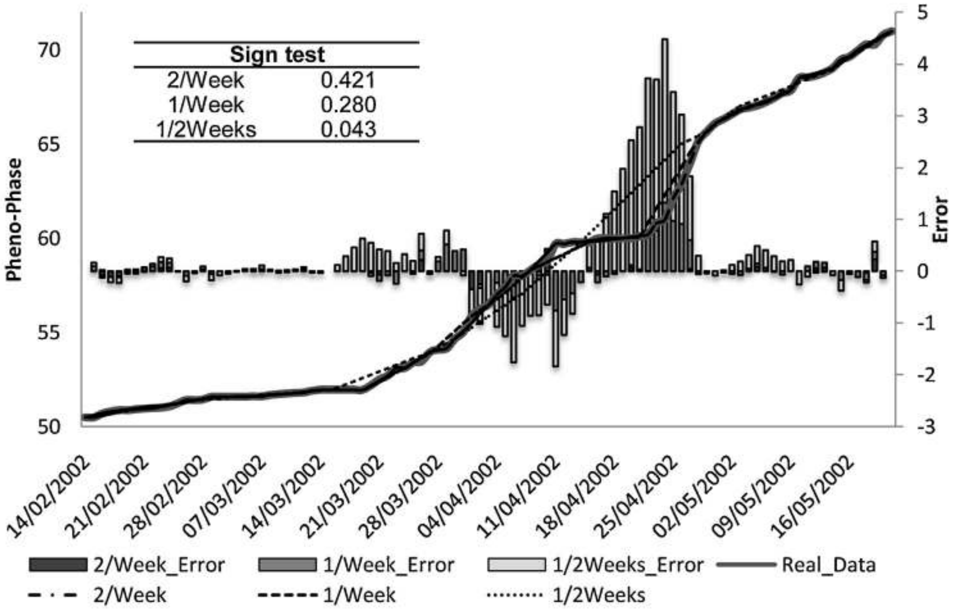

**Fig. 2.** Actual daily phenological data for the Alcolea site in 2002, compared with data interpolated from twice-weekly (2/week), weekly (1/week) and fortnightly sampling (1/2 weeks). Sign test to errors between actual and interpolated data are shown in the diagram.

## 3. Results

### 3.1. Phenological sampling frequency

Actual daily phenological values, together with those obtained by linear interpolation from weekly, twice-weekly and fortnightly data, are shown in Fig. 2. Significance levels using the Sign test are also provided. Although interpolated twice-weekly data displayed the greatest affinity with daily data, there were no significant differences with respect to interpolated weekly data. By contrast, interpolated fortnightly data exhibited significant differences with respect to actual daily data.

Analysis of the error between real and interpolated values (Fig. 2) showed that an increased interval between two samplings prompted greater error, and that greater error was detected in periods of faster phenological development. In the light of these findings, weekly sampling was deemed to be accurate.

### 3.2. Phenology and topography

Analysis of average phenophase timing at each site (Fig. 3) revealed a progressive delay in onset, as a function of altitude. Correlations between topographical and phenological variables are shown in Table 2. The results of regression analyses to determine the topographical causes of phenological differences detected between sampling sites are shown in Table 3.

Findings suggested that altitude and maximum slope orientation were the main factors responsible for differences in phenophase timing. Correlation and regression analysis confirmed that altitude was the topographical factor most influencing phenological development; a positive correlation was detected between delays in phenophase onset and increased altitude, but not between altitude and the phenophase amplitudes studied. Phenophase onset was also delayed as eastward orientation increased. Moreover, correlation analysis indicated that eastward orientation was associated with shorter flowering periods. Regression analysis confirmed that altitude accounted for over 60% of the variance in phenotypic expression of all phenophases, while percentage eastward slope accounted for over 20%. At some sites, however, topography accounted for over 90% of phenological variability.

**Table 2**
Spearman correlation coefficient for phenophases and topographical factors. PRE (preflowering period); FLOW (flowering period); POST (postflowering period); ALT (altitude); PEN (maximum slope); EW (percentage of maximum slope orientation to East and West); SN (percentage of maximum slope orientation to South and North).

| | ALT | PEN | EW | SN |
|---|---|---|---|---|
| Phenophase 51 | 0.891** | 0.018 | 0.642* | –0.207 |
| Phenophase 52 | 0.869** | 0.159 | 0.791** | –0.187 |
| Phenophase 54 | 0.939** | 0.134 | 0.679* | –0.226 |
| Phenophase 57 | 0.927** | 0.110 | 0.734* | –0.159 |
| Phenophase 61 | 0.903** | 0.159 | 0.697* | –0.116 |
| Phenophase 65 | 0.939** | 0.134 | 0.679* | –0.226 |
| Phenophase 67 | 0.939** | 0.134 | 0.679* | –0.226 |
| Phenophase 68 | 0.927** | 0.085 | 0.697* | –0.116 |
| PRE | 0.176 | 0.256 | 0.147 | 0.043 |
| FLOW | –0.245 | 0.225 | –0.688* | –0.548 |
| POST | –0.340 | –0.012 | –0.055 | 0.413 |

* $p < 0.05$.
** $p < 0.01$.

### 3.3. Phenology and weather-related variables

#### 3.3.1. Correlation analysis

A negative correlation was observed between water availability (Rf-ETc) in late January and the onset of all phenophases of pre-flowering and flowering. Thus, when

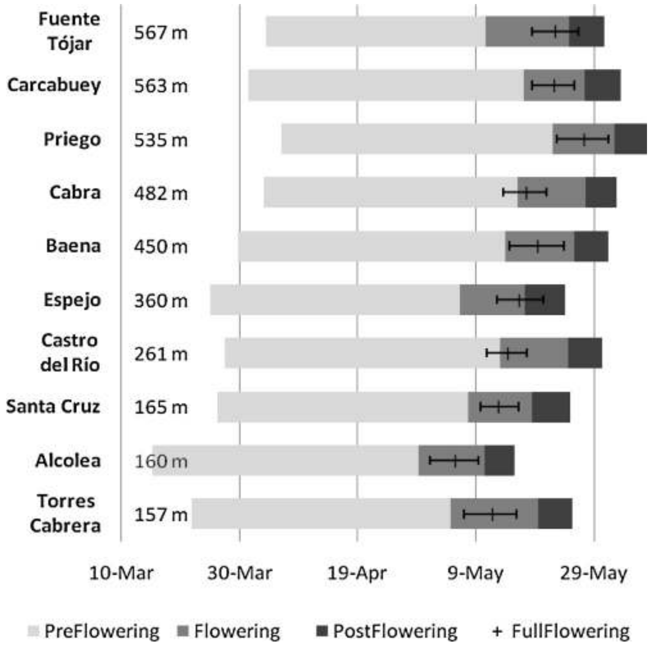

**Fig. 3.** Average phenological behaviour of each olive grove over the period 2003–2012. Full flowering (average date of phenophase 65 ± 95% confidence limit).

**Table 3**
Linear relationship between phenological behaviour and topographical data. ALT (altitude); EW (maximum slope orientation to east and west, %).

| Phenophase | Formula | Beta coefficient | $R^2$ | $p$ |
|---|---|---|---|---|
| 51 | PP51 = 75.527 + 0.028(Alt) + 0.045(EW) | Alt = 0.747EW = 0.228 | 0.772 | 0.006 |
| 52 | PP52 = 82.846 + 0.031(Alt) + 0.109(EW) | Alt = 0.643EW = 0.401 | 0.823 | 0.002 |
| 54 | PP54 = 94.256 + 0.032(Alt) + 0.101(EW) | Alt = 0.679EW = 0.377 | 0.847 | 0.001 |
| 57 | PP57 = 109.215 + 0.0293(Alt) + 0.078(EW) | Alt = 0.678EW = 0.325 | 0.778 | 0.005 |
| 61 | PP61 = 118.650 + 0.028(Alt) + 0.065(EW) | Alt = 0.718EW = 0.300 | 0.813 | 0.003 |
| 65 | PP65 = 125.000 + 0.028(Alt) + 0.053(EW) | Alt = 0.772EW = 0.260 | 0.856 | 0.001 |
| 67 | PP67 = 131.441 + 0.0275(Alt) + 0.048(EW) | Alt = 0.807EW = 0.251 | 0.908 | 0.000 |
| 68 | PP68 = 137.37 + 0.026(Alt) + 0.057(EW) | Alt = 0.770EW = 0.304 | 0.910 | 0.000 |

water was plentiful, the onset of floral bud development (51) was brought forward. Another water-related variable showing a strong influence at all sites was cumulative rainfall during March and April, especially in the pre-flowering period. Higher rainfall in these months increased the rate of phenological development. Net solar radiation in January, especially during the first fortnight, displayed a negative correlation with pre-flowering and flowering phenophase onset at all sites. Net solar radiation recorded in May displayed a strong negative correlation with the duration of post-flowering.

Air temperature was found to be the main factor influencing olive floral phenology. Maximum, minimum and mean air temperatures during flowering exhibited a strong negative correlation with the onset and duration of all phenophases at all sites. Higher temperatures led to advanced onset dates and shorter phenophase duration. Minimum temperatures in March exerted the greatest influence on the duration of both pre-flowering and flowering periods. Flower development phenophases, closer to full flowering (54 and 57) were especially influenced by temperatures in late February, March and early April, a strong negative correlation being observed with both maximum and minimum air temperatures. These variables, and particularly minimum air temperatures in March and April, displayed a strong negative correlation with the onset of flowering and the date of peak flowering (61 and 65). The heat-related variable most affecting post-flowering phenophases (67 and 68) was maximum temperature in May, especially in Baena (located at a higher altitude).

The number of Chilling Units accumulated during November, December and January correlated negatively with all phenophases, i.e. greater accumulation of cold prompted faster phenological development. The GDD° accumulated by the onset of flowering also displayed a strong negative correlation with the duration of flowering and post-flowering. A greater accumulation of GDD° led to faster phenological development and earlier flowering dates.

### 3.3.2. *PLSR analysis*

In order to determine which weather variables influenced phenological development and ascertain the magnitude of their effects, PLSR analysis was applied to the main phenological dates: onset of floral bud development (51), onset of flowering (61) and maximum flowering date (65). For phenophase 51, the resulting model included 2 principal components which jointly accounted for 92% of the variance shown by independent variables ($R^2X$) and 88% of the variance displayed by the dependent variable ($R^2Y$); the full cross-validation $Q^2$ was 0.77. For onset of flowering the model also included 2 principal components, jointly accounting for 78% and 83%, respectively, of the variance displayed by independent variables ($R^2X$) and the dependent variable ($R^2Y$); full cross-validation $Q^2$ was 0.71. Finally, for flowering the model accounted for 84% and 75%, respectively, of the variance exhibited by the independent variables ($R^2X$) and the dependent variable ($R^2Y$); full cross-validation $Q^2$ was 0.52.

As Fig. 4 shows, water availability at the beginning of the year (i.e. accumulated rainfall minus accumulated evapotranspiration, from 1 October to 31 January) had a marked influence on all phenophases, and especially on phenophase 51. Similarly, accumulated rainfall in March and April prompted an earlier flowering onset.

The variables most influencing phenological development were heat-related. An increase in both accumulated Chilling Units from 1 November to 31 January, and Growing Degrees Days from 31 January to 31 April prompted faster phenological development. The temperature range between January and April exerted an effect similar to that of heat accumulation. Average temperatures in February and minimum temperatures in March had a particularly strong influence on the onset of phenophase 51.

## 4. Discussion

Findings on floral phenology provide important information regarding the reproductive biology of crop species. A number of studies have examined olive floral development in a range of climatic areas (Melo-Abreu et al., 2004; Ribeiro et al., 2006; Tormo et al., 2011; Dimou, 2012). While most report a correlation between phenological development and weather-related variables (Avolio et al., 2008; Bonofiglio et al., 2009), others additionally note links with topographical features (García-Mozo et al., 2006; Aguilera and Ruíz-Valenzuela, 2009). The variety grown and the agricultural management regime used are also known to influence olive phenology (García-Mozo et al., 2009; Bacelar et al., 2009; Dias et al., 2012).

The present study provided statistical confirmation that the use of an average phenological stage representing each olive grove yields reliable results, as does the linear interpolation of weekly data in order to estimate daily phenological data. In view of the cost-benefit balance, weekly sampling would appear to be the best option.

Analysis of correlations between phenological development and topographical factors revealed that altitude was the single most influential variable, since at higher sampling sites the weather is colder. Similar findings are reported by numerous authors (Fornaciari et al., 2000; García-Mozo et al., 2006; Aguilera and Ruíz-Valenzuela, 2009). Delayed onset of phenophases was observed with increasing eastward orientation, perhaps because this determines the amount and quality of light reaching the plants. The olive variety grown is another key determinant of phenological behaviour; however, since "Hojiblanca" is by far the most widely grown cultivar in the study area, this had little effect on overall results.

The findings of this study confirm that air temperature is the factor most affecting phenophase onset and duration (Galán et al., 2005; Orlandi et al., 2013b). Weather conditions may have varying effects on the olive tree reproductive cycle, depending on the previous meteorological context, which might have a decisive influence on the plant's physiological status (Oteros et al., 2013a). This is borne out by analyses revealing that the same weather-related variables displayed different correlations with phenophase onset and duration at different sites. However, phenophases 54 and 57

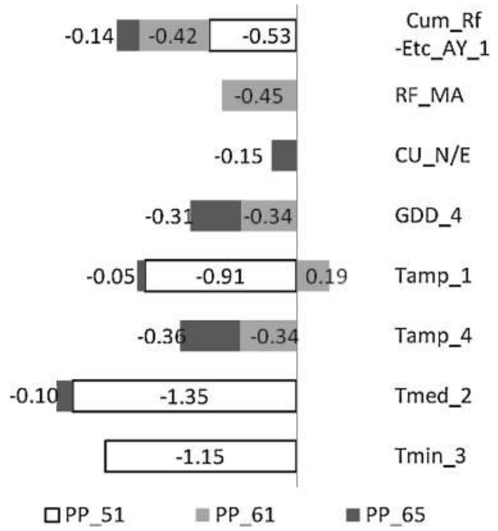

**Fig. 4.** Coefficients of important variables for onset of phenophases 51, 61 and 65.

(closer to flowering) were the most affected, probably because during this period the plant requires more energy as is related to pollen formation (Mert et al., 2013).

Water availability during the earlier floral phenophases (31 January) proved to be a major variable for all phenophases between 51 and 65. Here, limited water availability affected olive tree development at various phenological stages (Rapoport et al., 2012; Moorthy et al., 2011; Oteros et al., 2013b).

As also reported by Orlandi et al. (2004), the present findings highlighted the importance of the number of cold units accumulated between 1 November and 31 January, and of heat units accumulated between the end of the cold accumulation period and the onset of phenophase 51 or the start of flowering.

## 5. Conclusions

Statistical analysis to determine the optimal field phenological sampling periodicity reveals that weekly field monitoring can be recommended as the minimum acceptable time for future studies on olive reproductive phenology.

The topographical variables most influencing olive reproductive phenology were altitude and East–West orientation of maximum slope, while the most influential weather-related variables were temperature in winter and early spring and water availability for flowering.

Our results covering a wide area and a long time period will be useful for various purposes. The detailed knowledge of the influence of bioclimatical conditions determining phenological behaviour of *O. europaea* is valuable information to model the potential effects of climate change on olive tree, and to estimate the future adaptation of olive growing requirements in different geographical areas.

This response of the olive tree to climate change can have agricultural, economic, social, and public-health effects (allergy); advanced knowledge of its phenological behaviour will not only help us to better understand the reproductive biology of this specie but also to more accurately forecast crop yields.

The present findings should be borne in mind when reviewing measures to modify the olive agroecosystem in southern Europe.

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