

Quantitative forecasting of olive yield in Northern Portugal using a bioclimatic model

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Abstract In this work the objective was to develop a bioclimatic model to forecast olive yield based on airborne pollen, soil water content, and favourable conditions for phytopathological attacks. Olive airborne pollen was sampled from 1998 to 2006 using Cour traps installed in the Trás-os-Montes e Alto Douro region, in the provinces of Valença do Douro and Vila Nova de Foz-Côa. Meteorological data from a meteorological station located in Pinhão, near the pollen samplers, was used to calculate other independent variables. According to the bioclimatic model, at the flowering stage 63% of regional olive production can be predicted from the regional pollen index, with an average deviation between observed and predicted production of 10%. The variable soil water content enabled an increase in forecasting accuracy of about 30%, and a reduction in the average deviation between observed and predicted production of 6%. The final

regression with all three variables tested showed that the bioclimatic model was able to predict the annual variability of regional olive fruit production with an accuracy of 97%, the average deviation between observed and predicted production being 3% for internal validation and 6% for external validation.

Keywords Olive · Forecasting · Regional pollen index · Post-flowering · Principal-components analysis · Multiple regressions

1 Introduction

With oliviculture expansion and an increase of its economic importance in Mediterranean countries, representing 95% of world olive oil production, it has become necessary to improve and develop new cropping techniques, having in mind the maximization of agricultural yield. In this perspective, quantitative forecasting of yields is an important instrument in the support of the decision-making process of all the entities involved in the olive sector.

In recent years forecasting methods have made great progress especially concerning sampling and laboratory techniques and choice of explanatory variables for production variability. This has enabled higher accuracy and early-season indication of crop yields.

Aeropalynological applications for the purpose of explanation and forecasting of agricultural yields of vines and olives have been used in a great number

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of countries (Cour and Campo 1980; González-Minero et al. 1998; Moriondo et al. 2001; Cunha et al. 2003; Galán et al. 2004; Orlandi et al. 2005; García-Mozo et al. 2008). The use of aeropalynological data with the purpose of forecasting yields is based on the principle that the number of flowers per unit area of one determined species is superior in the most productive years, resulting in higher pollen production and, therefore, higher airborne pollen concentration. Also, it enables the integration of all pre-flowering conditions carried over from previous year(s) and easy updating of regional olive surface development (Cunha et al. 2003).

An important characteristic of olives is the long period between flowering and harvest date. Therefore, the plant is influenced by a number of agronomic and weather conditions after flowering, for example water deficit during fruit growth and phytopathological problems, which have a negative effect on fruit quantity and quality, and increasing interannual production, and an important impact on price levels and economic trade. Thus, the establishment of forecasting models based solely on airborne pollen sampling cannot be satisfactory when abnormal situations, responsible for limiting the crop production, occur between the flowering period and harvest.

The existence of a water deficit has great impact on whole plant development that can be observed at phenological, physiological, and production levels (Bacelar et al. 2007). In Mediterranean ecosystems, the summer months are characterized by high temperatures, high irradiance levels, and absence of rain. Stress resistance and low water requirements are physiological mechanisms developed by olive-trees to tolerate these xeric conditions. The occurrence of these climatic characteristics, in combination, for a long time, can, however, result in a severe decrease in production, because of reduction of the number, size, density, and oil content of the fruit and, therefore, reduction in its weight (Lavee and Wodner 1991; Chartzoulakis et al. 1992; Giorio et al. 1999; Patumi et al. 2002; Moriana and Orgaz 2003; Bacelar et al. 2006; Lavee et al. 2007).

Several authors have observed a positive close relationship between soil water content and fruit production but susceptibility to water deficit is not constant throughout the development phases (Proietti and Antognozzi 1996; Patumi et al. 1999; Lavee et al. 2007). According to Tombesi (1994) the critical period during which water stress has its great effect

on final production is that corresponding to the fruit-growing phase.

Another post-flowering condition which affects final yield is the occurrence of phytopathological attacks. The damage caused by these attacks during the flowering period is reflected by a reduction in the number of flowers and, consequently, in the amount of pollen released to the atmosphere. If the attack occurs during fruit maturing it can cause fruit size reduction, abscission, or even loss of oil content.

In Portugal several plagues and diseases, for example *Gloeosporium olivarum*, *Bactrocera oleae*, and *Prays oleae*, affect olive fruit production. They are very dependent on meteorological conditions during the fruit-maturing phase, namely warm temperatures, rain, and high levels of humidity (Cardoso et al. 2006; Talhinhos et al. 2006).

Despite all these affects on yield, as far as we are aware no forecasting model has yet integrated aeropalynological data with soil water content and conditions which favour occurrence of phytopathological attacks.

Therefore, the objective of this work was to develop a bioclimatic model for forecasting olive fruit production based on airborne pollen, soil water content during fruit growth, and conditions which favour the occurrence of phytopathological attacks during fruit maturing. With the proposed model it will be possible to update the forecast of olive production during the growing season.

2 Materials and methods

2.1 Study area and olive production

The olive (*Olea europaea* L.) covers around 11% (325,000 ha) of Portuguese utilized agricultural area (UAA), 80% being cultivated in rain-fed conditions.

Our study was conducted in the region of Trás-os-Montes e Alto Douro located in Northeast of Portugal. This region is Portugal's second largest olive-production area, accounting for 27 and 29% of the country's oil and fruit production, respectively. The most frequent olive varieties are Madural, Negrinha, Cobrançosa, Cordovil de Serpa, and Verdeal de Trás-os-Montes. The climate is characterized by the occurrence of very high temperatures in summer and very low temperatures in winter. According to reference meteorological data from

1961 to 1990, average minimum temperature in the winter varies between 0 and 2°C and in the summer average maximum temperature is between 26 and 32°C. The average annual number of frost days ranges between 70 and 110 while the number of hot days (maximum temperature higher than 35°C) ranges between 5 and 15 days. Mean annual accumulated precipitation varies between 900 and 1,400 mm, mainly centred in winter (Miranda et al. 2001). This region has relief features with a marked continental influence that contributes to the highest range in temperatures between summer and winter.

Information about annual olive fruit production expressed in tonnes (t) of olives recollected was obtained from the Statistical National Institute of Portugal.

The meteorological information was provided by ADVID and corresponds to data collected by the meteorological station located in Pinhão.

2.2 Model variables

The independent variables used to develop the bioclimatic forecasting model were the regional pollen index, soil water content, and number of rainy days with a mean temperature between 15 and 25°C.

Olive regional pollen was sampled during the flowering period, from 1998 to 2006, using Cour traps (Cour 1974) installed in the provinces Valença do Douro (VAD: 41°08'N, 7°33'W; altitude: 11 m) and Vila Nova de Foz-Côa (FOC: 41°09'N, 7°26'W; altitude: 10 m). The location of the samplers was chosen in accordance with analysis of the region's topography and the direction of the dominant winds during the flowering period (Fig. 1).

Pollen grains were trapped on vertical gauze filters (each exposed for 3 or 4 days), impregnated with silicone oil, with an area of 400 cm², fixed vertically on a wind-vane, which continually orientates the filters according to wind direction. After exposure, pollen grains were removed from the filter by use of several chemical treatments, including destruction of the gauze, acetolysis, and addition of glycerol (Cour 1974). *Olea* pollen qualitative and quantitative analysis was carried out, independently of pollen concentration, by means of three regular traverse movements of an optical microscope (×630) and average daily pollen was expressed as number of pollen grains transported per m² per day (Cour 1974).



Fig. 1 Location of the study area. Identification of sampling points (filled star VAD, Valença do Douro; filled star FOC, Vila Nova de Foz-Côa) and olive production area distribution (area shaded gray) considered in the study are represented

The regional pollen index was calculated as the sum of pollen sampled during the main pollination season (MPS). The MPS was determined using a pollen-emission model (Cunha et al. 2003; Ribeiro et al. 2007a). This model fits a non-linear logistic regression model to the values of the accumulated sum of daily airborne pollen concentration during a year (Cunha et al. 2003). A one-sided *t*-test was used at the 5% level, in order to estimate the beginning and end dates of the main pollen season. These dates correspond to the thresholds where the daily difference between the pollen emission model and its superior and inferior asymptotes was significant. The Levenberg–Marquardt method was used to fit the model by applying the “regression non-linear” function of the software SPSS 14.0.

Because the regional pollen indexes obtained in Valença do Douro and Vila Nova de Foz-Côa are linearly correlated, principal-components analysis was used to reduce the dimensions of the sampling and estimate a new variable that integrates into a linear combination the regional pollen index sampled in both sampling places—the scores of the principal component (Ribeiro et al. 2007b). This derived variable obtained was: $yj = (\gamma j_1 x_1 + \gamma j_2 x_2)$, where yj are the scores of the principal component, γj_1 , γj_2 are the variable loadings and x_1 , x_2 are the regional pollen indexes from Valença do Douro and Vila Nova de Foz-Côa, respectively. This analysis was performed using the “data reduction optimal scaling” function of the software SPSS 14.0. The new variable was the one used in the bioclimatic model.

Also, as observed previously by Ribeiro et al. (2007b), the best relationship between regional pollen index and olive production was logarithmic. This logarithmic relationship was always a better fit than the linear one, improving the R^2 values by 10%. Thus, before testing this variable in the bioclimatic model, a log-transformation was performed.

The soil water content, tested as an independent variable in the bioclimatic model, was calculated during the fruit-growing phase. Calculations were performed in accordance with the orienting lines recommended by FAO document no. 56 (Allen et al. 1998), where all procedures used to determine reference evapotranspiration (ET_0 mm day⁻¹) and crop evapotranspiration (ET_c mm day⁻¹) from meteorological data and from the cultural coefficient (K_c) are explained. The K_c values used were as measured by Orgaz and Fereres (1999).

Soil water content was calculated from the monthly sum of the difference between crop evapotranspiration (ET_c) and the occurrence of precipitation from June to August.

Reference evapotranspiration was calculated in accordance with the Hargreaves equation, Eq. 1.

$$ET_0 = \left[0.0023 (T_{\text{mean}} + 17.8) \times (T_{\text{maximum}} - T_{\text{minimum}})^{0.5} R_a \right] \text{nd} \quad (1)$$

where ET_0 is the reference evapotranspiration (mm day⁻¹); T_{mean} , T_{maximum} , and T_{minimum} are the monthly average, maximum, and minimum

temperatures (°C); R_a is the extra-terrestrial radiation (mm day⁻¹); and nd is the number of days in the month.

The occurrence of phytopathological attacks depends on warm temperatures, rain, and high levels of humidity, which are important control and metabolic regulation mechanisms of plagues and/or diseases. Therefore, a quantitative index relating the occurrence of a phytopathological attack to the number of rainy days with mean temperature between 15 and 25°C was developed. According to the literature, these conditions are associated with several key plagues and/or diseases of fruits (Cardoso et al. 2006; Talhinhos et al. 2006). This quantitative index was calculated during October.

2.3 Estimation and validation of the bioclimatic forecasting model

The bioclimatic model was fitted using stepwise multiple regression (Eq. 2) analysis in three different time periods:

$$y(i) = \beta_0 + \beta_1 \times x_1(i) + \beta_2 \times x_2(i) + \dots + \beta_n \times x_n(i) + \varepsilon_i \quad (2)$$

where $y(i)$ is the dependent variable, β_0 , β_1 , β_2 , and β_n are model coefficients, $x_1(i)$, $x_2(i)$, and $x_n(i)$ are the independent variables tested, and ε_i is the error which is not explained by the independent variables.

Olive production data from 1998 to 2006 were used to fit the model.

Regression analysis was evaluated and internally validated by use of a series of diagnostic tools namely the coefficient of determination (R^2), the adjusted R^2 , and the percentage deviation between real production data and data adjusted to the bioclimatic model (D (%)). The adjusted R^2 is a better indicator of the adjusted quality, as the addition of a new variable to the model only leads to an increase of this value if the error variance decreases in relation to the total variance. The global significance of the model and its estimated values were evaluated by ANOVA and by multiple t -tests performed on each estimated value. A Durbin–Watson test and a Kolmogorov–Smirnov test were also performed on residuals to verify their constant variance, null covariance, and normality. The degree of collinearity between the independent variables and potential presence of

outliers were evaluated using, respectively, *variance inflation factors* and *leverage* statistics.

Because the database available for this study covered nine years only, external validation of the forecasting models developed was performed using *leave-one-out* (LOO) cross-validation which evaluates the model prediction performance for a year not considered in the estimation step and provides independent estimates of the predictive power of selected models. This technique consists on the removal of one year from the database used and estimation of a new regression model with the remaining years. This new model will be used to predict the yield of the withdrawn year and calculate the deviation (%) between real production data and the adjusted data. This process was sequentially performed until all years of the database had been left out once (Gommes et al. 1981).

3 Results

During the period studied olive fruit production in the Trás-os-Montes e Alto Douro region was characterized by interannual variations. Maximum fruit production was registered in 2006 (110 thousand tonnes), being the highest for the previous 14 years, and minimum fruit production in 2000 (40 thousand tonnes), with an average of 76 thousand tonnes. Annual yields during the period studied were highly variable (coefficient of variation: 28%). The same tendency was observed in the regional pollen index (Fig. 2).

In accordance with the results of the pollen emission model, olive MPS occurred between the middle of May and the end of July, lasting on average 21 days. Application of principal-components analysis to

Valença do Douro and Vila Nova de Foz-Côa sampling results explained 96% of the total airborne pollen concentration variability.

Table 1 shows the regression results, significance of variables, model diagnostics, measures of model adequacy, and estimates of the regression coefficients for the bioclimatic model of Trás-os-Montes e Alto Douro regional olive production at three different stages of the olive-growing season (1A, flowering; 1B, end of fruit growth, and 1C, fruit maturing).

In the time period between flowering and fruit maturing the predictive power of the forecasting bioclimatic model was increased by inclusion in the stepwise regression model of post-flowering variables.

The model fitted at the flowering stage showed that 63% of regional olive production can be explained by pre-flowering conditions represented by the regional pollen index (Table 1, model 1A). Average deviation between observed and predicted production was 10% with a maximum value of 38%, observed in 2005 (Fig. 3). Results of external validation showed an average deviation between observed and predicted production of 13%.

Stepwise regression with inclusion of the variable sum of soil water content during June and August resulted in an increase in forecasting accuracy of approximately 30%. Average deviation between observed and predicted production was 6% for internal validation and 11% for cross validation, with maximum values of 15 and 38%, respectively, observed in 2000.

Final stepwise regression with all three variables tested showed that the bioclimatic model was able to predict regional olive fruit production annual variability with an accuracy of 97% (Table 1, model 1C).

Fig. 2 Interannual variations of the regional pollen index sampled in Valença do Douro and Vila Nova de Foz-Côa, and olive fruit production for the region of Trás-os-Montes e Alto Douro from 1998 until 2006

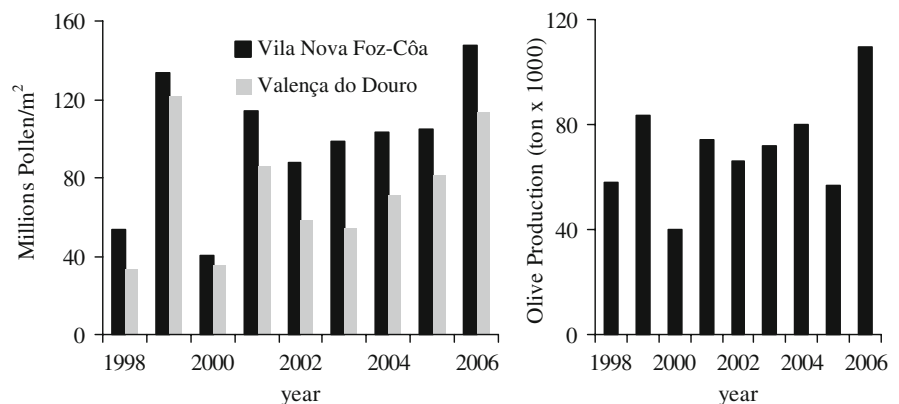


Table 1 Regression results, significance of variables, model diagnostics, measures of model adequacy, and estimates of the regression coefficients for the bioclimatic model of regional olive production of Alto Douro e Trás-os-Montes at three different stages

Model	Variables	Model summary				Model variables				Model diagnosis			
		R^2	R^2_{adj}	SE	Sig	β	β_{stand}	SE	Sig	D-W	Sig K-S	VIF	Lev
1A	Constant	–	–	–	–	59420.68	–	5436.39	0.000	–	–	–	
	Pollen	0.63	0.58	12803.88	0.011	22509.00	0.79	6502.17	0.011	2.58	0.77	1.00	<0.48
1B	Constant	–	–	–	–	141665.53	–	14060.09	0.000	–	–	–	
	Pollen	0.63	0.58	12803.88	0.011	19617.65	0.69	2727.07	0.000	–	–	1.03	
	ET _c -R	0.95	0.93	5283.39	0.000	–363.91	–0.57	61.41	0.001	2.12	0.96	1.03	<0.62
1C	Constant	–	–	–	–	160858.69	–	11020.52	0.000	–	–	–	–
	Pollen	0.63	0.58	12803.88	0.011	28745.97	1.01	3456.98	0.000	–	–	3.99	–
	ET _c -R	0.95	0.93	5283.39	0.000	–395.51	–0.62	40.94	0.000	–	–	1.10	–
	Nr + T°C	0.98	0.97	3409.14	0.000	–1449.28	–0.38	472.43	0.028	2.14	0.67	4.19	<0.66

1A, forecasting at the flowering stage; 1B, forecasting at the end of fruit growth; 1C, forecasting at the fruit-maturing stage; ET_c-R, water requirements during June to August; R^2 determination coefficient, R^2_{adj} adjusted determination coefficient, SE, standard error; sig, significance; K-S, Kolmogorov–Smirnov; D-W, Durbin–Watson; VIF, variance inflation factor; Lev, Leverage

Average deviation between observed and predicted production was 3% for internal validation, with a maximum value of 7% observed in 2004, and 6% for external validation, with a maximum value of 19% observed in 2000.

Analysis of the diagnostics and adequacy of the models showed that:

1. the global significance values of the regression model and its terms were <0.01;
2. residuals were randomly distributed around the value zero of the standardized prediction, indicating constant variance, the Durbin–Watson statistics were within the non-rejection of the H_0 hypotheses for residuals covariance, and significance values associated with the Kolmogorov–Smirnov test performed on residuals were higher than 0.05, the value below which the hypothesis of residuals normality is rejected; and
3. *variance inflation factors* values were lower than 4.19, indicating the absence of multicollinearity between the independent variables, and *leverage* values were lower than 0.66, indicating the absence of outlier observations.

4 Discussion

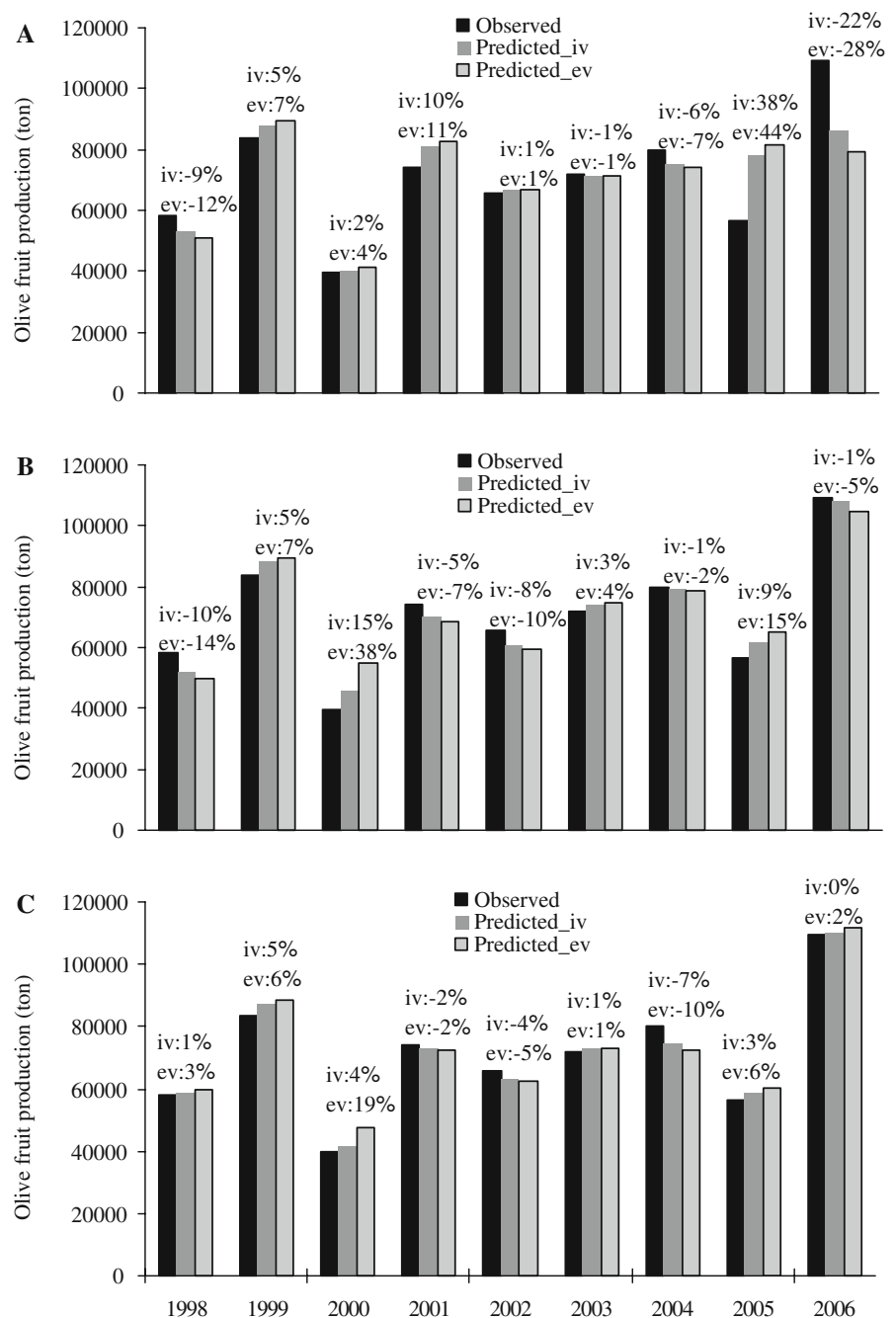
The Trás-os-Montes e Alto Douro production region is a large area characterized by the presence of different olive-tree varieties growing at different

altitudes, in different soils, and under specific meteorological conditions, for example dominant winds and temperature regimes. This heterogeneity has an important effect on the homogeneity of flowering, pollen emission, and pollen dispersion; as a consequence it reduces sampling precision. For this reason, the simultaneous use of more than one airborne pollen sampler to enable representation of these regional differences as the regional pollen index is advised (Fernandez-Mensaque et al. 1998; Cunha et al. 2003; Ribeiro et al. 2007b). However, the information acquired by use of several samplers is highly correlated because it corresponds to measurement of the behaviour of the same variable. Thus, use of principal-components analysis enabled reduction of the sample dimensions, summarizing the information of the original variables as an independent linear combination. This principal component represents almost all the information present in the original variables (total variability), losing the minimum possible information (only 4% in our study).

This technique enabled transformation of the regional pollen index calculated for Valença do Douro and Vila Nova de Foz-Côa into one variable only. Also, as observed in a previous study (Ribeiro et al. 2007b), it enabled improvement of the power of the forecasting model developed at the flowering stage when compared with use of information relevant to each sampling point separately.

Considering the regression models diagnosis, the forecasting models estimated during the olive-growing

Fig. 3 Differences (%) between observed and predicted fruit production (**A** forecasting at flowering; **B** forecasting at the end of fruit growth; **C** forecasting at fruit maturing)



season, and their variables, were significant, showing, therefore, their adequacy to explain the annual variability of olive fruit production. Also, regression residuals had constant variance, null covariance, and a normal distribution, corroborating the validity of the regression models computed. The presence of no extreme observations and no multicollinearity between

the independent variables indicates the models developed are statistically correct.

A log-transformation of the independent variable regional pollen index was performed. Usually the relationship between regional pollen index and olive production has been expressed as a linear relationship (González-Minero et al. 1998; Moriondo et al. 2001;

Galán et al. 2004; Orlandi et al. 2005). However a logarithmic relationship can be biologically more meaningful, because an important feature of anemophilous plants, such as the olive, is the production of a larger amount of flowers than mature into fruit. This results in fruit-to-flower ratios less than unity, because of a post-flowering mechanism, related to nutritional competition, controlling fruit abscission (Cuevas et al. 1995; Molina et al. 1996; Lavee et al. 1999).

Analysis of the standardized regression coefficients values, which allows comparison of the relative contribution of each variable to the forecasting model, revealed that the regional pollen index is the variable with the highest contribution to prediction of fruit production. The variable soil water content makes half the contribution of the regional pollen index to the forecast of fruit production, and the variable favourable conditions for the occurrence of phytopathological makes only a one-third of the contribution of the regional pollen index.

In fact, regional pollen index explained more than 63% of the interannual variability of olive production. This coefficient of determination was similar to those obtained in Spain, namely Cordoba ($R^2 = 0.75$) (Galán et al. 2004) and Seville ($R^2 = 0.62$) (González-Minero et al. 1998), and in Italy, namely Florence ($R^2 = 0.84$), Prato ($R^2 = 0.69$) (Moriondo et al. 2001), and Perugia ($R^2 = 0.54$) (Orlandi et al. 2005).

The significant influence of pre-flowering conditions (plagues, diseases, water deficit, or crop-management techniques observed in previous years) are reflected in the annual amount of flowers and pollen produced. Consequently, the regional pollen index will reproduce these variations, becoming a good biological indicator of potential crop production at flowering.

By considering the regional pollen index as the only variable explaining fruit production is possible to obtain a forecast 6–7 months before harvest, as a first evaluation of potential production acquired at flowering. The earliness of this forecast may compensate for the larger deviations between observed and predicted production obtained when compared with models integrating post-flowering variables.

Despite good fitting between the regional pollen index and olive production, there is still some potential to improve the forecasting model by considering the effect of post-flowering conditions

during fruit growth and maturing. This will enable updating of the forecasting model during the growing season, reducing the value of the multilinear regression function parameter ε_i .

Post-flowering variables, for example sum or mean precipitation and minimum or maximum temperatures during the months after flowering, have been used in forecasting models to represent the effect of the occurrence of favourable or unfavourable conditions on fruit production (Moriondo et al. 2001; Cunha et al. 2003; Galán et al. 2004).

The aim of updating the forecasting model at the end of fruit growth was to find a quantitative indicator of the effect of water deficit on olive fruit production.

The use of the soil water content as an independent variable is in accordance with results obtained by several authors showing the existence of a positive relationship between olive fruit production and water applied during the summer months (Proietti and Antognozzi 1996; Moriana and Orgaz 2003; Grattan et al. 2006; Lavee et al. 2007). According to Selles van Sch et al. (2006), the most sensitive olive-development stages in relation to water deficit are those involving cell enlargement processes, which are observed during the fruit-growth period.

In our study, a negative influence on fruit production of the variable soil water content was observed. Although olives are produced under dry-land conditions, and are very resistant to water deficit conditions, studies have shown that use of deficit irrigation can be one of the most important crop-production techniques in order to improve the yield of this plant. The use of irrigation results in an increase in fruit volume and weight, and an increase in pulp/pit ratio (Proietti and Antognozzi 1996; Patumi et al. 1999; Moriana and Orgaz 2003; Grattan et al. 2006; Lavee et al. 2007).

Updating the bioclimatic forecasting model by introduction of an index for conditions favourable for the occurrence of phytopathological attacks, which represents potential vulnerability to fruit damage caused by plagues or diseases, improved the accuracy of the fruit production forecasting model by approximately 10%. This independent variable can be adjusted to orchards from different ecological regions in accordance with the dependence of the bioecology of plant plagues and diseases on meteorological conditions.

Comparison of the values of the adjusted determination coefficients achieved by the bioclimatic model developed in our study at the end of fruit maturing phase revealed they were higher than those obtained by use of other forecasting models in Spain for Cordoba ($R^2 = 0.83$) (Galán et al. 2004) and in Italy for Prato ($R^2 = 0.77$) (Moriondo et al. 2001), which also used airborne pollen and post-flowering variables. Furthermore, the power of the bioclimatic forecasting model developed was higher than that of models which based forecasting of olive production on the amount of water applied (Grattan et al. 2006) or even on the value of crop evapotranspiration (Moriani and Orgaz 2003).

5 Conclusions

Our study demonstrated the ability of the bioclimatic model developed to predict olive fruit production. The average deviation from observed production was 3% and the average deviation from observed production for years not included in the model production was 6%. The dynamic construction of this bioclimatic model during different development stages can be highly relevant for every operator connected with the olive business, because it enables updating during the growing season. The prediction models developed in each phase were statistically accurate.

The regional pollen index is the variable with the highest effect on olive yield and can be used as an early-season indication of crop yields.

Our study also showed the weight of post-flowering variables related to plant-water stress and phytopathological attacks in the prediction of olive fruit production.

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