



Forecasting olive (*Olea europaea* L.) production using aerobiological and meteorological variables in Tétouan (NW Morocco)

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Abstract Airborne pollen and meteorological-related variables have proved to be a good indicator of flowering, olive fruit production and to predict harvest of upcoming crop, thus enabling efficient management and marketing strategies. This study describes the first forecasting models of the olive fruit production based on pre-peak airborne annual pollen integral (API_n) from *Olea europaea* L. and meteorological data prior and during the flowering and ripening olive trees in Tétouan (NW of Morocco) over a period of 11 years (2008–2018). Aerobiological sampling was conducted using Burkard volumetric Hirst trap. The data were analyzed by multiple regression analysis. Several forecasting models developed were validated using data of 2018 (not included in the models) and compared with real olive crop data obtained from the Provincial Directions of Agriculture of Tétouan. The main factors influencing the final olive crop were the rainfall registered prior to flowering (March) and during fruit growing and minimum temperatures in July and June. The most accurate forecast models for the 2018 harvest showed the highest coefficient of determination ($R^2 = 0.98$; $p < 0.001$) and predicted the lowest RMSE between expected and observed data

(452.80 and 398.75). The models developed provide efficient olive crop forecasting using independent variables which can be previously obtained. However, despite that the API_n is a reliable bio-indicator of regional crop yield forecasting in intensive farming areas it was not strongly representative in the regression equation probably due to the low airborne pollen concentrations recorded in Tétouan.

Keywords Crop forecasting · *Olea europaea* L. · Pollen integral · Meteorology · Tétouan

1 Introduction

The complex of olive cultivars and their wild relatives oleasters represent two botanical varieties of *O. europaea* subspecies (respectively, *europaea* and *sylvestris*) while most of the wild-looking forms of olive may include feral forms that escaped cultivation (Carrion et al. 2010). *Olea europaea* L. var. *europaea* is the most cultivated species in the Mediterranean and other worldwide regions. However, 95% of the total area under olive production is located in the Mediterranean countries (Barranco et al. 2008). One of the focal of the Green Moroccan Plan, launched in 2008, has been the olive sector, with the aim to modernize it and to increase olive cultivation to an area of 1,220,000 Hectares, while increasing production to

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2.5 million by 2020 (Ministry of Agriculture, Fisheries, Rural Development, Water and Forests (MAFRDWF 2020). The main regions of production cover almost the entire Moroccan country, except for the Atlantic coastal strip. The main variety produced is the “Moroccan Picholine” up to 96% of plantations (MAFRDWF 2020).

The olive tree is a largely wind-pollinated and generates large quantities of pollen ($1.10 \times 10^5 \pm 0.25 \times 10^5$ pollen grains per flower) (Rojo et al. 2015a) to ensure ovule fertilization. Although *Olea* pollen is considered in aerobiological studies due to its allergenicity, is also used as an indicator of flowering (Fornaciari et al. 1997, 1998; Osborne et al. 2000; Galán et al. 2005) and as a bioindicator of fruit production (Oteros et al. 2013a, 2014; Ben Dhiab et al. 2017; Aguilera and Ruiz-Valenzuela 2019), which is then useful in crop forecasting. Advanced knowledge about annual crop production is highly required from both biological and economic points of view (Aguilera and Ruiz-Valenzuela 2019; Orlandi et al. 2020).

Olive flower phenology is characterized by bud formation during summer, dormancy during autumn, budburst in late winter (February) and flowering in late spring (May–June) (Galán et al. 2005). Weather conditions such as temperature and water availability influence the beginning of flowering (Orlandi et al. 2009) and affect the olive pollen production (Ribeiro et al. 2006). A period of low temperature stops the growth of shoots and dormancy becomes generalized in all axillary buds in autumn (Rallo and Martin 1991). This period lasts until the temperature is favorable for bud growth and return to development, and reproductive bud burst can occur after sufficient chilling accumulation (Rallo and Martin 1991; Rallo and Cuevas 2017). Other factor influences the budding even if all the environmental conditions are favorable such as the growth regulators in particular the Gibberellic acid synthesized in the seed within the fruit setting. The flower bud induction is manifested by July, around the time of endocarp sclerification. The high numbers of olive fruit during the summer of the “on” year decrease or inhibit flower-bud formation for the next “off” year which contributes to the biennial production pattern (Fernandez-Escobar et al. 1992).

The amount of pollen released during pollination is a direct indicator of flowering intensity (Oteros et al. 2014; Rojo et al. 2015) and thus of final fruit yield

(Ribeiro et al. 2007). The presence of pollen in air can be used as a bio-indicator of fruit production. Similarly, meteorological parameters affect the timing and quantity of olive fruit development and must be taken into account for olive crop yield forecasting, especially in changing climatic conditions such as those of the Mediterranean region (Galán et al. 2004; Oteros et al. 2014; Orlandi et al. 2020).

The effect of meteorological parameters may differ considerably from each other depending on season and phenological stage. Research in this field found that rainfall and, especially, March temperature prior to flowering were the most influential meteorological-related factors (Oteros et al. 2013b). Water availability during spring is related to an increase in final fruit production in the Mediterranean basin at country scale for Spain, Italy and Tunisia. A decrease in fruit production was related with increasing temperature during winter and summer (Oteros et al. 2014). In Italy, minimum and maximum temperature during March–August showed a negative effect on olive production, while precipitation always showed a positive relationship (Orlandi et al. 2020). Air temperature also influenced final crop yield in three Tunisian provinces (Menzel Mhiri, Zarzis and Chaal), cumulative maximum temperature from budbreak to start of flowering contributed positively to yield in Menzel Mhiri, cumulative average temperature during fruit development had a positive impact on crop production in Zarzis, and cumulative maximum temperature prior to flowering negatively influenced crop yield. The amount, timing and distribution of rainfall between the previous autumn and budbreak influenced positively final olive harvest (Ben Dhiab et al. 2017).

The main aim of this study was to identify the main factors influencing olive fruit production and to develop predictive bio-meteorological models in Tétouan by using aerobiological pollen integral and meteorological parameters such as temperature and rainfall at different phenological stages. This study could help to provide a reliable harvest estimation to be used in agronomic and economic management strategies.

2 Materials and methods

The city of Tétouan (35° 34' N, 5° 22' W) is located in the western part of the Rif east of the Tingitana

Peninsula in the northwest of Morocco, in the thermomediterranean bioclimatic belt, at an altitude of 65 m not far from the Mediterranean coast. For the study years 2008–2018, the average annual mean temperature (T_{mean}) was 18.5 °C, and mean annual rainfall was 661.8 mm. The mean annual of maximum temperature (T_{max}) oscillated between 21.9 and 23.3 °C, whereas in the case of minimum temperatures (T_{min}), the average ranged from 13.9 to 17.7 °C (Table 1). The coldest period of the year is from December to February. Rarely, we recorded minimum temperature below 4 °C (2013, 2017 and 2018). The intra-annual variation of monthly average temperature and rainfall established for this period shows the pattern of the characteristic Mediterranean climate

Table 1 Average annual temperature (°C) and precipitation (mm) and their standard deviation recorded in Tétouan from 2008 to 2018

Years	T_{max}^a	T_{min}^b	T_{mean}^c	Rainfall
2008	22.5 ± 5.5	16.9 ± 4.2	19.7 ± 4.6	820.5 ± 8.5
2009	23.1 ± 5.4	17.7 ± 4.5	20.4 ± 4.9	837.3 ± 8.1
2010	23.1 ± 5.0	16.7 ± 4.2	19.9 ± 4.4	1008.4 ± 8.7
2011	22.4 ± 5.3	15.1 ± 5.0	18.7 ± 4.8	650.6 ± 6.6
2012	22.4 ± 6.0	14.4 ± 5.6	18.4 ± 5.4	517.8 ± 5.2
2013	21.9 ± 5.6	15.9 ± 4.9	17.1 ± 5.4	610.8 ± 6.1
2014	23.3 ± 5.2	14.9 ± 4.4	18.9 ± 4.5	477.04 ± 4.8
2015	23.1 ± 5.8	14.9 ± 5.1	18.7 ± 5.2	377.0 ± 3.7
2016	22.8 ± 5.2	15.1 ± 5.0	18.9 ± 4.7	633.0 ± 6.3
2017	22.9 ± 5.4	14.7 ± 5.4	18.6 ± 4.9	581.8 ± 6.2
2018	22.2 ± 5.3	13.9 ± 4.8	17.8 ± 4.7	734.8 ± 6.2
Mean	22.7 ± 4.8	15.9 ± 4.3	18.5 ± 4.5	661.8 ± 2.2

^a T_{max} = maximum temperature; ^b T_{min} = minimum temperature; ^c T_{mean} = mean temperature

(Fig. 1). The dry season starts from May to September. During this season, the amounts of rain are the lowest and the maximum of the average temperature was in August with 25.3 °C. The rainy season spans from October to April. The coldest period of the year is between December and February (Fig. 1). Due the geographical situation of the city between two mountain ranges, the dominant winds are those blowing from the NE (known locally as “Cherki”) and SW (known locally as “Gharbi”) (Aboulaïch et al. 2013).

Due to new plantations of the olive trees in the provinces of Tétouan and Mdiq-Fnideq, the total olive surface area increased to 30,823 ha oscillating between 13,600 and 17,460 ha for productive surface depending on the year. The annual output raised to 25,720 tonnes in 2015, 78% representing olive oil production and 22% self-consumption table and canned olives (Provincial Direction of Agriculture of Tétouan).

Aerobiological data were collected over a 11 years (2008–2018) period using a Hirst-type volumetric traps (Hirst 1952) (Burkard Lt model) located on the roof of the department of Biology of the Faculty of Sciences (University Abdelmalek Essaâdi) 15 m above ground level. As Tétouan city is located lower than 300 m a.s.l., the surrounding area with respect to the trap has the maximum influence at 59 km from the sampling point (Rojo et al. 2016). The sampler was calibrated to aspirate an air flow of 10 l/min. To collect daily airborne pollen, a trapping surface of Melinex film coated with 2% silicon solution was mounted on the drum rotating inside the sampler at a speed of 2 mm/h. The drum was changed weekly, and the exposed tape was cut into 7 pieces for daily pollen counts. The 24-h slide was analyzed by optical

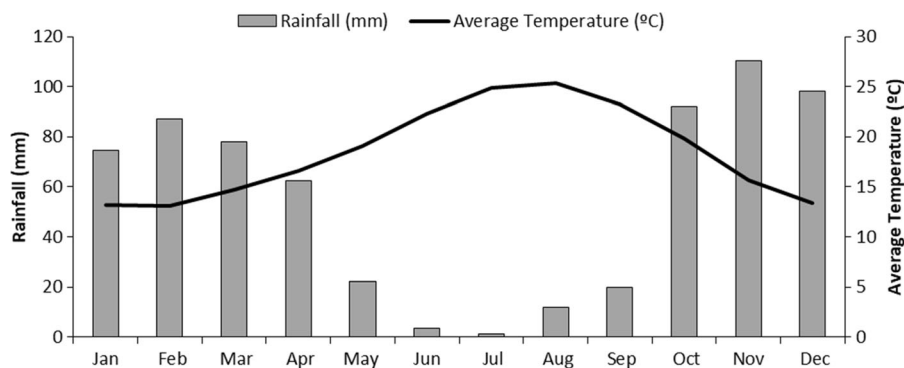


Fig. 1 Eleven year average data (2008–2011) for monthly mean temperature and monthly rainfall in the area of Tétouan

microscopy using 4 horizontal transects according to the method proposed by the Spanish Aerobiology Network (REA) (Galán et al. 2007). Average daily concentrations were expressed as the number of pollen grains per m³ of air and per day (p/m³).

The main pollen season (MPS) was determined by the 95% method according to Andersen (1991), assuming the beginning and end of the MPS as 2.5 and 97.5% of the annual pollen accumulated sums. The aerobiological variable used to forecast olive yield is pre-peak annual pollen integral (APIn) as the sum of daily pollen concentration from the start of the MPS to the maximum pollen concentration date (Fig. 2), as several studies indicate that pre-peak reflects the flowering period of a particular area, and the peak value in the curve occurred when most flowers are in anthesis (Aguilera and Ruiz Valenzuela 2009; Rojo and Pérez-Badia 2015).

The meteorological data included in the present study (Table 2) were delivered by the Biological department of the Faculty of Science which has an automatic meteorological station located near the sampler. Spearman's correlation test was performed to estimate the degree of relationships between olive fruit production and aerobiological and meteorological variables. Then, a stepwise multiple regression analysis was applied to produce the forecast models with olive fruit production as the dependent variable. The forecasting models were made from 2008 to 2017 using the aerobiological and monthly averages of temperature and rainfall data as independent variables. However, year 2018 was used to validate the forecast models. The forecast olive fruits production (expected values, POFP) were compared with the real olive crop

yield (observed value) produced by the Provincial Directions of Agriculture (PDA) of Tétouan. Therefore, the best model to forecast the harvest in future is the one showing the lowest RMSE between observed and expected olive fruits production. The statistical analysis was performed using Statistical Package for Social Sciences (SPSS) software (version 20.0).

3 Results

3.1 Pollen integral & olive fruits production in Tétouan

The average of daily olive pollen during the pollen season of the study period is shown in Fig. 2. The pollen season of the olive tree in Tétouan is registered basically from the beginning of April to the end of June recording 95.6% of the annual total pollen, although strong fluctuations appeared between years. May is the month which recorded the highest average daily peak value of 105 p/m³ during the study period of 2008–2018.

Although moderate quantities of pollen grains were collected in Tétouan, high interannual variation was observed between years. The year 2011 showed the lowest APIn and 2014 and 2015 showed higher APIn values in comparison with the other years being 2014 the year with the highest olive pollen records (Fig. 3). The link between precipitations and APIn shows that the higher pollen quantities are recorded with the lowest amount of precipitation registered during the pollen season, except for 2008 and 2009. Indeed, when the rainfall varied between 85 and

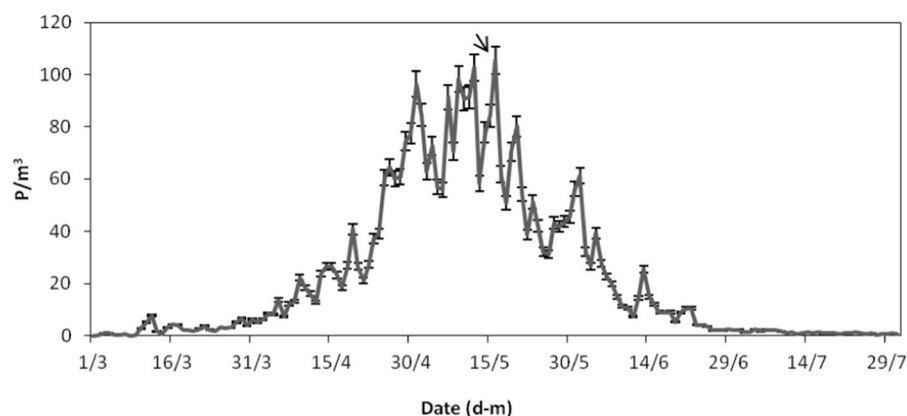
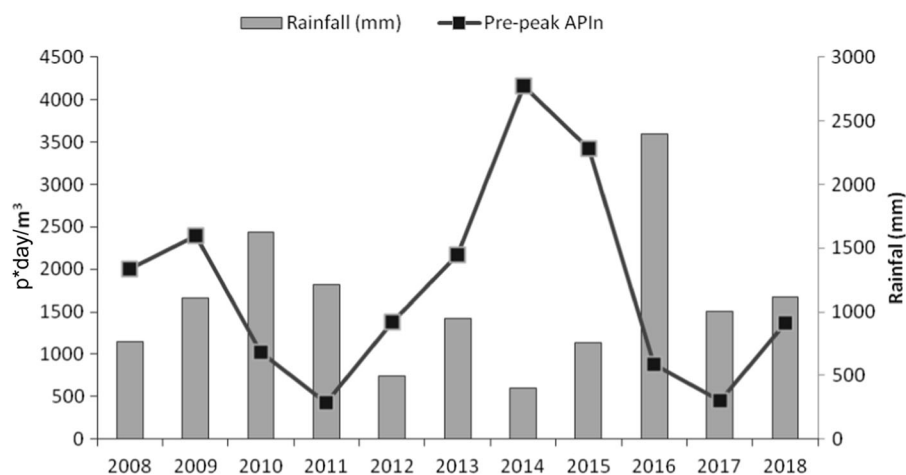


Fig. 2 Average daily *Olea europaea* pollen concentration and standard errors during the period 2008–2018

Table 2 Spearman's correlation coefficients between olive fruits production and biometeorological parameters in Tétouan

Independent variables	r Spearman
Pre-peak annual pollen integral (APIn)	0.543**
Daily maximum temperature of May (MxT _{May})	− 0.026
Daily maximum temperature of June (MxT _{June})	− 0.283**
Daily maximum temperature of July (MxT _{July})	− 0.010
Daily minimum temperature of May (MnT _{May})	− 0.306**
Daily minimum temperature of June (MnT _{June})	− 0.484**
Daily minimum temperature of July (MnT _{July})	− 0.273**
Average maximum temperature of May (AMxT _{May})	0.030
Average maximum temperature of June (AMxT _{June})	− 0.696**
Average maximum temperature of July (AMxT _{July})	− 0.058
Average minimum temperature of May (AMnT _{May})	− 0.261**
Average minimum temperature of June (AMnT _{June})	− 0.754**
Average minimum temperature of July (AMnT _{July})	− 0.319**
Daily rainfall of March (Rf _{March})	0.092
Daily rainfall of April (Rf _{April})	− 0.081
Total rainfall of March (TRf _{March})	0.257**
Total rainfall of April (TRf _{April})	− 0.543**
Total rainfall of October, November and December (TRf _{O-N-D})	− 0.543**

* $p < 0.05$, ** $p < 0.01$

**Fig. 3** Variation of rainfall and pre-peak annual pollen integral in Tétouan from 2008 to 2018

144 mm in 2010, 2011, 2016 and 2017, the APIn displayed the lowest value of 1025, 422, 844 and 449 $\text{p}^*\text{day}/\text{m}^3$, respectively.

Figure 4 illustrates the relationship between olive fruits production in Tétouan and the pre-peak APIn recorded during the study years. Pollen emission intensity of pre-peak displays strong interannual fluctuations and the bi-annual pattern characteristic of olive tree pollen production was not detected. The

average fruit production in the study period was 14,061 t. Annual crop production did not also show an alternating pattern for most of the study years. In later years, olive fruit production increased probably due the Green Moroccan Program (Plan Maroc Vert). A noticeable association between pollen emission and olive fruit production can be observed, and this pattern was not distinguished in 2008, 2011, 2016 and 2017.

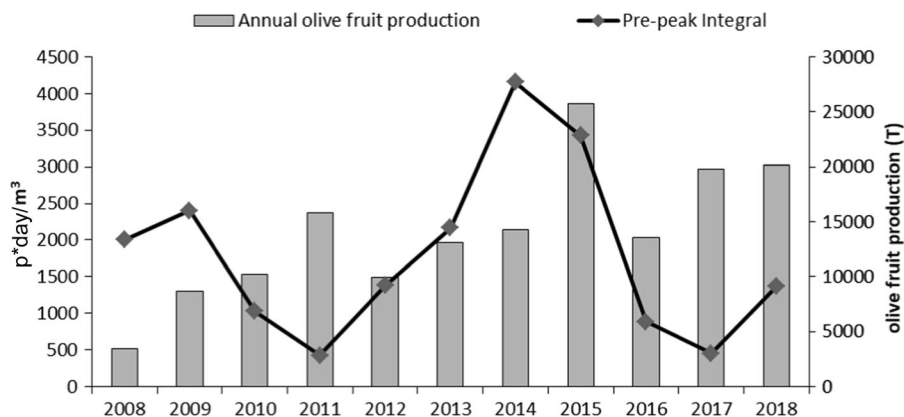


Fig. 4 Annual olive fruit production and pre-peak pollen integral in Tétouan from 2008 to 2018

3.2 Meteorological influence on crop production

The results of preliminary correlations between bio-meteorological parameters and olive fruits production (OFP) showed that temperature and rainfall were strongly correlated with olive production (Table 2). The correlation OFP and APIn was significantly positive. Daily minimum temperatures of May, June and July showed significant negative correlation coefficients. The same significance degrees were observed with the monthly average maximum temperatures of June and with the monthly average minimum temperatures of May–June–July, the highest coefficient of correlation was obtained with AMnT-June ($r = -0.754$, $p < 0.01$). Considering the rainfall, a strong significant positive correlation was obtained with total rainfall of March. The association between total rainfall recorded in April and autumn and OFP was significant negative. The correlation analysis also did not show a significant coefficient with maximum temperatures recorded in May and July.

3.3 Forecasting models for production

The forecast models developed for olive fruits production are complex and not based only on APIn but incorporate other meteorological variables that are determinants for *Olea* phenological traits such as monthly precipitations, minimum and maximum temperatures. Seven regression bio-meteorological forecasting models were constructed and integrate 2 to 6 variables (Table 3). The adjusted R^2 coefficients of determination values varied between 0.36 and 0.98. In

the models 6 and 7 with the highest R^2 , the variables exerting the strongest effect on crop production were minimum temperatures in June and July and to a lesser degree March and autumn rainfall (Table 3). Minimum temperature of July and March rainfall favoring positively crop development and minimum temperatures in June and autumn rainfall affecting negatively olive fruit production. The differences, in percentage, between observed and predicted fruit olive production, resulting from the validation of the models for the harvest of 2018, ranged from -5.23 to -33.27% . The most accurate forecasting models 6 and 7 predicted the lowest difference between expected and observed values with -5.94 and -5.23% , respectively (Table 3, Fig. 5).

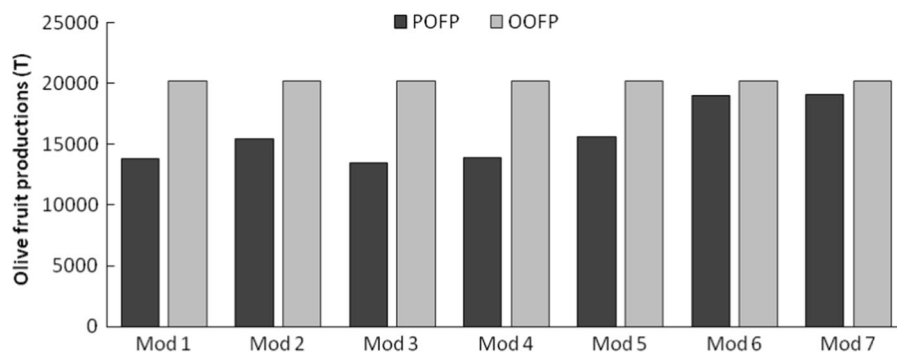
4 Discussion

Olea pollen is present in the atmosphere of Tétouan basically during the spring. The daily pollen spectrum showed significant interannual variability and the presence of several peaks of different intensities. The existence of these peaks can be explained by the non-synchronous release of pollen by the different varieties of cultivated olive trees, the different source areas of the pollen and to the mountainous topography of the northwest of Morocco. Thus, the south/south-west winds transport the pollen produced in mountainous areas of the interior in direction to Chefchaouen where the flowering of this taxon is delayed as the altitude is higher. These altitudinal fluctuations were observed previously in south-east of Spain (Aguilera and Ruiz

Table 3 Forecast models regression of olive fruit productions

Regression models	$R^{2a,b}$	POfP ^c	P-O ^d	RMSE
Mod ^e . 1 = 4450.702 + 3.290*API _n ^f + 18.337*TRf _{March} ^g	0.36	13,852	- 6318	2387.98
Mod. 2 = 6051.711 + 3.057*API _n + 21.381*TRf _{March} - 3.727* TRf _{N-O-D} ^h	0.37	15,428	- 4742	1792.31
Mod. 3 = -2771.481 + 3.383*API _n + 20.139*TRf _{March} + 323.462*AMnT _{July} ⁱ	0.36	13,460	- 6710	2536.14
Mod. 4 = 10,317.799 + 0.631*API _n + 14.586*TRf _{March} - 328.015*AMnT _{May}	0.36	13,907	- 6263	2367.19
Mod. 5 = 28,411.447 + 2.703*API _n - 2.551*TRf _{March} - 1123.364*AMnT _{June}	0.42	15,641	- 4529	1711.80
Mod. 6 = - 80,348.307 - 0.105*API _n + 33.614*TRf _{March} - 58.681*TRf _{N-O-D} - 4526.005*AMnT _{June} + 9250.454*AMnT _{July}	0.98	18,972	- 1198	452.80
Mod. 7 = - 80,348.307 - 0.105*API _n + 33.614*TRf _{March} - 58.681*TRf _{N-O-D} - 4526.005*AMnT _{June} + 9250.454*AMnT _{July} + 3.019. 10 ⁻¹¹ * AMnT _{May}	0.98	19,115	- 1055	398.75

^a R^2 = Adjusted Regression coefficient; ^b $p < 0.001$; ^c POfP, Predicted olive fruit productions; ^d P-O, difference between predicted (P) and observed (O) olive fruit productions; ^e Mod, model; ^f API_n, pre-peak annual pollen integral; ^g TRf_{March}, Total rainfall of March; ^h TRf_{N-O-D}, Total rainfall of November, October and December; ⁱ AMnT, Average minimum temperature

**Fig. 5** Comparison between predicted olive fruit productions developed by regression models (POFP) and observed harvest for 2018 (OOF)

Valenzuela 2012). In central Spain, the findings of Rojo and Pérez-Badia (2015) expected that the highest concentrations of olive pollen grains recorded during the peak flowering come from the nearby groves and showed that western, southern et southwestern winds transported pollen into the study area from earlier flowering groves located outside the territory. According to Rojo et al. (2016), Tétouan city located at an altitude lower than 300 m a.s.l receive pollen within a radius of 59 km as a maximum influence distance on pollen integral.

The phenological pollen seasons characteristics in Tétouan vary from year to year. Anthesis can be early and starts the first week of March as in 2008, or on the contrary, be later and starts at the end of the third week of April as in 2012, because it is strongly influenced by the meteorological conditions prior the season. The precipitations recorded in Tétouan (26 mm) for

12 days in April delayed the pollen season in 2012 (Achmakh et al. 2015). The onset of the pollen season at the south of the Mediterranean Sea occurred earlier compared to the Euro-Mediterranean countries (Liccardi et al. 1994; Dimou 2012; Galán et al. 2008; García-Mozo et al. 2008a, b; Achmakh et al. 2015; Plaza et al. 2016). Compared to other sites in the western Mediterranean (Aguilera et al., 2015), we can consider that the pollen season observed at Tétouan is significantly earlier. Indeed, the average start date is close to that observed in Tunisian sites and respects a latitudinal gradient of precocity compared to other sites of the north shore in Italy and Spain (Bouziiane et al. 2016).

The pollen production of olive trees in several sites in Spain and Italy displayed a biannual alternation, a year with a high pollen production followed by a decrease in the pollen production the following year

(Fornaciari et al. 1996; Diaz de la Guardia et al. 2003; Galán et al. 2004); this alternation was not noticed in Tétouan and masked by meteorological phenomena such as the large amounts of rainfall recorded during the pollen season in 2010 (103.2 mm), 2011 (144.6 mm), 2016 (85.2 mm) and 2017 (113.8 mm). This rainfall prevented the dispersion of *Olea* pollen during the pre-peak period and explains the low pollen concentrations recorded during these seasons. Vázquez et al. (2003) have shown a negative effect of rainfall on pollen integral during the pollination period due to the washout by raindrops. At the contrary, the higher pollen quantities reached in 2014 (4159 p/m³) and 2015 (3426 p/m³) coincided with low rainfall of 43.8 mm and 25.8 mm accumulated during the pollen season, respectively, in these years.

Olive tree are influenced by anthropogenic activities, and olive cultivation systems experienced technical agronomic innovations such as higher tree density with more productive cultivars, irrigation and material inputs (Orlandi et al. 2020). The olive fruit production in Tétouan shows considerable annual variations and increased last years. This increase could be explained by the high economic importance of olive growing and the increase on the land surface of this culture under the “Green Morocco Plan”. The olive fruits production was concomitant with pollen integral variation during the years 2010, 2012–2015 and 2018. However, this pattern was different, especially in 2008, 2011, 2016 and 2017, due to rainfall as outlined above. The temperature is also another climatic factor that strongly influences the interannual variations (Oteros et al. 2013a, b; Aguilera et al. 2014).

Airborne pollen is a reliable bio-indicator for both flowering intensity and for predicting harvests of the upcoming crop (Galán et al. 2004; Oteros et al. 2014; Aguilera and Ruiz-Valenzuela 2019). Knowledge of previous bio-meteorological factors influencing pollen production would help to develop more accurate predictions for olive fruits production. For that reason, the relationship between airborne pollen concentration and meteorological variables were used for modeling *Olea* crops in several areas (Orlandi et al. 2003, 2005, 2010; Galán et al. 2004, 2008; Ribeiro et al. 2007, 2008; García-Mozo et al. 2008b; Oteros et al. 2014; Aguilera and Ruiz-Valenzuela 2019). The use of aerobiological and meteorological data in Tétouan region (NW of Morocco) represents the first step forward in the development of crop forecasting

models. Preliminarily, the correlation between olive fruits production, meteorological variables and pollen integral was analyzed. The API_n affected significantly positive the olive fruit production. A strong and negative correlation was observed between olive crop harvests and minimum temperature of June–July and maximum temperature of June. Elevated temperature and evapotranspiration during fruit setting can lead to excessive fruit drop and a decline in the crop production. Similarly, Orlandi et al. (2020) reported a negative relationship between summer temperatures and olive production, coinciding with our results.

Accumulated rainfall is an important factor to take into account, March precipitations affected positively olive crop production. Water availability increases photosynthetic activity and number of flowers per inflorescence favoring crop production. This statement is supported by previous studies in Mediterranean basin (Oteros et al. 2014; Ben Dhiab et al. 2017; Orlandi et al. 2020). In contrast, rainfall recorded in April had a negative effect during the pollination due to the washout by rain drops. Rainfall during autumn impacted negatively olive production and seems not influence the “on” year olive harvest or excessive water may cause fruit damage and drop. However, the amount and timing of rainfall affect positively final olive harvest of the next year, since they determine the availability of water for the development of reproductive structures (Ben Dhiab et al. 2017). In Castilla-La Mancha (Central Spain), Spearman correlation analysis indicated that the annual pollen integral, the maximum temperature in March (for flowering) and September (for ripening) and the rainfall registered in October were the main variables influencing the final olive crop (García-Mozo et al. 2008b).

The forecast models developed for olive fruits production in Tétouan incorporate the pre-peak pollen integral and meteorological parameters before, during and after the flowering period. These parameters have the most influence on final olive crop production (Moriendo et al. 2001; Fornaciari et al. 2002; Aguilera and Ruiz-Valenzuela 2019). In the seven models obtained, the main positively influencing variables were minimum temperature in July and the rainfall registered in March; minimum temperatures during June and rainfall during autumn affected negatively crop production. A different result was observed in Andalusia (southern Spain), with the rainfall

registered in May, maximum temperature in June and APIn as the main influencing variables (Galán et al. 2004, 2008). It has been shown that rainfall accumulated during the final phase of fruit growing (autumn) also has a positive effect on crop harvest. Oteros et al. (2014) have developed predictive models for the Mediterranean basin (Tunisia, Italy and Spain). The findings show that higher pollen indexes and water availability during spring represented the most significant variables in all models, and they are related to an increase in final fruit production in the Mediterranean basin. Furthermore, the temperature has positive effects on crop production during the period prior to flowering and during autumn, and negative effects on crop production during the process of fruit setting in winter and then during summer, i.e., a decrease in fruit production is related with increasing air temperature during winter and summer (Oteros et al. 2014). The number of days with pollen concentrations ≥ 400 p/m³ was found as the aerobiological predictive variable most influencing the olive crop yield in Jaen (Spain), the maximum temperature and the cumulative rainfall in the pre-flowering period were factors of particular importance on the final olive fruit production (Aguilera and Ruiz-Valenzuela 2019).

The models resulted were validated using data of 2018 (not included in the models) and compared with real olive crop data from the Provincial Directions of Agriculture (PDA) of Tétouan. Using these bio-meteorological predictors, the regression equation obtained reached a highest coefficient of determination ($R^2 = 0.98$) and explain the lowest RMSE of 398.75 and 452.80 between expected and observed olive crop. The coefficient of determination improved when minimum temperature of July was incorporated into the models 6 and 7. However, despite that the APIn is a reliable bio-indicator of regional crop yield forecasting in anemophilous cultures it may not be strongly representative in the case of low pollen emission as in Tétouan. Bio-meteorological variables have been shown to be a useful tool in olive crop yield prediction for farmers and governments to estimate the upcoming crop, thus enabling more efficient resource management for plan strategies and price marketing and to minimize the environmental impact of crop treatment.

5 Conclusion

Olea pollen is present in the atmosphere of Tétouan in spring with high concentrations from April to June (95.6% of the annual total pollen). The onset of pollen season in Tétouan starts earlier compared to the Euro-Mediterranean countries. During the studied period (2008–2018), pollen integral and olive fruit production presented a strong inter-annual variability affected significantly by meteorological conditions. The best models used to predict the olive fruits production of *Olea* in Tétouan incorporate the rainfall registered in March, minimum temperatures in July favoring fruit development and minimum temperature in June and rainfall accumulated during autumn affecting crop development negatively. The models developed provided more accurate forecasts of UPCOMING crop production.

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References

- Aboulaich, N., Achmak, L., Bouziane, H., Mar Trigo, M., Recio, M., Kadiri, M., et al. (2013). Effect of meteorological parameters on Poaceae pollen in the atmosphere of Tetouan (NW Morocco). *International Journal of Biometeorology*, 57(2), 197–205.
- Achmak, L., Bouziane, H., Aboulaich, N., Trigo, M. M., Janati, A., & kadiri, M. (2015). Airborne pollen of *Olea europaea* L. in Tetouan (NW Morocco): heat requirements and forecasts. *Aerobiologia*, 31, 191–199.
- Aguilera, F., & Ruiz Valenzuela, L. (2009). Study of the floral phenology of *Olea europaea* L. in Jaén province (SE Spain) and its relation with pollen emission. *Aerobiologia*, 25, 217–225.
- Aguilera, F., & Ruiz Valenzuela, L. (2012). Altitudinal fluctuations in the olive pollen emission: An approximation from the olive groves of the south-east Iberian Peninsula. *Aerobiologia*, 28, 403–411.
- Aguilera, F., Ruiz Valenzuela, L., Fornaciari, M., Romano, B., Galán, C., & Oteros, J. (2014). Heat accumulation period in the Mediterranean Region phenological response of the olive in different climate areas (Spain, Italy and Tunisia). *International Journal of Biometeorology*, 58, 867–876.
- Aguilera, F., Ben, D. A., Msallem, M., Orlandi, F., Bonofiglio, T., Ruiz-Valenzuela, L., et al. (2015). Airborne-pollen maps for olive-growing areas throughout the Mediterranean region: spatio-temporal interpretation. *Aerobiologia*, 31(3), 421–434.

- Aguilera, F., & Ruiz Valenzuela, L. (2019). A new aerobiological indicator to optimize the production of the olive crop yield in intensive farming areas of southern Spain. *Agricultural and Forest Meteorology*, 271, 207–213.
- Andersen, T. B. (1991). A model to predict the beginning of the pollen season. *Grana*, 30, 269–275.
- Barranco, D., Fernández-Escobar, R., & Rallo, L. (eds). (2008). *Olive Cultivation, 6th ed, Sevilla*. Spain: Junta de Andalucía y Ediciones Mundi-Prensa. p 846.
- Ben Dhiab, A. B., Mimoun, M. B., Oteros, J., Garcia-Mozo, H., Domínguez-Vilches, E., Galán, C., et al. (2017). Modeling olive-crop forecasting in Tunisia. *Theoretical and Applied Climatology*, 128, 541–549.
- Bouziane, H., Janati, A., Kazzaz, M., & Ater, M. (2016). Aéropalynologie de l'olivier à Tétouan (Maroc). In: Ater, M., Essalouh, L., Ilbert, H., Moukhli, A. & Khadari B. (eds.). *L'Oléiculture au Maroc de la préhistoire à nos jours: pratiques, diversité, adaptation, usages, commerce et politiques*. Montpellier: *CIHEAM*. 215 p. (Options Méditerranéennes: Série A. Séminaires Méditerranéens; n. 118).
- Carrión, Y., Ntinou, M., & Badal, E. (2010). *Olea europaea* L. in the north Mediterranean Basin during the Pleniglacial and the Early-Middle Holocene. *Quaternary Science Reviews*, 29(7–8), 952–968.
- Díaz De La Guardia, C., Alba, F., Trigo, M. M., Galán, C., & Sabariego, S. (2003). Aerobiological analysis of *Olea europaea* L. in different localities in southern Spain, forecasting models. *Grana*, 42, 234–243.
- Dimou, M. (2012). Comparison of phenological, aerobiological and mellissopalynological patterns of *Olea europaea*. *Apidologie*, 43, 103–112.
- Erdtman, G. (1945). Pollen morphology and plant taxonomy. III. *Morina* L. With an addition on pollen morphological terminology. *Svensk Botanisk Tidskrift*, 39, 279–285.
- Fernández-Escobar, R., Benlloch, M., Navarro, C., & Martín, G. C. (1992). The time of floral induction in the olive. *Journal of the American Society for Horticultural Science*, 117, 304–307.
- Fornaciari, M., Bricchi, E., Frenguelli, G., & Romano, B. (1996). The results of 2-year pollen monitoring of an urban network in Perugia, Central Italy. *Aerobiologia*, 12, 219–227.
- Fornaciari, M., Pieroni, L., Ciuchi, P., & Romano, B. (1997). A statistical model of airborne pollen grains and some meteorological parameters (*Olea europaea* L.). *Agriculture Mediterranea*, 127, 134–137.
- Fornaciari, M., Pieroni, L., Ciuchi, P., & Romano, B. (1998). A regression model for the start of the pollen season in *Olea europaea* L. *Grana*, 37, 110–111.
- Fornaciari, M., Pieroni, L., Orlandi, F., & Romano, B. (2002). A new approach to consider the pollen variable in forecasting yield models. *Economic Botany*, 56(1), 66–72.
- Galán, C., Cariñanos, P., Alcázar, P., & Domínguez, V. E. (2007). *Manual de calidad y gestión de la Red Española de Aerobiología*. Spain: Service of Publications of the University of Córdoba.
- Galán, C., García-Mozo, H., Cariñanos, P., Alcázar, P., & Domínguez, E. (2001). The role of temperature in the onset of the *Olea europaea* L. pollen season in south-western Spain. *International Journal of Biometeorology*, 45(1), 8–12.
- Galán, C., García-Mozo, H., Vázquez, L., Ruiz, L., Díaz de la Guardia, C., & Trigo, M. M. (2005). Heat requirement for the onset of the *Olea europaea* L. pollen season in several sites in Andalusia and the effect of the expected future climate change. *International Journal of Biometeorology*, 49(3), 184–188.
- Galán, C., García-Mozo, H., Vázquez, L., Ruiz, L., Díaz De La Guardia, C., & Domínguez, E. (2008). Modeling olive crop yield in Andalusia Spain. *Agronomy Journal*, 100, 98–104.
- Galán, C., Vázquez, L., García-Mozo, H., & Domínguez, E. (2004). Forecasting olive (*Olea europaea*) crop yield based on pollen emission. *Field Crops Research*, 86, 43–51.
- García-Mozo, H., Chuine, I., Perez-Badía, R., & Galán, C. (2008). Aerobiological and meteorological factors influence on olive (*Olea europaea* L.) crop yield in Castilla-La Mancha (Central Spain). *Aerobiologia*, 24, 13–18.
- García-Mozo, H., Orlandi, F., Galán, C., Fornaciari, M., Romano, B., Ruiz, L., et al. (2008). Olive flowering phenology variation between different cultivars in Spain and Italy: modelling analysis. *Theoretical and Applied Climatology*, 95, 385–395.
- Hirst, J. (1952). An automatic volumetric spore trap. *The Annals of Applied Biology*, 39, 257–265.
- Liccardi, G., Russo, M., Saggese, M., Lobefalo, G., Noschese, P., & Piccolo, A. (1994). Clinical significance of allergenic sensitization to *Olea europaea* L. pollen in Naples area Italy. *Aerobiologia*, 10(1), 59–64.
- MAFRDWF (Ministry of Agriculture, Fisheries, Rural development, Water and Forests). (2020). https://www.ada.gov.ma/Plan_Maroc_Vert/planmarocvert.php and www.agriculture.gov.ma/pages/la-strategie (Accessed February 2020).
- Moriondo, M., Orlandini, S., De Nuntis, P., & Mandrioli, P. (2001). Effect of agrometeorological parameters on the phenology of pollen emission and production of olive trees (*Olea europaea* L.). *Aerobiologia*, 7, 225–232.
- Orlandi, F., Carlo, S., Bonofiglio, T., Ruga, L., Romano, B., & Fornaciari, M. (2010). Yield modelling in a Mediterranean species utilizing cause–effect relationships between temperature forcing and biological processes. *Scientia Horticulturae*, 123, 412–417.
- Orlandi, F., Ferranti, F., Romano, B., & Fornaciari, M. (2003). Olive pollination: flowers and pollen of two cultivars of *Olea europaea*. *New Zealand Journal of Crop and Horticultural Science*, 31, 159–168.
- Orlandi, F., Fornaciari, M., & Romano, B. (2002). The use of phenological data to calculate chilling units in *Olea europaea* L. in relation to the onset of reproduction. *International Journal of Biometeorology*, 46, 2–8.
- Orlandi, F., Ruga, L., Romano, B., & Fornaciari, M. (2005). Olive flowering as an indicator of local climatic changes. *Theoretical and Applied Climatology*, 81, 169–176.
- Orlandi, F., Sgromo, C., Bonofiglio, T., Ruga, L., Romano, B., & Fornaciari, M. (2009). A comparison among olive flowering trends in different Mediterranean areas (south-central Italy) in relation to meteorological variations. *Theoretical and Applied Climatology*, 97, 339–347.
- Orlandi, F., Rojo, J., Picornell, A., Oteros, J., Pérez-Badía, R., & Fornaciari, M. (2020). Impact of Climate Change on Olive

- Crop Production in Italy. *Atmosphere*, 11, 595. <https://doi.org/10.3390/atmos11060595>
- Osborne, C. P., Chuine, I., Viner, D., & Woodward, F. I. (2000). Olive phenology as a sensitive indicator of future climatic warming in the Mediterranean. *Plant Cell and Environment*, 23(7), 701–710.
- Oteros, J., García-Mozo, H., Vázquez, L., Mestre, A., Domínguez-Vilches, E., & Galán, C. (2013). Modelling olive phenological response to weather and topography. *Agriculture, Ecosystems & Environment*, 179, 62–68.
- Oteros, J., García-Mozo, H., Hervás, C., & Galán, C. (2013). Biometeorological and autoregressive indices for predicting olive pollen intensity. *International Journal of Biometeorology*, 57, 307–316.
- Oteros, J., Orlandi, F., García-Mozo, H., Aguilera, F., Ben Dhiab, A., & Bonofiglio, T. (2014). Better prediction of Mediterranean olive production using pollen based models. *Agronomy for Sustainable Development*, 34(3), 685–694.
- Plaza, M. P., Alcázar, P., & Galán, C. (2016). Correlation between airborne *Olea europaea* pollen concentrations and levels of the major allergen Ole e 1 in Córdoba, Spain, 2012–2014. *International Journal of Biometeorology*, 60, 1841–1847.
- PDA (Provincial Direction of Agriculture of Tétouan) (2019). Ministry of Agriculture, Fisheries, Rural development, Water and Forests.
- Rallo, L., & Martin, G. C. (1991). The role of chilling and releasing olive floral buds from dormancy. *Journal of the American Society for Horticultural Science*, 26, 751–751.
- Rallo, L., & Cuevas, J. (2017). Fructificación y producción (Fruiting and production). In D. Barranco, R. Fernández-Escobar, & L. Rallo (Eds.), *El Cultivo del Olivo (Olive Growing)* (pp. 145–186). Madrid: Mundi-Prensa.
- Ribeiro, H., Cunha, M., & Abreu, I. (2008). Quantitative forecasting of olive yield in Northern Portugal using a bioclimatic model. *Aerobiologia*, 24, 141–150.
- Ribeiro, H., Cunha, M., & Abreu, I. (2007). Improving early-season estimates of olive production using airborne pollen multi-sampling sites. *Aerobiologia*, 23, 71–78.
- Ribeiro, H., Santos, L., Abreu, I., & Cunha, M. (2006). Influence of meteorological parameters on *Olea* flowering date and airborne pollen concentration in four regions of Portugal. *Grana*, 45, 115–121.
- Rojó, J., Salido, P., & Pérez-Badía, R. (2015). Flower and pollen production in the ‘Cornicabra’ olive (*Olea europaea* L.) cultivar and the influence of environmental factors. *Trees*, 29, 1235–1244.
- Rojó, J., & Pérez-Badía, R. (2015). Spatiotemporal analysis of olive flowering using geostatistical techniques. *Science of The Total Environment*, 505, 860–869.
- Rojó, J., Orlandi, F., Pérez-Badía, R., Aguilera, F., Ben Dhiab, A., Bouziane, H., et al. (2016). Modeling olive pollen intensity in the Mediterranean region through analysis of emission sources. *Science of The Total Environment*, 551–552, 73–82.
- Vázquez, L. M., Galán, C., & Domínguez-Vilches, E. (2003). Influence of meteorological parameters on *Olea* pollen concentrations in Córdoba (South-western Spain). *International Journal of Biometeorology*, 48(2), 83–90.