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Termo-pluviometric Variability of Val d'Orcia Olive Orchards area (Italy)

Variabilità termo-pluviometrica degli oliveti della Val d'Orcia (Italia)

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Abstract. In a context of climate change, the knowledge of local meteorological trend and variability is a very useful tool in precision farming for improving crop production and quality. The aim of this study is to analyze the thermo-pluviometric variability of Val d'Orcia olive orchards area (Tuscany, Italy), a hilly region characterized by a great orographic variability that lacs of historical termo-pluviometric information. The trend of thermo-pluviometric indices (TX, TN, TG, FD, RR and GDD) for the period 2012-2017 in three weather stations located at different altitude and orientation in the Val d'Orcia area are presented. During the study period, yearly extra virgin olive oil (EVO) yield was also analyzed. The variability observed in precipitation confirms the strong influence of topography and atmospheric circulation on local precipitation distribution. While the analysis of thermal regimes and frost days evidence the strong presence of thermal inversion phenomenon in this area. A strong relationship was found between yearly EVO yield and GDD during the vegetative period.

Keywords. Olive orchards, microclimate, agrometeorology.

Abstract. Nell'attuale contesto di cambiamento climatico, aumentare le informazioni disponibili in merito ai trend ed alla variabilità meteorologica locale costituisce un utile strumento all'agricoltura di precisione volta al miglioramento della produttività e della qualità dei prodotti agricoli. Lo scopo di questo studio è di analizzare la variabilità termo-pluviometrica dei territori della Val d'Orcia (Toscana) a vocazione olivicola, un'area collinare caratterizzata da una elevata variabilità orografica e che manca di serie storie di questo tipo. In questo studio sono quindi presentati alcuni indici termo-pluviometrici (TX, TN, TG, FD e RR) ed alcuni indici legati alla fenologia dell'Olivo, come i GDD di tre stazioni localizzate a diverse altitudini e con diversa esposizione nel territorio della Val d'Orcia, nel periodo 2009 – 2017. Nello stesso periodo sono state analizzate le rese in olio extra-vergine di oliva (EVO). I risultati mostrano una forte variabilità pluviometrica legata all'orografia del territorio, mentre le analisi degli indici di temperatura evidenzia la presenza nell'area di una forte escursione termica. Infine, una forte relazione è stata osservata tra i GDD nel periodo vegetativo e la resa annuale in olio delle olive.

Parole chiave. Oliveti, microclima, agrometeorologia

INTRODUCTION

Agrometeorology deals with the influence of climate on agriculture. Two of the most important agrometeorological variables influencing crop growth and development are air temperature and precipitation which have also a direct influence on pest and disease incidence (Rosenzweig *et al.*, 2001).

Many studies highlighted that a general increase in extreme events such as frequency and persistence of high temperatures and changes in total precipitation and rainy days are among the most impact-relevant consequences of climate warming (Brunetti *et al.*, 2001; Manton *et al.*, 2001; Yan *et al.*, 2002; Beniston and Stephenson, 2004). Therefore, knowing the meteoclimatic trend and in particular the interseasonal and interannual variability of air temperature and precipitation could be decisive for adopting climate change mitigation and adaptation strategies in agriculture techniques.

Olive (*Olea europaea* L.) is considered a good indicator of the ongoing climate change in Mediterranean area where is one of the most important socio-economic crop (Osborne *et al.*, 2000; Orlandi *et al.*, 2005; Loumou and Giourga, 2003). Air temperature and precipitation have a significant influence on the timing of olive trees phenological stages. A low temperature period prior to bud development is essential to reach the base temperature and interrupt dormancy, then the plant accumulates heat until flowering starts (Galán *et al.*, 2001). As olive trees produce allergenic pollen, the effects of temperatures on olive trees flowering can also affect human health (Murray and Galán, 2016; Massetti *et al.*, 2015). Despite its tolerance to drought stress by means of morphological, physiological and biochemical adaptations for optimal yield olive needs of a relative wet period during anthesis and fruits ripening (Sofo *et al.*, 2008). On the contrary, precipitation and high relative humidity during anthesis tending to reduce pollen airborne concentrations (Recio *et al.*,1996).

The role of olive orchards in maintaining the traditional Tuscan (Italy) agricultural landscape is indisputable especially in Val d'Orcia (southern-east Tuscany), a hilly region characterized by a great orographic variability, where olive trees are cultivated on the slopes and hilltops from the seventh century AD (Milanesi *et al.*, 2011). Recent studies on the seasonal and annual variability of air temperature and precipitation over Tuscany has shown a general increase in minimum and maximum temperatures and extreme temperature events, a decrease in wet days and an increase in precipitation fraction (Bartolini *et al.,* 2008; Bartolini *et al.,* 2014).

Having weather-climatic information as specific as possible together with the monitoring of temperature and precipitation variability, it could be helpful to optimize some crop management practices like foliar fertilization, phytosanitary treatments, olive fly control. Before now, no specific agroclimatic analysis have been conducted in the Val d'Orcia olive orchards.

According to these premises, the aim of this study is to analyse and characterize the agroclimatic variability of Val d'Orcia olive orchards applying unifactorial bioclimatic indices in order to improve olive management techniques introducing the most advanced precision farming techniques.

MATERIALS AND METHODS

Study area

The Val d'Orcia is a valley crossed by the Orcia river in central-western Italy at about latitude 43°4'0"N, and longitude 11°33'0"E. It is approximately 669 km^2 and is located in the central-southern part of Tuscany (Fig. 1). It is geographically defined by the border of five Communities (Castiglione d'Orcia, Montalcino, Pienza, Radi-

Fig. 1. Localization of Val d'Orcia area in Tuscany (in yellow) and in Italy.

Fig. 1. Localizzazione della Val d'Orcia in Toscana (in giallo) ed in Italia.

cofani, and San Quirico d'Orcia) of the province of Siena. The area is characterized by a hilly morphology with slopes from weak (5-10%) to moderate (10-15%). The elevation of this area ranged from 160 to 690 m a.s.l..

Basing on the Köppen-Geiger (1936) climate classification system, which is useful for climate classification in terms of geographical area, the Val d'Orcia is characterized by a temperate climate of the sublittoral types.

Val d'Orcia is a predominantly agricultural area, and dedicated to agricultural tourism thanks to its typical landscapes. The main crops cultivated in Val d'Orcia are cereals, vines and, above all, olives. The most important olive cultivars in Val d'Orcia are 'Frantoio', 'Moraiolo', 'Leccino', and the autochthonous 'Olivastra Seggianese'.

Meteorological data

No historical termo-pluviometric series are available for the Val d'Orcia. Validated and continuous data are provided by the Regional Hydrological Sector of Tuscany (SIR) and are available only from 2012. The SIR meteorological stations collect hourly temperature and precipitation data that are made available as daily data of minimum, maximum, average temperature and cumulative precipitation. Three of them meteorological stations are located in olive orchards area (Tab. 1).

In order to analyze meteoclimatic trend, and interseasonal and interannual thermos-pluviometric variability of Val d'Orcia olive orchard area, Walter end Lieth climate diagrams were performed as a mean of station for the entire period in exam and annually for each single station (Walter and Lieth, 1960).

Indices

Aiming at defining the agro-meteorological resources of the area and the limitations imposed by climate to agricultural practice, an agro-climatic characterization was carried out using agro-meteorological techniques. Considering daily temperature and rainfall values recorded in the period 2009-2017 and 2012-2017 respectively, general and specific unifactorial bioclimatic indices were calculated according to the European Climate Assessment (ECA) indices definition (Peterson *et al.*, 2001):

TX - monthly mean of daily maximum temperature (°C)
TN - monthly mean of daily minimum temperature (°C)
TG - monthly mean of daily mean temperature (°C)
FD - frost Days: days with minimum temperature lower than 0 °C
RR - sum of days with precipitation higher than 0 mm

Furthermore, air temperature data was used to calculate the Growing Degree Days (GDD) by the following formula: GDD = S (T daily mean temperature – T threshold). T threshold is the minimum temperature for olive biothermic accumulation and it is assumed to be 7.5°C (Bonofiglio *et al.*, 2008).

GDD_{VP} were calculated for the whole olive vegetative period (from 1st of march to 31st of October) and separately for each season:
GDD_{MAM} - between 1st of March to 31 of May (Spring);
GDD_{JJA} - between 1st of June to 31 of August (Summer);
GDD_{SO} - between 1st of September to 31st of October (Autumn).

Yearly EVO yield (Y, %) was calculated from 2009 to 2017 by data provided by the Val d'Orcia Oil Mill, located in Castiglione d'Orcia (SI) .

RESULTS AND DISCUSSION

The analysis of thermo-pluviometric data, as a mean of the three stations for the period 2012-2017, confirms that Val d'Orcia olive orchard area is characterized by a temperate climate of the sublittoral types according to Koppen-Geiger climate classification system. The area has an average annual temperatures of 14.2 °C, an average temperature of the coldest month of 5.8 °C, three months with thermal averages above 20 °C, and annual temperature range (difference between average tempera-

Tab. 1. Meteorological station of Regional Hydrological Sector of Tuscany (SIR) in Val d'Orcia olive orchards area.
Tab. 1. Lista e localizzazione delle stazioni meteorologiche localizzate in oliveti della Val d'Orcia del Servizio Idrogeologico Regionale della Toscana (SIR).

Number	Meteorological station code	Meteorological station name	Altitude m a.s.l.	WGS84 Coordinates	
				Lat.	Long.
1	TOS11000067	Buonconvento	188	43.092	11.439
2	TOS11000059	Ripa d'Orcia	506	43.027	11.582
3	TOS11000058	Castiglione d'Orcia	672	42.961	11.618

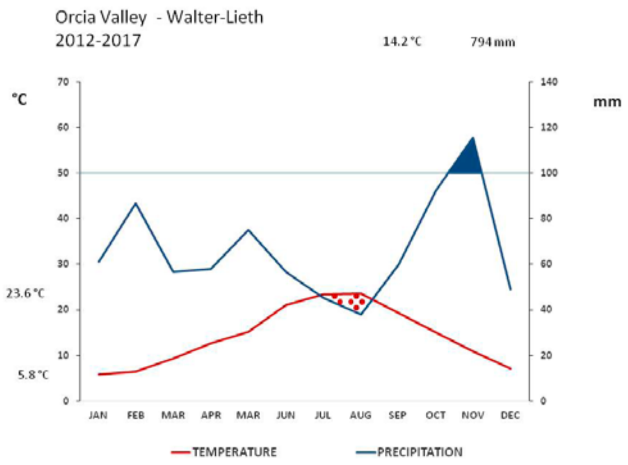

Fig. 2. Walter and Lieth climate diagram of Val d'Orcia for the period 2012-2017.

Fig. 2. Diagramma di Walter e Lieth della Val d'Orcia per il periodo 2012-2017.

ture of the coldest month and of the warmest one) equal to 17.8 °C (Fig. 2).

The mean rainfall of the area is 794 mm and it is distributed fairly evenly throughout the year, with a peak during autumn. The wettest period coincides with the autumn months with the 35% of the average annual rainfall; the wettest month is November, with an average value of 117 mm of rainfall. Summer results to be the less rainy season with 18% of the total average rainfall. Finally, rainfall is equally spread in spring and winter with an average annual rainfall of about 23% in both seasons. August seems to be the driest month with about 40 mm of monthly cumulative precipitation (Fig. 2).

Walter end Lieth climate diagram were also annually performed for each single station. The monthly temperature and precipitation trend was similar between stations and no differences were observed in interseasonal trend (data not shown). On the contrary, during the study period interannual differences were observed; as no differences in temperature and precipitation trend were observed according to altitude, annual Walter and Lieth climate diagram were shown only for station 2 (Ripa d'Orcia) (Fig. 3).

The years 2012, 2013, 2014, and 2016 were characterized by wet periods: in 2012, 2013, and 2014 the wet period was recorded during the autumn, in 2013 during the fall with the addition of the month of May, while in 2016 in February and June. The wettest year was 2014, with 908 mm, while 2017 was the driest (409 mm) characterized by the largest number of consecutive dry months (5 months). Also 2012 and 2015 were very dry years, with 6 dry months. The dry period is usually concentrated in summer and occasionally in the other seasons: in 2012 during winter, in 2015 during autumn and winter, in 2017 during spring and autumn. In 2013 no dry months were observed, while only one dry month (August) and two dry months (July and August) were observed in 2014 and 2016, respectively. Annual temperature range varied from 13.6 °C in 2014 and 23.6 °C in 2012. Although the difference between the average annual temperatures was 1 °C between the coldest (2013) and the warmest (2017) years, marked differences were observed between years in the mean temperature values of the warmest month (between 26.6 °C in 2017 and 21.4 °C in 2014) and the average temperature of the coldest one (between 2.3 °C in 2012 and 7.8 °C in 2014) (Fig. 3).

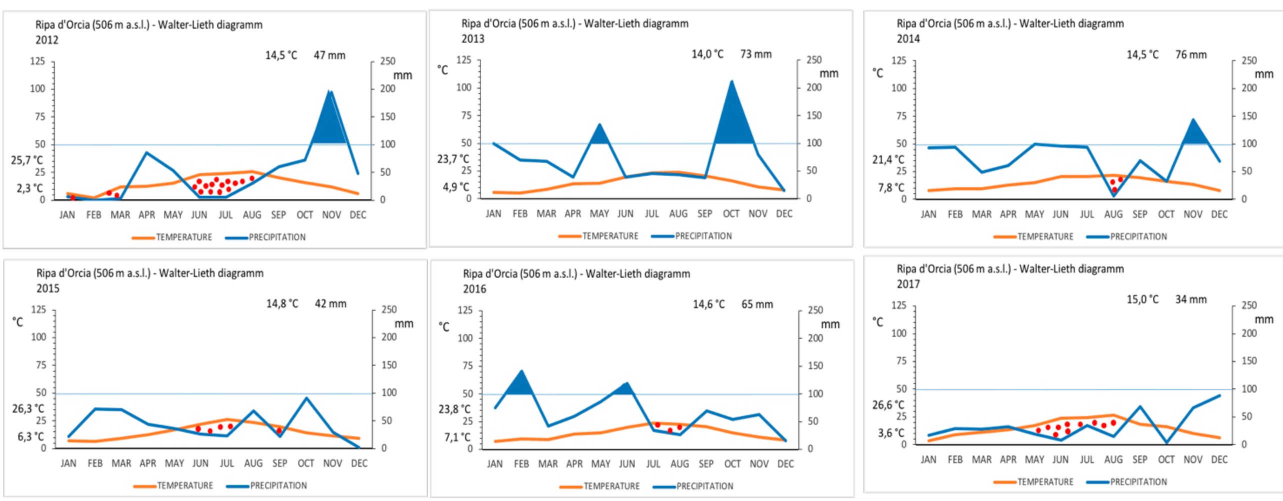

Fig. 3. Walter and Lieth climate diagram of Ripa d'Orcia meteorological station (station 2) for the period 2012-2017.

Fig. 3. Diagramma annuale di Walter e Lieth della stazione di Ripa d'Orcia (statione 2) per il periodo 2012-2017.

So, ultimately, the Val d'Orcia climate is typical of the Mediterranean area, characterized by the presence of mainly hot-dry summers and relatively cold winters.

The olive phenological response is insensitive to photoperiod (Osborne *et al.*, 2000) but strictly dependent on the monthly temperature regime (Bonofiglio *et al.*, 2009), knowing its trend may help to adopt management strategies in a timely manner and in yield forecasting. The Val d'Orcia monthly thermal regime during the period 2009-2017 is shown in Table 2. Monthly maximum air temperature (TX), minimum air temperature (TN) and average air temperature (TG) were

Tab. 2. Val d'Orcia monthly thermal regime. Monthly maximum air temperature (TX), minimum air temperature (TN) and average air temperature (TG) for each year and for the whole study period (2009-2017).
Tab. 2. Regime termico mensile della Val d'Orcia. Temperatura mensile massima (TX), temperatura mensile minima (TN), temperatura mensile media (TG) per ogni anno dello studio e media per tutto il periodo (2009-2017).

Month	2009	2010	2011	2012	2013	2014	2015	2016	2017	2009-2017
TX (°C)										
JAN	7.9	6.8	8.5	8.4	7.9	9.5	8.9	9.1	6.9	8.2
FEB	9.0	8.9	10.2	4.5	7.5	12.4	9.0	11.7	12.7	9.6
MAR	13.2	11.2	11.3	15.8	10.8	12.5	11.7	11.4	15.9	12.6
APR	17.2	16.2	16.8	15.7	17.1	16.2	16.1	17.8	18.5	16.9
MAY	23.9	18.8	20.6	19.0	17.2	18.7	20.8	18.8	22.5	20.0
JUN	24.5	24.5	24.0	27.8	23.7	24.9	26.2	24.0	29.6	25.5
JUL	29.4	29.9	25.3	29.6	27.6	24.4	31.3	28.6	30.6	28.5
AUG	31.2	27.1	28.7	30.8	28.2	25.5	28.3	27.0	32.7	28.8
SEP	24.9	20.7	25.5	23.7	24.6	22.5	23.4	24.1	23.6	23.7
OCT	18.1	16.3	17.8	18.6	18.9	19.2	16.7	17.3	20.7	18.2
NOV	14.4	13.1	14.2	14.1	12.5	15.5	13.7	13.9	13.6	13.9
DEC	9.6	8.7	10.7	8.2	9.9	9.4	10.7	10.7	9.1	9.7
TN (°C)										
JAN	1.1	1.3	3.1	3.2	2.9	5.3	3.9	4.5	-0.5	2.8
FEB	1.3	3.0	2.9	-0.9	1.2	6.3	2.8	6.0	4.6	3.0
MAR	4.4	4.3	4.0	7.4	4.8	5.9	5.5	4.9	5.7	5.2
APR	8.5	7.3	9.3	7.9	9.3	8.6	8.1	9.6	7.3	8.4
MAY	12.3	10.7	12.2	10.4	10.0	10.5	12.4	10.8	11.1	11.2
JUN	14.4	14.4	15.5	17.2	14.3	15.9	16.9	15.2	16.6	15.6
JUL	17.1	18.7	16.2	18.4	18.4	16.1	20.8	18.4	17.3	17.9
AUG	18.9	16.9	18.9	20.1	18.5	16.7	18.5	17.2	19.2	18.3
SEP	14.9	8.9	16.6	15.6	15.6	15.1	15.3	15.8	12.6	14.5
OCT	9.1	9.2	10.3	12.0	12.8	12.5	10.9	10.9	9.9	10.8
NOV	7.1	7.2	6.5	8.8	7.3	10.7	8.5	7.7	5.4	7.7
DEC	3.2	2.9	4.5	3.2	5.3	5.3	6.6	5.3	2.2	4.3
TG (°C)										
JAN	4.5	4.1	5.8	5.8	5.4	7.4	6.4	6.8	3.2	5.5
FEB	5.2	6.0	6.6	1.8	4.4	9.4	5.9	8.8	8.7	6.3
MAR	8.8	7.8	7.7	11.6	7.8	9.2	8.6	8.1	10.8	8.9
APR	12.9	11.7	13.1	11.7	13.2	12.4	12.1	13.7	12.9	12.6
MAY	18.1	14.8	16.4	14.7	13.6	14.6	16.6	14.8	16.8	15.6
JUN	19.5	19.5	19.8	22.5	19.0	20.4	21.5	19.6	23.1	20.5
JUL	23.3	24.3	20.8	24.0	23.0	20.2	26.0	23.5	24.0	23.2
AUG	25.0	22.0	23.8	25.4	23.4	21.1	23.4	22.1	25.9	23.6
SEP	19.9	14.8	21.1	19.7	20.1	18.8	19.4	20.0	18.1	19.1
OCT	13.6	12.7	14.0	15.3	15.8	15.9	13.8	14.1	15.3	14.5
NOV	10.7	10.1	10.4	11.5	9.9	13.1	11.1	10.8	9.5	10.8
DEC	6.4	5.8	7.6	5.7	7.6	7.3	8.6	8.0	5.6	7.0

calculated for each year and for the whole study period (2009-2017). The hottest months resulted to be July and August, with very similar TX, TN and TG values; while the coldest month was January, with a TG of 5.8 °C. The interannual thermal variability during the whole study period showed that February was the month with the highest variability: 7.9 °C in TX, 7.2 °C in TN and 7.6 °C in TG. On the contrary, April resulted to be the month with lower interannual thermal variability, with 2.8 °C in TX, 1.7 °C in TN and 2 °C in TG.

Flowering date seemed to be influenced in a decisive way from the trend of average air temperature. (Bonofiglio *et al.*, 2009), in a 26 years study (1982-2007) conducted in Central Italy, registered an anticipation of the flowering period, which was due mostly to an increase of the average temperature during the months of March, April, May and June, especially from May (start flowering) to June (full flowering). In our study period we observed the following average air temperature trend (Tab. 2): in March it ranged between 7.8 °C (2010 and 2013) and 11.6 °C (2012), in April between 11.7 °C (2010 and 2012) and 13.7 °C (2016), in May between 13.6 °C (2013) and 18,1 °C (2009) and in June between 19.0 °C (2013) and 23.1 °C (2017).

An annual average of 23 FD were recorded in the Val d'Orcia olive orchards area: 33, 15, and 22 FD in station 1, 2, and 3 respectively (Tab. 3). FD were recorded during the winter, in early spring and in late autumn. As expected, the months with a maximum number of FD were the winter ones (on average 7.9, 6.6 and 6.2 respectively in January, February and December), following by November with an average of 1.2 FD and March with an average of 1.8 FD.

The annual maximum number of FD (47) was recorded in 2017 by station 1 which (positioned at the lowest altitude). While, an FD value of 31 was recorded by station 3 evidencing the occurrence of a strong thermal inversion that is characteristic of the study area. The annual minimum number of FD (4) was recorded in 2016 in station 1 and in 2014 in station 2 (data not shown).

The olive tree is moderately resistant to below zero temperatures but suffers frost injury when specific thermal thresholds are exceeded: -16 °C for xilema and twig cambium, -12 °C for buds and leaves, and -6 °C for roots (Larcher, 1970). However, persistent temperatures below –7 °C can damage aerial parts and seriously reduce the productivity (Palliotti and Bongi, 1996). The most characteristic symptoms of frost damage include tip burn of shoots tips and nearby leaf tips, leaf chlorosis, defoliation, bark split on branches and also damages to buds and fruits (Barranco *et al.*, 2005).

During the study period the minimum average temperature values never dropped below -6 °C. The maximum minimum temperature (-8.2 °C) was reached only for a few consecutive hours in February 2012, in December 2016 and in January 2017 in station 3, such as not to damage olive trees, (data not shown).

An annual average of 91.3 RRs were recorded in the monitored area: 91.5, 88.0, and 94.3 RRs in station 1, 2, and 3 respectively. The maximum average number of RRs (116) were recorded in 2013 and 2014, while the lowest average number of RRs was recorded in 2017 (66) (Tab. 4).

RRs were continuously distributed throughout the year; no months without RRs were recorded during the observation period. On average, the largest number of RRs was recorded in spring (26,4 RRs), than in winter and autumn (25,1 RRs) and finally in summer (14,7 RRs). The month with the maximum average number of RRs was November (10,6 RRs) while the month with the minimum number was August (3,3 RRs) (Tab. 5).

Phenology can be considered a bio-indicator for climate change as a proxy for temperatures (Menzel, 2002). Heat accumulation, quantified by GDD, is the major factor for the determination of bud development, budburst, flower blooming and other phenological phases (Hänninen, 1990). During our study period, an average of 2434 GDD_{VP} was achieved in the whole Val d'Orcia. GDD_{VP} decreased as the altitude increased. Considering the annual average of the three stations, the hottest years were 2012 and 2017 when 2565.7 GDD_{VP} and

Tab. 3. Monthly and annual average Frost Days (FD) collected in Val d'Orcia during the study period (2009-2017) in the three stations: station 1: Buonconvento (altitude 188 m asl); station 2: Ripa d'Orcia (altitude 506 m asl); station 3: Castiglione d'Orcia (altitude 672 m asl).
Tab. 3. Valori medi mensili ed annuali dei Giorni di Gelo (Frost Days - FD) osservati in Val d'Orcia durante il periodo di studio (2009-2017) nelle tre diverse stazioni: stazione 1: Buonconvento (altitudine 188 m slm); stazione 2: Ripa d'Orcia (altitudine 506 m slm); stazione 3: Castiglione d'Orcia (altitudine 672 m slm).

2009-2017	G	F	M	A	M	G	L	A	S	O	N	D	TOT
Station 1	10.9	8.4	2.3	0	0	0	0	0	0	0	2.1	9.9	33.6
Station 2	5.9	4.7	1.1	0	0	0	0	0	0	0	0.4	3.2	15.3
Station 3	7.1	6.7	2.1	0	0	0	0	0	0	0	1.1	5.4	22.4
Average	7.9	6.6	1.8	0	0	0	0	0	0	0	1.2	6.2	23.7

Tab. 4. Annual and total amount of rainy days (RR) collected in Val d'Orcia during the study period (2012-2017) in the three stations: station 1: Buonconvento (altitude 188 m asl); station 2: Ripa d'Orcia (altitude 506 m asl); station 3: Castiglione d'Orcia (altitude 672 m asl).
Tab. 4. Numero di giorni piovosi (RR) annuale e totale per il periodo di osservazione (2012-2017) nelle tre stazioni: stazione 1: Buonconvento (altitude 188 m asl); station 2: Ripa d'Orcia (altitude 506 m asl); station 3: Castiglione d'Orcia (altitude 672 m asl).

RR	2012	2013	2014	2015	2016	2017	Tot.
Station 1	84	106	118	75	105	61	91.5
Station 2	75	117	115	69	93	59	88.0
Station 3	76	125	115	78	94	78	94.3
Average	78.3	116.0	116.0	74.0	97.3	66.0	91.3

2613.0 GDD_{VP} were achieved respectively. The coldest year was 2014 with 2196.3 GDD_{VP}. Considering the seasonal average values after summer (1383.1 GDD_{JJA}) the hottest season was autumn (565.4 GDD_{SO}). Only in 2017 spring was warmer (546.0 GDD_{MAM}) than autumn (533.3 GDD_{SO}) resulting to be the hottest in the period under review (Tab. 6). This result is consistent with the global warming trend: a progressive European warming might promote elongation of the summer period into the autumn (Fischer and Schär, 2009). However no trend in GDD was observed in our study, probably because of the limited number of years analyzed.

During the warmest years, values of 2748 GDDVP (2011) and 2735 GDDVP (2017) were achieved in station 1, whereas in the coldest one (2014), the GDDVP value was 2317. In spring, GDD varied between 430 (2013) and 622 (2011), in summer between 1250 (2014) and 1573 (2017), in autumn between 551 (2015) and 657 (2011).

In station 2, in the warmest years GDDVP values ranged about 2650 (2012) and 2732 (2017) in the warmest years, whereas in the coldest one (2014) GDDVP value was about 2281. The hottest season resulted to be always the summer, followed by autumn. In spring, GDD varied between 420 (2013) and 585 (2017), in summer between 1217 (2017) and 1585 (2017), in autumn between 554 (2015) and 632 (2013). The 2017 was the year characterized by the hottest summer and spring.

In station 3, the warmest years were 2012 and 2017 when 2378 GDDVP and 2372 GDDVP were achieved, respectively. The coldest year was 2014 reaching 2191 GDDvp. The hottest season resulted to be the summer followed by autumn and spring.

Contrary to what has been observed in other stations in 2017 spring was colder (458 GDD_{MAM}) than autumn (471 GDD_{SO}), although it was the warmest spring in the period under review. The autumn of 2017 was the coldest (471 GDD_{SO}) of the period. The GDD ranged between 320 in 2013 and 466 in 2011 during spring, between 1104 in 2014 and 1443 in 2017 during summer, and between 471 in 2017 and 568 in 2013 during autumn. 2013 was confirmed the year with the coldest spring and hottest autumn.

Finally, Table 8 shows yearly EVO yield (Y)

Tab. 5. Monthly amount of rainy days (RR) collected in Val d'Orcia during the study period (2012-2017) in the three stations: station 1: Buonconvento (altitude 188 m asl); station 2: Ripa d'Orcia (altitude 506 m asl); station 3: Castiglione d'Orcia (altitude 672 m asl).
Tab. 5. Numero mensile di giorni piovosi (RR) registrati durante il peiriodo di studio (2012-2017) nelle tre stazioni della Val d'Orcia: stazione 1: Buonconvento (altitude 188 m asl); station 2: Ripa d'Orcia (altitude 506 m asl); station 3: Castiglione d'Orcia (altitude 672 m asl).

RR 2012-2017	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Station 1	8.0	11.2	8.2	8.5	9.5	5.8	3.3	3.0	6.5	8.0	11.2	8.3
Station 2	7.7	9.5	8.3	7.5	9.8	6.7	4.5	3.3	7.5	6.7	10.7	5.8
Station 3	7.7	10.2	8.7	8.5	10.2	7.8	5.8	3.7	7.7	7.3	10.0	6.8
Average	7.8	10.3	8.4	8.2	9.8	6.8	4.6	3.3	7.2	7.3	10.6	7.0

Tab. 6. Mean growing degree days (GDD) of the Val d'Orcia olive orchards area in the period 2009-2017 for the whole olive vegetative period (GDD_{VP}) and separately for each season (GDD_{MAM}, GDD_{JJA}, GDD_{SO}).
Tab. 6. Media dei gradi giorno (GDD) per il periodo di osservazione per l'area degli oliveti della Val d'Orcia per il periodo 2009-2017 relativi a tutto il periodo vegetativo (GDD_{VP}) e per ogni singola stagione: primavera (GDD_{MAM}) estate (GDD_{JJA}) e autunno (GDD_{SO}).

	2009	2010	2011	2012	2013	2014	2015	2016	2017	Ave 2009 - 2017
GDD_{MAM}	546.0	532.0	534.3	477.7	390.0	429.7	475.0	450.7	546.0	486.8
GDD_{JJA}	1390.3	1355.0	1346.0	1502.3	1303.0	1190.3	1471.3	1297.7	1533.7	1376.6
GDD_{SO}	562.3	571.7	608.3	585.7	613.0	576.3	527.7	556.3	533.3	570.5
GDD_{VP}	2498.7	2458.7	2488.7	2565.7	2306.0	2196.3	2474.0	2304.7	2613.0	2434.0

Tab. 7. Mean growing degree days (GDD) of the three SIR meteorological stations in Val d'Orcia olive orchards area in the period 2009-2017 for the whole olive vegetative period (GDD_{VP}) and separately for each season (GDD_{MAM}, GDD_{JJA}, GDD_{SO})
Tab. 7. Gradi giorno (GDD) medi relativi a tutto il periodo vegetativo (GDD_{VP}) e per ogni singola stagione: primavera (GDD_{MAM}) estate (GDD_{JJA}) e autunno (GDD_{SO}) nelle tre stazioni della Val d'Orcia per tutto il periodo di osservazione (2009-2017): stazione 1: Buonconvento (altitudine 188 m slm); stazione 2: Ripa d'Orcia (altitudine 506 m slm); stazione 3: Castiglione d'Orcia (altitudine 672 m slm).

Station 1	2009	2010	2011	2012	2013	2014	2015	2016	2017	Ave. 2009 - 2017
GDD_{MAM}	597	595	622	515	430	470	511	487	595	535.8
GDD_{JJA}	1414	1412	1469	1546	1358	1250	1523	1348	1573	1432.6
GDD_{SO}	588	596	657	608	639	597	551	568	567	596.8
GDD_{VP}	2599	2603	2748	2669	2427	2317	2585	2403	2735	2565.1
Station 2	2009	2010	2011	2012	2013	2014	2015	2016	2017	Ave. 2009 - 2017
GDD_{MAM}	575	564	549	511	420	460	498	473	585	515.0
GDD_{JJA}	1430	1395	1340	1529	1335	1217	1500	1329	1585	1406.7
GDD_{SO}	596	597	606	610	632	604	554	599	562	595.6
GDD_{VP}	2601	2556	2495	2650	2387	2281	2552	2401	2732	2517.2
Station 3	2009	2010	2011	2012	2013	2014	2015	2016	2017	Ave. 2009 - 2017
GDD_{MAM}	466	437	432	407	320	359	416	392	458	409.7
GDD_{JJA}	1327	1258	1229	1432	1216	1104	1391	1216	1443	1290.7
GDD_{SO}	503	522	562	539	568	528	478	502	471	519.2
GDD_{VP}	2296	2217	2223	2378	2104	1991	2285	2110	2372	2219.6

Tab. 8. Yearly EVO yield (Y) expressed in percentage (%) in the Val d'Orcia area in the period 2009-2017. Data provided by the Val d'Orcia Oil Mill, located in Castiglione d'Orcia (SI).
Tab. 8. Resa annuale e totale del periodo 2009-2017 delle olive (Y) espressa in percentuale (%) nell'area della Val d'Orcia. Dati forniti dalla Società Agricola Frantoio della Val d'Orcia con sede in Castiglione d'Orcia (SI).

	2009	2010	2011	2012	2013	2014	2015	2016	2017	Ave.
Y (%)	17.2	18.3	17.6	18.5	14.4	13.9	17.6	13.9	18.7	16.7

expressed in percentage (%). During the study period, Y was approximately of 16.7%, with maximum values in 2012 and 2017 with 18.5% and 18.7 % respectively, and minimum values in 2014 and 2016 with 13.9%.

In order to investigate if EVO yield was linked to thermo-pluviometric and GDD variables, a linear regression was made between Y and each index previously described. A positive trend was observed between Y, TX and TG, while a negative one was observed between Y and TN. No trend was found between T and RR and FD. On the contrary, a strong relationship was found between Y and GDD: in particular, a strong relationship was between Y and GDD_{JJA} (R^2 = 0.715) and with GDD_{VP} (R^2 = 0.819), while only a positive trend was observed with GDD_{MAM} and a negative one with GDD_{SO} (Figure 4).

The strong relationship observed between Y and GDD_{VP} and GDD_{JJA} confirmed how heat accumulation period (expressed ad GDD) can influence EVO yield and suggesting that GDD during the summer season (GDD_{J-JA}) can be a predictor of olive yield.

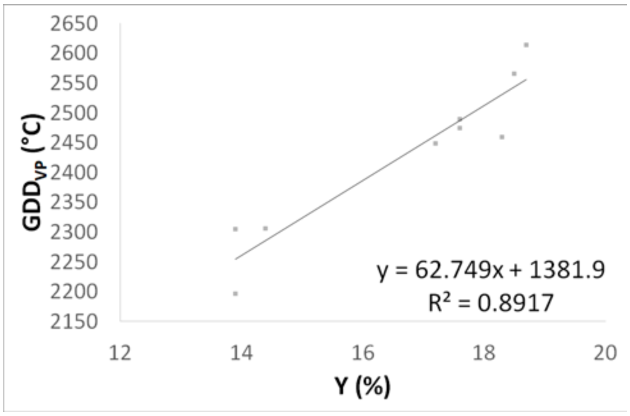

Fig. 4. linear regression between EVO yield (Y) and Growing degree days of the vegetative period (GDDVP) for the period 2009-2017.
Fig. 4. regressione lineare tra resa annuale di olio extra vergine di oliva (Y) e gradi giorno durante la stagione vegetativa dell'olivo (GDD_{VP}) nel periodo 2009-2017.

CONCLUSIONS

This is a preliminary analysis of thermo-pluviometric variability of Val d'Orcia olive orchards area (Tuscany, Italy), a not well investigated area despite of its agro-economic relevance.

The knowledge of the trend and the interseasonal and interannual behaviour and variability of air temperature in olive orchards area is essential to forecast some phenological phase that play an important role in olive production, i.e. flowering stage, helping to prevent agronomic problem such as biotic and abiotic diseases, i.e. olive fly, olive peacock spot, etc.

The variability observed in precipitation in areas very close together shows the strong influence of topography and atmospheric circulation on local precipitation distribution. This outcome could be linked to an ongoing change in the Mediterranean weather circulation which increasingly determines heavy precipitation events but extremely localized. The strong relationship observed between EVO yield and heat accumulation period during the summer season (GDD_{JJA}) suggests that this index can be a good predictor of olive yield.

The results of this study help to increase the knowledge of agro-climatic variability of Val d'Orcia olive orchards area. Moreover, they could be useful for implementing precision farming techniques in this area, such as the optimization of some olive management practices, and the application of models for evaluating the development of plants and plant pathogens.

DATA AVAILABILITY

Thermo pluviometrioc data used in this paper can be requested to the Regional Hydrological Sector of Tuscany (SIR) following the instructions on the website www.sir.toscana.it/

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