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Effect of pedoclimatic variables on analytical and organoleptic characteristics in olive fruit and virgin olive oil

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ABSTRACT

Due to the expansion of olive oil cultivation around the world and the increasing effects of climate change, *Olea europaea* (L:) cultivation must deal with ever higher temperatures and drought conditions, with productivity and virgin olive oil (VOO) quality issues. At the same time the demand for premium quality products with high nutraceutical value, chemical and organoleptic characteristics related to specific areas of cultivation is steadily rising. Within this framework a deep knowledge of the olive variety with regards to environment interaction is necessary to achieve VOO production and qualitative standards required by the market. Rainfed adult olives (cv Bosana) cultivated in five typical areas of north and central Sardinia (Italy) were the subject of a three-year study, with the aim to investigate the influence of pedoclimatic variability on olive and olive oil characteristics. Physical and chemical attributes of fruits (morphometric features, firmness, pH, titratable acidity, sugar content, moisture, and oil yield) and VOO (fatty acid and sensory profile) were analysed at harvest and related to monthly weather data (precipitation, maximum, average, and minimum temperatures) of the whole fruit development period and soil composition. Monthly maximum temperatures were the most relevant variables. However, the role of each meteorologic variable was specific per olive and olive oil parameters and their relevance varied according to the period of the season. An emblematic example is that the maximum temperatures during summer months reduced oil yield and improved oleic acid concentration, but during the following months, the same variable exerted an opposite effect. This suggests the presence of a maximum temperature threshold in the olive fruits, for lipogenesis processes. Meteoclimatic conditions during maturation were the principal element responsible for VOO sensory profile: high precipitation and low thermal amplitude promoted an attribute's intensities.

1. Introduction

The recent spread of olive tree cultivation in novel countries, such as China, Brazil, India, Perú, Argentina, Australia, Ethiopia (International Olive Oil Council) ((IOC), 2022a), and the upcoming changes in climate, with expected increased temperatures throughout the year, heat waves, heavy precipitation events and longer drought periods (Brito et al., 2019), induce the scientific community to evaluate the adaptability of each olive cultivar to a large range of climatic conditions, different from those typical of their area of origin (Navas-Lopez et al., 2020; Ben-Ari et al., 2021).

The main environmental factor affecting olive tree cultivation is temperature. In particular, high temperatures occurring during several olive phenological phases seriously limit productivity, while inadequate chill unit amounts may cause shifts of phenological phases exposing plants to increased risks of weather injuries (e.g. late spring frosts or heat waves) (Ben-Ari et al., 2021). Extreme high summer temperatures delay fruit development and consequently lipogenesis (García-Inza et al., 2018; Benlloch-González et al., 2019). Moreover, during early fruit development stress conditions, determined by elevated temperature and drought, limit mesocarp and endocarp cell division and growth, causing lower fruit weight at harvest (Rapoport et al., 2004; Nissim et al., 2020.,

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Miserere et al., 2022).

Since virgin olive oil (VOO) fatty acid (FA) profile is a parameter of primary importance for adulteration control and should comply within specific purity criteria (IOC, 2022b), its relationships with climate have been largely studied over the last years, principally in new areas of cultivation (Mailer et al., 2010; Rondanini et al., 2014; García-Inza et al., 2014, 2018; Sánchez-Rodríguez et al., 2019a; Nissim et al., 2020; Miserere et al., 2022). However, due to ongoing climate changes and due to the need of geographical origin certification (Mastralexi and Tsimidou, 2021), the knowledge of varietal interaction with environmental conditions is an aspect of primary importance also in the traditional Mediterranean olive growing areas, where scientific attention has mainly focused on the effect of altitude and distance of cultivation from water basins (Di Vaio et al., 2013; Navas-Lopez et al., 2020; Dib et al., 2021; Mafrica et al., 2021; Jukić Špika et al., 2021) and seasonal variability (Lombardo et al., 2008). A gradual reduction in oleic acid percentage and higher values of linoleic, linolenic, and palmitic acids were found to be related to increased air temperatures. Other environmental variables, which in turn affect air and plant tissue temperatures, like evapotranspiration, radiation, thermal amplitude, precipitation, relative humidity, vapor pressure deficit and wind speed were found to be less relevant and respective relevance changed according to the variety and VOO compounds (García-Inza et al., 2018; Sánchez-Rodríguez et al., 2019a; Nissim et al., 2020).

Probably due to the numerous tolerance strategies adopted by olive trees in response to drought, water availability seems to marginally affect FA composition (Brito et al., 2019). Moreover, contrasting effects were reported by literature. Precipitations during the earliest stages of maturation exerted negative effects on oleic acid content (Beltrán et al., 2004), whereas, according to García et al. (2020), late summer and autumn rains fostered MUFA concentration.

On the other hand, high rainfall during maturation period is important to enhance VOO quality in terms of sensorial evaluation and volatile compounds (Tura et al., 2009; Mafrica et al., 2021; Jukić Špika et al., 2021). The volatile compounds of VOO belong to the chemical classes of alcohols, aldehydes, esters, furans, hydrocarbons, ketones, and terpenes (Genovese et al., 2021). Most of them come from the complex enzymatic process called “lipoxygenase pathway”, where polyunsaturated fatty acids (PUFA) are the substrate of these enzymatic reactions, whilst phenolic compounds, more specifically secoiridoids, are the direct culprit of bitter and pungent tastes (Genovese et al., 2021). The relative intensity of sensory attribute is in part determined by the same environmental variables that affect both FA and phenolic compounds (Deiana et al., 2021). The products of secondary metabolism like phenols are synthetized at the earliest stages of ripening principally as a physiological defense to drought and high temperatures (Deiana et al., 2021).

Notwithstanding the fact that the relationships between environmental conditions and the quality of olive tree products have been largely studied during the last years, only a few varieties have been considered and information about some fruit components, also relevant for table olive production, like pH, acidity, and sugar content, as well as VOO sensory profile, are still missing. Moreover, the majority of previous studies have focused on a specific period of fruit development or on a specific meteoclimatic variable, mostly average temperatures.

In order to contribute to filling the gap of knowledge on this topic of common interest, the present study aims to investigate at a mesoscale the relationship between the meteoclimatic variability and olive and olive oil characteristics. Adult and rain-fed olives of the cultivar Bosana cultivated in five typical areas of north and central Sardinia (Italy) were the subject of a three-year study. Bosana is the most widespread variety in Sardinia (Italy), whose population has been estimated about 3 million plants, mainly concentrated around the municipality of Sassari, North-West of the Island (Bandino and Dettori, 2001). This cultivar is genetically close to the Italian cultivars Coroncina and Peranzana (Sarri et al., 2006). Bosana VOO is well known for its unique organoleptic and nutraceutical characteristics (Rotondi et al., 2010) and polyphenol richness (Fancello et al., 2022).

Physical and chemical attributes of fruits (morphometric characters, firmness, pH, titratable acidity, sugar content, moisture, and oil yield) and VOO (FA profile and sensory profile) were analysed at harvest and put in relation, through a multivariate statistical approach, with monthly meteoclimatic data (precipitations, maximum, average, and minimum temperatures) considering the whole fruit development period.

Probably due to the difficulties of experimental plan implementation, the influence of soil properties on both fruit and oil components is still poorly investigated (Rallo et al., 2018). With the aim to improve the knowledge on this topic, and since soil is an intertwined component of a specific terroir, the present study also takes into account the influence of the physical and chemical soil properties.

2. Materials and methods

2.1. Study areas

The study was conducted during the 2012, 2013, and 2014 growing seasons in North-Central Sardinia, where five areas, different for orographic, pedological and meteoclimatic characteristics (Madrau et al., 2006; Canu et al., 2015) corresponding to the municipalities of Alghero (80 – 110 m a.s.l.), Berchidda (230 – 360 m a.s.l.), Ittiri (370 – 430 m a.s.l.), Sassari (170 – 330 m a.s.l.), and Seneghe (260 – 280 m a.s. l.), were identified. In Seneghe areas the study was performed only during the 2012 and 2013 growing seasons. Three representative olive orchards with uniform characteristics ascribable to the traditional cultivation systems (tree age above 50 years, low plant density, rain-fed systems, mechanical or facilitated harvest, and homogeneous pest management) were selected within each study area.

Meteorological data (monthly cumulative precipitations, monthly mean, maximum, and minimum temperatures, and Δ between maximum and minimum temperatures) were provided by the Department of Meteorology and Climatology of the Environmental Protection Agency of Sardinia (ARPAS) and spatially interpolated according to the regression kriging method to obtain weather variables specific for each of the fifteen sites (Motroni, 2015; Canu et al., 2015). Since the present study focused on the fruit characteristics and respective oils, the meteoclimatic variables considered were those of the months usually involved in *cv.* Bosana fruit growth process, from fruit set (first days of June) to fruit maturation (last days of November) (Nieddu et al., 2002; Deiana et al., 2019).

Aridity index, water balance, and continentality index are commonly used to characterize bioclimates. They were calculated per each year and site. The aridity index, specific of each year and site of study, was calculated as the ratio between the cumulative annual precipitations (P) and cumulative potential evapotranspiration (ETo) calculated with the Hargreaves and Samani equation. The yearly water balance was calculated as the difference between P and ETo (Culeddu et al., 2017). Finally, the continentality index, representing the influence of proximity to water areas and temperature fluctuations (Canu et al., 2015), was calculated as the difference between the average temperatures of the warmest and the coldest month of the year (Canu et al., 2015).

The bioclimate of Sardinia is characterized by mild and relatively rainy winters followed by hot and dry summers and classified as Mediterranean Pluviseasonal-Oceanic (Canu et al., 2015). Precipitations are concentrated during autumn and winter months. Along the areas of this study, cumulative yearly precipitations range between 500 and 650 mm. The five study areas spread within three isobioclimates: “Upper Thermomediterranean, Upper Dry, Euoceanic Strong” (Alghero), “Lower Mesomediterranean, Upper Dry, Euoceanic Weak” (Sassari and partially Ittiri, Seneghe, and Berchidda), “Lower Mesomediterranean, Lower Subhumid, Euoceanic Weak” (Ittiri, Seneghe, and Berchidda).

The physical and chemical soil properties (depth, texture, pH, carbon, organic matter, total nitrogen, available phosphorus, macro, and trace elements) of each experimental site were determined according to the official methods for the soil analysis of the Italian Republic (Gazzetta Ufficiale Serie Generale, 1999). Details about soil data can be found in Santona (2016).

2.2. Olive sampling and fruit analysis

Fruit sampling was carried out between the last ten days of November and the first ten days of December of each year, when about half of drupes achieved the veraison stage, corresponding to a maturation index (MI) around 2 (IOC, 2011). About 150 drupes were collected manually all around the canopy at a height of 1.5–2 m from 10 representative trees, uniform for morphological and productive characteristics.

The following morphological measurements were carried out: fruit fresh weight (FW, g), pit weight (PitW, g), FW/PitW ratio, fruit length and width (mm). Fruit firmness (kg cm^{-2}) was determined on the drupe equatorial zone throughout a manual penetrometer with a 1 mm tip (Di Vaio et al., 2013). Fruit moisture (%) was determined on 10 g of fresh and homogenized mesocarp samples after 48 h drying at 105 °C. Oil Yield (%) was determined on the dried samples throughout the Soxhlet method. An aliquot of 10 g of grinded fruits blended with 40 mL of distilled water was used to determine pH and titratable acidity. Titratable acidity was measured by titrating with 0.1 mol/L NaOH to pH 8.2; the results were expressed as percentage of malic acid in fresh weight (Fadda and Mulas, 2010). Since titratable acidity provides a measure of weakly bound hydrogen ions potentially released from the acids (Lobit et al., 2002), in the present work acidity was measured as an indirect estimation of the total organic acid concentration. Reducing sugars were determined according to the Fehling method as described by Fadda and Mulas (2010). In brief, 20 g of grinded fruits were diluted with 50 mL of Ca_2CO_3 saturated solution and left overnight. The solution was clarified by adding 10 mL of lead acetate and subsequently 10 mL of sodium oxalate. The filtered solution was used to titrate a standard solution with 5 mL of Fehling A, 5 mL of Fehling B, and 40 mL of distilled water. Reducing sugars were expressed as percentage of fresh weight.

2.3. Oil extraction and fatty acid analysis

Every year, simultaneous to fruit sampling, from the same trees, olives were harvested for oil extraction. Olive samples (about 100 kg) were processed by the same operator in a two-phase small scale mill (TEM Oliomio) following a standard protocol. Malaxation temperatures varied between 22 and 24 °C. The temperatures of the following phases of the extraction process were kept below 25 °C. VOO samples were subsequently filtered and stored at 15 °C in 250 mL dark glass bottles. On VOO samples fatty acid methyl esters were determined according to the cold transesterification method described by the European Union regulation (Regulation, 1991).

2.4. Sensory analysis

A fully trained analytical taste panel (composed of 8 people) of the AMAP (Agency for Innovation in the Agri-food and Fisheries sectors) performed the sensory analysis. The panel was recognized by the IOC and by the Italian Ministry for Agriculture, Food, and Forestry Policy. The panel evaluated all oil samples following an incomplete randomized block design. The panel test established for the present study used a standard profile sheet (IOC, 1996) modified by AMAP (Rotondi et al., 2010).

2.5. Statistical analysis

The effects of location and growth year on fruit and VOO parameters were evaluated through two-way ANOVA; statistical differences among sites and years were assessed with Tukey's test. The η^2 value was calculated to determine the percentage of variance related to each factor and the interaction. Data were analysed by R-Studio software (version 4.1.2, 2021–11–01, (R Core Team, 2021). The "Stats" package (R Core Team, 2021) was used to perform analysis of variance ("aov" function), compute Tukey Honest Significant Differences test ("TuKeyHSD" function) and to perform the factorial linear model (function "lm"). The function "anova_stats" from the "sjstats" package (Lüdecke, 2021) was used to calculate the η^2 values.

To check some common trends and clusters among meteorological variables a preliminary data overview through unsupervised PCA analysis was performed. Then, with the aim to assess the relationship between environmental conditions (weather and soil) (set as independent variables: X) and 1) olive fruit characteristics, 2) VOO fatty acids, and 3) VOOs sensory profile (set as dependent variables: Y) three Partial Least Square (PLS) regression models were performed (Fancello et al., 2022). Since most of the olive fruit parameters considered were poorly correlated between each other, individual Orthogonal PLS (OPLS) models were performed for those that reported the highest model accuracy in the PLS analysis. OPLS, being an extension of PLS, can give a simplified interpretation of multivariate data. In the OPLS method, the variation from X matrix not correlated to the response variable Y is separated from the predictive information, which is focused in one component (Deiana et al., 2019).

Model accuracy was expressed by means of R^2Y and Q^2Y values, indicating respectively the percentage of variation explained by the model and the proportion of variance predictable by the model (Culeddu et al., 2017). Throughout these multivariate approaches it is possible to identify the specific environmental variables mostly relevant in determining the olive fruit and VOO characteristics at harvest. To improve the model accuracy and avoid overfitting, preliminary PLS models that included all X variables ($n = 51$) were performed. Then, all those variables with variable influence on projection (VIP) values above 0.8 were selected to perform further enhanced models (Deiana et al., 2022). On the final models, VIP were calculated and those variables showing values above 1 were considered relevant (Deiana et al., 2022). For this reason, each model differed for type and number of X variables. To validate the PLS and OPLS models and assess over-fitting, 7-fold cross-validation and permutation tests were performed (Deiana et al., 2022). SIMCA-P software version 13.0 (Umetrics AB, Umea, Sweden) was used to perform PLS and OPLS analyses.

3. Results

3.1. Environmental conditions

A first look at meteoclimatic data (see Supplementary Material 1 and 2a, (SM1 and SM2a)) revealed that the main source of variability was related to the growing season rather than to the geographic location. According to the aridity and water balance indexes, 2012 and 2014 were drier years, if compared to 2013, reporting values between the ranges 0.42 – 0.63 and − 741 – − 409, respectively. Oppositely, in 2013 both indexes reported the highest values (0.68 – 1.17 and −388 to 176, respectively). The areas of Seneghe and Ittiri were generally the most humid areas, whilst Berchidda sites were the driest. The highest values of continentality index were registered in 2013 (18.9 – 19.7) and the lowest in 2014. In this case, Berchidda was the area with the greatest temperature fluctuations, whereas Alghero sites were the ones with the lowest.

As shown by PCA-X analysis (SM2a), based on the meteoclimatic conditions occurred during fruit growth period, data were clearly separated according to the year. In particular, 2014 strongly differed from the others by a relatively rainy summer (June and July) with consequently mild temperatures (below 30 °C) followed by a 3-month dry period with higher temperatures and thermal amplitudes (Fig. 1). On the other hand, 2012 was characterized by a hot and dry summer

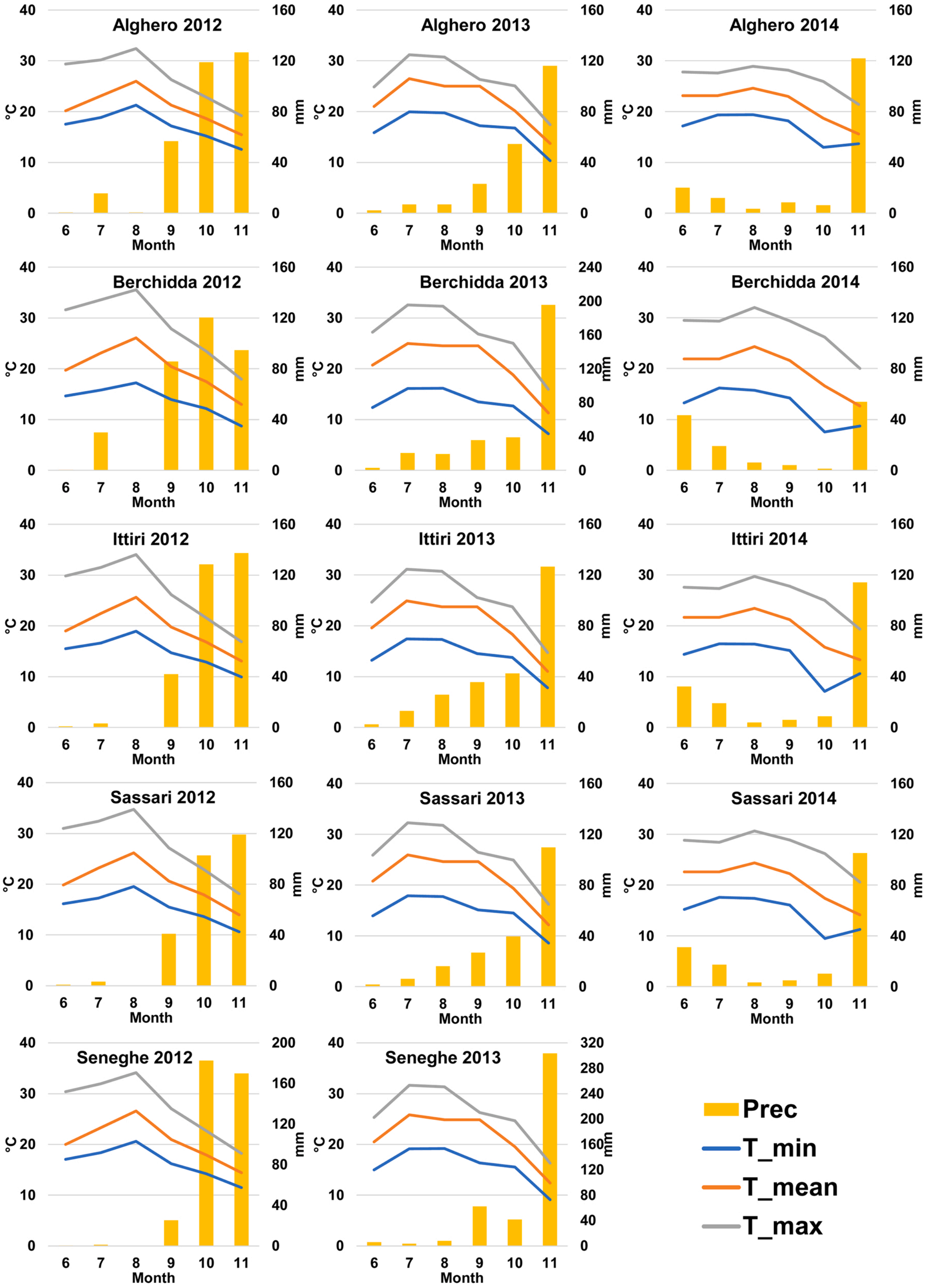

Fig. 1. Meteorological conditions occurred in the five Sardinian locations during the olive fruit growth period of 2012, 2013, and 2014: maximum temperature (Tmax), minimum temperature (Tmin), mean temperature (Tmean), and Precipitations (Prec).

followed by three rainy months with a sudden temperature reduction. The summer-autumn period of 2013 reported intermediate values except for the extreme precipitation events occurring during November in Berchidda and Seneghe areas. Looking at the site-specific characteristics, milder temperatures and lower thermal amplitude were observed in Alghero coastal areas, whilst the highest summer temperatures and the lowest autumn temperatures were observed in Berchidda and Ittiri inland areas. The area of Seneghe stood out for the greatest precipitations concentrated in the October-November period.

3.2. Olive fruit composition

Among the olive fruit morphological parameters, fresh weight (2.00 – 2.33 g), length (1.87 – 2.08 cm), and width (1.38 – 1.49 cm) were those less influenced by growing area and year. PitW and flesh FW/PitW (2.24 – 3.37) were significantly affected by both growing area and crop year (Table 1). The effect of the latter was generally predominant, indeed growing year exerted statistical differences between sites only in FW/PitW and fruit moisture. Environmental conditions of 2013 were favorable for oil concentration (47.7% on average). Fruit firmness (312.1 – 491.6 g mm^{-2}), a relevant physical parameter for both oil and table olive production, showed high variability between years. A decreasing trend along the three years was observed in titratable acidity. The influence of growing season was effective, in minor extent, also on reducing sugars. The lowest sugar concentrations (1.45%) were observed in 2012, the highest (1.93%) during the following year. The pH fruit mesocarp was not significantly affected by the two examined factors.

The PLS analysis performed to assess the relationship between fruit composition (Y variables) and pedoclimatic variables (X variables) confirmed the strong influence of growing season. Indeed, the observation scores represented in the PLS biplot (SM2b) clustered in three groups corresponding to the three growing years. The PLS model allowed to identify the fruit parameters mostly affected by pedoclimatic variables. Only PitW, moisture, oil yield, acidity, and firmness achieved significant R^2Y and Q^2Y values (Table 2). Moreover, the results of the model clarified some relationships within Y variables. FW/PitW, pulp moisture, pulp firmness, and acidity behaved similarly and were higher in the 2012 season. A strong opposite relationship between PitW and FW/PitW was observed. Conversely, FW/PitW showed a weak bond with FW. Although located distantly into the biplot space (SM2b), PitW and sugars were positively related to 2014 scores.

Upon first glance at the X variables' performance (SM2b), interest was piqued by the recurrent opposite effect on fruit components of tmax against tmean and tmin. Indeed, the minimum and mean temperatures during the early growth period favored fruit dimensions (mainly in terms of width, FW, and FW/PitW), firmness, and oil yield. However, oil yield, width, PitW, and sugars, were negatively affected by maximum temperatures of June. Similarly, maximum temperatures during September and October limited oil accumulation, acidity, and firmness.

To better understand the relationship between pedoclimatic variables and fruit components, OPLS regression models were developed separately for PitW, FW/PitW, Moisture, firmness, oil yield, acidity, and

Table 2
Autofit* results of PLS model's specific Y variables.

PLS Model	Y variable	R^2Y	Q^2Y	cv-ANOVA p-value
Fruits general model	length	0.091	0.024	n.s.
	width	0.248	0.169	n.s.
	FW	0.137	0.070	n.s.
	PitW	0.368	0.280	0.013
	FW/PitW	0.330	0.164	n.s.
	Moisture	0.303	0.242	0.027
	Oil Yield	0.375	0.284	0.014
	pH	0.047	-0.051	n.s.
	Acidity	0.515	0.306	0.009
	Sugars	0.204	0.073	n.s.
	Firmness	0.745	0.680	0.000
Fatty Acids	C16:0	0.491	0.382	0.001
	C16:1	0.559	0.399	0.001
	C18:0	0.475	0.387	0.001
	C18:1	0.631	0.534	0.000
	C18:2	0.581	0.473	0.000
	C18:3	0.203	0.119	n.s.
	C20:0	0.343	0.205	n.s.
	C20:1	0.487	0.422	0.000
Sensory profile	Olive Fruity	0.513	0.401	0.000
	Grass	0.436	0.311	0.008
	Almond	0.196	0.085	n.s.
	Artichoke	0.353	0.243	0.033
	Bitter	0.222	0.096	n.s.
	Pungent	0.399	0.302	0.008
	Fluidity	0.208	0.081	n.s.

*R^2Y and Q^2Y indicate respectively the percentage of variation explained by the model and the proportion of variance predictable by the model. cv-ANOVA p-value indicates the statistical significance of the investigated model, it is obtained by the analysis of variance (ANOVA) in the cross-validated (cv) residuals of each Y-variable.

Table 1
Morphological, physical, and chemical characteristics[1] of olive fruits of Bosana cultivar during the three-years study from five different geographical areas.

		Length	*Width*	*FW*	*PitW*	*FW/PitW*	*Moisture*	*Oil Yield*	*Firmness*	*pH*	*Acidity*	*Sugars*
Area	***Alghero***	1.90 ± 0.11	1.46 ± 0.13	2.21 ± 0.48	0.64 ± 0.11ab[2]	2.42 ± 0.27b	60.3 ± 4.2ab	46.6 ± 3.4a	423.6 ± 113.3ab	5.26 ± 0.38	0.83 ± 0.12	1.63 ± 0.38
	Berchidda	1.86 ± 0.17	1.38 ± 0.12	2.00 ± 0.47	0.55 ± 0.12c	2.78 ± 0.95ab	63.5 ± 1.9a	40.9 ± 6.2b	380.4 ± 81.0b	5.18 ± 0.14	1.18 ± 0.65	1.99 ± 0.49
	Ittiri	1.87 ± 0.08	1.43 ± 0.06	2.14 ± 0.25	0.59 ± 0.08abc	2.64 ± 0.50b	62.3 ± 2.9a	45.0 ± 3.6ab	377.5 ± 83.3b	5.06 ± 0.26	1.12 ± 0.40	1.82 ± 0.37
	Sassari	1.94 ± 0.08	1.42 ± 0.09	2.19 ± 0.31	0.65 ± 0.06a	2.37 ± 0.35b	56.7 ± 5.6b	45.2 ± 5.9ab	408.6 ± 65.0ab	5.11 ± 0.17	0.93 ± 0.34	1.71 ± 0.47
	Seneghe	2.08 ± 0.36	1.48 ± 0.07	2.33 ± 0.29	0.54 ± 0.10bc	3.37 ± 0.43a	63.4 ± 2.8a	43.7 ± 3.7ab	452.4 ± 70.9a	5.23 ± 0.35	1.09 ± 0.25	1.49 ± 0.50
Year	***2012***	1.93 ± 0.25	1.39 ± 0.09 y	2.07 ± 0.35	0.52 ± 0.10 y	3.03 ± 0.73x	64.0 ± 3.5b	42.8 ± 4.5 y	491.6 ± 47.8x	5.23 ± 0.42	1.35 ± 0.54x	1.45 ± 0.44 y
	2013	1.95 ± 0.11	1.49 ± 0.08x	2.33 ± 0.37	0.64 ± 0.09x	2.64 ± 0.45xy	59.6 ± 4.1a	47.7 ± 3.5x	386.7 ± 35.8 y	5.16 ± 0.06	0.87 ± 0.06 y	1.93 ± 0.26x
	2014	1.86 ± 0.13	1.41 ± 0.1xy	2.06 ± 0.33	0.63 ± 0.05x	2.24 ± 0.4 y	59.3 ± 4.2a	41.5 ± 5.0 y	311.7 ± 45.1z	5.08 ± 0.13	0.80 ± 0.09 y	1.91 ± 0.47x
Factorial analysis[3]	***Area***	n.s.	n.s. (0.10)[4]	n.s. (0.07)	* * (0.20)	* * (0.28)	* * (0.34)	* (0.16)	* (0.10)	n.s.	n.s. (0.12)	n.s. (0.13)
	Year	n.s.	* * (0.19)	n.s. (0.12)	* ** (0.28)	* * (0.18)	* * (0.23)	* ** (0.29)	* ** (0.68)	n.s.	* ** (0.38)	* * (0.24)
	Area vs Year	n.s.	n.s. (0.26)	* (0.33)	* (0.23)	* (0.21)	n.s. (0.05)	n.s. (0.18)	n.s. (0.06)	n.s.	n.s. (0.15)	n.s. (0.21)

[1] fruit length and width are expressed as cm; fruit weight (FW) and pit weight (PitW) as g; pulp moisture is expressed as %; Oil Yield is expressed as % of oil in mesocarp dry matter; firmness as g mm^{-2}; Acidity and Sugars as % of fresh pulp; [2] different letters "a, b, c" within a row indicate significant difference at 5% level, according to one-way ANOVA (Tukey method), for the growing area factor while "x, y, z" letters indicate significant differences between years; [3] Significance levels for factorial analysis (two-way ANOVA) are as follows: * = p-value < .05, ** = p-value < .01 or *** p-value < .001, n.s. not significant; [4] values in brackets are the η^2 values, explaining the percentage of the variance explained by the model related to the factor.

reducing sugars. All models achieved significant autofit results (Table 3). Firmness ($R^2Y = 0.765$, $Q^2Y = 0.731$), oil yield ($R^2Y = 0.627$, $Q^2Y = 0.497$), and acidity ($R^2Y = 0.600$, $Q^2Y = 0.428$) reported the best performances. According to the OPLS loadings of the predictive component, pit weight (Fig. 2a) was principally promoted by higher tmean of June, July, and September, October tmax and soil pH values. Tmax of July – August period, together with precipitations during September-October exerted a negative effect. The same variables showed similar statistical relevance but opposite effects on FW/PitW (Fig. 2b), pulp moisture (Fig. 2c) and firmness (Fig. 2d). The FW/PitW ratio, index of great importance for both table olive quality and olive oil production, was also promoted by higher Mg and Fe soil concentrations, whereas higher Zn and K values were positively related with moisture. On the other hand, pulp firmness only depended on weather, specifically by rainfall. Rainy conditions during the second growth period (September – November) also increased FW/PitW and fruit moisture.

Increased ΔT during the whole fruit growth period reduced oil yield (Fig. 3a). Such negative influence was also noticeable, with a less extent on PitW and width during summer months. On the other hand, higher ΔT and tmax during the June-August period favored organic acids (Fig. 3b) whereas sugars (Fig. 3c) took advantage of September-November ΔT but were reduced by high temperatures of the preceding three months. The cumulative monthly precipitations occurring during the first growth period (June – August) were positively associated to sugar content, whilst negatively to acidity. Within the same period, the final oil yield was negatively affected by June precipitations but received advantage from August rainy conditions. September – November precipitations were positively relevant only for organic acid content.

Even though soil characteristics marginally affected oil yield, acidity, and sugars content, according to p1 loadings in Fig. 3b and c, we can hypothesize that low fertility soils (higher gravel fraction, poor in carbon, K, and N concentrations) may contribute to producing olive fruits with higher acidity and reducing sugars content.

Table 3
Autofit* results of PCA-X, PLS, and OPLS models.

Model name	Type	R^2X	R^2Y	Q^2Y	n. Components	n. X variables
Meteo variables	PCA-X	0.996		0.969	9	33
* ***Fruits general model**	PLS	0.725	0.296	0.214	2	21
* ***Fatty acids**	PLS	0.490	0.471	0.366	2	31
* ***Sensory profile**	PLS	0.653	0.333	0.217	2	19
PitW	PLS	0.577	0.473	0.318	2	17
	OPLS	0.577	0.473	0.334	1 + 1	17
FW/PitW	PLS	0.493	0.530	0.319	2	21
	OPLS	0.493	0.530	0.300	1 + 1	21
Moisture	PLS	0.503	0.572	0.337	2	19
	OPLS	0.630	0.602	0.408	1 + 2	19
Oil Yield	PLS	0.578	0.594	0.450	2	19
	OPLS	0.701	0.627	0.497	1 + 2	19
Firmness	PLS	0.679	0.765	0.719	2	20
	OPLS	0.679	0.765	0.731	1 + 1	20
Acidity	PLS	0.566	0.600	0.421	2	20
	OPLS	0.566	0.600	0.428	1 + 1	20
Sugars	PLS	0.585	0.463	0.320	2	20
	OPLS	0.585	0.463	0.328	1 + 1	20

*R^2X, R^2Y, and Q^2Y indicate respectively the percentage of variation related to the X variables explained by the model, the percentage of variation related to the Y variables, and the proportion of variance predictable by the model.

* *The autofit results reported here are those referred to the comprehensive performance of the model, which differ to those of Table 2 because related to the specific Y variables.

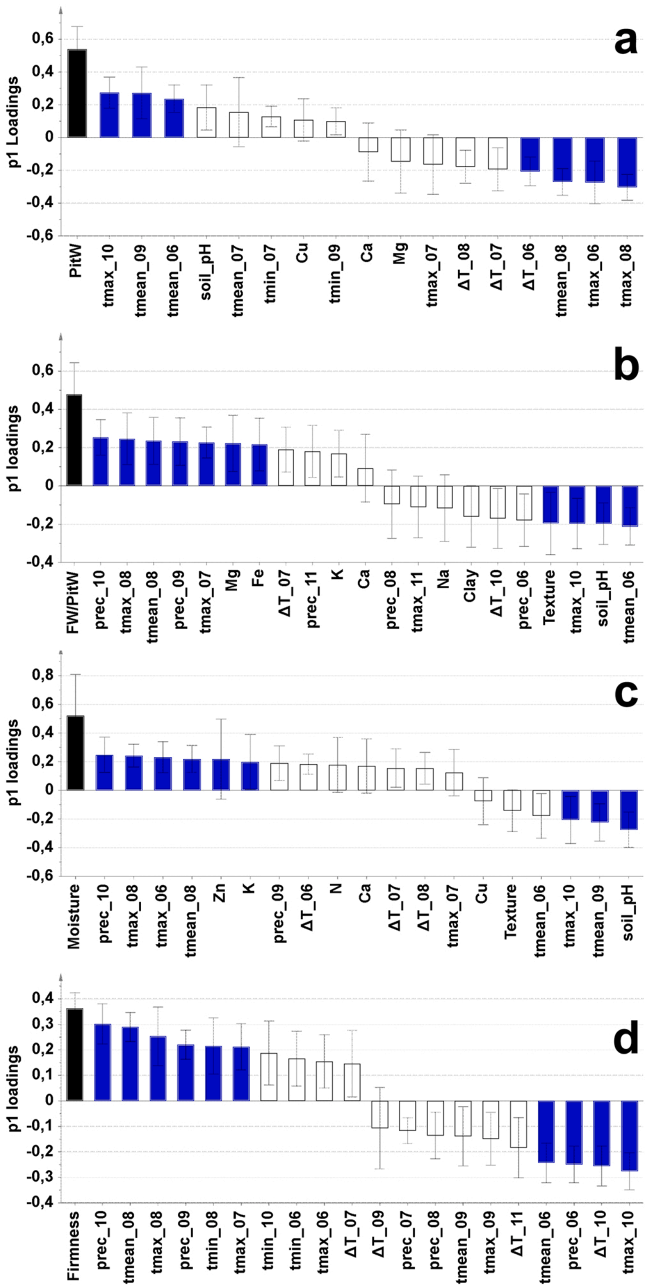

Fig. 2. Bar plot representing the loading values of the OPLS regression model predictive component, respectively for pit weight (a, PitW), flesh to pit ratio (b, FW/PitW), flesh moisture (c), and Firmness (d), Y variables (black bars). X variables[1] highlighted in blue are those with VIPs values above 1. Loadings summarize the relationships among the variables of a model. Error bars are obtained through the Jack-knifing cross-validation uncertainty bars at a confidence level of 95%. [1]X variables abbreviations: tmax = maximum temperature; tmin = minimum temperature; tmean = average temperature; ΔT = temperature amplitude (Tmax – Tmin); prec = precipitations; the "_n." following the abbreviation of meteo variable indicates the month (for instance tmean_06 = average temperature of July).

3.3. *Virgin olive oil fatty acids*

According to the analysis of variance, the VOO fatty acid composition was affected both by growing area and season (Table 4). The variability of saturated fatty acids was principally related to the growing area, whilst unsaturated fatty acids variability to the growing season. The interactive effect of area and year was significant in palmitic, oleic,

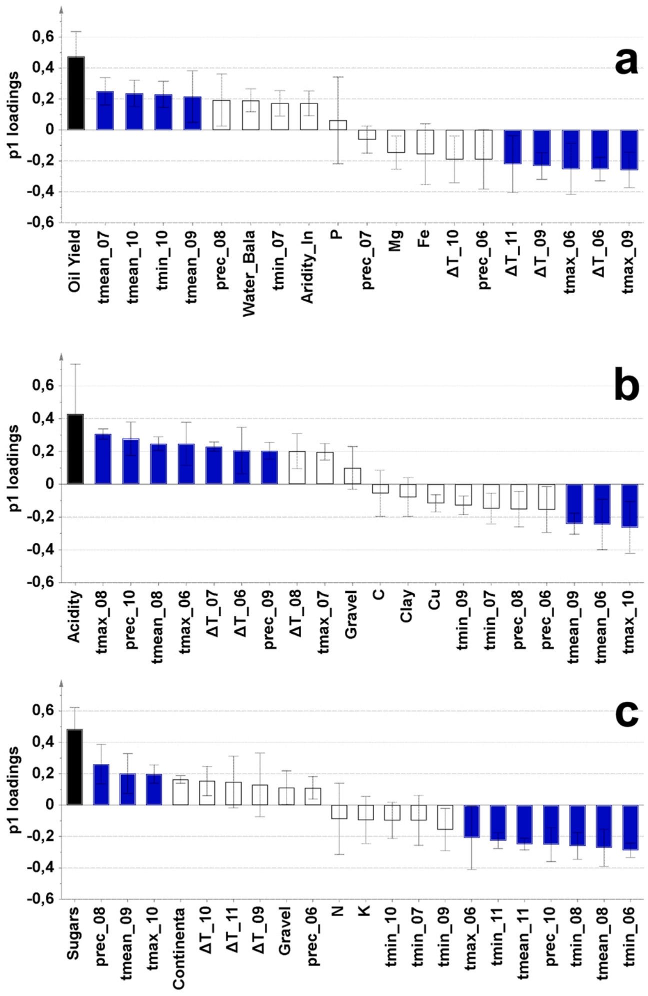

Fig. 3. Bar plot representing the loading values of the OPLS regression model predictive component, respectively for Oil Yield (a), Acidity (b), and Sugars (c), Y variables (black bars). X variables[1] highlighted in blue are those with VIPs values above 1. Loadings summarize the relationships among the variables of a model. Error bars are obtained through the Jack-knifing cross-validation uncertainty bars at a confidence level of 95%. [1]X variables abbreviations: tmax = maximum temperature; tmin = minimum temperature; tmean = average temperature; ΔT = temperature amplitude (Tmax – Tmin); prec = precipitations; the "_n." following the abbreviation of meteo variable indicates the month (for instance tmean_06 = average temperature of July); Water Bala = water balance index; Aridity_In = aridity index; Continenta = continentality index.

linolenic, and arachidic acid models, but only for C18:3 did interaction cover the highest fraction of model variance. Oleic acid (C18:1) concentrations only differed between VOOs from the hilly areas of Ittiri and Sassari (72.3 – 73.1%) and coastal areas of Alghero. Similarly, differences between Ittiri and Alghero VOOs were also observed for linoleic (11.5% and 8.8%, respectively) and palmitic acids (14.3% and 12.8%, respectively). The amounts of the remaining fatty acids were very similar between the studied areas (Table 4). Oleic acid assumed a decreasing trend during the three years of study, while an opposite behavior of linoleic and palmitic acid was observed. The relationship between VOO fatty acid composition and pedoclimatic variables was investigated through PLS analysis. The PLS results are represented by the biplot in Fig. 4. Here it is possible to observe that Y variables (fatty acids) aggregated into two groups. The first one comprised C18:1 and C20:1 (eicosenoic acid) and the second one the remaining fatty acids. Another result that stood out looking at Fig. 4 is that the PLS model separated clearly the three growing seasons. The first group of Y variables was positively related with the 2012 scores, whereas the second group with 2014 ones. According to the cross-validated ANOVA on the individual Y variables regressions (Table 2), only linolenic acid (C18:3) and arachidic acid (C20:0) were not significant. The best autofit results were obtained for C18:1 and C18:2 ($R^2Y = 0.63$ and 0.58; $Q^2Y = 0.53$ and 0.47, respectively). The temperatures of the whole fruit growing period (June – November) played the principal role on VOO fatty acid profile determination. Tmax from July to November and June tmean, together with tmean and precipitations of June and November, ΔT of July and the continentality index were the most effective variables (Fig. 4 and SM3). Temperatures affected differently fatty acid composition according to the growth period. Indeed, high temperatures during July – August were associated with higher C18:1 and lower C16:0 and C18:2 percentages; the effect was opposite during June and September-November period. Also, precipitations during September and October, and a higher continentality index contributed to increasing C18:1 values. Although with low relevance, the fatty acids PLS model included five soil variables (Silt, C, organic matter, Na, Cu), whose values were positively correlated with C16:0, C18:0, C18:2 and negatively with C18:1.

3.4. Sensory profile of virgin olive oils

The organoleptic attributes identified by the sensorial analysis were olive fruity, grass, almond, and artichoke, together with the bitter, pungent, and fluidity sensations (Table 5). Bosana VOOs were characterized by medium intensity of olive fruity-ness, well balanced with pungent and bitter tastes, also present at medium intensity levels (IOC, 1996). Grass and artichoke were the prevalent flavors, but with low intensity. Very similar profiles between growing areas were observed. Significant differences were established among studied years for all organoleptic attributes (Table 5). VOOs with more intense olive fruity,

Table 4
Fatty acid composition (%) of virgin olive oils from Bosana cultivar obtained during three years of study from five different geographical areas.

		C16:0	*C16:1*	*C18:0*	*C18:1*	*C18:2*	*C18:3*	*C20:0*	*C20:1*
Area	***Alghero***	14.3 ± 0.5a[1]	1.0 ± 0.1	2.9 ± 0.4a	68.6 ± 2.6b	11.5 ± 1.9a	0.7 ± 0.1ab	0.5 ± 0.0a	0.3 ± 0.0b
	Berchidda	13.9 ± 1.0ab	0.9 ± 0.1	2.7 ± 0.4ab	69.8 ± 3.7ab	10.9 ± 2.3ab	0.7 ± 0.1a	0.5 ± 0.0a	0.3 ± 0.0ab
	Ittiri	12.8 ± 0.6c	0.9 ± 0.1	2.4 ± 0.1b	73.1 ± 1.9a	8.8 ± 1.4b	0.6 ± 0.0b	0.4 ± 0.0ab	0.3 ± 0.0a
	Sassari	13.2 ± 0.6bc	1.0 ± 0.1	2.3 ± 0.3b	72.3 ± 2.0a	9.5 ± 1.3ab	0.6 ± 0.0ab	0.4 ± 0.0b	0.3 ± 0.0ab
	Seneghe	13.2 ± 0.6abc	0.9 ± 0.1	2.4 ± 0.2b	72.0 ± 1.6ab	9.7 ± 1.0ab	0.7 ± 0.1ab	0.4 ± 0.0ab	0.3 ± 0.0ab
Year	***2012***	13.1 ± 0.6 y	0.8 ± 0.1 y	2.5 ± 0.3 y	72.9 ± 1.8x	8.8 ± 1.1 y	0.7 ± 0.1 y	0.5 ± 0.0xy	0.3 ± 0.0x
	2013	13.4 ± 0.9 y	1.0 ± 0.1x	2.4 ± 0.3 y	71.4 ± 2.4x	10.2 ± 1.4 y	0.6 ± 0.0 y	0.4 ± 0.0 y	0.3 ± 0.0x
	2014	14.1 ± 0.8x	1.0 ± 0.0x	2.9 ± 0.4x	68.3 ± 3.0 y	11.7 ± 2.2x	0.7 ± 0.1x	0.5 ± 0.0x	0.3 ± 0.0 y
Factorial analysis[2]	***Area***	* ** (0.42)[3]	n.s. (0.12)	* ** (0.39)	* ** (0.34)	* ** (0.29)	* (0.15)	* ** (0.35)	* * (0.23)
	Year	* ** (0.25)	* ** (0.46)	* ** (0.27)	* ** (0.41)	* ** (0.39)	* * (0.21)	* * (0.20)	* ** (0.36)
	Area vs Year	* (0.15)	n.s. (0.11)	n.s. (0.11)	* (0.11)	n.s. (0.12)	* * (0.32)	* (0.18)	n.s. (0.11)

[1] different letters (a, b, c) within a row indicate significant difference at 5% level, according to Tukey test, for the growing area factor while "x, y, z" letters indicate significant differences between years; [2]Significance levels for factorial analysis (two-way ANOVA) are as follows: * = p-value < .05, ** = p-value < .01 or *** p-value < .001, n.s. not significant; [3]values in brackets are the η^2 values, explaining the percentage of the variance explained by the model related to the factor.

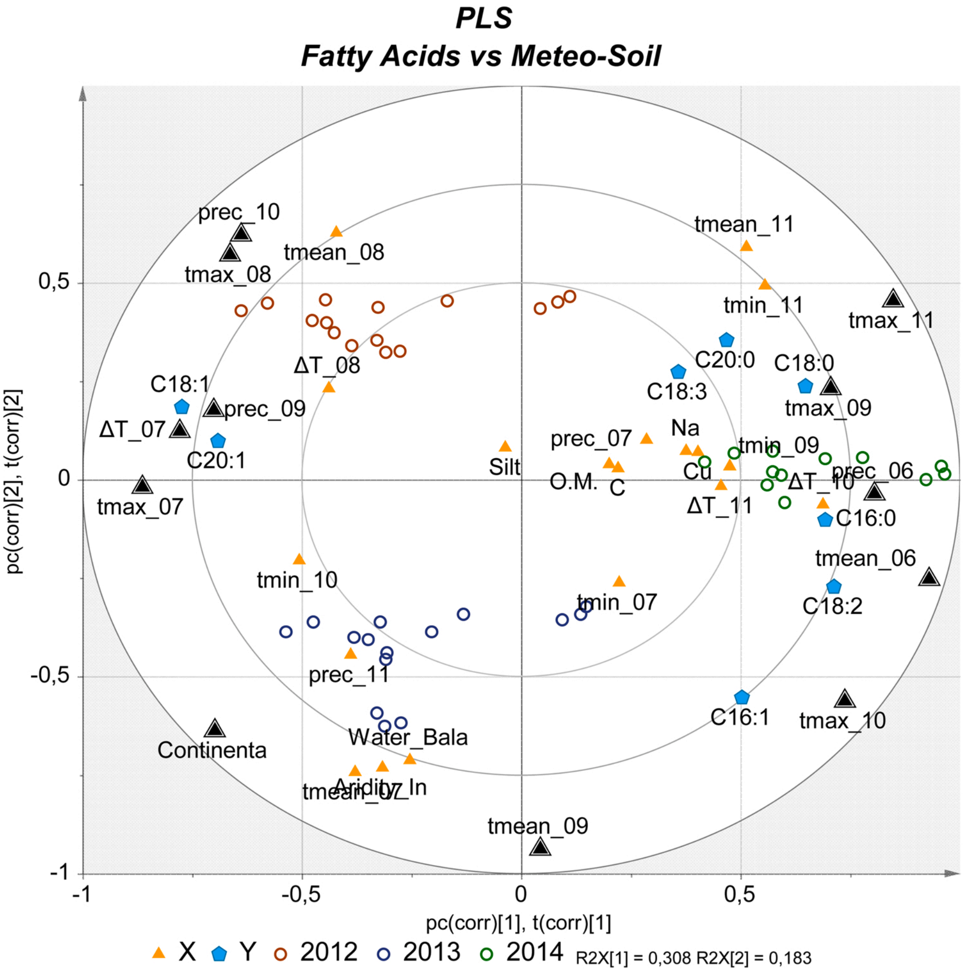

Fig. 4. Biplot representing the distribution of X variables (meteo and soil), Y variables (VOO fatty acid composition) and scores (colored by harvest year) on the first two components of PLS models. X variables[1] highlighted with black triangles are those with VIPs values above 1. [1]X variables abbreviations: tmax = maximum temperature; tmin = minimum temperature; tmean = average temperature; ΔT = temperature amplitude (Tmax – Tmin); prec = precipitations; the "_n." following the abbreviation of meteo variable indicates the month (for instance tmean_06 = average temperature of July); Water Bala = water balance index; Aridity_In = aridity index; Continenta = continentality index. O.M. = organic matter.

Table 5
Sensory profile of virgin olive oils from Bosana cultivar obtained during three years of study from five different geographical areas.

		Olive Fruity	*Grass*	*Almond*	*Artichoke*	*Bitter*	*Pungent*	*Fluidity*
Area	***Alghero***	4.6 ± 0.8	2.4 ± 0.9	1.6 ± 0.7	2.2 ± 1.2	3.6 ± 0.8	3.8 ± 0.7	4.8 ± 0.6
	Berchidda	4.3 ± 0.7	2.2 ± 1.0	1.2 ± 0.7	1.9 ± 1.3	3.4 ± 0.7	3.6 ± 0.7	4.8 ± 0.4
	Ittiri	4.4 ± 0.5	2.2 ± 0.7	1.4 ± 0.5	2.2 ± 0.7	3.6 ± 1.1	3.7 ± 0.9	4.7 ± 0.5
	Sassari	4.5 ± 0.6	2.3 ± 0.8	1.5 ± 0.3	2.4 ± 0.6	4.0 ± 0.7	4.1 ± 0.7	5.3 ± 0.5
	Seneghe	4.2 ± 0.4	2.2 ± 0.7	1.8 ± 0.3	1.8 ± 0.6	3.3 ± 0.4	3.8 ± 0.3	4.5 ± 0.9
Year	***2012***	4.9 ± 0.5x[1]	2.9 ± 0.6x	1.7 ± 0.3x	2.7 ± 0.7x	3.9 ± 0.6x	4.2 ± 0.5x	4.9 ± 0.5
	2013	4.3 ± 0.6 y	1.9 ± 0.8 y	1.4 ± 0.6xy	1.8 ± 1.0 y	3.6 ± 0.8xy	3.8 ± 0.5x	4.7 ± 0.7
	2014	4.0 ± 0.4 y	1.9 ± 0.5 y	1.2 ± 0.6 y	1.7 ± 0.8 y	3.3 ± 0.9x	3.2 ± 0.8 y	4.9 ± 0.7
Factorial Analysis[2]	***Area***	n.s. (0.05)[3]	n.s. (0.01)	n.s. (0.10)	n.s. (0.06)	n.s. (0.11)	n.s. (0.08)	n.s.
	Year	* ** (0.46)	* ** (0.37)	* (0.15)	* ** (0.25)	* (0.14)	* ** (0.36)	n.s.
	Area* vs *Year	n.s. (0.17)	n.s. (0.21)	n.s. (0.28)	* ** (0.43)	n.s. (0.26)	n.s. (0.13)	n.s.

[1]different letters (x, y, z) within a row indicate significant difference at 5% level, according to Tukey test, for the year factor; [2]Significance levels for factorial analysis (two-way ANOVA) are as follows: * = p-value < .05, ** = p-value < .01 or *** p-value < .001, n.s. not significant; [3]values in brackets are the η^2 values, explaining the percentage of the variance explained by the model related to the factor.

grass, almond, artichoke, and pungent attributes were obtained during the first year of study. Fluidity was a stable attribute, weakly altered by location or growing season.

PLS model results (Fig. 5) underlined the strong correlation existing between the VOO flavors, which consequently tend to behave similarly towards pedoclimatic conditions. Anyway, the autofit results and the cross-validated ANOVA of the individual attributes (Table 2) revealed that the pedoclimatic variables were able to significantly explain the variability of only olive fruity, grass, artichoke, and pungent attributes. The first one reported the best performances ($R^2Y = 0.513$, $Q^2Y = 0.401$). Conversely, the variability of almond and bitter intensity, together with fluidity sensation, seem not to be dependent on environment. Precipitations during the fruit maturation period (September-November), together with low maximum temperatures and thermal amplitudes were the meteo variables that first promoted flavor's intensity (Fig. 5, SM4). Hot and dry conditions during summer (June-August) also contributed to increasing olive fruity and pungent values. As well as for olive fruit characteristics and fatty acid profile, soil properties played a marginal role in determining VOO sensory profile. Only soil pH was positively correlated with bitterness (SM4).

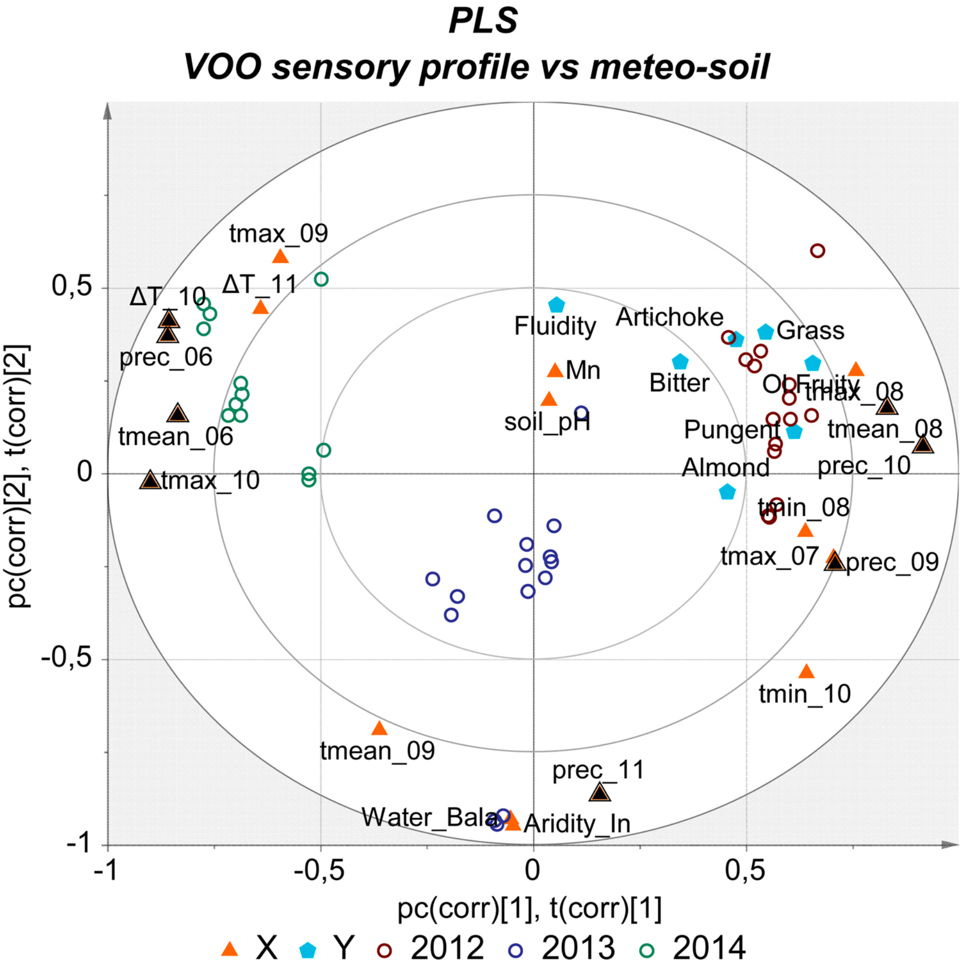

Fig. 5. Biplot representing the distribution of X variables (meteo and soil), Y variables (VOO sensory profile) and scores (colored by harvest year) on the first two components of PLS models. X variables highlighted with black triangles are those with VIPs values above 1. [1]X variables abbreviations: tmax = maximum temperature; tmin = minimum temperature; tmean = average temperature; ΔT = temperature amplitude (Tmax – Tmin); prec = precipitations; the "_n." following the abbreviation of meteo variable indicates the month (for instance tmean_06 = average temperature of July); Water_Bala = water balance index; Aridity_In = aridity index.

4. Discussion

4.1. Olive fruit composition

Morphological traits of Bosana fruits were consistent with previous literature (Bandino and Dettori, 2001; Piga et al., 2001). The present study showed that, for cv Bosana, the parameters like fruit length, width, and fresh weight were poorly influenced by environment variability. However, previous studies showed that, according to the variety, several environmental components, like altitude and distance from the sea affected also olive fruit morphology (Di Vaio et al., 2013; Nissim et al., 2020; Mafrica et al., 2021). On the other hand, the higher FW/PitW and lower moisture values than our findings reported by Piga et al. (2001) could be justified by the different growing areas and seasons involved. Indeed, as revealed by OPLS analysis, these parameters were significantly affected by both soil and meteo parameters. Furthermore, FW/PitW and moisture were the fruit parameters that showed the strongest relationships with soil components. This finding is consistent with two-way ANOVA results that underlined the influence of growing area. The principal limiting factor for pit growth seemed to be the maximum and Δ temperatures occurring soon after fruit set, therefore the period in which the rate of cell division is highest in olive fruit (Rapoport et al., 2004), whereas increased late summer temperatures promoted pit growth. Rapoport et al. (2004), investigating the effect of water stress on fruit development of the Leccino cultivar, observed that early drought conditions constrained pit development but, as water availability was reestablished, at 22 weeks after full bloom, the fruits from the stressed plants retrieved the pit dimensions of non-stressed ones. Although we did not observe any influence of water availability, our findings agree with those of Rapoport et al. (2004) about the period of fruit development involved in pit growth. The weak influence of precipitations on fruit development that we observed could be related to the adaptation to water stress conditions of the rain-fed 50-year-old trees that were the objects of study. Indeed, adult rain-fed plants have improved tolerance and avoidance capacity, since they are usually characterized by an expanded high-density radical apparatus and high root/canopy ratio (Brito et al., 2019). Other authors observed a negligible effect of irrigation treatments on pit weight but a relevant influence of crop season (d'Andria et al., 2009; Sánchez-Rodríguez et al., 2019b). Moreover, the inverse correlation with August temperature but positive correlation with September-October temperatures lead to hypothesize the presence of an optimum range of temperatures favorable for pit growth, above which the process slows down (SM5).

On the other hand, precipitations, mainly those occurring during the later fruit development period, significantly increased FW/PitW, moisture, and firmness. The positive effect of rainfall to fruit moisture reflects the ability of olive fruits to rehydration after a water stress period, which could also contribute to the expansion of mesocarp cells and then to an increase in the flesh to pit ratio (Rapoport et al., 2004; Sánchez-Rodríguez et al., 2019b). In the case of firmness, the effect of the different temperature parameters (tmin, tmean, tmax, and ΔT) was coherent. However, the effect of increased temperature values was opposite if we compare the June-August and September-November periods. The negative effect during the second one is probably the consequence of an acceleration of the ripening process, in which the action of pectolytic enzymes responsible for fruit softening is involved (Karagiannis et al., 2021). Albeit the presence of cultivar-specific maturation process dynamics and firmness values, the observed relationships between this parameter and seasonal meteoclimatic variables are consistent with previous findings (Mafrica et al., 2021). Soil variables did not influence fruit firmness. Emmanouilidou et al. (2020) comparing different olive varieties, reported that pulp firmness and moisture had a negative relationship with oil concentration. According to the same authors, varieties with oil production attitude reported higher oil to moisture ratio than those suitable for table olive production. In the present study a direct correlation between the two fruit components was not found, but they showed opposite relationships with numerous meteoclimatic variables, principally temperatures.

According to several authors, increased temperatures from pit hardening until one month before harvest have a negative effect on oil accumulation (García-Inza et al., 2014; Miserere et al., 2022). These findings, probably due to different seasonal thermal trends between the study areas, agreed with ours only on summer period. Afterwards (September and October) maximum and mean temperatures were positively associated with oil concentration. Consistently with what was observed on pit weight, such an aspect suggests that the oil accumulation rate increases with increased temperatures until the achievement of an upper threshold, above which the plant turns into thermal stress and slows down its metabolism, causing a delay in lipogenesis (Benlloch-González et al., 2019). According to our findings regarding cv Bosana, this upper threshold could be identified between 25 and 29 °C (SM5). As described by recent studies from different geographical areas (Andalusia, Argentina, and Israel), the responses and plasticity, in terms of oil yield and quality, to air temperature is varietal-specific, thus the presence of specific upper thresholds is conceivable (Rondanini et al., 2014; Navas-Lopez et al., 2019; Nissim et al., 2020). Moreover, our outcomes, in line with García-Inza et al. (2018) findings, stresses the importance to consider in the studies on the temperature response of olive fruit and oil composition the effects of thermal amplitude as a reliable marker of both thermal and water stress conditions. Indeed, thermal amplitude is inversely related with precipitations, which in turn contribute to lower maximum temperatures and keep higher minimum temperatures. Although relevant for the OPLS model, the effect of precipitation variables was weaker than those related to temperature. Rainfall regime of June and August apparently contributed to lower and rise oil yield, respectively. These findings are consistent with those of Gucci et al., (2007, 2019) which reported that oil content in mesocarp was promoted, with specific varietal response, by water availability during the period of highest oil accumulation rate. However, oil content at harvest, in terms of dry weight percentage, was lower in growing seasons characterized by a rainy summer. According to Cherbiy-Hoffmann et al. (2015) artificial shading during fruit set negatively affects final oil concentration. A similar effect could be attributed to the lower irradiance caused by clouds of early summer rainy days.

Regarding Bosana cultivar, previous studies employed in similar geographical areas and during the same growing seasons reported slightly different oil content (Morrone et al., 2018). Such differences could be related to different soil composition. Indeed, as revealed by OPLS, also the concentration of some soil nutrients (e.g. Fe, Mg, and P) contribute to determine oil accumulation in olive mesocarp.

Data obtained by this work on the primary metabolites of olive fruits, organic acids (expressed as acidity) and sugars, revealed that environmental conditions differently affected the two types of metabolites. Acidity, as revealed by the higher than sugars model accuracy, was more dependent on pedoclimatic conditions. Meteo conditions of the whole fruit development period significantly affected both components, even if for sugar content the meteoclimatic conditions occurring during the later maturation process showed a stronger importance. These findings agree with previous literature, which reported sugar and organic acid biosynthesis activity until the late ripening process (Arslan and Özcan, 2011; Karagiannis et al., 2021). An increase in organic acid synthesis during early stages of fruit development, followed by an opposite trend at late fruit maturation was observed on several fruit species, like grapes and kiwifruit (Famiani et al., 2015). It was also reported that increased temperatures during fruit growth, and higher daily thermal amplitudes promoted leaf and fruit respiration with consequently organic acid biosynthesis. Increased respiration rate involves organic acid products, like malate and citrate, as intermediates in Krebs Cycle rather than for glucogenesis. On the contrary, higher temperatures during fruit maturation hasten the process, decreasing titratable acidity and promoting sugar biosynthesis (Famiani et al., 2015). To our knowledge the present study describes for the first time the relationships, under a statistical point of view, between temperatures and olive fruit acidity and sugar content. Additional studies will be necessary to verify such relationships under a physiological point of view. It is important to emphasize that, unlike pit growth and oil accumulation, our findings did not indicate the presence of upper temperature limits for titratable acidity. It is conceivable that during this period, the intermediate products of Krebs Cycle were accumulated in vacuoles delaying their use as glucogenesis and lipogenesis substrate. Moreover, similarly to Martinelli et al. (2012) acidity was promoted by water availability during September-October months, the period usually corresponding to the onset of maturation of Bosana fruits in Sardinian environments (Deiana et al., 2019). Precipitations, strictly correlated with lower temperatures, are responsible in turn for delaying the maturation process.

4.2. Relationship between the VOO fatty acid composition and pedoclimatic variables

The previous studies on Bosana VOO FAs showed similar profiles and variability to our findings (Deiana et al., 2021). According to Culeddu et al. (2017) high unsaturation in Bosana VOOs was caused by arid climates (FAO aridity index) of southern Sardinia. Authors suggested a positive relationship between air temperature and FA desaturation degree and fruit maturation rate. Although consistent with Culeddu et al. (2017), in the present study only stearic (C18:0) and arachidic acids (C20:0) showed significant negative Pearson correlations with aridity index. In line with our findings, Morrone et al. (2018) reported that Bosana VOOs with higher MUFA levels were produced from the hilly areas of Sassari and Ittiri, when compared with those from the plain coastal areas of Alghero. In the present study, hilly areas (Ittiri, Seneghe, and Berchidda) had also the highest continentality index values. The positive influence of altitude and continentality on oleic acid concentration should be attributed to the lower temperatures during late summer and autumn typical of such areas (Di Vaio et al., 2013; Dib et al., 2021). Indeed, numerous studies described a concomitant increase in C18:2 and C18:3, derived by C18:1 desaturation process, and air temperatures during fruit growth (Lombardo et al., 2008; Rondanini et al., 2014; García-Inza et al., 2014, 2018; Sánchez-Rodríguez et al., 2019a; Nissim et al., 2020; Miserere et al., 2022). According to Hernández et al. (2021) the transcription level of OeFAD2–2 and OeFAD2–5 genes, the principal element responsible for linoleic acid biosynthesis, is promoted by different environmental factors, mainly temperature, and in some varieties its expression increases along with olive fruit development. Our results agree partially with previous literature since we observed that June and August maximum temperatures were strongly positively correlated with oleic acid levels. This aspect is consistent with the hypothesis that high temperatures above an upper threshold (25–29 °C) induce reduced lipogenesis rate on Bosana trees, thus probably affecting the oleate desaturation process. On the other hand, the strong negative correlation between oleic acid levels and June tmean we observed is in line with Lémole et al. (2018) findings and interpretations. The authors hypothesized that the lower linoleic and higher oleic acids levels observed in Arbequina drupes subjected to shading during the earliest period of fruit development (from fruit set to pit hardening) was caused by consequent decreased temperatures, which limited FAD2 and FAD6 transcription. In light of the present and previous findings, it seems clear that the main characteristics of a growing area that could influence the fatty acid content are the maximum temperatures during the whole fruit growth season.

Also, rainfall, specifically those occurring in June and September-October, significantly affected FA composition. The former period reduced oleic acid percentage, whilst the second had an opposite effect. Similar findings were reported by Jukić Špika et al. (2021). However, the rainfall influence reported by the authors was delayed by one month. Such delay can be related to the different microclimate of growing areas, colder than Sardinia, and to the different varietal phenology. Beltrán et al. (2004) postulated that summer rainfall limited KAS II activity causing a reduction of both stearic and oleic acid levels in Picual VOOs. Conversely, the positive effect of late summer-autumn rainfall on oleic acid amount is probably related to the mitigating effect of temperatures at leaf and fruit level, as suggested by García et al. (2020).

Linolenic and arachidic acids were weakly affected by pedoclimatic conditions. The stability among different environments of these minor fatty acids is common of other cultivars, like Arbequina, Barnea, Frantoio, which in contrast have high oleic/linoleic sensitivity (Mailer et al., 2010).

Even if the PLS model did not assign strong relevance to soil variables, significant correlations with several fatty acids were noted. Total carbon and organic matter percentage promoted palmitic, stearic, and linoleic acid amounts, and disadvantaged oleic acid. These results could be interpreted by the contribution of soil fertility in mitigating environmental stress conditions, as for instance improving water availability and keeping plant metabolism rate. Similar findings about soil organic matter influence on FAs were reported by Cetinkaya and Kulak (2016). Soil texture is an essential property since it determines water and nutrient retention and availability, aeration, drainage, and root spread (Lechhab et al., 2022). In the case of FA composition, positive relationships were found between the monounsaturated fraction and clay percentage, whereas the effect of ($CaCO_3$) percentage in soil exerted contrasting results in literature (Bucelli et al., 2011; Lechhab et al., 2022).

4.3. Relationship between the VOO sensory profile and pedoclimatic variables

The sensory profile of Bosana VOOs, characterized by grass and artichoke attributes, was the typical one observed for this cultivar (Rotondi et al., 2010). Previous findings on the same variety reported that sensory attributes (e.g. pungent, artichoke, and grass) were significantly affected by growing site (Campus et al., 2013; Morrone et al., 2018). Conversely, the present findings did not emphasize large variability between the growing areas, but slightly higher levels of intensity in Alghero and Sassari, those areas closer to the sea.

A first outcome which stands out from the present study is that crop year significantly influenced Bosana VOO sensory attributes, as observed also previously on other cultivars (Jukić Špika et al., 2021). Moreover, pedoclimatic variables affected similarly the flavors characterizing Bosana VOO aroma, but with different sensitivity. Conversely, Jukić Špika et al. (2021) observed opposite relationships with meteoclimatic variables and different groups of organoleptic attributes. In particular, the “sweet” aromas of apple and almond stood out from the “green” ones. The different behavior of some classes of attributes reflects the specific sensitivity to environmental conditions of the enzymes and biological substrates (mainly linoleic and linolenic acids, polyphenols and aminoacids) that originate the volatile compounds responsible for oil aroma (Benelli et al., 2015; Caporaso, 2016).

Among pedoclimatic variables, the most relevant, maximum temperatures and rainfall, were concentrated during fruit maturation (from September to November). The two variables exerted an opposite effect on flavor intensity, this is probably due to the drop-off effect of rainfall on daily temperatures. The determinant favorable influence of rainfall, and in general water availability, during the same period was also noticed on other varieties like Frantoio and Moraiolo (Bucelli et al., 2011; Benelli et al., 2015). Benelli et al. (2015) also underlined the effective role of light intensity on determining quantitative and qualitative VOO volatile composition. On the other hand, Caporaso (2016) reported that some volatile compounds were negatively related with rainfall or continuous irrigation. The same author stressed the importance of varietal factor on the formation and sensitivity to pedoclimatic variability of the oil aroma. According to Jukić Špika et al. (2021) findings, the effect of rainfall was different according to the period of fruit development and it was consistent with those of the present study but delayed, as well as for FA.

5. Conclusions

Although OPLS and PLS models highlighted those periods of fruit growth crucial for each fruit component, to understand better the reason of the final fruit composition the whole growth period should be considered. The multivariate approach adopted confirmed the usefulness of separate temperature variables like maximum, minimum, mean temperatures and thermal amplitude, which affect differently individual olive and olive oil components. The knowledge about the role of a specific meteoclimatic variable, during a specific period, will be a useful tool in managing operations aimed to alleviate (or promote) summer heat and water stress, such as foliar applications or deficit irrigation treatments.

To the best of our knowledge, this is the first time that the relationships between pedoclimatic variables and olive fruit components like pit weight, firmness, acidity, and sugar concentration, as well as VOO sensory attributes, has been analyzed through a multivariate approach.

The present study suggests, for the cultivar Bosana in Sardinia, the presence of a maximum temperature threshold ranging from 25° to 29°C, which slows down several processes involved in fruit development, lipogenesis among others. Air temperatures above the hypothesized threshold are responsible for lower oil yields and pit weight but higher C18:1 concentration. Further studies, considering during the growth season daily temperature values and wider ranges, will help to define better both maximum and minimum threshold temperatures for the studied fruit components and to improve the model accuracy of other important olive quality aspects and VOO sensory attributes. Moreover, if extended to different growing areas, the experimental approach described in the present study could be a useful tool to assess the site-specific suitability, under a qualitative point of view, of other olive cultivars as well as other tree species.

Finally, this study provided novel insights about the influence of soil characteristics on olive fruit and VOO composition, which, although its secondary role after meteorological conditions, resulted as relevant for some morphometric parameters of olive fruit like PitW, FW/PiTW, and moisture. This aspect, together with the effect of the growing sites noticed at a relatively local scale, support the possibility to apply the concept of *terroir* also to olive and olive oil markets, contributing to promote and valorize high-quality productions, cultural heritage of rural areas, and geographic labels.

Author Contributions

Conceptualization: SD, MRF, MS; Data curation: BA, PD, MRF, AM, MS; Investigation: PD, MS; Methodology: PD, MS; Data and statistical analysis, PD; Supervision: NC, SD, MRF, LM, GN, MS; writing—original draft preparation: PD, MS; writing—review and editing: BA, PD, SD, AM, LM, GN, MS. All authors have read and agreed to the published version of the manuscript.

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CRediT authorship contribution statement

Conceptualization: SD, MRF, MS; Data curation: BA, PD, MRF, AM, MS; Investigation: PD, MS; Methodology: PD, MS; Data and statistical analysis, PD; Supervision: NC, SD, MRF, LM, GN, MS; writing—original draft preparation: PD, MS; writing—review and editing: BA, PD, SD, AM, LM, GN, MS. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2023.126856.

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