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Yield and physical-chemical quality of table olives in different hedgerow canopy positions (cv. Manzanilla de Sevilla and Manzanilla Cacereña) as affected by irradiance

Pilar Rallo[a,*], Eduardo Trentacoste[b], Guillermo Rodríguez-Gutiérrez[c], María Rocío Jiménez[a], Laura Casanova[a], María Paz Suárez[a], Ana Morales-Sillero[a]

[a] Departamento de Agronomía, ETSIA, Universidad de Sevilla, Carretera de Utrera, km 1, Sevilla 41013, Spain
[b] Estación Experimental La Consulta, (Instituto Nacional de Tecnología Agropecuaria), Mendoza, Argentina
[c] Instituto de la Grasa, Consejo Superior de Investigaciones Científicas (CSIC), Campus Universitario Pablo de Olavide, Edificio 46, Ctra. de Utrera, km. 1, Seville 41013, Spain

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ABSTRACT

Unlike olive orchards intended for olive oil, the production of table olives in narrow hedgerows is very recent and the information available about this cropping system is yet very scarce. In this work, we studied for the first time in table olive hedgerows (3.75m x 1.35m, N-S oriented) of Manzanilla de Sevilla and Manzanilla Cacereña cultivars, the distribution within the canopy of yield components and physical-chemical fruit quality traits in response to the incident irradiance. Hedgerow canopies were divided into four positions on each side (East and West) according to height aboveground: 0.5–1.0m, 1.0–1.5m, 1.5–2.0m, 2.0–2.5m, and an additional top canopy position (> 2.5m) integrated for both sides. Total production, number of fruits and size distribution were recorded for each position and the following fruit traits were assessed: fresh weight, length, equatorial diameter, pulp-to-pit ratio, color index, bruising percentage, oil content, water content, total sugars and total phenols. Individual phenolic compounds were also quantified. The incident irradiance at each position was calculated over the fruit growth period using a model based on hedgerow parameters, resulting in a positive gradient from base to top canopy positions. For both cultivars, yield components and most quality traits were positively affected by incident irradiance as they followed a similar trend showing larger mean values with increasing canopy heights. Conversely, the total contents in sugar and phenols and individual phenolic compounds were not affected by the canopy positions. No remarkable differences between East and West sides of the hedgerow were observed.

1. Introduction

Hedgerow orchards have been developed for different fruit crops, such as apple, pear, grapevine, almond, and stone fruits (peach and cherry) as a way to reduce the production costs by facilitating pruning and harvesting (manual or mechanized) (Connor et al., 2014). Commercial hedgerows for olive crop were developed for mill production in the 1990s and spread rapidly from Spain to the rest of the world (Connor et al., 2014). Narrow hedgerows orchards are associated with super-high density or superintensive layouts (with more than 1,000 trees per hectare) that allow achieving early bearing and continuous hedges, as well as increasing the solar radiation intercepted with the consequent improvement in productivity (Jackson, 1980). The selection of varieties of high early yield production and low vigor plays a key role, and hedgerow dimensions should allow the mechanization of the harvesting with straddle harvester-type machines, which reduces labor costs, harvest time, and dependence on manual labor (Trentacoste et al., 2015).

The production of table olives in narrow hedgerows has been extended recently, since the studies initiated by the University of Seville in the 2010′s (Morales-Sillero et al., 2014). As olives are intended for consumption, the damage suffered during harvest, called bruising, is the most limiting factor that decreases their quality and, therefore, depreciates their commercial value. In fact, manual harvesting of the fruits, to avoid high levels of bruising, is a common practice in some of the commercial table olive SHD orchards that currently exist. Nonetheless, different studies have shown the influence that variety (Jiménez et al., 2017), straddle harvester (Pérez-Ruiz et al., 2018) and environmental conditions (Morales-Sillero et al., 2023) have on the damage caused when fruits are harvested in these superintensive orchards. Besides, the

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[*] Corresponding author.
E-mail address: prallo@us.es (P. Rallo).

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incidence of bruising can be drastically reduced by transporting the harvested fruits in diluted sodium hydroxide solutions (Morales-Sillero et al., 2014), as it was previously demonstrated for olives harvested by trunk shakers (Rejano et al., 2008; Zipori et al., 2021). However, little is yet known about the design and management of narrow hedgerows for table olive.

Hedgerow design aspects such as row orientation, row distance, hedge width, hedge height and porosity determine the irradiance received at different positions in the canopy and influences yield parameters, as fruit number, and quality. However, the relationship between irradiance and production and quality of both the olive fruit and olive oil has been studied only on oil varieties, mainly ‘Arbequina’. The fruits are usually smaller and tend to have a more elongated shape at the base of the hedges. In the highest canopy positions, fruits mature faster, they have a larger size and a higher oil content that is characterized by the highest stability to oxidation and total phenols, all of which have been related to the higher incidence of solar radiation (Gómez-del-Campo and García, 2012; Grilo et al., 2019, 2021; Trentacoste et al., 2015, 2016). A simulation model of irradiance distribution within olive hedgerows is currently available to explain the relationships with fruit production and oil quality and, therefore, to evaluate different strategies of hedgerows design and management (Connor et al., 2016; Trentacoste et al., 2021).

Concerning table olives, the fruit distribution in different canopy positions within hedgerows and their characteristics have not yet been studied. Consequently, neither has the relationship with irradiance. An important aspect to bear in mind is that quality in table olives depends on a large number of attributes apart from the absence of bruising (Rallo et al., 2018). The size, pulp-to-pit ratio, shape, and color of the fruit acquire a greater importance than in olive oil varieties. The consumer usually prefers medium to large olives ($>$ 3g fruit^{-1}), a high pulp-to-pit ratio ($\geq$ 5:1), a spherical rounded shape (often preferred also by the industry as the olives are pitted easier), and a good surface color, close to the green color in the ‘Spanish-style’ green olives. Besides, like olive oil, table olive is considered a staple food of the Mediterranean Diet and its consumption has been associated with beneficial health effects (Accardi et al., 2016; Rocha et al., 2020). This is so because of its nutraceutical quality, which depends on the chemical composition. Table olives are rich in oil (20–30% of total weight) whose excellent quality is, as known, largely due to the richness in monounsaturated fatty acids, mainly oleic acid (47–84%) and palmitoleic acid (0.3–3.5%). Essential acids as the polyunsaturated linoleic and linolenic acids are also present in the olive fruit. These fatty acids are not synthesized by humans, so they have to be ingested as part of the diet (Servili et al., 2016). To a lesser extent, it is the pulp sugar content (3.5–6%), which is related to olive texture. Sugars are precursors of oil biosynthesis and provide energy for metabolic changes. Besides, during table olive processing, they are the raw material for the lactic fermentation process and give rise to the secondary metabolites that are responsible for the flavor of the final product. On the other hand, the olive is also rich in phenolic compounds. The content of these bioactive compounds represents 1–3% of the fresh pulp weight. Oleuropein is the main phenolic component in the pulp. As it degrades, it increases the content of hydroxytyrosol, a phenolic compound that protects the body from oxidative damage and has anti-inflammatory and antioxidant activity (Rocha et al., 2020). Phenols are also related to the organoleptic features of the olive, such as the bitter taste, and to the color of black olives (Johnson and Mitchell, 2018).

With the general objective of optimizing the design of narrow hedgerows for table olive production and its subsequent management, the specific aims of this work were to: i) determine fruit production, fruit traits and chemical composition at different canopy heights on opposing sides of N-S hedgerows of two table olive cultivars; ii) determine the influence of the cultivar; and iii) explore the relationships between the irradiance received in different canopy positions (heights and sides), estimated by simulation, and fruit production and quality.

2. Material and methods

2.1. Site and orchard

The study was carried out in 2016 in nine-year old hedgerows of two traditional table olive varieties, ‘Manzanilla de Sevilla’ and ‘Manzanilla Cacereña’ (Fig. 1a), in a commercial orchard located in Campo Maior, Portugal (latitude: 38 ° 55 ′ 55.1 ′ N; longitude: 7 ° 02 ′ 36.8 ′ W). Trees were spaced 3.75 × 1.35m in a North-South orientation. Both cultivars were planted in adjacent plots of 1ha approximately. Trees were drip irrigated and trained to a central leader system. Mechanical pruning was performed during the previous winter and thick branches and stumps were removed with a chainsaw or pruning shears. Environmental conditions, cultivar characteristics, and irrigation doses are fully described in Morales-Sillero et al. (2023). Total fruit yield was of 6,300kg ha^{-1} for ‘Manzanilla de Sevilla’ and 17,100kg ha^{-1} for ‘Manzanilla Cacereña’.

2.2. Canopy positions

For each cultivar, four individual olive trees with similar crop load were randomly chosen, mainly in the center of the rows. Olive canopies were divided into four positions aboveground based on height on each side (East and West) of the hedgerows (Fig. 1b): 0.5–1.0m, 1.0–1.5m, 1.5–2.0m, and 2.0–2.5m. The canopy top ($>$ 2.5m) with both sides of

Fig. 1. (a) General view of the super-high-density field studied with hedgerows of ‘Manzanilla de Sevilla’ and ‘Manzanilla Cacereña’. (b) Example of canopy positions in a sampled tree of ‘Manzanilla de Sevilla’.

the hedgerows integrated, was also considered. In total nine positions per tree were evaluated.

Hedgerow dimensions were determined in each tree per cultivar, as the maximum height, average width, and porosity. Tree width was determined at 0.80 and 1.70m. Hedgerow porosity was measured by image analysis of digital pictures at each canopy position. Photographs were taken with a Nikon D600 reflex camera (Nikon Corp., Tokyo, Japan). The camera was positioned perpendicular to the hedgerow surface background, where a red sheet had been previously placed. Later, the images obtained were processed digitally using the CobCal software ver. 2.0 (Bs As, Argentina), which allows to estimate in the images the average percentage of gaps by dividing the number of red pixels (i.e., background sheet) by the total number of red and green pixels (i.e., leaves and stems).

2.3. Fruit yield, weight, and number

Fruits were hand-picked on September 14, close to maturity index 1 (Ferreira, 1979), with a green to yellowish skin color. For each hedgerow position (height and side) within each tree replicate, total fruit fresh weight (fruit yield, g) was determined, and the average fruit weight (g) was obtained from a subsample of 100 fruits. Later, the total number of fruits was estimated from the fruit yield and the average fruit weight. For size distribution, the unitary fruit weight was determined using the same subsample of 100 fruits. Fruit classes were based on fruit number per kilo and were established according to the following size designations by the US Standards for Grades of Green Olives (USDA, 2019): Large (220–240); Medium and Small (241–300); Petit (301–400); Subpetite (401–420) and smaller than subpetite (>420), the latter considered commercially unsuitable by the table olive industry.

2.4. Pulp-to-pit ratio, fruit length and equatorial diameter, color index and non-bruised fruits

The pulp-to-pit ratio in fresh weight was estimated for each hedgerow position using a sample of 0.5kg as the difference between the fruit and pit weights. The maximum longitudinal and equatorial diameters (mm) were measured with a digital caliper in 50 fruit subsamples, and fruit shape was determined as the ratio between them. The skin color index was estimated as indicated in Morales-Sillero et al. (2023) on the equatorial zone of 30 fruits using a Minolta CM-700d (Konica Minolta Inc., Tokyo, Japan) spectrophotometer. The proportion of non-bruised fruits (%) was determined on another 100 fruits subsample two hours after harvesting.

2.5. Water, oil content and total sugars

To determine the water content (%) in olives, approximately 250mg were weighed in a crucible, and the sample was placed in an oven at 105°C for 8 h, after which the crucible was left to cool down in a desiccator until constant weight was reached. The fruit oil content (%) was measured in the dry samples by nuclear magnetic resonance on a Maran Ultra spectrometer (Oxford Instruments, UK). Total sugars (mg g^{-1} of dry matter) were analyzed by the colorimetric method Antrona, as described in a previous work (Witham et al., 1971), using a spectrophotometer (BIO-RAD imark Microplate Reader, USA).

2.6. Total phenolic concentration and phenolic composition

The olive samples were frozen and prepared by removing the stone in a manual pitting machine. Pitted olives were ground for 30 s in a Lady max GOURMET blender (Spain). Samples of 10g of ground paste were weighed and quickly introduced into 20mL of a methanol and water solution in a ratio of 8:2 (v/v). The mixture was ground in an Ultra Turrax IKA T 25 blender for 60 s and centrifuged for 20 min at 21°C and 13,180x g in a Sorvall RT 6000 D centrifuge. The extraction was repeated twice. The two extracts obtained were mixed, filtered through filter paper, and finally stored at −20°C for phenol and sugar analysis.

Total phenols were determined using the Folin-Ciocalteu's method. Samples of 20µL were mixed with Folin-Ciocalteu's reagent as described by Singleton and Rossi (1965) and expressed as mg of gallic acid equivalents per gram. The absorbance was measured at 655nm in a BIO-RAD iMark Microplate Reader (USA).

High-performance liquid chromatography (HPLC) system (Hewlett-Packard 1100 series) equipped with a diode array detector (the wavelength used for quantification was 280nm) was used for the identification and quantification of the individual phenolic compounds. The HPLC has an automatic injector (20µL of sample) and the column used was Teknokroma Tracer Extrasil OSD2 (particle size 5µm, internal diameter 250mm and length 4.6mm). The mobile phases were water acidifier with trichloroacetic acid (0.01%) and acetonitrile. The gradient for 55min was: 95% A initially, 75% A after 30min, 50% A after 45min, 0% A after 47min, 75% A after 50min, 95% A after 52min until the end of the run. The quantification and identification were made using commercial standards by comparing the retention times and the UV spectra (200–360nm). The quantification was made using the regression curve of each phenolic compound. The results were expressed as mg of each phenolic compound per g of the initial olive referred to dry matter.

2.7. Irradiance profiles and relation with production and fruit traits

The incident irradiance at each canopy position was calculated using a model developed to evaluate radiation in porous olive hedgerow orchards (Connor et al., 2016). The model uses specific site and hedgerow parameters: latitude, day of year, hedge height, canopy width at base, row orientation, horizontal porosity (Table 1) and row spacing. The model was used to calculate daily incident irradiance at each canopy position (i.e., heights and sides) from fruit set (day of year, DOY 50) to fruit harvest (DOY 280) and then was obtained by averaging all daily values for that period (Table 1). The relationships between fruit traits and simulated irradiance were fitted by linear or linear-plateau functions using the non-linear routing of GraphPad Prism version 5.01 software (La Jolla, CA, USA).

2.8. Statistical analysis

To determine the effects of the canopy positions on fruit yield and quality, an analysis of variance with trend studies was performed using the Statgraphics Plus 5.1 (Statpoint Technologies, The Plains, Virginia) software package. The data were previously transformed using the arcsine of the square root or Box-Cox power transformations (Box and Cox, 1964) when necessary to achieve normality and homogenize the variance. Tukey's test ($P < 0.05$) was used to discriminate significant differ-

Table 1
Canopy porosity (± s.d.) and simulated daily irradiance values (± s.d.) under clear-sky conditions for fruit set – harvest period at the studied hedgerow canopy heights in two olive cultivars. Hedgerows were N-S oriented and both sides (E-W) received the same irradiance. Average daily incident irradiance is 58.3mol PAR m^{-2}.

	Manzanilla Cacereña		Manzanilla de Sevilla	
Canopy height	Porosity (%)	E-W irradiance (molPAR m^{-2})	Porosity (%)	E-W irradiance (molPAR m^{-2})
>2.5 m	49.5 ± 6.0	46.1 ± 0.22	14.4 ± 4.9	51.3 ± 0.62
2.0–2.5	12.1 ± 2.9	34.9 ± 0.62	8.5 ± 0.7	36.1 ± 1.62
1.5–2.0	17.7 ± 6.0	28.0 ± 0.76	9.6 ± 4.0	27.1 ± 1.89
1.0–1.5	20.7 ± 4.7	22.5 ± 0.77	25.6 ± 4.9	20.4 ± 1.81
0.5–1.0	68.4 ± 16.6	14.1 ± 0.57	64.3 ± 5.5	14.3 ± 1.52

ences between cultivars and canopy positions (heights and sides) of the hedgerow.

3. Results

3.1. Hedgerow structure and irradiance profiles

Hedgerows of both cultivars showed similar hedge average width (1.5m) and height (2.4m for ‘Manzanilla Cacereña’ and 2.5m for ‘Manzanilla de Sevilla’) and close to target dimensions appropriate for the mechanical harvester (1.20m x 2.5m). The four trees selected per cultivar had the same dimensions (height and width) and similar crop load showing a low coefficient of variation among trees for total production: 18.2% for ‘Manzanilla Cacereña’ and 24.4% for ‘Manzanilla de Sevilla’. Canopy porosity showed a general pattern that was the highest at the base and decreased in successively higher positions until the top (> 2.5m), where porosity increased more markedly in cv. Manzanilla Cacereña than cv. Manzanilla de Sevilla (Table 1). Consequently, the canopy of ‘Manzanilla Cacereña’ hedgerows showed an average porosity of 34%, higher than ‘Manzanilla de Sevilla’ hedgerows (24%). Regardless of cultivar, the irradiance consistently followed a general pattern of increasing from the lowest to highest positions in the hedgerow. In ‘Manzanilla Cacereña’, where the top canopy position was more porous, the irradiance within hedgerow was lower than in the top position of ‘Manzanilla de Sevilla’.

3.2. Influence of canopy position on production and fruit traits

Table 2 shows the mean values of production, yield components (number of fruits and fruit weight) and fruit physical traits according to the five different heights on both sides (East and West) of the hedgerows. The coefficients of variation per position among trees ranged from 6.7% to 16.8% for fruit weight and from 3.6% to 12.8% for pulp-to-pit ratio (data not shown).

Most traits showed significant positive linear trends with height in ‘Manzanilla de Sevilla’ hedgerow, so that production, fruit number, fruit length and equatorial diameter, and fruit color index were usually larger from base to top canopy position. For instance, production ranged from 242.2g at 0.5–1m height to 1055.2g above 2.5m height: the number of fruits between 85.7 and 306.3, fruit weight between 2.9g and 3.4g and color index between 23.9 and 25.8. This pattern was slightly more significant in the West side of the hedgerow for production, fruit number, length, and equatorial diameter. Pulp-to-pit ratio was not significantly influenced by the canopy height. A significant linear and quadratic tendency was observed for the percentage of fruits without bruising damage after manual harvesting only on the West side of the hedgerow so that bruising was higher in the lowest canopy position: 46.8% of undamaged fruits at 0.5–1.0m vs. values above 75–80% in the remaining heights.

A similar overall pattern was observed for cv. Manzanilla Cacereña. Production (321.2g to 1183.5g from base to top), fruit number (91.6 to 343.6), weight (2.9 to 3.6g), equatorial diameter (15.8 to 17.2mm), color index (25.1 to 26.9) and the percentage of non-bruised fruits (64.3 to 77.3) increased with canopy height, although trends were rather quadratic than linear and, in some traits, only significant in one of the sides. In fact, the highest production and fruit number values were observed at 2.0 to 2.5m height in contrast with Manzanilla de Sevilla cultivar, where the largest values were achieved at the top (> 2.5m). No significant differences between heights were found for pulp-to-pit ratio, nor for fruit length.

Regarding the hedgerow sides (East and West), no significant differences in mean values of any feature were observed with two exceptions: production and number of fruits were higher on the West side only at 1.5–2.0m and 2.0–2.5m height in ‘Manzanilla de Sevilla’ and ‘Manzanilla Cacereña’ hedgerows, respectively.

Significant differences were found between cultivars for most features, with the ‘Manzanilla Cacereña’ hedgerows showing higher production and number of fruits, which were longer and less susceptible to bruising than fruits from ‘Manzanilla de Sevilla’ hedgerows.

In addition to the mean fruit weight presented in Table 2, fruit size distribution according to commercial standards was recorded for each canopy height and is shown in Figs. 2 and 3.

A clear size improvement from base to top of the canopy was observed in both cultivars. For instance, considering the first two categories “Large” (L) and “Medium-Small" (M-S) (200–300 fruits per kilogram), there was a gradual increase from the lowest position (0.5 to

Table 2
Mean values of production, fruit number and fruit physical traits at different canopy heights and sides (E= East; W= West) of a N-S olive hedgerow of two table olive cultivars: Manzanilla de Sevilla and Manzanilla Cacereña.

	Production (g)		Fruit number		Fruit weight (g)		Pulp-to-pit		Length (mm)		Equatorial diameter (mm)		Color Index		Non bruised fruits (%)	
Canopy height (m)	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W
‘Manzanilla de Sevilla’																
>2.5	1055.2		306.3		3.4		5.8		20.2		17.2		25.8		80.5	
2.0 - 2.5	477.0	697.5	151.2	226.8	3.2	3.1	5.6	5.3	19.8	19.6	16.6	16.6	26.2	24.9	86.5	78.0
1.5 - 2.0	611.3A	905.2B	198.3A	294.1B	3.1	3.1	5.7	5.5	19.4	19.4	16.4	16.3	25.1	24.7	88.5	84.3
1.0 - 1.5	487.0	685.7	157.0	236.3	3.1	2.9	5.5	5.4	19.3	19.3	16.3	16.0	24.5	24.2	83.3	78.0
0.5 - 1.0	346.7	242.2	116.2	85.7	3.0	2.9	5.8	5.4	19.3	18.8	16.1	15.6	23.9	24.5	82.5	46.8
Trends																
L	*	**	*	**	ns	**	ns	ns	*	**	**	***	**	*	ns	*
Q	n.s	ns	ns	**	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*
Cultivar	X	X	X	X					X						X	X
‘Manzanilla Cacereña’																
>2.5	1183.5		343.6		3.6		6.4		20.6		17.2		26.9		77.3	
2.0 - 2.5	1354.0A	2547.7B	408.4A	789.5B	3.4	3.2	6.3	6.1	20.4	20.3	16.9	16.8	26.8	25.6	95.5	94.3
1.5 - 2.0	1299.0	1724.2	378.6	523.0	3.4	3.3	6.4	6.0	20.9	20.6	17.4	16.7	25.4	25.2	95.0	94.0
1.0 - 1.5	1215.5	1484.5	357.2	500.0	3.4	3.0	6.4	6.0	20.8	20	16.9	16.2	25.0	24.7	95.8	93.3
0.5 - 1.0	321.2	615.5	91.6	201.3	3.4	2.9	6.5	6.0	20.5	19.4	16.5	15.8	25.1	25.8	64.3	91.0
Trends																
L	*	*	ns	ns	ns	*	ns	ns	ns	ns	ns	**	**	ns	ns	ns
Q	*	**	**	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	**	*	ns
Cultivar	Y	Y	Y	Y					Y						Y	Y

A/B letters indicate significant differences between East and West sides of the hedgerow (Tukey $P \leq 0.05$); X/Y letters indicate significant differences between cultivars (Tukey $P \leq 0.05$); Trends with canopy heights may be $L =$ Linear; $Q =$ quadratic (*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; ns, not significant).

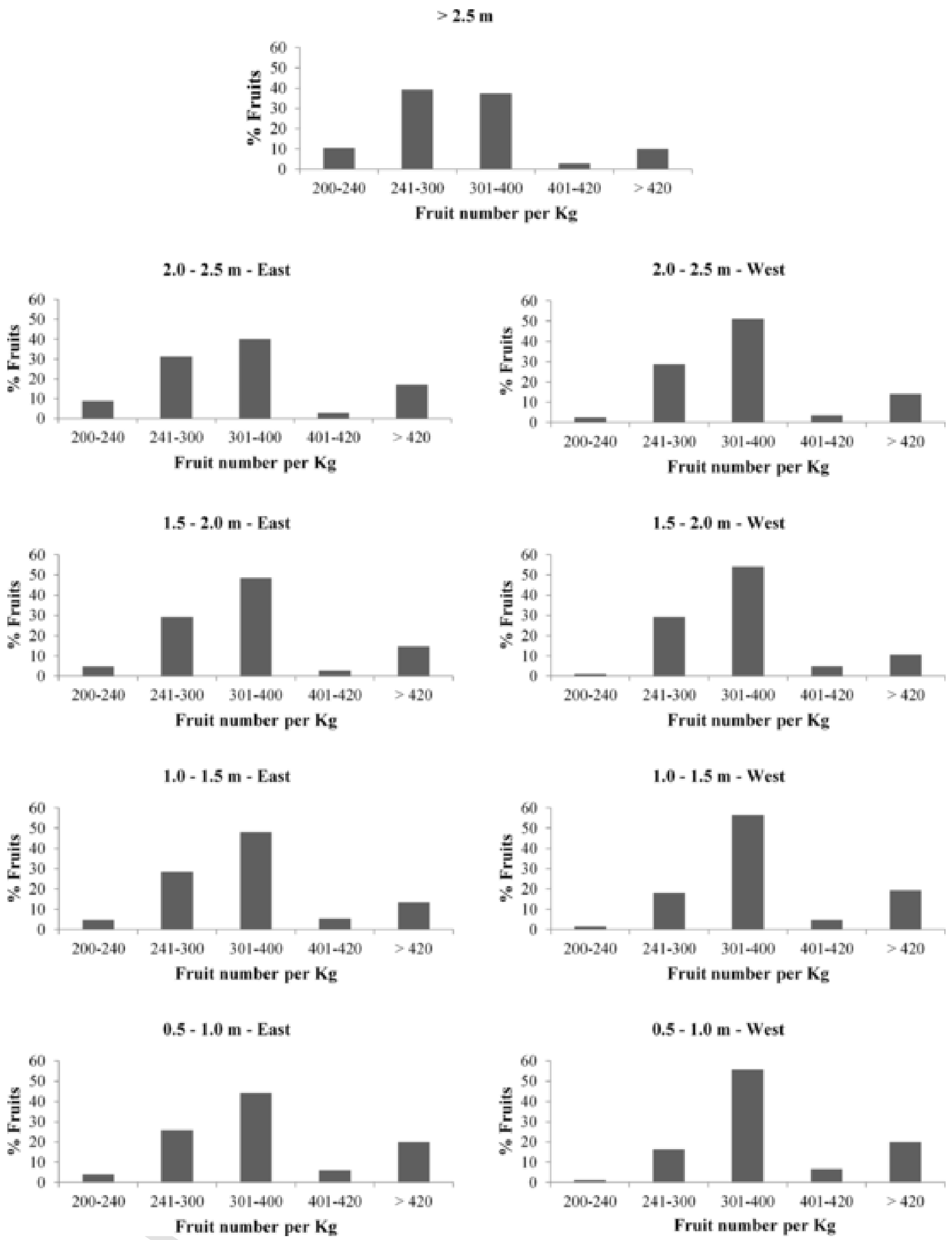

Fig. 2. Fruit size distribution at different canopy heights and sides of a N-S 'Manzanilla de Sevilla' olive hedgerow. Size classes (fruits kg^{-1}) follow the US Standards for Grades of Green Olives (USDA, 2019): Large (220–240); Medium and Small (241–300); Petit (301–400); Subpetit (401–420) and smaller than subpetite (>420).

1.0m) to the top one (>2.5m), ranging from 29.8% to 49.7% in 'Manzanilla de Sevilla' and from 41.4% to 57% in 'Manzanilla Cacereña'. Likewise, the percentage of fruits unsuitable for table olive commercialization due to their very small size (fruit number per kilogram >420), was higher at the lowest position in both cultivars, around 20% in 'Manzanilla de Sevilla' and 18.6% (mean value of both sides) in 'Manzanilla Cacereña', and it clearly decreased with height, reaching values of 9.9% and 4.6%, respectively, at the top of the hedgerow.

Fruits harvested on the East side generally showed a higher frequency of the larger fruit classes (L and M-S) compared to the West side at all canopy heights, regardless of the cultivar. The differences in fruit size distribution between sides of the hedgerows were particularly noticeable for the percentage of non-commercial fruits in 'Manzanilla Cacereña', that reached values close to 30% at the western lowest canopy height (0.5–1.0m) compared to values around 8% at the eastern lowest canopy height. Nonetheless, for most remaining canopy positions, it was generally below 10%.

Regarding differences between cultivars, 'Manzanilla Cacereña' generally showed higher percentage of fruits in the larger classes compared to 'Manzanilla de Sevilla'. Similarly, the percentage of non-commercial fruits was lower in 'Manzanilla Cacereña' for most canopy positions, apart from the above mentioned one (0.5–1.0m West).

3.3. *Influence of canopy position on the chemical composition of the fruit*

Mean values of fruit chemical characteristics on each canopy position are presented in Table 3. For both cultivars, the canopy height had a significant influence on the oil content, with a clear linear positive trend. Oil content ranged from base (0.5–1m) to top (>2.5m) between 18.5% and 26.1% in 'Manzanilla de Sevilla' and from 10.8% to 15% in 'Manzanilla Cacereña'. For the remaining traits, no significant trends along the canopy height were observed except for the water content, that showed a slight negative linear trend (69.8% to 67.5% from base to top) only in the West side of 'Manzanilla Cacereña' hedgerow.

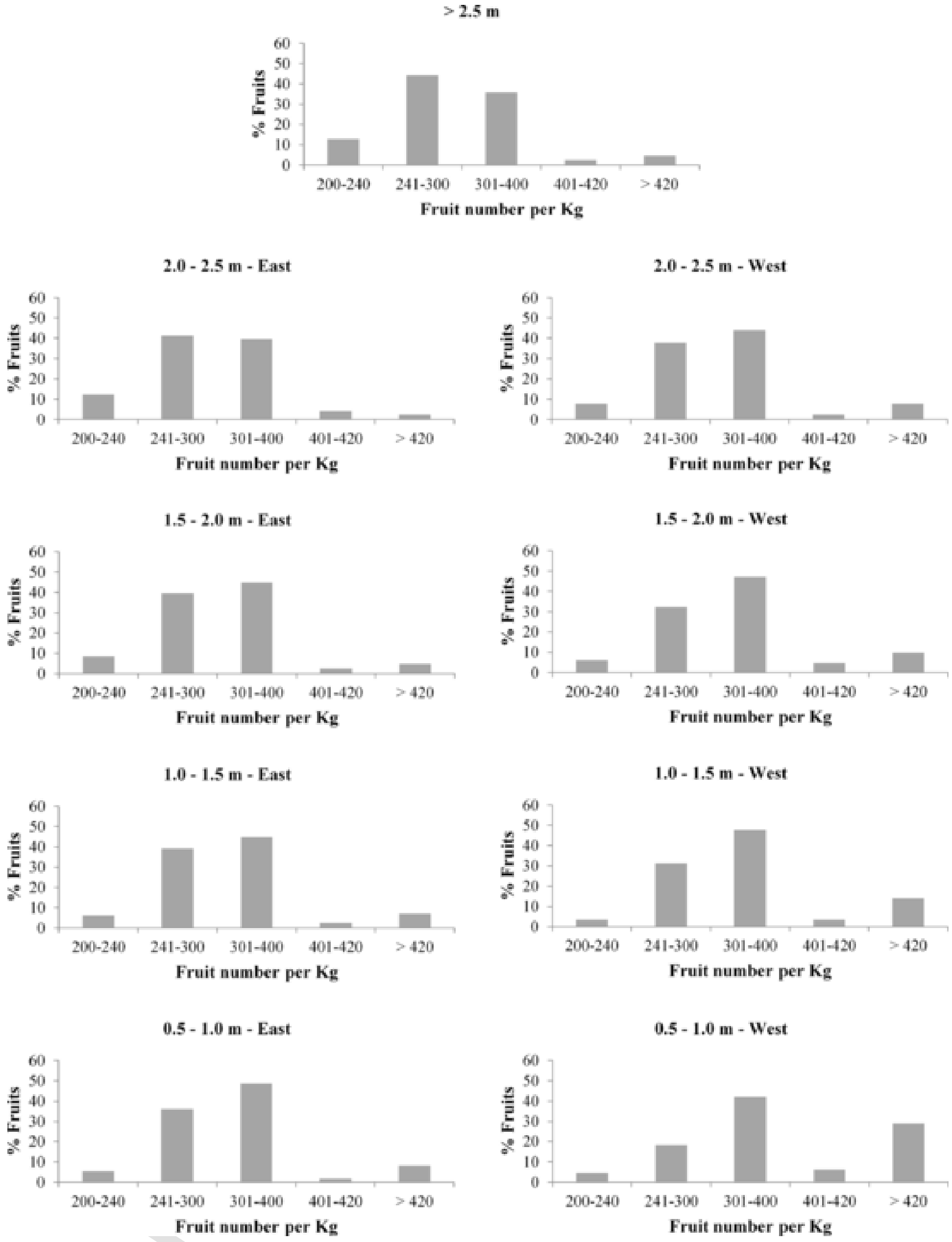

Fig. 3. Fruit size distribution at different canopy heights and sides of a N-S ‘Manzanilla Cacereña’ olive hedgerow. Size classes (fruits kg^{-1}) follow the US Standards for Grades of Green olives (USDA, 2019): Large (220–240); Medium and Small (241–300); Petit (301–400); Subpetit (401–420) and smaller than subpetite (>420).

Overall, ‘Manzanilla de Sevilla’ showed higher mean oil content (22.7%), total phenols (50.5mg g^{-1}) and total sugars (163.3mg g^{-1}) (all on dry weight basis) than ‘Manzanilla Cacereña’ fruits (13.2%; 34.6mg g^{-1}; 57.7mg g^{-1}, respectively). Water content was slightly higher in ‘Manzanilla Carecereña’ (68.4%) compared to ‘Manzanilla de Sevilla.’

Regarding individual phenolic compounds (Table 4), very few of them were influenced by the canopy height, and only in Manzanilla de Sevilla cultivar: luteonin and ferulic acid showed strong positive linear trends, ranging from 0.1 to 0.5mg g^{-1} dw the former and from 0.03 to 0.3mg g^{-1}dw the latter. Hydroxytyrosol seemed also to be influenced by the canopy height showing a quadratic trend ($p > 0.5$) but only on the East side of the hedgerow, ranging from 0.4mg g^{-1} in the lowest position to 2.6mg g^{-1} in the second layer (1–1.5m). As above-mentioned, for ‘Manzanilla Cacereña’, no significant trends along the canopy height were observed for any phenolic compounds.

Similarly, differences between the East and West side of the hedgerow were only detected in very few compounds (luteonin and ferulic acid in ‘Manzanilla de Sevilla’; and hydroxytyrosol, luteonin and vanillic acid in ‘Manzanilla Cacereña’) and only at certain heights. Although they were rare, in all the mentioned cases the mean values were higher in the East side of the hedgerow.

Significant differences between cultivars were also observed for oleuropein, hydroxytyrosol, vanillin, and vanillic acid, with ‘Manzanilla de Sevilla’ showing larger amounts of all these compounds (3.6, 1.9, 1.9 and 0.2mg g^{-1}, respectively) than ‘Manzanilla Carereña’ (1.4, 0.7, 1.2 and 0.04mg g^{-1}). On the contrary, the ferulic acid content was significantly higher for ‘Manzanilla Cacereña’ (0.4mg g^{-1}) compared to ‘Manzanilla de Sevilla’ (0.15mg g^{-1}).

3.4. Relationship between production, fruit traits and profiles of irradiance

Relationships of profiles of olive production and yield components (fruit number and fruit fresh weight), fruit dimensions, color, and composition to mean daily PAR irradiance over fruit set to harvest in both

Table 3

Mean values of fruit chemical characteristics at different canopy heights and sides (E= East; W= West) of a N-S olive hedgerow of two table olive cultivars: 'Manzanilla de Sevilla' and 'Manzanilla Cacereña'. dw = dry weight.

	Oil Content (% dw)		Water content (%)		Total Phenols (mg g^{-1} dw)		Total Sugar (mg g^{-1} dw)	
Canopy height (m)	E	W	E	W	E	W	E	W
'Manzanilla de Sevilla'								
> 2.5	26.1		65.1		55.0		167.6 Y	
2.0 - 2.5	24.5	22.5	64.8	65.6	49.4	53.6	144.2	153,0
1.5 - 2.0	24.2	21.2	65.8	66.4	58.4	58.5	148.7	158.8
1.0 - 1.5	24.0	21.3	66.2	66.1	54.1	37.0	168.3	170.4
0.5 - 1.0	22.6	18.5	66.2	66.5	50.5	38.3	190.0	168.6
Trends								
L	*	***	ns	ns	ns	ns	ns	ns
Q	ns	ns	ns	ns	ns	ns	ns	ns
Cultivar	Y	Y	X		Y	Y	Y	Y
'Manzanilla Cacereña'								
> 2.5	15.0		67.5		36.3		48.0	
2.0 - 2.5	14.2	13.4	68.0	68.1	38.7	35.9	73.6	39.5
1.5 - 2.0	13.5	13.2	68.7	67.5	36.1	33.5	71.3	53.4
1.0 - 1.5	13.8B	11.8A	68.5	68.8	34.6	37.3	64.7	49.2
0.5 - 1.0	12.7	10.8	69.3	69.8	27.7	31.6	71.8	47.6
Trends								
L	**	***	ns	*	ns	ns	ns	ns
Q	ns	ns	ns	ns	ns	ns	ns	ns
Cultivar	X	X	Y		X	X	X	X

A/B letters indicate significant differences between East and West sides of the hedgerow (Tukey $P<0.05$); X/Y letters indicate significant differences between cultivars (Tukey $P<0.05$); Trends with canopy heights may be $L=$ Linear; $Q=$ quadratic (*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; ns, not significant).

cultivars are presented in Fig. 4. Fruit production and fruit number were related to irradiance by a bilinear model fitted individually for each cultivar. Fruit production increased linearly with increasing irradiance, with a slope of 105 and 48g mol PAR^{-1} for 'Manzanilla Sevilla' and 'Manzanilla Cacereña', respectively, until irradiance reached a threshold of 25mol PAR m^{-2} (42% horizontal incident), similar for both cultivars. Similarly, fruit number increased linearly with increasing irradiance with a slope of 32 and 16 fruits mol PAR^{-1} for 'Manzanilla Sevilla' and 'Manzanilla Cacereña', respectively, until it reached a threshold 24mol PAR m^{-2} (40% horizontal incident). The irradiance estimated profiles were significantly associated with fruit fresh weight ($R^2 = 0.44$; $p<0.001$), fruit equatorial diameter ($R^2 = 0.63$; $p<0.001$) and color index ($R^2 = 0.48$; $p<0.001$) in a single model, when data from hedgerows from both cultivars were pooled. The fruit water content decreased linearly 0.04% and 0.06% per mol PAR m^{-2} in 'Manzanilla Sevilla' and 'Manzanilla Cacereña', respectively. The total phenols were positively associated to irradiance estimations using a bilinear model in 'Manzanilla Sevilla' and a linear model in 'Manzanillla Cacereña'. No correlation to irradiance was observed in any cultivar for the pulp-to-pit ratio and sugar concentration in dry weight basis (Fig. 4).

4. Discussion

The microenvironment surrounding olive fruits and leaves can be manipulated by hedgerow design (row orientation, row spacing, and free alley width/canopy height). In table olive production, fruit morphological and chemical characteristics are key to processing and commercial quality (Rallo et al., 2018), so understanding the causes and effects of irradiance on fruit traits and composition within a tree is a prerequisite to target optimum design and subsequent canopy management. In this context, we studied for the first time in table olive hedgerows, the distribution within the canopy and the interaction of yield components and fruit characteristics in response to the irradiance gradient resulting from the hedgerow structure. In order to obtain a wide gradient of irradiance, olive fruits of 'Manzanilla Sevilla' and 'Manzanilla Cacereña' cultivars were sampled at harvest from different

Table 4

Mean values of fruit phenolic compounds (mg g^{-1} dw) at different canopy heights and sides (E=East; W=West) of a N-S olive hedgerow of two table olive cultivars: Manzanilla de Sevilla and Manzanilla Cacereña. Individual phenolics: oleuropein, hydroxytyrosol (HT), 4-β-D-glucoside (HT-Glu), vanillin, tyrosol (Ty), luteonin (Lu), ferulic acid (Fe), 3,4-dihydroxyphenylglycol (DHPG) and vanillic acid (Va).

	Oleuropein		Oleacin		HT		Vanillin		HT-Glu		Ty		Lu		Fe		DHPG		Va	
Canopy height (m)	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W
'Manzanilla de Sevilla'																				
> 2.5	3.9		2.6		1.9		1.8		0.8		0.6		0.5		0.3		0.1		0.1	
2.0 - 2.5	3.2	3.9	1.5	3.2	1.9	1.8	1.4	1.9	0.6	0.7	0.5	0.6	0.4B	0.3A	0.2	0.1	0.5	0.1	0.1	0.1
1.5 - 2.0	4.1	3.9	1.7	1.9	2.2	2.0	1.9	2.2	0.7	0.7	0.6	0.6	0.4B	0.2A	0.2B	0.1A	0.1	0.1	0.1	0.1
1.0 - 1.5	4.3	3.4	1.8	1.5	2.6	1.9	1.9	2.2	0.7	0.7	0.8	0.6	0.3	0.2	0.2B	0.1A	0.1	0.1	0.1	0.1
0.5 - 1.0	2.1	3.3	1.9	0.8	0.4	2.0	1.9	1.7	0.5	0.5	0.2	0.5	0.1	0.1	0.03	0.08	0.1	0.1	0.6	0.1
Trends																				
L	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	***	***	**	**	ns	ns	ns	ns
Q	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cultivar	Y	Y			Y	Y	Y	Y							X	X			Y	Y
'Manzanilla Cacereña'																				
> 2.5	1.4		2.3		0.7		1.5		0.7		0.4		0.4		0.4		0.2		0.03	
2.0 - 2.5	1.2	1.3	1.5	1.7	0.7	0.8	1.1	0.9	0.6	0.7	0.4	0.5	0.4	0.5	0.4	0.4	0.2	0.1	0.04	0.05
1.5 - 2.0	1.5	1.1	1.9	1.2	0.9 B	0.5A	0.8	0.9	0.7	0.6	0.4	0.3	0.5B	0.2A	0.5	0.3	0.1	0.1	0.05B	0.03A
1.0 - 1.5	1.5	1.4	1.7	1.5	0.8	0.7	0.7	0.7	0.7	0.7	0.4	0.3	0.4	0.3	0.6	0.3	0.1	0.2	0.04	0.04
0.5 - 1.0	1.1	1.7	1.1	1.7	0.6	0.8	1.0	1.0	0.6	0.8	0.4	0.4	0.3	0.5	0.3	0.4	0.2	0.1	0.05	0.04
Trends																				
L	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Q	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cultivar	X	X			X	X	X	X							Y	Y			X	X

A/B letters indicate significant differences between East and West sides of the hedgerow (Tukey $P<0.05$); X/Y letters indicate significant differences between cultivars (Tukey $P<0.05$). Trends with canopy heights may be $L=$ Linear; $Q=$ quadratic (*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; ns, not significant).

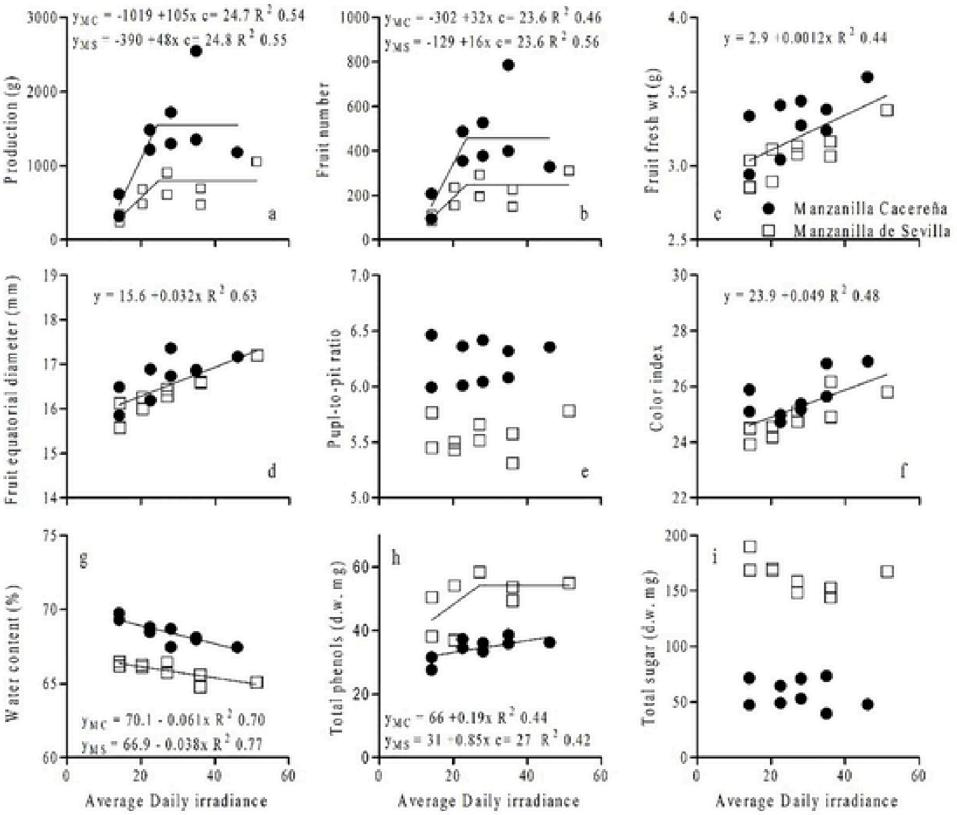

Fig. 4. Relationships between profiles of olive production (a), fruit number (b), fruit traits (weight (c), equatorial diameter (d), pulp-to-pit ratio (e), and color (f)) and fruit composition (water content (g), total phenol (h) and sugar (i)) and mean daily irradiance simulated within 5 canopy heights on both sides (E = East; W = West) of N-S hedgerows of cultivars Manzanilla de Sevilla and Manzanilla Cacereña over the period DOY 150–180. Average daily incident irradiance is 58.3mol PARm^{-2}.

heights and sides of narrow hedgerows (3.75m x 1.35m) oriented N–S. The low values of CVs among trees for production and fruit traits mentioned in the results section confirm the representativeness of the sample, and are similar to those reported by Trentacoste et al. (2015) and Gómez-del-Campo et al. (2017) for 'Arbequina' hedgerows.

On both sides of the N–S hedgerow solar irradiance incident over the fruit growth period decreased markedly at increasingly lower canopy positions (decreasing hedgerow height) (Table 1) as reported by Connor et al. (2016). The distribution of olive production and fruit number down individual sides of hedgerows was similar for both cultivars, with maximum production and fruit number in upper canopy positions, then decreasing towards the base (Table 2), an observation previously reported by Trentacoste et al. (2015) for olive hedgerows cv Arbequina using a design with a wide row spacing range. In 'Manzanilla Cacereña' hedgerows, few fruits were observed at the top canopy height, which had less dense shoots and higher porosity (Table 1). The canopy porosity reached the highest value in the lowest positions of the hedgerows and decreased markedly towards higher positions, with the exception of the top, where it increased again as mentioned above. The canopy porosity integrates differences in density of both shoots and leaf area density (Castillo-Ruiz et al., 2016) making it a valuable canopy descriptor of incident irradiance within hedgerows (Connor et al., 2016) that is shown here to be negatively related to production, as previously observed in olive hedgerows (Gómez del Campo et al., 2017). In our work, one harvest season was evaluated, however, olive production and yield components distribution among canopy position (sides and heights) seems to be maintained over the seasons, as has been observed in the above-mentioned studies.

The data reveal that olive production and number respond to irradiance below a maximum ca 40–43% of horizontally incident, above this value there was no detectable relationship between irradiance and production (Fig. 4). The irradiance threshold of 40% of horizontal incident was similar in both cultivars and the threshold reported in narrow hedgerows cv. Arbequina (Connor et al., 2016). The response of production and fruit number to irradiance provides valuable information for designing and managing the hedgerow to maximize productivity at both plant and orchard levels. The hedgerows studied here presented a free alley width [i.e., row spacing (3.75m) minus hedgerow width (1.5m)] to canopy height (2.4) ratio equal to 0.93. A ratio of free alley width/canopy height higher than 1 has been recommended to ensure incident irradiance higher than 45% of horizontally incident (Connor et al., 2016). Thus, for the design of hedgerows with table varieties and mechanical harvesting, row spacing greater than 4.0m may be required.

In both table olive cultivars hedgerows, olive traits: fruit size, color index and oil content showed maximum values at the top, decreasing linearly to minimum values at the base of the hedgerow (Tables 2 and 3), in close correspondence with incident irradiance, which increased with increasing canopy height (Table 1). These findings confirm the results obtained in a previous study conducted in olive cv. Arbequina hedgerows by Gómez-del-Campo et al. (2009), which showed that fruit weight, oil accumulation and maturity are affected by canopy heights and are positively correlated with incident irradiance on the canopy. Beyond the average fruit weight, fruit size grading according to commercial categories based on the number of fruits per kilogram is essential in the table olive industry (USDA, 2019; IOC, 2004). Homogeneous distribution of fruits within the best commercial categories and the absence of very small fruits unsuitable for processing (fruit number above 420) are key for obtaining high-quality table olives (Sánchez-Gómez et al., 2006). In this work, as for the above-mentioned traits, size distribution positively improved from base to top, with an increase in the frequency of the larger size categories and a reduction of non-commercial fruits (Figs. 2 and 3).

Fruit water content showed the inverse pattern and increased successively from the top to the canopy base (Table 3). For table olives, fruit water content at harvest is technologically important because it has an influence in the lye treatment during green olives processing, a key step to eliminate the bitter taste of the olive fruit caused by oleuropein (Sánchez-Gómez et al., 2006). The water content accelerates lye penetration; thus, duration should be shortened in olives with high moisture content to avoid developing undesirable colors.

The pulp-to-pit ratio is one of the most important qualitative parameters for table olive production (Rallo et al., 2018). This trait was not significantly different between canopy positions within each side of the hedgerows (Table 2), in contrast to a previous study by Trentacoste et al. (2018) and Bartolini et al. (2014) who reported a higher pulp-to-pit ratio in the better-illuminated positions of the canopy of narrow hedgerows. The current results seem to indicate that both fruit pulp weight (mesocarp) and pit weight (endocarp) were proportionally affected by canopy positions, resulting in a similar pulp-to-pit ratio. The response of an increase in both pulp and especially pit tissues to the availability of assimilates can be attributed to cultivar-specific features (Trentacoste et al., 2016).

The total sugar content measured in olives harvested from different canopy positions was not significantly different between positions in either of the two table olive cultivars evaluated and was not significantly associated with solar radiation. The results can be explained by the fact that sugars are the substrate for oil biosynthesis (Conde et al., 2008), which increased significantly in fruits from more illuminated positions (Table 3). Consequently, during early fruit growth period, the sugar substrate concentration must have been higher in the most illuminated positions of the hedgerows.

Total phenolic compounds concentration measured in olives harvested from different canopy heights did not differ significantly between different positions in either of the two table olive cultivars studied (Table 3), but a significant relationship was found between total phenolic compound concentration and incident irradiance (Fig. 4) This is consistent with the findings by Grilo et al. (2019; 2021) and Trentacoste et al. (2021), who found a positive linear relationship for phenolic content with irradiance. However, the comparison between the studies should be made with caution; while we measured the phenolic compounds in the fruit, the other studies measured the phenolic content in the oil. Olive fruit has a high phenolic concentration, but only a very low proportion (range 0.1 to 2%) is transferred to olive oil during industrial processing (Talhaoui et al., 2016). The process of phenol transfer from fruit to oil is influenced by a large number of factors related to the fruit features (cultivar, fruit maturity, oil and water content of the fruit) and the oil extraction process (Jerman Klen et al., 2015). An increase in total phenols leads to an increase in the main olive phenols, the secoiridoids like oleuropein, which are the precursors of both the phenols that mainly pass into the oil, such as oleacein, and simple phenols like hydroxytyrosol (Johnson, and Mitchell, 2018).

No effect of canopy position has been observed for individual phenolic compounds with very few exceptions (luteonin and ferulic acid) and only in ‘Manzanilla de Sevilla’ (Table 4). These results contrast with those of Gómez-del-Campo and García (2012) who found significant differences between the lowest and the highest position in a N-S hedgerow cv Arbequina, particularly noticeable for orthodiphenols and secoiridoids. Again, a careful comparison should be made since the latter study was carried out in olive oil, and our work analyzes phenolics in fresh fruit. Besides the nutraceutical properties of phenolic compounds in the olive fruit (Rocha et al., 2020), these compounds play an important role in the elaboration process of table olives. In fact, hydrolysis of oleuropein to eliminate the bitter taste of fresh fruit is achieved through lye treatment with NaOH (Sanchez-Gómez et al., 2006), considered to be the most important step when processing green olives. The concentration and duration of lye treatment is critical to obtain a final quality product, so the fact that oleuropein contents are stable within all canopy positions might be an advantage since no differential treatments should be applied.

Production, physical and chemical characteristics of the olives showed similar values between the opposite sides of the N-S hedgerows, consistent with equal incident irradiance on East and West sides (Table 1). Few exceptions were observed, being the size distribution in ‘Manzanilla Cacereña’ (Fig. 3) the more remarkable case: the frequency of fruits unsuitable for processing (fruit number per kg > 420) was higher in the West side, particularly in the lower canopy positions. Since incident irradiance on both sides was equal, we do not have a clear explanation for this finding, besides a possible effect of the higher temperature reached at the West side that may lead to a slightly higher yield on this side and, consequently, lower fruit sizes, as it may be observed in Table 1, although only significant in certain heights.

Even though both studied cultivars showed similar response to radiation, significant differences were detected for most studied traits (Tables 1–3). ‘Manzanilla Cacereña’ showed an overall higher production and number of fruits, in accordance with the higher total yield of this cultivar in the trial (17,100kg ha^{-1}*vs* 6,300kg ha^{-1}). Similar differences in productivity between both cultivars were previously reported (Morales-Sillero et al., 2014) although no effect of the crop load on mean fruit weight (3.3 *vs* 3.1g) has been observed in the present work. In fact, these values are low compared to pomological descriptions of these cultivars (Barranco et al., 2005) and other studies in the same trial (Morales-Sillero et al., 2023), and may be explained by an early sampling date, some days before optimal maturity index (when fruits reach final fruit size), as suggested by color index and confirmed by final data of the trial recorded two weeks later (data not shown). ‘Manzanilla Cacereña’ has also been highlighted by the lower susceptibility of fruits to bruising in accordance with Jiménez et al. (2017).

The fruit chemical composition is largely dependent on the cultivar, since significant differences have been observed for all chemical traits measured (Table 2) and for most individual phenolic compounds (Table 3). Oil content, total phenols and total sugar were 1.7, 1.5 and 2.8 times higher, respectively, in ‘Manzanilla de Sevilla’ compared to ‘Manzanilla Cacereña’. The higher oil content of ‘Manzanilla de Sevilla’ has been previously reported (Barranco et al., 2005, and Morales-Sillero et al., 2014), even though actual values in this work are low because fruits for table olive processing are harvested when they are still green-yellowish in color, which is earlier than for olive oil production. Significant differences between the same cultivars for total sugars and phenols were also observed by González-Fernández (2018) in irrigated hedgerows, showing ‘Manzanilla de Sevilla’ 1.5 to 2 times the amount of these compounds compared to ‘Manzanilla Cacereña’. Likewise, Marsilio et al. (2001) observed a large variability among table olive cultivars for sugar contents in fresh fruits (57.7 - 84.5mg *g*$^{-1}$) within the range of the ones reported here. The cultivar is also one of the main factors defining the profile of phenolic compounds in the olive fruit, along with the ripening stage or season (Charoenprasert and Mitchell, 2012).

5. Conclusions

The effect of incident irradiance from N-S narrow hedgerows intended for table olive production has been studied for the first time in two cultivars: ‘Manzanilla de Sevilla’ and ‘Manzanilla Cacereña’. Solar irradiance incident over the fruit growth period decreased markedly with decreasing hedgerow height, on both sides of the hedgerows. Similarly, production, number of fruits and important quality traits for table olive (fruit weight, length, equatorial diameter, size distribution, color and oil content) were positively affected by radiation, as values improved from base to top canopy positions. Conversely, the total contents in sugar and phenols and individual phenolic compounds were not affected by the canopy positions.

No differences between sides nor cultivars have been detected in the response to solar irradiance or canopy position although mean values of most measured traits were significantly different between cultivars. ‘Manzanilla de Sevilla’ showed lower production and number of fruits, which were more susceptible to bruising, and higher oil content, total sugars, total phenols and larger amounts of the more abundant phenolic compounds in fresh olives (oleuropeine and hydroxytyrosol).

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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