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Characterization of light intensity and quality, vegetative, flowering and fruiting traits in high and super-high density olive hedgerows

Federico J. Ladux[a], M. Cecilia Rousseaux[a,c], Eduardo R. Trentacoste[b,*]

[a] Centro Regional de Investigaciones Científicas y Transferencia Tecnológica de La Rioja (CRILAR-Provincia de La Rioja-UNLaR-SEGEMAR-UNCa-CONICET), Entre Ríos y Mendoza s/n, Anillaco 5301, La Rioja, Argentina

[b] Estación Experimental Agropecuaria La Consulta (Instituto Nacional de Tecnología Agropecuaria), Mendoza 5567, Argentina

[c] Departamento de Ciencias Exactas, Físicas y Naturales (DACEF y N), Universidad Nacional de La Rioja, Av. Luis M. De la Fuente s/n, Ciudad Universitaria de la Ciencia y de la Técnica, La Rioja 5300, La Rioja, Argentina

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ABSTRACT

Orchard design (intra- and inter-row distance) defines the space allotted to each tree and the light environment for growth in olive hedgerows. Shading between neighboring trees affects the light intensity and quality, modifying the tree vegetative, flowering and fruiting characteristics. In this study, the incident photosynthetically active radiation (PAR) was simulated and the red-to-far-red ratio (R/FR) reflected by neighboring hedgerows down the canopy walls was measured. An analysis is presented of the response of olive vegetative, flowering, fruiting and productive traits to hedgerows of high (HD) and super-high density (SHD) orchards. The study was carried out during the 2018–2019 and 2019–2020 seasons in two 10-year-old olive cv. Genovesa orchards, one in HD (7 x 3.5 m) and the other in SHD (4 x 1.5 m). In both systems, continuous rows were used for measurements of light environment and vegetative, flowering and fruiting characteristics. The R/FR ratio and mean daily horizontal incident PAR were significantly higher in HD than in SHD. One-year-old shoots of HD hedgerows had shorter internodes in L position than U, M and L positions of SHD. Inflorescence number per shoot in the M and L positions of HD were triple than those of corresponding positions of SHD hedgerows. The mean yield per ha for both seasons was similar between HD and SHD hedgerows (average 9.3 and 9.4 t/ha, respectively). A greater planting density in olive hedgerows reduces the R/FR ratio reflected by neighboring trees while reducing incident PAR with increases in the hedgerow height. As a result, more illuminate HD hedgerows have greater specific leaf mass, higher leaf area density and higher axis-order angle compared to SHD hedgerows. This study seeks a new way to understand and measure the suitability of an olive cultivar trained in hedgerows at different planting densities.

1. Introduction

During the last two decades world olive production has increased through both greater productivity per unit area and expanded planted area (FAO, 2023). After grape, olive is the most important fruit crop in the central-western region of Argentina (Banco et al., 2023). In new olive orchards, the most common planting density is from 400 to 800 trees ha^{-1}, usually referred to as high-density (HD). In Argentina, HD systems cover more than 70 % of planted area (Tous et al., 2014; Vita Serman et al., 2021). The need to adopt mechanical harvesting in large commercial plantations has further led to the development of super-high density orchards (SHD) with more than 1000 trees ha^{-1} (Lo Bianco et al., 2021). In both systems, HD and SHD, trees form continuous hedgerow structures once each tree has filled its allotted space. For efficient management, hedgerow dimensions must be designed and maintained to allow mechanical harvesting with straddle harvesters while ensuring appropriate distribution of photosynthetically active radiation (PAR) within the canopy for maximum yield (Connor et al., 2014; Tous et al., 2014).

Orchard design in hedgerow systems is defined by intra- and inter-row distances that modify canopy structure because it defines the space allotted to each tree for growth and hedgerow light environment (Carella et al., 2022; Connor, 2006; Rosati et al., 2021). Hedgerows of SHD systems have the advantage of greater PAR interception during early stages of development than do HD (Gómez-del-Campo et al., 2017; León et al., 2007). Excessive canopy growth or inadequate maintenance

* Corresponding author.
E-mail address: trentacoste.eduardo@inta.gob.ar (E.R. Trentacoste).

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of hedgerow dimensions, which grow to excessive height for the available free-alley space between rows, may lead to shading within individual or between neighboring trees that reduces fruit yield (Connor, 2006; Larbi et al., 2011; Rosati et al., 2021). The reduction of PAR incidence (canopy shading), within and over the hedgerow canopy height may cause shoots to seek light and locate photosynthetically active leaf area in more illuminated positions (upper and external), changing the balance between woody structures and leaf distributions (Cherbiy-Hoffmann et al., 2013; Rosati et al., 2018).

In addition, changes in light quality due to proximity of neighboring trees can become another determining factor for canopy growth. Green leaves efficiently absorb radiation in the red wavelength (R, 660 nm) and reflect radiation in the far-red wavelength (FR, 730 nm) thus reducing the red-to-far-red (R/FR) ratio, an indicator of plant proximity. These R/FR changes are detected by the photoreceptors phytochromes, which are involved in triggering plant morphological responses (Ballaré and Casal, 2000; Casal, 2012). In this way, olive tree foliage can modify the surrounding light quality environment (Ladux et al., 2021), so that measuring the distribution of PAR and R/FR in HD and SHD hedgerows may help understand how vegetative, flowering and fruiting traits are affected by planting density.

Morpho-anatomical traits of olive trees are modified significantly under limiting PAR. Under artificial shade that reduced the incident PAR, the stem elongation and diameter were greater, and the internode length was shorter in sun-exposed cv. Arbosana plants than in shaded plants (Ajmi et al., 2018). Low incident PAR within the canopy, or using artificial shading, also modifies olive leaf morphology, increasing individual leaf size while reducing both specific leaf mass (Gregoriou et al., 2007; Larbi et al., 2015) and total plant leaf area. This happens due to decreases in total leaf number (Ladux et al., in process). Morphological responses to R/FR manipulations have also been reported for other fruit crops (review by Bastías and Corelli-Grappadelli, 2012). Photo-selective films that reduced R/FR induced increases in shoot elongation in peach and cherry trees (Schettini et al., 2011), while other species, like *Vitis vinifera*, seem to be unresponsive to strong reductions in R/FR (González et al., 2016). We observed cultivar-specific responses in young olive trees in an experiment using mirrors that reflected FR reducing horizontal R/FR ratio (Ladux et al., 2021). Whereas cv. Arbequina reduced individual leaf area and above/below ground biomass ratio and cv. Arauco increased individual leaf area while above/below ground biomass ratio was not affected.

In olive, stem nodes formed during the present season define the potential flowering sites for the following season (Acebedo et al., 2000; Castillo-Llanque and Rapoport, 2011). One-year-old shoots developed in less illuminated canopy positions had fewer inflorescences than more illuminated shoots (Acebedo et al., 2000; Ajmi et al., 2018; Gregoriou et al., 2007). Inflorescence development is also influenced by PAR incident on olive canopy. Total flower number and the proportion of perfect flowers per inflorescence were greater for inflorescences developed in more illuminated canopy positions (Bartolini et al., 2022; Trentacoste et al., 2022; 2017). Other studies in olive, in both field and/or controlled conditions, have shown that fruit number and their characteristics are affected by PAR intensity (Acebedo et al., 2000; Cherbiy-Hoffmann et al., 2013; Gregoriou et al., 2007). Fruit number, size and maturity were greater in upper, more illuminated canopy positions than in lower positions (Gómez-del-Campo et al., 2009; Trentacoste et al., 2016; 2015). In contrast, response of olive fruit characteristics to light quality environment (R/FR) is not evident. In the only study so far in olive, Rousseaux et al. (2020) found no relationship between R/FR ratio and the fatty acid composition of oil.

In recent years, several studies have been carried out in the most important olive growing regions of the world to evaluate the productive and vegetative responses of several cultivars in SHD orchards (e.g. Proietti et al., 2015; Reale et al., 2019), all with the similar objective to find alternatives to the most widely used cv. Arbequina. In Argentina, the Spanish cultivar Genovesa is widely used in HD olive orchards as an alternative to cv. Arbequina, due to its earlier maturity, higher oil content and oil quality (Banco et al., 2021), but its adaptation in SHD has not been evaluated. Based on this review of literature, we propose a study to characterize the light environment of HD and SHD olive hedgerows together with various growth and flowering traits. The objectives were to characterize PAR received, determined using a simulation model, and the measured R/FR ratio reflected by neighboring olive trees in different canopy positions of HD and SHD hedgerow systems and to evaluate associated vegetative, flowering and fruiting traits to better understand the response and functioning of both hedgerow systems.

2. Material and methods

2.1. Site and orchards

The study was carried out during 2018–2019 and 2019–2020 in commercial olive orchards located in Cañada Honda Valley (31 °58′ Lat. S; 68 °32′ Long. W; 610 m.a.s.L.) San Juan, Argentina. The climate is arid with annual rainfall of 195 mm concentrated during summer months and an average annual temperature of 18.5 °C. The soil is sandy-loam with high gravel content below 0.8 m of depth (Trentacoste et al., 2018).

Measurements were made in two adjacent olive orchards (100 m apart, 5 ha total) planted in 2008 with cv. Genovesa in North-South (N-S) oriented hedgerows at 7 x 3.5 m (HD) and 4 x 1.5 m (SHD), respectively. In the SHD orchard, the trees were trained to a central leader on a 2.5 m wooden stake. Winter pruning was carried out annually, removing branches into the alleys and a mechanical topping was applied at 3.0 m height aboveground to facilitate the passage of the harvester. In the HD orchard, from planting in 2008, the trees were trained in an open vase configuration with 4–5 main branches. In the winter 2015, when a continuous wall was achieved, the main branches extending into the alleys were removed. From winter 2016, HD hedgerows were mechanically topped annually to a height of 4.5 m aboveground. Irrigation was supplied to satisfy the crop water requirements using drip irrigation with 2.0 L h^{-1} emitters spaced at 0.8 m. In the SHD, irrigation was supplied with a single line, while in the HD it was supplied with a double-irrigation line per row spaced 1 m apart (more details in Monasterio et al., 2021).

2.2. Hedgerow structure and canopy positions

In each orchard, three experimental units of three contiguous trees in three contiguous rows (i.e., nine trees) with representative canopy dimensions were selected. The trees of central rows were used for measurements while the lateral rows were used as border plants. Canopy structure was described by measuring height from the soil to the top of the hedgerow, trunk circumference at 30 cm aboveground, base of canopy (distance from the ground to the first layer of leaves), and canopy width in East-West (E-W) and N-S directions. Canopy height was determined as the difference between tree height and canopy base height, and free-alley width as the difference between row spacing and E-W canopy width.

The representation of light environment and the vegetative, flowering and fruiting traits measurements were made in various positions in the hedgerows. Each tree canopy volume was divided into six positions based on height and side (see Fig. 1 A). On both sides (E and W) of HD hedgerow three heights measured from base of canopy were designated: 0.0–0.8 m (Lower, L), 0.8–1.6 m (Middle, M) and $\geq$ 1.6 m above base of canopy (Upper, U). Corresponding heights on SHD hedgerows were designed 0.0–1.0 m (L), 1.0–2.0 m (M), $\geq$ 2.0 m aboveground (U). E and W sides of N-S oriented hedgerows receive similar diurnal and seasonal irradiance (Trentacoste et al., 2015), but the W side could experience higher canopy temperature in the afternoon than the E side in the morning for the same solar irradiance. In this work, we focused on quantity and quality radiation influences on vegetative, flowering and

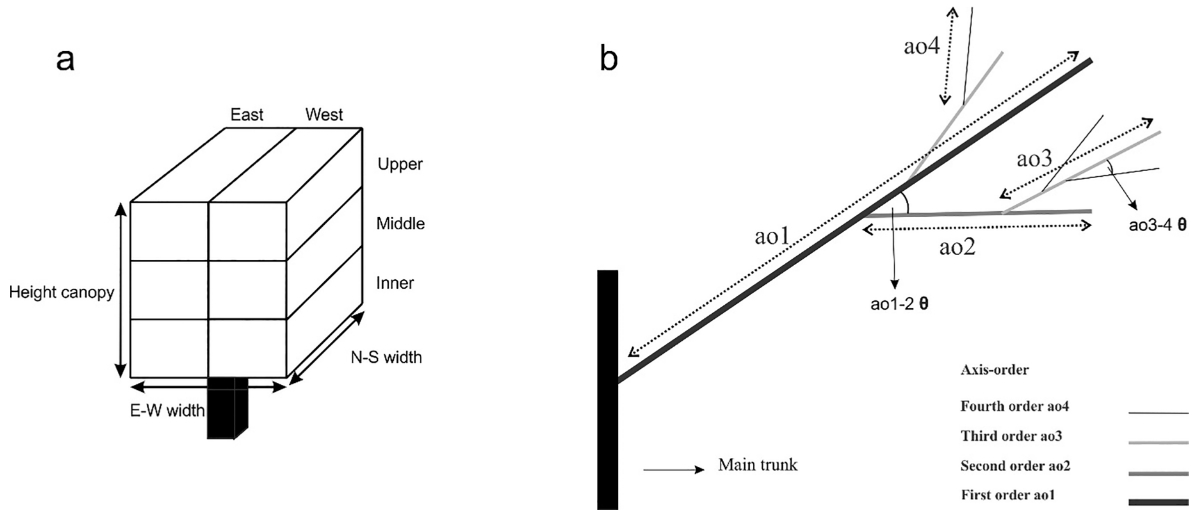

Fig. 1. Representative scheme of hedgerow structure and dimensions. Canopy position is defined according to canopy height divisions and side (a). Branching pattern of a branch with four years of growth. (b).

fruiting comparisons at different heights. For which we decided that the samples and measurements from both E and W were averaged at the same height to compensate canopy temperature differences between hedgerow sides.

2.3. Light quality measurements and PAR irradiance simulations

Horizontally incident radiation measurements were performed at the L, M and U positions on a sunny day, November 7, 2019 in the central tree of the central row of each experimental unit of both hedgerow systems. The R/FR ratio (660 and 730 nm wavelengths, respectively) was measured using a R/FR sensor (μmol m^{-2} s^{-1}; SKR 110, Skye Instruments Ltd., Llandrindod Wells, UK). The sensor head was positioned at the outer limit of the canopy at the L, M and U positions of the central tree and oriented perpendicular to the canopy to measure the horizontal changes in R/FR ratio associated with the presence of intra and inter rows neighboring trees (Ladux et al., 2021). The measurements were performed at four azimuthal orientations (N, S, E and W) and at five times during the day (8:00, 10:00, 12:00, 14:00 and 16:00 h solar time).

The model developed by Connor et al. (2016) was used to calculate horizontal incident PAR (mol PAR m^{-2}) under clear-sky conditions within both hedgerow systems at each evaluated position. The model uses parameters of latitude, date, row spacing and orientation, and canopy height, width and horizontal porosity. We estimated the horizontal porosity from leaf area density measurements (explained below) based on Connor et al. (2016). The complete model description and performance was explained and validated in Connor et al. (2016). Incident PAR of each canopy position was calculated every 10 days from January to December. Then, average daily irradiance was calculated as average of 9 days within spring, summer, autumn and winter seasons.

2.4. Vegetative measurements

On October 10, 2019, 20 one-year-old shoots from each canopy position at each experimental unit were randomly selected for measurement of length, basal diameter and number of nodes. Five leaves, selected from each shoot, were harvested for dry mass, after measuring length and width. Individual leaf area of the same five leaves was determined by sampling leaf disks of known area. Leaves and disk samples were dried in a forced-air oven at 70 °C to reach a constant dry weight. The individual leaf area was calculated by dividing leaf dry weight by the specific leaf mass (SLM).

On October 16, 2019, a branch (vegetative structure with shoots of different age category of growth) was selected in the central position of the canopy in each experimental unit of both hedgerow systems. The insertion angle between the branch and the main trunk was measured before being cut and bagged for storage at 4 °C for further measurements. In the laboratory, branching patterns were assessed by characterization of axis-order distinguished by age of the wood (Costes et al., 2006). The main axis was the first-order axis (four-year growth wood), the second ramification the second-order axis (three-year growth wood), the third ramification the third-order axis (two-year growth wood) and the fourth-order axis (one-year growth wood) (Fig. 1 B). For each order axis, we measured the length, basal diameter, branch angle and counted the number of nodes of each shoot. Branch axis angle was determined manually using a protractor as the anticlockwise angle of insertion on the previous branch, i.e. the angle of the first-order axis formed with the main trunk, the second-order axis with the first-order axis, the third-order axis with the second-order axis and the fourth-order axis with the third-order axis. The axes lengths and node numbers were calculated as the sum of all measurements of length and node number of shoots corresponding to each axis-order.

We counted the number of leaves inside a cube of known volume (8000 cm^3) at three points in each side on each canopy position. Leaf area density (LAD; cm^2 cm^{-3}) per canopy position was calculated as the product of leaf number and mean individual leaf area.

2.5. Flowering measurements

On October 11, 2019, the number of inflorescences per node and per shoot were counted on 20 selected shoots at each canopy position in each experimental unit. The percentage of reproductive buds per shoot was estimated as the ratio of inflorescences number per shoot and the bud number per shoot (node number x 2).

On October 30, 2019, 20 randomly selected inflorescences of one-year shoot from the central zones of each canopy position were cut and immediately preserved in water. In the laboratory, in each inflorescence we measured the length, number of flowers, and open and perfect flowers. Percentages were then calculated of perfect and open flowers per inflorescence.

2.6. Fruiting measurements

Prior to mechanical harvesting of the orchards, measurements were made of fruit retention force on 20 fruits at each canopy position in each experimental unit in both hedgerow systems. On April 5, 2019 and March 5, 2020, all fruits were manually harvested from each canopy position of the central tree in each experimental unit of both hedgerows.

Harvested fruits were immediately weighed to obtain fruit yield per tree. Fruit yield was expressed per ha as fruit yield tree^{-1} x tree number ha^{-1}. The fruit number per lineal of meter of row was calculated as fruit number/intra row spacing.

A sample of 40 fruits from each canopy position was retained for laboratory measurement of fresh weight and determination of maturity index (MI, coloration of the skin and pulp with a scale of 0 to 7) (Uceda and Frías, 1975). Fruits were then dried in a forced-air oven at 70 °C to reach a constant dry weight for the calculation of dry mass and moisture. Fruit number per canopy position was estimated as the ratio between fruit yield per position and average fruit fresh weight, and fruit density as fruit number per volume of canopy position. The comparisons of fruit characteristics between both systems at hedgerow level were made from values obtained in each position weighted by the ratio between the fruit numbers at each position and the total fruit numbers per tree.

2.7. Statistical analyses

An analyses of variance (ANOVA) was used for the comparisons of R/FR ratio between HD and SHD hedgerows at different canopy positions using the mean value of the four azimuthal orientation within each tree (replicate). For the shoot, leaf and flowering variables comparison between HD and SHD at different canopy position, an ANOVA were used using each trees as a replicated. Prior to the analysis, the percentage of open flower data were transformed using the Napierian logarithm to achieve normality and homogenize the variance. ANOVA were used for HD and SHD hedgerows comparison of branch order using the selected branches within each tree as a replicate. ANOVA was used to compare fruit yield and characteristics of HD and SHD at whole hedgerows level. An analyses of co-variance (ANCOVA) using the maturity index as covariate was used to compare fruit moisture and fruit retention force at whole hedgerows level. Tukey post-test was used to detect the significance of differences between means ($p < 0.05$) in variables related to light quality, vegetative, flowering and fruiting. The statistical analyses were performed with INFOSTAT software (Di Rienzo et al., 2020). We are aware that the replicates are plots within the same orchard but judge that the closeness and homogeneity of the two systems makes the statistical comparison reliable.

3. Results

3.1. Hedgerow structure and canopy light environment

The SHD top of hedgerow was 3.8 m, slightly lower than HD 4.0 m (Table 1). The canopy width was 2.3 and 1.8 m for HD and SHD, respectively. After seven years of planting, the canopies of individual trees in HD hedgerows had not completely filled their allotted space, with diameters along rows averaging 2.9 m. Inter-row spaces were 3.5 and 1.5 m in HD and SHD, respectively. The average canopy height of HD and SHD hedgerows were of 3.4 m, and the relationship between canopy height and free-alley width was 0.7 and 1.5 in HD and SHD, respectively.

Table 1
Characteristics of olive hedgerows cv. Genovesa planted in N-S oriented rows at high (HD) and super-high (SHD) densities. Values are averages of the 2019 and 2020 seasons.

	HD	SHD
Inter- and intra-row planting (m)	7 x 3.5	4 x 1.5
Plants ha^{-1}	408	1666
Top of hedgerow (m)	4.0	3.8
Trunk perimeter (m)	0.5	0.4
Base of canopy (m)	0.6	0.4
Canopy height (m)	3.4	3.4
Canopy width (m) in E-W	2.3	1.8
Canopy width (m) in N-S	2.9	2.0
Free alley (m)	4.7	2.2
Canopy height/free alley	0.7	1.5

The horizontally reflected R/FR ratio at the outer limit of the canopy, when averaged over the azimuth orientations and canopy positions during the course of the day, was greater in the three selected canopy positions from HD (average 0.66) than in canopy positions in SHD (average 0.49). Within each hedgerow system, the ratio did not vary between the canopy positions (Fig. 2). The R/FR ratio was greater in the U, M and L positions (0.68, 0.65 and 0.64, respectively) in HD hedgerows compared with M and L positions (0.49 and 0.45, respectively) in SHD. The simulated incident PAR was greater in HD than SHD hedgerows comparing each canopy position (Table 2). In both systems, daily PAR showed similar patterns, being greatest in U positions decreasing toward L positions. Proportion of horizontal daily irradiance decreased towards the base of canopy strongly in SHD hedgerows (40, 13 and 7 % in the U, M and L, respectively) than in HD (45, 16 and 12 % in the U, M and I, respectively). Seasonally, average incident PAR across three canopy positions was 5, 4, 6 and 4 % lower in SHD than HD, in spring, summer, autumn and winter, respectively.

3.2. Vegetative traits

Shoots located in the L position of HD hedgerows were significantly shorter than shoots from M and U in HD and shoots from L and U positions in SHD (Fig. 3 A). In addition, shoots selected from L positions in HD and M positions in SHD had 19 and 26 %, respectively, fewer number of node than shoots from U position in HD hedgerows (Fig. 3 B). Shoot internodes were shorter in the L position of HD hedgerows than in the U, M and L positions of SHD (Fig. 3 C). There were no statistical differences in shoot diameter within canopy positions from each hedgerow systems (Fig. 3 D).

No apparent differences were detected in individual leaf area between canopy positions within HD and SHD (Table 3). SLM was greater in the U position from HD than in M and L positions of SHD hedgerows. LAD was greater in the M position of HD than L of HD and the L and U positions of SHD hedgerows. In addition, in SHD hedgerows, LAD was not significant different within canopy positions.

Branch characteristics were more responsive to branch axis-order than hedgerow system (Table 4). In HD hedgerows, shoots at the second axis-order were longer than fourth axis-orders. Similarly, in SHD hedgerows, shoots at the second axis-order were longer than fourth axis-

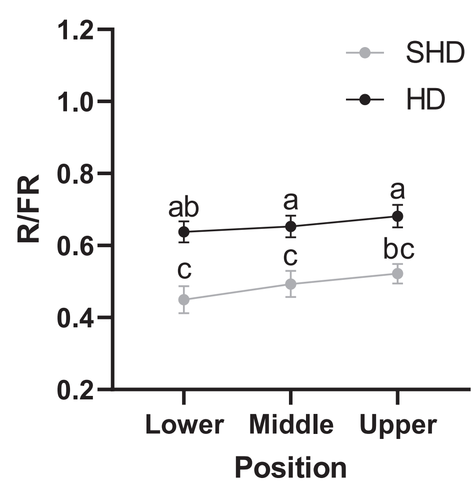

Fig. 2. Red / far-red (R/FR; A) ratio of horizontally reflected light of neighboring trees in high density (HD) and super-high density (SHD) orchards of cv. Genovesa. Symbols present averages ± SE of the measurements performed at four azimuthal orientations and three canopy heights (lower, middle and upper) over the course of the day on three trees (n = 3). Different letters indicate significant differences in the R/FR ratio between planting density and canopy position using the Tukey LSD post-test ($p < 0.05$).

Table 2
Mean simulated daily PAR at three canopy positions in high (HD) and super-high density (SHD) orchards of cv. Genovesa. Each value is the mean of 9 days for each seasons.

	Mean daily irradiance (mol PAR m^{-2})							
Season	Spring		Summer		Autumn		Winter	
Hedgerow	HD	SHD	HD	SHD	HD	SHD	HD	SHD
Incident irradiance	59.86		62.52		36.18		32.76	
Upper	28.09	24.71	29.59	26.43	14.76	13.19	12.92	11.54
Middle	10.65	8.60	11.27	9.31	5.16	4.07	4.44	3.47
Lower	7.58	4.37	8.00	4.75	3.80	2.07	3.29	1.76
Average	15.44	12.56	16.29	13.50	7.91	5.59	6.88	5.59

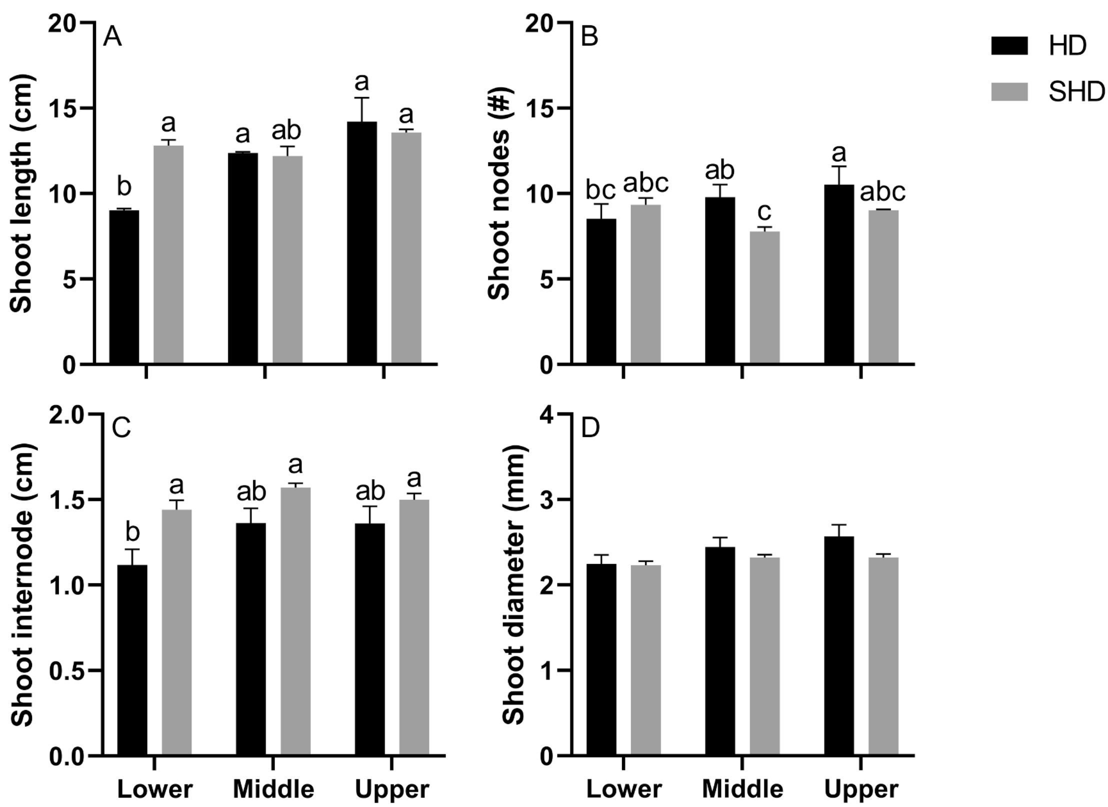

Fig. 3. Shoot characterization of olive cv. Genovesa in high (HD) and super-high (SHD) density hedgerows. Average values of variables related to shoot vegetative growth according to each canopy position ± SE (n = 3). Different letters indicate significant differences between the means for a given vegetative variable using the Tukey post-test ($p < 0.05$), only presented when ANOVA indicated significant effect.

Table 3
Leaf characteristics of olive cv. Genovesa in high (HD) and super-high (SHD) density hedgerows. Average values are according to each of three canopy positions ± SE (n = 3). Different letters indicate significant differences between the means for a given vegetative variable using the Tukey post-test ($p < 0.05$), only presented when ANOVA indicated significant effect. SLM is specific leaf mass.

	HD			SHD		
Variables	Lower	Middle	Upper	Lower	Middle	Upper
Individual leaf area (cm^2)	3.99 ± 0.1	4.20 ± 0.2	3.81 ± 0.2	4.49 ± 0.1	4.40 ± 0.3	4.30 ± 0.3
SLM (mg cm^{-2})	23.72 ± 0.3 ab	23.40 ± 0.4 ab	28.41 ± 1.1 a	22.40 ± 0.4 b	22.44 ± 1.3 b	24.33 ± 1.7 ab
Leaf area density (cm^2 cm^{-3})	3.58 ± 0.7 b	6.71 ± 0.3 a	4.13 ± 0.2 ab	2.24 ± 0.2 b	4.88 ± 0.4 ab	3.45 ± 1.1 b

orders. No apparent differences between axis-order were detected in main axis nodes and internode length within each hedgerow systems. In both HD and SHD, shoot diameter of second, third and fourth axis-orders were smaller than first axis-orders. Shoot-angle of HD hedgerows showed a mean order angle of 78° higher than the 54° observed in SHD hedgerows.

3.3. Flowering traits

In HD hedgerows, selected bearing shoots from U, M and L positions had similar inflorescences number per shoot between them, and significantly higher than the M and L positions in SHD (Fig. 4 A). In addition, in SHD hedgerows the inflorescences number per shoot were similar between canopy positions. The inflorescence numbers per shoot in the M and L positions of HD were triple than those of corresponding positions

Table 4
Branch characteristics of olive cv. Genovesa, in high (HD) and super-high (SHD) density hedgerows. For each branching order, average values ± SE (n = 3) for length, basal diameter, number of nodes, internode length, angle and branch density. Different letters indicate significant differences between the means for a given branch order characteristics variable using the Tukey post-test ($p < 0.05$), only presented when ANOVA indicated significant effect.

	Branching order	Mean axis length (cm)	Main axis nodes (#)	Internode length (cm)	Length (cm)	Diameter (mm)	Angle (°)
HD	First	12.17 ± 0.4 bc	4.67 ± 0.3	2.63 ± 0.1 ab	12.17 ± 0.4 b	9.58 ± 0.8 ab	76.67 ± 8.8 a
	Second	31.79 ± 9.2 ab	19.00 ± 10	2.14 ± 0.5 ab	46.92 ± 3.3 b	4.61 ± 1.5 cd	75.00 ± 11 a
	Third	23.30 ± 4.0 abc	12.00 ± 1.2	2.00 ± 0.2 ab	165.47 ± 26 ab	3.54 ± 0.4 d	79.2 ± 5.5 a
	Fourth	6.90 ± 1.3 c	5.67 ± 0.7	1.24 ± 0.1 b	300.6 ± 106 ab	1.98 ± 0.2 d	82.21 ± 6.1 a
SHD	First	22.00 ± 6.3 abc	5.00 ± 1.5	4.76 ± 1.6 a	22.00 ± 6.3 b	11.53 ± 0.9 a	54.67 ± 2.9 b
	Second	36.91 ± 5.2 a	13.67 ± 2.3	2.95 ± 0.6 ab	97.07 ± 16 ab	6.73 ± 0.5 bc	55.05 ± 15 b
	Third	17.10 ± 1.6 abc	8.33 ± 0.9	2.39 ± 0.5 ab	538.73 ± 206 a	3.04 ± 0.2 d	52.56 ± 1.6 b
	Fourth	8.85 ± 2.8 c	5.67 ± 0.7	1.73 ± 0.5 ab	304.51 ± 125 ab	1.92 ± 0.1 d	54.08 ± 2.7 b

of SHD hedgerows. Bearing shoots in HD hedgerows had mostly single inflorescences per node, 1.18, 0.99 and 0.98 in the U, M and L canopy positions, respectively, greater in all cases than SHD hedgerows, 0.63, 0.37 and 0.35, respectively (Fig. 4 B).

Inflorescences in U and M positions in HD hedgerows had more flowers than L position in SHD (Fig. 4 C). In both hedgerow systems, there were less flowers per inflorescence in L than U position. The percentage of perfect flowers per inflorescence was not significantly different between canopy positions in each hedgerow system (Fig. 4 D). In SHD hedgerows the inflorescences located in the L position showed higher percentages of open flowers than M position of SHD and similar to the rest of studied canopy positions (Fig. 4 E).

3.4. Fruiting traits

The yield from the M position was greater than from the U and L positions in HD hedgerows and from all positions in SHD hedgerows. In SHD, the yield was similar among canopy positions (Table 6). The mean of fruit density of HD was greater than SHD hedgerows, 243 and 132 (# m^{-3} canopy), respectively. The fruit density of M position of HD hedgerows was greater than L position of SHD hedgerows. Individual fruit fresh weight from the U and M positions in HD hedgerows was greater than M and L positions in SHD. Further, the individual fruit dry weight from the U position in HD hedgerows was greater than from M and L positions in SHD. Fruit moisture in the L and M position of HD hedgerows was greater than the L, M and U positions of SHD. No apparent differences were detected in fruit moisture within HD positions. In SHD hedgerows, the fruit moisture was higher in L than U position. In each hedgerows systems the fruit retention force was higher at U than L position.

The yield per hectare in HD hedgerows was 14.3 t ha^{-1} in 2020 greater than the 4.4 t ha^{-1} in 2019. In SHD hedgerows, yield was similar between years with 10.4 and 8.4 t ha^{-1} in 2019 and 2020, respectively (Table 5). The fruit number per lineal meter of row was greater in 2020 than 2019 in HD and similar between years in SHD. In each hedgerow systems, the individual fruit fresh weight was greater in 2019 than 2020, and the lowest individual fruit fresh weight was observed in SHD in 2020. The individual fruit dry weight in HD hedgerows was greater in 2019 than in 2020 and greater than SHD in both seasons. In each hedgerow system, the fruit retention force were higher in 2019 than in 2020, with no differences between hedgerows in both seasons. The ratios between fruit retention force and fruit fresh weight (FRF/FWF) were 1.1 and 0.6 in HD, and 1.0 and 0.8 in SHD, in 2019 and 2020, respectively.

4. Discussion

We evidence how hedgerow dimensions and leaf area density impact on the internal light environment and consequently affect vegetative, flowering, and fruiting responses, determining the productivity and management of cv. Genovesa hedgerows, as previous studies have shown for cv. Arbequina (Connor et al., 2014; Rosati et al., 2021; Tous et al., 2010; Trentacoste et al., 2017). Here, we considered the cultivar Genovesa which has different characteristics of fruit and canopy architecture than other olive cultivars normally used in SHD hedgerows. Also, we evaluated the R/FR ratio changes in olive hedgerows, a light environmental factor not considered in previous studies, and reported the vegetative, flowering and fruiting traits of cv. Genovesa to the two hedgerow systems most used in the new commercial orchards in Argentina.

4.1. Structure, light environment and canopy characteristics

The HD hedgerows was slightly taller and wider (4.0 and 2.3 m) than SHD (3.8 and 1.8 m, respectively). The HD hedgerows 4 m height and 3.5–4.0 m width are suitable for the Colossus harvester while the SHD hedgerows 3.3 m height and 1.0–1.5 m width can be harvested with modified grape harvesters (Tous, 2011). The SHD height higher than 2.5 m could cause damages in vertical and little flexible branches growing in the canopy top when the hedgerows are harvested. However, in our study with cv. Genovesa, vertical branches at the top of the SHD hedgerows did not show significant damage, possibly because the shoots were few and enough elastic to bend over during harvester passage. Future studies could usefully quantify other determinants of hedgerow structure such as shoot density, flexibility and topology (e.g. mixed, vegetative, suckers). The importance of these characteristics has recently been emphasized in a study of mechanical pruning in SHD hedgerows (Lodolini et al., 2023).

Measurements of tree width revealed that while trees in SHD had filled allotted space (1.5 < 2.0 m) along rows to form a continuous canopy, trees in HD intra-row (2.9 < 3.5 m) had not done so. This means that after 7 years of plantation, the SHD hedgerow may achieved a potential in terms of crop cover, previously related to maximum productivity (Gómez-del-Campo et al., 2017). The HD hedgerows had a long period to achieve maximum of both crop cover and productivity, which could be refers as a lost time (Gómez-del-Campo et al., 2017).

The incident PAR on canopy walls of HD hedgerows was higher than of SHD. In summer, HD hedgerows received 47 and 13 % of the horizontal irradiance on the top of canopy on U and L positions, while the corresponding values in SHD were only 41 and 7 % (Table 2). These data highlight the importance of the ratio of canopy height/free alley to PAR distribution with height in hedgerows. Here, the ratio was close to one in HD hedgerows (0.7) but much larger (1.5) in SHD. It has been estimated that a ratio close to 1 provides an optimum distribution of PAR for maximum growth. In contrast, values of the canopy height/free alley higher than 1 can reduce yield by PAR limitations in lower positions of the canopy (Connor and Gómez-del-Campo, 2013; Trentacoste et al., 2015). As Ladux et al. (2021) observed, the optical properties of olive leaves can also modify the light quality reflected by the tree canopy. The R/FR ratio measured in the HD hedgerows was consistently higher than in SHD (Fig. 2), showing that the proximity of neighboring trees does reduce the R/RF ratio in olive hedgerows, as previously suggested by Gommers et al. (2013) for other agroecosystems such as grasslands and forest understories.

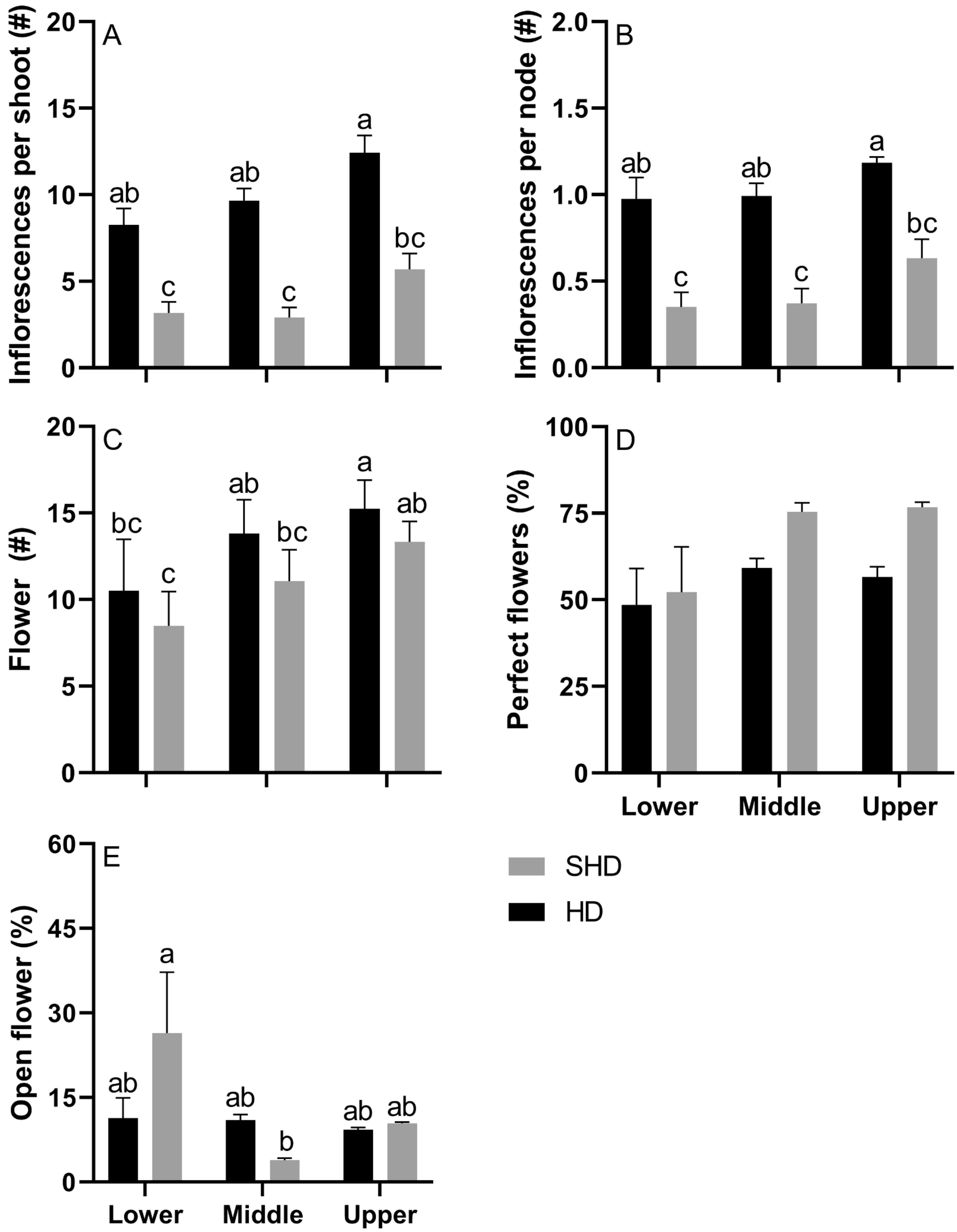

Fig. 4. Flowering characterization of olive cv. Genovesa plants in high (HD) and super-high (SHD) hedgerows. Average values of reproductive characteristics according to canopy position ± SE (n = 3). Different letters indicate significant differences between the means for a given vegetative variable using the Tukey post-test ($p < 0.05$), only presented when ANOVA indicated significant effect.

The shoots of HD hedgerows had a similar length than those of SHD except in the L position, while nodes number per shoot was similar, except in the M position of HD hedgerows. These observations occurred even when positions of HD hedgerows were exposed to high PAR and high R/FR ratio. In a previous study, we observed consistently higher both length and node number in young olive plants exposed to high PAR and high R/FR ratio (Ladux et al., in process). Differences between hedgerow systems were in the lower position, where HD had shoots with shorter internodes and greater SLM compared to SHD (Fig. 3 and Table 3), as a result of a better distribution of PAR in the HD than SHD canopy, similar to that observed by Larbi et al. (2015) in olive hedgerows. On the other hand, HD hedgerows had more leaf area per canopy volume and greater shoot axis-order angle compared to SHD. These results seem to suggest a better light transmission and wind flow within HD hedgerow canopy. Proietti et al. (2015) compared two Italian olive cultivars (Maurino and Leccino) and the Spanish cultivar Arbequina, all planted in SHD. The authors observed better light distribution within hedgerow canopy of cv. Maurino, despite the fact that it was the cultivar with the highest LAD. They attributed this finding to the fact that Maurino had lower number of empty spaces in the canopy and more vertical leaves orientation, reducing shading of the leaves in the middle and lower canopy positions by leaves located in the upper canopy position. Regarding branch characteristics, SHD hedgerows of cv. Genovesa showed the lower axis-order angle, which is a positive aspect to

Table 5
Fruiting characteristics of olive cv. Genovesa in high (HD) and super-high (SHD) density hedgerows. Average values are per plant ± SE (n = 3) for 2019 and 2020 years. Different letters indicate significant differences between the means for fruits characteristics variable using the Tukey post-test ($p < 0.05$).

	HD		SHD	
Variables	2019	2020	2019	2020
Fruit number (# linear m^{-1})	489 ± 60 b	2156 ± 119 a	759 ± 246 b	927 ± 163 b
Yield (t ha^{-1})	4.37 ± 0.6 b	14.27 ± 1.1 a	10.43 ± 2.9 ab	8.38 ± 1.1 ab
Fruit fresh weight (g)	6.24 ± 0.04 a	4.63 ± 0.13 b	5.65 ± 0.24 a	3.68 ± 0.19 c
Fruit dry weight (g)	3.06 ± 0.03 a	1.90 ± 0.04 c	2.57 ± 0.16 b	1.89 ± 0.08 c
Fruit moisture (%)	52.90 ± 0.6 b	57.47 ± 0.5 a	55.40 ± 1.1 ab	47.60 ± 0.9 c
Fruit retention force (N)	7.10 ± 0.2 a	2.83 ± 0.6 b	5.63 ± 0.1 a	2.95 ± 0.3 b

Table 6
Fruiting characteristics in olive cv. Genovesa in high (HD) and super-high (SHD) density hedgerows. Average values according to the canopy position ± SE (n = 3). Different letters indicate significant differences between the means for fruits characteristics variable using the Tukey LSD post-test ($p < 0.05$).

	Canopy position	Yield (kg)	Fruit density (# m^{-3} canopy)	Fruit fresh weight (g)	Fruit dry weight (g)	Fruit moisture (%)	Fruit retention force (N)
HD	Upper	5.16 ± 0.8 b	234 ± 36 ab	5.68 ± 0.1 a	2.66 ± 0.05 a	54.6 ± 0.3 ab	6.0 ± 0.3 a
	Middle	11.92 ± 2.3 a	262 ± 42 a	5.45 ± 0.1 a	2.48 ± 0.05 ab	55.3 ± 0.4 a	4.5 ± 0.6 abc
	Lower	5.75 ± 0.4 b	233 ± 9 ab	5.17 ± 0.1 ab	2.30 ± 0.03 abc	55.6 ± 0.4 a	4.2 ± 0.4 bc
SHD	Upper	1.48 ± 0.3 b	140 ± 33 ab	5.02 ± 0.1 abc	2.53 ± 0.04 ab	50.4 ± 0.5 d	5.5 ± 0.1 ab
	Middle	3.19 ± 0.4 b	143 ± 19 ab	4.68 ± 0.2 bc	2.22 ± 0.10 bc	51.1 ± 0.6 cd	4.1 ± 0.3 bc
	Lower	0.98 ± 0.2 b	114 ± 33 b	4.31 ± 0.3 c	1.94 ± 0.17 c	52.8 ± 0.9 bc	3.0 ± 0.1 c

improve the vibration transmission and consequently the harvest efficiency of the straddle harvester systems (Carella et al., 2022), and to reduce damages to lateral branches (Proietti et al., 2012; Pérez-Ruiz et al., 2018).

4.2. Flowering and fruiting

The fruit bearing shoots of HD hedgerows had more inflorescences in all canopy positions than SHD (Fig. 4 A and B). This finding is supported by Trentacoste et al., (2022), who reported a strong association between inflorescence production and PAR incident on the canopy in olive trees. In addition, inflorescences number was not related to shoot length, as also reported previously by Castillo-Llanque and Rapoport (2011). However, there was a negative relationship between inflorescence number and internode length (data not shown). In both hedgerow systems, inflorescences that received lower irradiance showed significantly fewer flowers per inflorescence as canopy height increased (U and M > L positions). The percentage of perfect flowers was similar among canopy positions within each system, in contrast to previous reports (Bartolini et al., 2022; Trentacoste et al., 2022; 2017) where inflorescences that developed in more illuminated canopy positions showed a higher percentage of perfect flowers. Across the seasons, HD and SHD had similar average yields per ha (Table 5). However, there were some differences between the years. Yield per ha in HD hedgerows was higher in 2020 than in 2019 (i.e. more alternate production), in contrast to SHD hedgerows where yield was similar between years. The higher alternated production in the less dense hedgerows was also reported by Diez et al. (2016), but no by Gómez-del-Campo et al. (2020), who reported higher inter-annual variation in production in more intensive hedgerows of cv. Arbequina. In HD hedgerows, individual fruit weight, both fresh and dry, were inversely related to fruit number per linear meter of row, but this relationship was not observed in SHD hedgerows. This indicates that in SHD the individual fruit weight was not limited by photoassimilate availability (Fernandez et al., 2018; Trentacoste et al., 2010). The ratio FRF/FWF is a parameter related to the efficiency of mechanical harvesting (Farinelli et al., 2012; Ferguson et al., 2010). Values equal to or less than 2.3 ensure a harvest efficiency above 85 %. Here the results of the FRF/FWF ratio were always less than 2.3 in both HD and SHD hedgerows. Fruit retention force was not different between HD and SHD hedgerows in both seasons. In addition, fruit retention was consistently higher in 2019 than 2020, showing that environmental conditions and the fruit load play an important role (Tombesi et al., 2017).

The yield and fruit density were greater in HD than SHD hedgerows comparing each canopy position (Table 6). The high fruit density throughout the HD hedgerows canopy than SHD could be explicated to the higher PAR incident and better PAR distribution (Table 2) which lead to observed higher inflorescence number per node (Fig. 4). In addition, whereas the fruit dry weight of HD hedgerows differed only between the U and L positions, in SHD it diminished consistently with canopy height.

5. Conclusions

This study seeks a new way to understand and measure the behavior of olive cultivars trained in hedgerows at different planting densities. First, the light environment characterization shows how a greater planting density reduces the R/FR ratio reflected by neighboring trees while reducing incident PAR with height in hedgerow canopies. Further, the traits of bearing shoots, leaves and flowering intensity reveal development in more shaded positions in SHD than HD hedgerows. Canopy position in HD have higher leaf area density and higher axis-order angle compared to canopy positions in SHD suggesting higher light distribution within canopy but lower performance of straddle harvesters (i.e. lower vibration transmission and more damage of branches). Hedgerows must be designed for climatic conditions, cost of establishment, plantation size, mechanical harvester type and cultivar. More studies are needed to establish behavior of further cultivars to hedgerow design, importantly to the distribution of light quality as well as intensity, taking care to work with different but equally optimal hedgerow designs.

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Ethical Statement

As this manuscript does not involve research on humans or animals, nor does it include vulnerable populations, an ethical statement is not applicable.

CRediT authorship contribution statement

Federico J. Ladux: Conceptualization, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **M. Cecilia Rousseaux:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition. **Eduardo R. Trentacoste:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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.

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