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Aboveground tree traits on various production systems and positions of the canopy on olive (*Olea europaea* L.) orchards. A review

Características aéreas del árbol en varios sistemas de producción y posiciones de la copa en fincas de olivo (Olea europaea L.). Una revisión

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Abstract

Interception of solar radiation and light distribution within the tree canopy are altered on different production systems and positions within such canopy during its growth and development in the orchard. The objective of this review was to determine several aboveground tree traits on various production systems and positions within their canopy (upper, medium, lower) which lead to obtain different values for such traits on olive (*Olea europaea* L.) orchards. The production systems included different (1) shading treatments, (2) orientations (N-S or E-W) or exposures (E-W in the N-S orientation, and N-S in the E-W orientation) of the tree rows, and (3) planting densities (low, moderate, high and very high). The studied traits included the (1) evaluation of bud and shoot development; (2) inflorescence characteristics, and (3) tree size optimization (height and width). In general, the more illuminated areas produced greater values than the less illuminated ones in the canopy of olive trees on various production systems and canopy positions for different morphophysiological, inflorescence and tree size traits.

Resumen

La intercepción de la radiación solar y la distribución de luz dentro de la copa del árbol son alterados en diferentes sistemas de producción y posiciones dentro de dicha copa durante su crecimiento y desarrollo en la finca. El objetivo de esta revisión fue determinar varias características del árbol en varios sistemas de producción y posiciones en su copa (superior, media, inferior) que conducen a obtener diferentes valores para dichas características en fincas de olivo (Olea europaea L.). Los sistemas de producción incluyeron diferentes (1) tratamientos de sombreado, (2) orientaciones (N-S o E-O) o exposiciones (E-O en la orientación N-S, y N-S en la orientación E-O) de las hileras *de árboles, y (3) densidades de plantación (baja, moderada, alta y muy alta). Las características estudiadas fueron (1) la evaluación del desarrollo de yemas y del tallo; (2) características de las inflorescencias, y (3) la optimización del tamaño del árbol (altura y ancho). En general, las áreas más iluminadas produjeron mayores valores que las menos iluminadas en la copa de árboles de olivo en varios sistemas de producción y posiciones dentro de su copa para diferentes características morfofisiológicas, de la inflorescencia y del tamaño del árbol.*

Keywords: radiation absorption; Olea europaea, aboveground organs, fruit quality

Palabras clave: *absorción de radiación, Olea europaea, órganos de la parte aérea, calidad de los frutos*

Introduction

Currently, Argentina is the main producer and exporter of olive oil of South America and the 10th at a worldwide level. The major producer Provinces are Catamarca, La Rioja, San Juan, Mendoza and Córdoba. These Provinces concentrate more than 95% of the total oil country production, with more than 100,000 ha implanted with olive (COI, 2015). The southwestern region of the Province of Buenos Aires, Argentina, is integrated by the semiarid, arid and subhumid-dry Pampas, with 6,500,000 ha divided in 12 districts. Since the conditions of soil and climate of this region are very different from those of the northwestern Provinces, farmers of the southwestern region of Buenos Aires are very interested in developing management techniques adequate to this region. Its agricultural productivity is lower than the rest of the Pampa region, due to the prevailing agro-ecological conditions (Cincunegui et al., 2019). Such region is ecologically suitable for the olive culture, and such culture contributes to reduce the advancement of the desertification in the region (Elías & Barbero, 2017). This region has competitive advantages derived from (1) the port of greater depth in the country (Port of Ingeniero White), (2) and adequate transporting system, and (3) the provision of associated services necessary for the commercialization and general development of the activity (Cincunegui et al., 2019).

The expansion of olive-growing areas, the cultivation intensification, and the development of novel cultural practices determined a worldwide increase in the olive (*Olea europaea* L.) production over the last fifty years (Lombardo & Lanotta, 2002). At the beginning of the 1990s, super high-density olive orchards (1000-3000 trees.ha^{-1}) started to be planted in Spain (Díez et al., 2016). This production system is now used in America, Europe, Australia, north Africa and Saudi Arabia (Connor *et al*., 2012). Currently, it is estimated to occupy about 11.3 million ha out of the total worldwide area planted to olive (Dhiab et al., 2020). The early production, the easiness of disease and pest control, and the reduction of production costs are the main advantages of this production system because of harvest and pruning mechanization (Connor et al., 2012). A disadvantage, however, are the high establishment costs (Tous et al., 2015).

For an optimal yield and maximum light interception, optimum planting density should be determined (Rallo et al., 2014). In addition to tree spacing, cultivar, climate, harvest method, tree training system, fertilization, irrigation management, and soil conditions should be appropriately considered. Along with the reduction of row spacing (ranging from 7 to 3 m), the management of orchard light interception should be taken into consideration (Jackson, 2017). Even more, interception of solar radiation and radiation distribution within the tree canopies during the orchard development are altered by an increasing tree planting density (Jackson, 2017). This allows for managing the efficiency of solar radiation used for different processes including photosynthesis, flower bud formation, growth, and fruit quality. Jackson (2017) reported that both interception of maximum amount of radiation and optimization of the radiation distribution within the canopy are important factors to maximize orchard production and efficiency. The control of tree size to a level that (1) enables an efficient mechanical harvesting and (2) ensures the illumination of a canopy cropping area are the major long-term problems of the super high-density (SHD) orchard systems (Connor et al., 2014).

Enhancement of fruit yield and quality are the main goals of adopting SHD for olive cultivation. Two objectives need to be fulfilled to optimize the production of assimilates and its conversion to economic yield: to (1) find ways to maximize light interception by trees, and (2) optimize light distribution within the canopy and its interception by different parts of the tree so as maximize the efficiency of light interception in photosynthesis (Rosati et al., 2021).

Interception of solar radiation and radiation distribution within the olive tree canopies are altered during the orchard development (Dhiab et al., 2020; Rosati et al., 2021; Maldera et al., 2021). This determines changes in the values of various morphophysiological, and of the inflorescence and tree traits in olive orchards (Guerreiro & Vitagliano, 1973; Tombesi et al., 1999; Trentacoste et al., 2017; Ajmi et al., 2018; Dhiab et al., 2020; Maldera et al., 2021; Rosati et al., 2021). In spite of this, no manuscripts have reviewed up to date the extent of those trait changes in different production systems (shading treatments, and tree row orientations and exposures, and planting densities) and positions within the tree canopy (upper, intermediate, lower). The objective of this manuscript was to review how those tree traits change on those production systems and positions within the canopy on olive trees (*Olea europaea* L.).

Tree trait types on different production systems and positions within the tree canopy.

Morphophysiological

Rosati et al. (2021) found that overall photosynthetically active radiation (PAR) interception in SHD systems was significantly less than that in high-density [(HD; about 800 trees ha-1 (3.5 x 3.5 m spacing)] production systems (Table 1). However, the former systems had a much greater spatial variability of transmitted PAR than the HD systems (Table 1). This corresponded to a greater variability in the frequencies of daily PAR values, with the more shaded positions receiving greater frequencies of low PAR values. The much lower PAR levels under the tree rows in the SHD systems (Table 1), compared to any position in the HD systems, imply greater self-shading in lower-canopy positions (Rosati et al., 2021) (Table 1). Knowing the overall PAR interception does not allow an understanding of differences in PAR distribution on the ground and within the canopy and their possible effects on canopy radiation use efficiency (RUE) and performance between different architectural systems.

An extensive work was made by Guerriero & Vitagliano (1973) by shading "Frantoio" and ''Moraiolo" trees with nets of different thicknesses. It was difficult to reach clear conclusions from this work because of the varied responses depending on genotype, intensity of shadowing and obscured exposure of the tree. Nevertheless, they often found reductions in flowering density, and in number and size of fruits produced under nets (Table 1). Other authors also experimented with shading (using nets to reduce the external light to about 10%) to elucidate the organs (fruits or leaves) involved in crop losses under limited light conditions (Tombesi et al., 1999). Shading leaves caused lighter fruits with lower oil concentrations (Table 1), mainly due to reduced pulp/stone ratios, in their study. Shading fruits, conversely, affected oil concentration, but not fruit size.

Differences in light distribution among olive canopy positions may be partially responsible for different patterns of vegetative growth, flowering, fruit distribution, fruit size and oil content among positions of the tree canopy, i.e., bottom (0-1m), medium (1-2m) and top (>2m) canopy positions on olive trees (Dhiab et al., 2020). These authors reported that PAR decreased progressively from the upper to the bottom part of the canopy (Table 1). This decrease was more accentuated when there was a significant increase of tree size. The variation in PAR availability within the canopy affected the vegetative growth, fruit set, average fruit weight, fruit maturity index, and oil concentration (Table 1).

Plant responses to shade application (mean PAR of 650 μmol $m^{-2}.s^{-1}$) may be classified as short- and long-term ones (Ajmi et al., 2018). Shoot growth was started to be affected 18 months after shading application (Table 1), and after that date a total suppression of growth was determined. However, both leaf surface and leaf angle insertion (Table 1) were affected from the beginning of the experiment (3 months). Shaded leaves had higher area and lower thickness (Table 1). Palisade and spongy parenchyma thickness were reduced in shaded plants (Table 1). Stomatal density, net photosynthetic rate, stomatal conductance and transpiration rate were also reduced by shade (Ajmi et al, 2018). In addition, shading induced a significant decrease in the concentration of chlorophyll a, β-carotene, lutein and pigments within the xanthophyll cycle (Table 1). A significant decrease of fruits number was observed in shaded plants after one year of shading application, while with prolonged shade, a total absence of fruits was observed (Ajmi et al., 2018) (Table 1). Nevertheless, these authors concluded that the olive tree has a morphological and physiological plasticity that allows it to adapt to light stress.

On the selected shoots on each of the three studied canopy positions (top, middle, bottom) of olive trees cv. ''Arbequina", and the two studied years, the total number of buds was counted by Dhiab et al. (2020) in a SHD cropping system. From this information, these authors calculated later the percentage of buds forming (1) inflorescences (flower buds), (2) a shoot (vegetative buds), and (3) quiescent buds. The percentage of the flower, vegetative and quiescent buds in the first studied year, and of the flower and vegetative buds in the second studied year, did not differ significantly among the top, medium and bottom canopy positions in the olive trees (Dhiab et al., 2020) (Table 1). However, in the second studied year, the percentage of quiescent buds was more than 16% significantly higher at the bottom than at the top canopy position (Table 1). Maldera et al. (2021) studied the effects of two row orientations (N-S and E-W), two exposures within each orientation (E and W in the N-S orientation, and N and S in the E-W orientation), and different canopy positions (top, middle and bottom positions: 120–180 cm, 60–120 cm and 0–60 cm above the soil surface, respectively) in southern Italy on the total, and flower and wood bud numbers; leaf area index (LAI), and photosynthetically active radiation (PAR) at different times during the growing cycle in a SHD almond orchard. The number of flowers per shoot was recorded at full bloom. They found that the mean total bud number was similar among the three canopy positions at the E-W exposures within the N-S orientation, and at the N exposure at the E-W orientation (Table 1). The only exception was at the S exposure within the E-W orientation, where the mean total bud number per shoot was higher at the upper than at the lower canopy position (Table 1). Within the N-S orientation, the E and W exposures showed a similar mean total bud number per shoot on each of the three canopy positions (Table 1). However, within the E-W orientation, the N exposure showed a higher mean total bud number than the S exposure (Table 1). These authors also determined that the mean number of flower buds per shoot was higher in the bottom than in the top position at the E and W exposures within the N-S orientation, and at the N exposure within the E-W orientation (Table 1). The only exception occurred at the S exposure within the E-W orientation, where the mean number of flower buds per shoot was higher at the top than at the bottom position (Table 1). Also, this variable was similar at the E and the W, and at the N and the S exposures in both orientations on each of the three canopy positions (Table 1). Maldera et al. (2021) also studied the mean number of wood buds per shoot. They determined that it was greater on the upper than the lower canopy positions in the E and W exposures at the N-S orientation, and the N and S exposures at the E-W orientation (Table 1). The mean number of wood buds per shoot was similar between exposures in both orientations (N-S and E-W) on each of the three canopy positions. (Table 1).

Maldera et al. (2021) also reported that the LAI was strongly influenced by day of the year and tree canopy position, but not by row orientation. Leaf development began in late winter, reaching maximum values in early summer, and then gradually decreasing until late summer. This pattern was confirmed by Sakar et al. (2019) in almond. LAI was highest at the bottom position and smallest at the upper position on both exposures (E-W for the N-S orientation, and N-S for the E-W orientation) (Maldera et al., 2021) (Table 1). These authors found that a PAR gradient was found from the top to the bottom position due to less light intercepted in the lowest part of the canopy (Table 1). For the lowest position, PAR was least on the E and S exposures, and highest on the W and N exposures (Maldera et al., 2021) (Table 1). In the middle position, the situation was quite similar: E showed lower PAR than W exposure, while N and S exposures received about the same PAR. These results may be related to a thicker canopy, normal on the S exposure in southern Italy (Maldera et al., 2021) (Table 1). An unusual finding was that the same was found for the eastern exposure (Table 1). This could be explained by the fact that the net assimilation rate in the morning hours was higher than in the afternoon due to the better physiological conditions of the tree. With W exposure, the light was captured in the afternoon, when the physiological condition of trees suffers from closed stomata (Maldera et al., 2021). Higher afternoon temperatures could also lead to a reduction in photosystem efficiency (Casanova-Gascón et al., 2019). In the upper canopy position the situation is different, with the highest PAR on the W exposure (Table 1), decreasing towards N (Maldera et al., 2021). Mariscal et al. (2000) determined that when leaves are erect, especially in the upper canopy positions, the incident radiation at low zenith angles is better distributed toward lower positions, increasing their maximum photosynthesis in olive orchards located in Spain. They also showed that once the angle between the vertical and the leaf within the interval 0° to 180° was measured at the field, it allowed them to calculate the density function of this inclination. When they separated the inclination density function from the upper and lower tree hemisphere, the number of erect leaves (those with the peduncle below the vertex) increased toward the upper canopy parts while the number of pendulum leaves (those with the vertex below the peduncle) increased toward the lower canopy positions (Table 1). However, the leaf inclination distributions (0°-90°) were similar in the upper and lower part of the tree (Table 1).

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 characteristics (Ladux et al., 2023). These authors reported on an analysis of the response of irrigated olive cv. ''Genovesa" vegetative traits to hedgerows of HD (intra- and inter-row distance= 7 x 3.5 m) and SHD (4 x 1.5 m) orchards. Measurements were taken at different tree heights measured from the base of canopy. In the HD hedgerow these heights were: 0.0–0.8 m (Lower, L), 0.8–1.6 m (Middle, M) and ≥ 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), ≥ 2.0 m aboveground (U). They determined that the R/FR ratio (660 and 730 nm wavelengths, respectively) and mean daily horizontal incident PAR were significantly higher in HD than in SHD (Table 1). In the HD and SHD hedgerows, shoots were significantly shorter at the L than the M and U positions (Table 1). In addition, shoots from U position in HD hedgerows had higher number of nodes than shoots selected from L positions in HD (+81%) and M positions in SHD (+74%) (Table 1). The

L position of HD hedgerows had shorter shoot internodes than the U, M and L positions of SHD ones (Table 1). Shoot diameter did not statistically differ within canopy positions from each hedgerow system (Table 1).

Dhiab et al. (2020) reported that olive shoot growth (cm $shoot^{-1}$) was significantly lower at the base of the canopy in a SHD cropping system (Table 1). The competition for carbohydrate between growing shoots and flowering, fruit formation and fruit filling probably determined the depression of vegetative growth observed in the second studied year compared to the previous year in all studied positions (Dhiab et al., 2020) (Table 1). Pastor et al. (2007) indicated that olive shoots located at the top of the canopy in the same cultivar ('Arbequina') grew much more than those of the middle and the base of the canopy (Table 1). These authors also determined that the cumulative fruit production at 1,904 $trees.ha^{-1}$ (3.5 m x 1.5 m) was 60,096 $kg.ha^{-1}$, while the yields at 204 trees ha^{-1} (7 m x 7 m), 408 $trees.ha^{-1}$ (7 m x 3.5 m) and 816 $trees.ha^{-1}$ (3.5 m x 3.5 m) were 32,513; 60,125 and 76,149 $kg.ha^{-1}$, respectively, at the end of the sixth producing year (Table 1). They also showed that fruit oil content at 1,904 trees ha^{-1} was less than that in all the other densities (Table 1), and cumulative oil yields for the first six producing years were 6,829; 12,853; 14,973 and 10,113 $kg.ha^{-1}$ at the 204 $trees.ha^{-1}$, 408 $trees.ha^{-1}$, 816 $trees.ha^{-1}$ and 1,904 $trees.ha^{-1}$, respectively (Table 1). As a result, they concluded that the SHD system, in its current form and management, is less productive and probably less sustainable than orchards planted at densities such as that of 408 $trees.ha^{-1}$.

Inflorescence characteristics

Olive trees bear their fruits on the previous season's shoot growth, and bloom on panicles containing hermaphrodite and male (pistil aborted) flowers. The extent of pistil abortion depends on genotype, and largely on nutritional conditions (Rapoport et al., 2022).

Moreno Alías et al. (2018) determined that radiation reception highly depends on canopy height and row orientation and spacing in an intensive hedgerow orchard. These authors found that the more highly illuminated south exposure received 28% overall more irradiance than the north exposure, and that the upper position irradiance was greater than that at the bottom position, 4.1 and 1.8 times for north and south exposures, respectively. They found that the inflorescence structure, flower number and perfect flower proportion were similar at different heights on the south exposure (Table 1). At the north exposure, however, upper position inflorescences were longer and had more nodes, total flowers and perfect flowers than those at lower hedgerow heights (Table 1). Finally, ovary tissue sizes did not vary among heights on each exposure (Table 1), but were higher on the south than north exposure due to endocarp size (Table 1). As a result, their results emphasize the importance of irradiance at different hedgerow exposures and heights on olive inflorescence and floral structures. Bartolini et al. (2022) reported that more illuminated external than internal canopy sites on clones of ''Lecino" cultivar had a greater (1) inflorescence length, (2) number of flowers per inflorescence, (3) percentage of open flowers and (4) percentage of viable pollen grains on flowers (Table 1). This latter finding agrees with that of Anguilar-Garcia et al. (2018) who reported that in a Cactaceae species, flowers intercepting lower PAR had worse quality pollen (Table 1).

Trentacoste et al. (2017) evaluated flowering and fruiting parameters in 5 hedgerow positions (defined by hedgerow exposure and vertical position above the soil) for N–S (North-South) and E–W (East–West) olive hedgerows (cv. ‘‘Arbequina”). These authors found that the numbers of inflorescences and fruits per position increased from the less illuminated base to the more illuminated upper canopy positions (Table 1). Axillary bud number per shoot also increased toward more illuminated positions (Table 1), while the proportion of floral buds was unresponsive to the irradiance at the different positions within the hedgerows (Table 1). Inflorescence length, node and flower number per inflorescence, and perfect flower percentage increased with position illumination (Table 1). Despite improved flowering parameters with greater irradiance, no consistent differences among positions were found for percentage of inflorescences bearing fruit and fruit number per inflorescence (Table 1). Instead, their results indicated that different fruit numbers among canopy positions were primarily due to an irradiance effect on vegetative growth, causing more and longer fruiting shoots (Table 1). As a result, this resulted in more total flowering sites (nodes) per position, with only a small contribution by inflorescence structure and flower quality. With higher illumination at the top positions, ovaries were larger but ovule development was not influenced (Table 1). These authors concluded that fruit number was affected more by flowering site (bud) number than by flower quality.

Mezghani et al. (2021) showed that multiple sequential processes determined a higher productivity of trees at the periphery of them, with respect to those arising from the interior and lower parts of the canopy (Table 1). They reported that various parameters participated in causing differential productivity among well (i.e., top canopy positions) and poorly (middle and bottom canopy positions) illuminated canopy areas. Acevedo et al. (2000) informed that the number of inflorescences and of fertile inflorescences, and the number of fruits and fruit dry weight per twig were always significantly highest on twigs located at the top compared with those positioned in the interior and low locations in the canopy of the olive cultivars ‘‘Arbequina” and “Picual” (Table 1). Similarly, the number of flowers and of hermaphrodite flowers in cultivar “Arbequina” and of flowers in cultivar “Picual” were always significantly highest on inflorescences located at the top canopy positions compared with those located at the middle and bottom canopy positions (Acebedo et al., 2000) (Table 1). The general compensation mechanism, that makes fruit size diminishes when the number of fruits is higher, did not occur among different zones of the same tree (Acevedo et al., 2000).

Dhiab et al. (2020) determined the percentage of staminate flowers on the inflorescences, the inflorescence length and the average number of flowers in each inflorescence in the canopy of olive trees grown under a SHD cropping system. In both study years, the percentage of pollen germination was significantly greater (> 21%) on the top than the bottom positions (Table 1). The inflorescence length (mean=2.47 cm) was similar on the three studied positions in both years (Table 1). The top position had a significantly greater percentage (> 50.5%) of staminate flowers in both years than the bottom position (Table 1). The number of flowers per inflorescence was significantly greater (> 106%) at the bottom than at the top position only in the second studied year, although it was similar among positions in the previous year (Table 1).

Optimization of tree size

For maximizing light interception by the orchard and to maintain an adequate irradiance distribution within the canopy it is essential to optimize tree size in olive HD planting orchards (Connor, 2006). He reported that optimally illuminated canopy hedgerow walls receive enough irradiance at the base of the canopy which allows a good fruit productivity in all parts of the canopy (Table 1). Nevertheless, shading problems can occur when the hedgerow height and width exceed the adequate dimensions, and as a result olive yield will be negatively affected (Connor et al., 2009). Dhiab et al. (2020) indicated that the distribution of intercepted radiation within the canopy was not homogeneous when the top, the medium, and the bottom positions of the canopy were compared. Even more, in the second year of the study, the decreased intercepted solar radiation was more pronounced by the central and bottom canopy positions (Table 1). This may be due to the increased tree height (from 3.6 to 3.9 m) and canopy width (from 1.7 to 2.1 m) between the 2nd and 3rd growth seasons (Dhiab et al., 2020). An increase of the olive hedgerow width from 1 to 1.5 m should be accompanied by a reduction of the hedgerow height from 3.5 to 2.5 m to guarantee maximum fruit yield (Connor et al., 2009). The amount of intercepted irradiance at the base of the canopy was lower (717 and 582 µmol m^{-2} s^{-1} in the 2nd and 3rd growing seasons, respectively) than the threshold value required for photosynthesis saturation of olive sclerophyllous leaves (800 µmol m^{-2} s^{-1} (Dhiab et al., 2020). Similar to the results of Dhiab et al. (2020), Pastor et al. (2007) reported that very little radiation reached the base of the canopy (0-1.5 m) in a very highly intensive olive orchard (1975 trees.ha^{-1}) with a tree height close to 4 m (Table 1). Canopy size should be managed to improve light interception by the hedgerow to make HD olive orchards more economically profitable. Mechanical pruning becomes then a necessary management practice when canopy height and width become too large. The use of either growth regulators or new dwarf cultivars might also be considered to overcome the problem of excessive vigor of the cultivars currently cultivated (Dhiab et al., 2020).

Managing canopy size to improve light interception by the hedgerow

Use of rootstocks, achievement of new cultivars and mechanical pruning

Olive trees require cold temperature for flower differentiation but at the same time are moderately sensitive to cold (Connor & Fereres, 2010) such that productivity can be reduced by low temperature; vegetative organs can be damaged below −7 °C and whole trees can be seriously damaged at −12 °C. Under cold autumn conditions fruits can be damaged at −0.4 °C (Sanzani et al., 2012) requiring earlier harvesting to avoid fruit damage and obtain oil of high quality (Gracia et al., 2012). Cultivars differ in cold resistance. 'Cornicabra' and 'Arbequina' are highly resistant to vegetative damage (Barranco et al., 2005) while 'Cobrançosa' and 'Manzanilla cacereña' are also relatively well adapted to cold conditions (Barranco et al., 2000). Despite these climatic limitations, olive hedgerow orchards are expanding in cold areas due to the benefit there of high oil quality. Low temperature increases oleic content, phenolic and aromatic components (Di Vaio et al., 2012).

Wild subspecies of *Olea europaea* constitute a source of genetic variability with huge potential for olive breeding to face global changes in Mediterranean-climate regions. Díaz-Rueda et al. (2020) thought to identify wild olive genotypes with optimal adaptability to different environmental conditions to serve as a source of rootstocks and resistance genes for olive breeding. The SILVOLIVE collection includes 146 wild genotypes representative of the six *O. europaea* subspecies and early-generations hybrids. These genotypes came either from olive germplasm collections or from direct prospection in Spain, continental Africa and the Macaronesian archipelago. The collection was genotyped with plastid and nuclear markers, confirming the origin of the genotypes and their high genetic variability. Morphological and architectural parameters were quantified in 103 genotypes allowing the identification of three major groups of correlative traits including vigor, branching habits and the belowground-to-aboveground ratio. They showed the occurrence of strong phenotypic variability in these traits within the germplasm collection. Furthermore, these authors emphasized that wild olive relatives are of great significance to be used as rootstocks for olive cultivation. Centeno et al. (2019) highlighted that various wild genotypes used as rootstocks were shown to regulate vigor parameters of the grafted cultivar "Picual" scion, which could improve the productivity of high-density hedgerow orchards.

In other fruit trees (apple), dwarfing rootstocks have been used for a very long time as a way to reduce tree canopy and vigor, and thus increase planting density (Lordan et al., 2018). However, rootstocks have been scarcely used on olive trees because of the ease of self-rooting of this species (Warschefsky et al., 2016), although some rootstocks have been selected for *Verticillium* Wilt (Jiménez-Fernández et al., 2016) and frost (Pérez-López et al., 2008) resistance. Several attempts at selecting dwarfing rootstocks in olive have also been made as reviewed by Rugini & Pace (2016).

The measurement of the geometrical properties of every tree crown is required in the evaluation of the dwarfing effect of the different rootstocks in breeding field experiments. Manual measurement of the plant properties is a laborious task in the olive tree, whose crown has an irregular geometry (Rallo et al., 2020). Different technologies have been used in recent years for the acquisition of 3D information to efficiently alleviate the hard manual work required in phenotyping experiments (Paulus, 2019). Among the alternative technologies, there is one used in the generation of 3D point clouds representing the crops. This is possible through the application of photogrammetric techniques to images acquired with an unmanned aerial vehicle. In these point clouds, each point provides a set of X, Y, Z coordinates representing the surface of the crop and the soil. Unmanned aerial vehicle photogrammetry has been successfully in phenotyping of woody crops such as almond (López-Granados et al., 2019) and olive (Rallo et al., 2020). The typically large number of points in the cloud generated by the use of these new technological tools in breeding experiments requires robust and efficient analysis algorithms (Perez-Sanz et al., 2017). The object-based image analysis paradigm, based on the segmentation of images or point clouds, has been used in the creation of analysis algorithms of point clouds in phenotyping experiments in olive (de Castro et al., 2019).

Hedgerow orchard is a recent olive growing system where trees are planted at much higher density (1200 to 2500 trees.ha^{-1}) than the high density (about 400 trees.ha^{-1}) or the traditional, widely-spaced olive orchards (often 50 to 160 trees ha^{-1}). This intensive cropping system is currently widely adopted in the Mediterranean region and countries like Argentina, Chile, Perú and Australia (Centeno & Gómez del Campo, 2019). This is mainly because of advantages such as they are adapted to fully mechanized harvesting, easy disease and pest control, early bearing, and a relatively constant high productivity (Fernández-Escobar et al., 2013). However, the main constraint of this growing system is that SHD planting leads to the need for low vigor cultivars with good productivity level: there is a scarcity of traditional cultivars with these characteristics

Since little information is available concerning adaptation of olive cultivars to cold conditions, Centeno & Gómez del Campo (2019) evaluated seven olive cultivars in hedgerows during nine years in the cold area of central Spain (Toledo). These cultivars included "Arbequina", ''Arbosana", ''Koroneiki", ''Cobrançosa", ''Cornicabra", ''Manzanilla cacereña" and 'Sikitita'. ''Koroneiki" showed the highest growth rate from the first year and very few trees were damaged by harvesting. In the 7th year, the most vigorous cultivars were "Koroneiki", 'Arbequina' and "Cornicabra" and the least were 'Arbosana' and 'Sikitita'. Regarding hedgerow architecture, ''Koroneiki"' and 'Arbosana" hedgerows were narrow while 'Arbequina' and 'Manzanilla cacereña' were wide. After 9 years, 63% of the ''Cobrançosa" trees were severely damaged by harvesting. "Arbosana", "Koroneiki" and ''Arbequina" produced the greatest number of fruits and most oil. After 7 years, they remained the most productive cultivars but by then oil yields of ''Cornicabra" and "Sikitita" were comparable. "Manzanilla cacereña" and "Cobrançosa" were not recommended for hedgerow orchards by Centeno et al. (2019) because of high alternate bearing, low production and susceptibility to damage during machine harvesting. "Cornicabra" and ''Arbosana" are of questionable use in cold conditions because of high susceptibility to *Pseudomonas savastanoi*. Considering all agronomic aspects, ''Koroneiki", ''Sikitita" and "Arbequina" were the recommended cultivars for hedgerow production in similarly cold environments. Other cultivars available for SHD orchards in southern Italy include ''Urano" (Camposeo & Godini, 2010), ''Abunara", "ADE", ''KALAT", ''Cerasuola" and "Piricuddara" (Marino et al., 2017).

Farinelly & Tombesi (2015) compared ''Arbequina" and four Italian cultivars in SHD orchards (1667 trees.ha^{-1}) in central Italy under cold conditions. They evaluated vegetative vigour, productivity and oil quality on the four local cultivars

("Frantoio", "Leccino", ''Maurino" and ''Moraiolo") in comparison with the standard ''Arbequina" in a SHD orchard. They concluded that ''Maurino", showing low vegetative vigor and compact growth, early and high yield, adaptation to mechanization, good oil quality and shelf life, resulted to be the most suitable cultivar for SHD systems in their study. Días et al. (2018) established a SHD orchard in Moura, Portugal, with the cultivars ''Azeiteira", ''Cobrançosa", ''Cordovil de Serpa", ''Galera vulgar" and ''Redondi". The harvested yield of these cultivar ranged, not significantly, between 3467.8 and 5462.7 $kg.ha^{-1}$ on average for the two planting densities (1250 $trees.ha^{-1}$ and 1850 $trees.ha^{-1}$).

Super high-density olive orchards are rapidly expanding since the first plantation was set up in Spain in the 1990s. Because there are no long-term studies characterizing these systems, it is unknown if densities above a certain threshold could trigger competition among fully-grown trees, compromising their development. As a result, Diez et al. (2016) evaluated the performance of the major olive cultivars currently planted in SHD systems ("Arbequina," Arbequina IRTA-i·18, "Arbosana," "Fs-17," and "Koroneiki") over a period of 14 years under warm conditions in the south of Andalucía, Spain. They also evaluated the effects of nine SHD designs ranging from 780 to 2254 $trees.ha^{-1}$ for the cultivar "Arbequina." Remarkably, the accumulated fruit and oil production of the five cultivars increased linearly over time. Their data indicated the favorable long-term performance of the evaluated cultivars with an average annual oil production of 2.3 $t.ha^{-1}$. Only "Fs-17" did not perform well to the SHD system in their conditions, and it yielded about half (1.2 $t.ha^{-1}$) of the other cultivars. In the density trial for "Arbequina," both fruit and oil accumulated production increased over time as a function of tree density. Thus, the accumulated oil yield ranged from 16.1 $t.ha^{-1}$ for the lowest density (780 $trees.ha^{-1}$) to 29.9 $t.ha^{-1}$ for the highest one (2254 $trees.ha^{-1}$). In addition, they observed that the accumulated production per unit surface area showed a better correlation with the hedgerow length than the tree density. Thus, the current planting designs of SHD olive orchards can be further improved taking this parameter into account. Despite other studies observed some irregular patterns of crop distribution, their olive hedgerows were still fully productive after 14 years of planting. This result contradicts previous experiences that showed declines in production seven or eight years after planting due to high vigor, shading, and limited ventilation, and suggests that plant competition is not compromising tree development at the SHD used in the studied orchards.

Recently, it has been reported a high variability on the initial growth of one-year-old potted plants of "Picual" when grafted with a collection of wild genotypes (Díaz-Rueda et al., 2020). Nevertheless, there are a wide range of traditional cultivars that, although not suitable for high-density orchards due to their high vigor, could have other characteristics such as high oil content or high oleic acid in oil that, together with their adaptation to different agro-climatic conditions, could make them very interesting for being used in breeding programs for hedgerow plantations (Navas-López et al., 2019; 2020). The shortage of traditional cultivars to be used in SHD hedgerow systems is mainly due to the heterozygosity of this species, which produces a high variability on the breeding crosses making it difficult to find a genotype having all the desirable traits; and to the extended juvenile period of olives that makes the breeding selection process very long. These factors have hampered the obtaining of new cultivars through the combination of good adaptation to SHD with other traits such as oil quality or resistance to pests and diseases. As a result, looking for dwarfing rootstocks that could reduce the canopy vigor of some traditional cultivars, so that they could fit in to the modern hedgerow olive orchards, would be of great interest for this emerging olive growing system. This would allow having a wide range of olive cultivars able to be planted in hedgerow orchards and the ability to design multi-varietal orchards. This could have many advantages such as the production of olive oils with a wide range of composition and organoleptic properties (Navas-López et al., 2020) and different sources of resistance to pests and diseases (Fernández-Escobar et al., 2013). Other advantages of the availability of a wider range of olive cultivars would be the possibility of combine pollinators and a higher efficiency in the use of machinery related to a potential lengthening of the harvest period.

Uncontrolled tree vigor is a major problem in SHD orchards (over 1500 trees ha^{-1}) where local conditions can allow it (Trentacoste et al., 2019). An excessive growth of the canopy produces difficult mechanical harvesting (Lo Bianco et al., 2021) and a reduction of the long-term orchard productivity life from mutual shading problems which conduct to an irregular distribution of the incident solar radiation into the canopy (Connor et al., 2014). In dry areas where water is scarce, a deficit irrigation strategy is needed, specially under future climatic predictions (Galindo et al., 2018). Besides the substantial water savings that can be achieved using deficit irrigation strategies (Ben-Gal et al., 2021), they could help to control excessive vegetative growth. This is the case of regulated deficit irrigation, one of the most effective deficit irrigation strategies for SHD orchards (Fernández-Escobar et al., 2013). Regulated deficit irrigation can help to reduce the problem of excessive growth because it consists of replacing the crop evapotranspiration in the phases of the growing cycle when the crop is most sensitive to water stress, especially vegetative growth, and reducing irrigation for the rest of the cycle (Chalmers et al., 1981). In olive, the irrigation periods coincide partially with the periods of maximum rate of both vegetative growth and fruit growth and ripening, reducing the resource competition at critical stages (Connor & Fereres, 2010).

The use of different irrigation levels to modify the growth patterns of aboveground organs (leaves, trunks, fruits) through the control of photosynthesis limitation may constitute a tool to avoid excessive vegetative biomass production and optimize reproductive growth (Connor et al., 2014), saving a considerable amount of water. With this in mind, Hernandez-Santana et al. (2017) conducted a study using four irrigation treatments in a SHD olive orchard: a full irrigation treatment (control) and three regulated deficit irrigation treatments with increasing levels of water reduction scaled to replacing 60%, 45% and 30% of the irrigation needs. The plant water stress produced by the regulated deficit irrigation reduced photosynthesis, which resulted in a significant decline of leaf area. At the same time in their study neither the single fruit weight nor the total fruit yield (normalized by leaf area) was adversely affected by the regulated deficit irrigation. They found significant and positive relationships between photosynthesis and leaf area, and between leaf area and fruit yield. These authors concluded that while leaf area is mainly determined by photosynthesis, fruit yield is mostly determined by leaf area. Finally, they emphasized that photosynthesis and leaf area are the main variables to control tree growth without reducing fruit yield. The lowest regulated deficit irrigation levels (30% and 45%) led to greater water savings than 60%, with a similar effect on leaf area and fruit yield. Therefore, any of their lowest irrigation strategies is preferred to achieve the best balance between crop water consumption and fruit yield (Hernandez-Santana et al., 2017). Similarly, Trentacoste et al. (2019) studied the effect of spring–early summer deficit irrigation as a tool to reduce vegetative growth and its influence on inflorescence development, oil yield, and its components. During three seasons in an olive hedgerow (cv. ''Arbosana''), they evaluated a control irrigated at 70% crop evapotranspiration over the season, and two regulated deficit irrigation treatments (50% and 30% crop evapotranspiration) during the shoot growth period (from August to January), and then 70% crop evapotranspiration until harvest (May). Hedgerows were mechanically topped and pruned annually on alternate exposures. They observed that the two regulated deficit irrigation treatments (50% and 30% crop evapotranspiration) reduced hedgerow height and width increment after hedging by 15% and 20%, respectively, compared to the control. Inflorescence structures were not affected by water deficit, but the control treatment showed on average 5.8 fruits per fruiting inflorescence, significantly higher than 2.4 fruits per fruiting inflorescence observed in the 30% crop evapotranspiration regulated deficit irrigation treatment. After the third season, the two regulated deficit irrigation treatments (50% and 30% crop evapotranspiration) were 174% and 146% more productive, respectively, than control hedgerows, where the pruned exposures showed excessive vigor with lower floral bud induction in the following seasons. Fruit size and oil accumulation were also higher in both than in control, due to greater fruit exposure to irradiance in most deficit treatments. Compared with control, the two regulated deficit irrigation treatments (50% and 30% crop evapotranspiration) allowed water savings of 17% and 35%, respectively, but 50% crop evapotranspiration was more productive and had lower alternate bearing than 30% crop evapotranspiration.

The adequacy of olive canopy dimensions for over-the-row harvesting machinery is one of the most important management practices in SHD olive orchards (Dias et al., 2018). Manual pruning performed every year can control canopy dimensions and also exposure of the tree to sunlight. An adequate balance is required between the removal of woody non-productive branches and the maintenance of a large quantity of reproductive shoots. When excessive canopy development occurs, a severe pruning intervention can be a solution to recover orchard productivity. Dias et al. (2018) studied the effects of a rejuvenation pruning of a SHD orchard with excessive canopy dimensions established in Moura, Portugal. The orchard has two densities, 1850 trees.ha^{-1} and 1250 trees. ha^{-1}, planted with six cultivars (‘’Azeiteira”, ‘’Cobrançosa”, “Cordovil de Serpa”, ‘Galega vulgar”, ‘’Redondil” and ‘’Arbequina”). The pruning was performed after eight years of the orchard establishment. It consisted of mechanically topping the canopy parallel to the ground at 2.5 m and hedging of each exposure close to the central leader of the trees, followed by a manual pruning complement to remove the remaining branches. Olive production was recovered in the second year after pruning. Both planting densities showed a non-significantly different harvested yield (4742.9 kg.ha^{-1} at 1250 trees.ha^{-1}, and 5108.9 kg.ha^{-1} at 1850 trees.ha^{-1}). The highest yield was registered in the third year after pruning (overall mean of 8138.8 kg.ha^{-1}). Arbequina showed a higher yield (6959 kg.ha^{-1}) than the other five cultivars, which did not significantly differ in their harvested yield (overall mean= 4519.3 kg.ha^{-1}). Additional research is needed to study tree responses to pruning. They will determine how hedgerow size can be maintained by horticultural practices on different cultivars and under different environmental conditions.

Conclusions

The production of assimilates and its conversion to economic yield need to be optimized through (1) finding ways to maximize light interception by trees, and (2) optimizing light distribution within the canopy and its interception by different parts of the tree so as maximize the efficiency of light interception in photosynthesis. Several studies demonstrated that photosynthetically active radiation (PAR) interception in SHD systems was significantly less than that in high-density (HD) systems. However, the former systems had a much greater spatial variation of transmitted PAR within the tree canopy than the HD systems. The much lower PAR levels under the tree rows in the SHD systems, compared to any position in the HD systems, implied greater self-shading in lower-canopy positions, despite a similar overall interception in both systems. As a result, knowing the overall PAR interception does not allow an understanding of differences in PAR distribution on the ground and within the canopy and their possible effects on canopy radiation use efficiency (RUE) and performance between different architectural systems. Other studies also determined that radiation reception also highly depends on canopy row orientation (i.e., N-S; E-W) and exposure (N-S within the E-W orientation; and E-W within the N-S orientation).

Along with the reduction of row spacing in SHD compared to HD systems, the management of orchard light interception should be taken into consideration. Interception of solar radiation and radiation distribution within the tree canopies during the orchard development are altered by increasing the planting density in a SHD system in comparison with a HD one. This allows for managing the efficiency of solar radiation used for determining the values of several morphophysiological, inflorescence, and tree traits on different production systems and positions within the tree canopy.

Table 1. Comparison of aboveground plant traits among different production systems (shading treatments, planting densities, tree row orientations and exposures) and between positions in the tree canopy (upper, lower) within each plant trait type in olive and other fruit species. Similar, higher or lower values for the plant traits among production systems or between canopy positions are indicated by the =, + or – symbols, respectively. References are provided for each comparison. It has to be noted that the results presented in the table also included the effects of cultivar, cultural practices, harvest dates, climate conditions, and/or PAR radiation intercepted by the canopy. x= Planting density any given author worked with in his/her study. ⊠= increase. 0= no effect. PAR= Photosynthetically active radiation. R/FR= red (660 nm)/far red (730 nm). LAI= Leaf area index. NA= Not Available

Tabla 1. Comparación de características aéreas de la planta entre diferentes sistemas de producción (tratamientos de sombreado, densidades de plantación, orientación y exposición de las hileras) y posiciones en la copa del árbol (superior, inferior) dentro de cada tipo de característica de la planta en olivo y otras especies frutales. Valores similares, superiores o inferiores para las características de la planta entre sistemas de producción o posiciones en la copa son indicadas por los símbolos =, + o -, respectivamente. Se proveen referencias para cada comparación. Se debe observar que los resultados presentados en la tabla también incluyeron los efectos de cultivares, prácticas culturales, fechas de cosecha, condiciones climáticas, y/o radiación PAR interceptada por la copa. x= Densidad de plantación con la que trabajó cada autor en su estudio. ⊠= incremento. 0= no efecto. PAR= Radiación fotosintéticamente activa. R/FR= rojo (660 nm)/rojo lejano (730 nm). LAI= Índice de área foliar. NA= no disponible

Abovegrund plant trait	Shading			Planting density				Tree row		Canopy position		Re-fe-ren-ce
	Tree	Leaf	Fruit	Low	Me-dium (MD)	High (HD)	Very high (SHD)	Orientation (N-S or E-W)	Exposure (E-W in the N-S orientation or N-S in the E-W orien-tation)	Upper	Lower	
Morphophysiological												

Overall PAR interception						+ or =	- or =					1
Spatial variability of transmitted PAR						-	+					
PAR levels under the tree rows						+	-					1
Self-shading in lower canopy positions						-	+					
PAR levels within the tree canopy							x			+	-	2, 3
PAR levels							x		E and S < W and N exposures for the lowest position in the canopy	Highest at the W exposure		
Fruit yield (kg ha-1)				HD > SHD=MD > LD at the end of the 6th year of study								4
Fruit number	-			NA								5; 6
Fruit size	-											
Fruit weight		-	0	Trees were 5 x 5 m apart						+	-	7
Fruit oil concentration		-	-									

PAR levels							x			+	-	2
Vegetative growth							x			+	-	
Fruit set							x			+	-	
Fruit maturity index							x			+	-	2
Fruit weight							x			+	-	
Fruit oil content							x			+	-	
				SHD < HD, MD and LD								4
Oil yield/ha				HD > MD > SHD > LD at the end of the 6th study year								
% of Flower buds							x			=		2
% of Vegetative buds							x					
% of Quiescent buds							x			= or -	= or +	
Shoot growth depression							x			= or -	= or +	

Shoot growth				x	x	x	x			+	-	4
							x			+	-	2
	-			NA								6
Leaf surface area	+											
Leaf angle insertion with respect to vertical	+											
Leaf thickness	-											

Palisade and spongy parenchyma thickness	-			NA								6
Stomatal density	-											
Net photosynthetic rate	-											
Stomatal conductance	-											
Transpiration rate	-											
Chlorophyll a, B-carotene, Lutein and pigments concentrations within the xanthophyll cycle	-											
Total bud number/shoot							x		= at the E and W exposures	= at the E-W and N expo- sures		3
							x		+ at the N than the S exposure	+ at the S exposure	- at the S exposure	

Flower bud number/shoot							x		= at the E and the W, and at the N and the S expo-sures	- at the E-W and N expo-sures	+ at the E-W and N exposures	3
							x			+ at the S exposure	at the S exposure	
Wood bud number/shoot							x		= at the E-W and N-S exposures	+ in the E and W, and the N and S exposures	- in the E and W, and the N and S exposure	
LAI							x			- at the E-W and N-S expo-sures	+ at the E-W and N-S exposures	
Canopy thickness							x		> on the S and E exposures in southern Italy			
Number of erect leaves				NA						+	-	8
Number of pendulum leaves										-	+	
Leaf inclination distributions (0-90o)										=		

R/FR ratio						+	-					9
Mean daily horizontal incident PAR						+	-					
Shoot length						x	x			+	-	
Number of nodes/shoot						x	x			+	-	
Shoot internode length						SHD > HD						
Shoot diameter						x	x			=		
Inflorescence characteristics												
Flowering intensity	-			NA								5
Inflorescence structure							x		South exposure	=		10; 11
Flower number							x					
Perfect flower proportion							x					

Inflorescence length							x		North exposure	+	-	10; 11
Node number/ inflorescence							x			+	-	
Total flowers/ inflorescence							x			+	-	
Perfect flowers/ inflorescence							x			+	-	
Ovary tissue size							x		S > N	=		
Inflorescence length ↑					x				More illuminated external than internal canopy exposures			12; 13
Flower number/ inflorescence ↑					x							
% of open flowers ↑					x							
% of viable pollen grains on flowers ↑					x							
Pollen quality ↑				NA				More [S (i.e., equator) > N] than less illuminated sites				14

Number of inflorescences							x			+	-	11
Number of fruits												
Axillary bud number/shoot												
Proportion of floral buds										=		
% inflorescen-ces bearing fruits												
Fruit number/ inflorescence												
Fruiting shoot number										+	-	
Fruiting shoot length												
Number of flowering nodes												
Ovary size												
Ovule develop-ment										=		
Tree yield				NA						+	-	15

Number of inflorescences/ twig				x						+	-	12
Number of fertile inflores-cences/twig				x						+	-	
Fruit number/ twig				x						+	-	
Fruit dry weight/twig				x						+	-	
Number of flowers/inflores-cence				x						+	-	
Number of hermaphrodite flowers/inflores-cence				x						+	-	
% pollen germi-nation							x					2
Inflorescence length							x			=		
% staminate flowers/inflores-cence							x			+	-	
Number of flowers/inflores-cence							x			- or =	+ or =	

Optimization of tree size												
Good fruit productivity										=		16
Intercepted solar radiation because of tree growth				x	x	x	x			+	-	2; 4

1 Rosati et al., 2021; 2 Dhiab et al., 2020; 3 Maldera et al., 2021; 4 Pastor et al., 2007; 5 Guerriero & Vitagliano, 1973; 6 Ajmi et al., 2018; 7 Tombesi et al., 1999; 8 Mariscal et al., 2000; 9 Ladux et al., 2023; 10 Moreno Alias et al., 2018; 11 Trentacoste et al., 2017; 12 Acevedo et al. 2000; 13 Bartolini et al., 2022; 14 Anguilar -García et al., 2018; 15 Mezghani et al., 2021; 16 Connors, 2006

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