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# Analysis of fruit and oil quantity and quality distribution in high-density olive trees in order to improve the mechanical harvesting process

Francisco J. Castillo-Ruiz, Francisco Jiménez-Jiménez, Gregorio L. Blanco-Roldán, Rafael R. Sola-Guirado, Juan Agüera-Vega, and Sergio Castro-Garcia*

*University of Cordoba, Department of Rural Engineering. Campus de Rabanales, Ctra. Nacional IV, km 396, Córdoba, Spain.*

## Abstract

Olive fruit production and oil quality distribution with respect to canopy distribution are important criteria for selection and improvement of mechanical harvesting methods. Tests were performed in a high-density olive orchard (*Olea europea* L., cv. Arbequina) in southern Spain. Fruit distribution, fruit properties and oil parameters were measured by taken separate samples for each canopy location and tree. Results showed a high percentage of fruits and oil located in the middle-outer and upper canopy, representing more than 60% of total production. The position of these fruits along with their higher weight per fruit, maturity index and polyphenol content make them the target for all mechanical harvesting systems. The fruits from the lower canopy represented close to 30% of fruit and oil production, however, the mechanical harvesting of these fruits is inefficient for mechanical harvesting systems. Whether these fruits cannot be properly harvested, enhance tree training to raise their position is recommended. Fruits located inside the canopy are not a target location for mechanical harvesting systems as they were a small percentage of the total fruit (<10%). Significant differences were found for polyphenol content with respect to canopy height, although this was not the case with acidity. In addition, the ripening index did not influence polyphenol content and acidity values within the canopy. Fruit production, properties and oil quality varied depending on fruit canopy position. Thus harvesting systems may be targeted at maximize harvesting efficiency including an adequate tree training system adapted to the harvesting system.

**Additional key words:** *Olea europaea* L.; canopy shaker; straddle harvester; trunk shaker; tree training.

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**Correspondence** should be addressed to Sergio Castro-Garcia: scastro@uco.es

## Introduction

There is currently a wide range of available production systems for olive oil with significant variation according to irrigation resources and investment level. These systems range from traditional systems with 30-173 trees/ha and yields between 1.1-4.5 t/ha to super high-density production systems with 1700-3000 trees/ha and yields between 2.7-17.5 t/ha (Vossen, 2007). In Spain, 73.5% of the olive growing surface has a plantation density <200 trees/ha, 18.4% are planted with between 200 and 1,000 trees/ha, and only 1.4% are planted using a plantation density >1,000 trees/ha (ESYRCE, 2013). Worldwide, only 80,000 ha, about 1% of the total crop surface, are planted following the super high-density model (Tous *et al.*, 2010). Fruit harvesting is the most expensive process in olive production, often representing more than 40% of the total costs (AEMO, 2010). The mechanical harvesting of olive trees is transforming the crop and producing more modern and competitive orchard models (Vieri & Sarri, 2010; Ferguson & Castro-Garcia, 2014).

High-density production systems are characterized by rectangular tree layouts and orchard densities between 150 and 800 trees/ha, which facilitates the use of machinery and harvesting operations (Rallo *et al.*, 2013). Nowadays, such production systems are among the most widely used, due to their greater profitability and ease of mechanization. High-density olive trees are harvested manually (Cicek *et al.*, 2010), as well as using trunk shakers (Castro-Garcia *et al.*, 2007), canopy shakers (Ferguson, 2006) or other integral mechanical harvesting systems (Ravetti & Robb, 2010) (see Suppl. Fig. S1 [pdf online]).

However, there is a trend towards intensifying olive orchards and the integral mechanization of harvesting (Metzidakis *et al.*, 2008). Field tests have shown that espalier training in high-density hedgerows does not reduce yield. Moreover, these orchards can be harvested using canopy contact or trunk shaker systems (Ferguson *et al.*, 2010). At the same time, varieties better adapted to high-density orchards and which have reduced vigour, such as ‘Arbequina’, ‘Arbosana’ or ‘Koroneiki’, are replacing more traditional and higher vigor cultivars (De la Rosa *et al.*, 2007; Tous *et al.*, 2007).

Orchard design together with formative pruning and tree production are key factors in the efficiency of harvesting systems (Tombesi *et al.*, 2002; Dias *et al.*, 2012). Current systems must be improved and new harvesting methods must be developed to increase the percentage of fruit harvested and reduce possible damage caused to the fruit and tree, as well as to reduce harvesting costs (Vieri & Sarri, 2010). In fact, table olive groves in California are undergoing a transformation driven by the available mechanical harvesting technologies, in order to achieve harvester efficiency of around 80% and to improve the economic sustainability of the sector (Ferguson & Castro-Garcia, 2014). Although no harvest system is capable of collecting 100% of the fruit from the tree, machine design should always take into account the need to maximize harvest efficiency and obtain the best quality olive oils.

Traditionally, olive trees have been trained based on the requirements of manual harvesting. In traditional olive orchards, pruning for manual harvesting has shown that the poorest quality fruits are produced at the lower and inner areas of the canopy, which are close to the ground, thick and receive little sunlight (Ortega Nieto, 1969). However, fruits obtained from better-lit areas are of better quality, larger and have a higher oil yield (Acebedo *et al.*, 2000). Similar results have been reported in citrus orchards (Whitney & Wheaton, 1984). Orchard intensification would give rise to shading problems that affect oil quantity and quality (Connor, 2006). By increasing the canopy volume of the orchard (from 8,000 to 12,000 $m^3$/ha), the most productive area of the canopy is at the top of the trees, which receives the most sunlight (Pastor Muñoz-Cobo & Humanes Guillén, 2010). However, canopy volume regulation by manual or mechanized pruning is necessary in order to allow mechanical harvesting and to produce marketable harvests (Ferguson & Castro-Garcia, 2014).

The location of the fruit in the canopy directly affects olive oil composition and quality (Gómez-del-Campo *et al.*, 2009), although its effect is less evident with respect to the sensory attributes of the oil (Gómez-del-Campo & García, 2012). Olive oil acidity and total phenol content is affected by the ripening stage, although acidity does not show statistical differences (Gutierrez *et al.*, 1999). However, fruit canopy position strongly affects the efficiency of the harvesting system used, although the row or direction in which the tree faces is less significant for mechanical harvesting. Canopy shape becomes important in facilitating access to the most numerous fruits with the best quality of oil.

This study aims to enhance the mechanical harvesting process for high-density olive orchards. Fresh weight, oil content, fruit retention force, ripening index and detachment force of fruits were selected as important parameters in terms of enhancing the harvest efficiency of mechanical harvesting technologies and were analysed at different canopy positions. Oil acidity and polyphenol content were also studied. It is within the scope of this study to establish criteria for olive training and adaption to commercial harvesting technologies. In this process, crop mechanization usually tends to be a two-stage process: first crops are adapted to the harvester and then the harvester is adapted to the crop (Gil-Ribes *et al.*, 2014).

## Material and methods

The tests were performed in a commercial high density orchard of *Olea europaea* L. cv. Arbequina in Cordoba, southern Spain (37.648890 N, -4.731579 W) during the third week of December 2011 and the last week of November 2013. The orchard was in good phytosanitary condition and had irrigation. Fruits were harvested within the appropriate harvest period (Wiesman, 2009), which occurs when the fruit is yellowish but less than half of the fruit epicarp has become purple. Both test years produced yields of 10,000-12,000 kg/ha. Trees were 10-12 years old, vase-shaped, with two or three main branches and a 0.8 m-high trunk, and planted at 7 × 5 m spacing (285 trees/ha). The mean tree height remained constant at 3.2 m although mean canopy volume increased from 11.7 $m^3$ in 2011 to 12.6 $m^3$ in 2013. The same 12 trees were selected in both harvesting seasons to perform the tests. The chosen sample size was intended to restrict data scatter and to avoid bias by obtaining a representative sampling plot.

Each tree canopy was divided into four areas according to the height from the ground: fruits on the ground; lower canopy, < 1.0 m; middle canopy, 1.0-2.2 m; upper canopy, 2.2-3.2 m. Fruit position in terms of depth inside the tree canopy was also considered and divided into two groups: outer canopy, which was the first 0.5 m measured inwards from the external canopy surface, and inner canopy, including the rest of the canopy. The outer area of the canopy encompasses the lower, middle and upper locations. Figure 1 shows the canopy locations studied. Any fruit that had fallen to the ground prior to harvesting due to natural causes was also included in the study. Fruit was harvested separately from each canopy volume studied.

Fruit detachment force was determined for 30 randomly selected fruits from each location, using a dynamometer (Correx, Haag-Streit, Switzerland) adapted for this purpose, with a range of 1-10 N and 0.2 N accuracy. The fruits from each location were then harvested and weighed. For each location and tree, three fruit samples were taken in order to determine the study parameters, two of which related to chemical properties (oil, acidity and polyphenol content) and the other to weight and maturity measurements. Fruit weight and level of maturation were obtained from a randomly-taken sample of 100 healthy fruits. The level of olive maturation was calculated according to the ripening index using the Jaen method (García *et al*., 1996; Uceda & Hermoso, 1998), according to Eq. [1]:

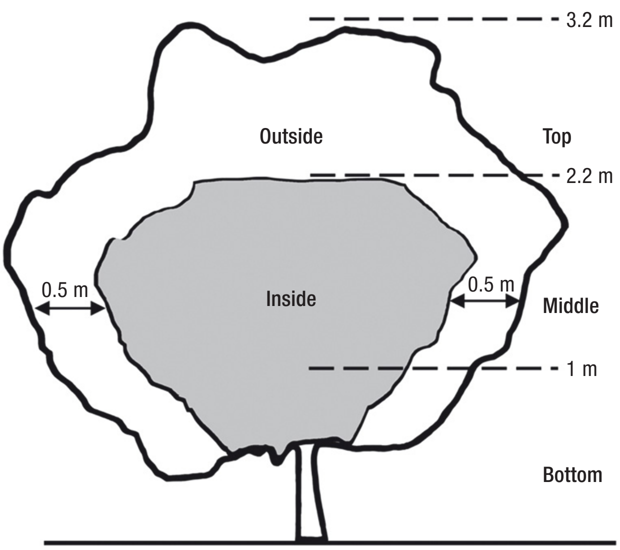


**Figure 1.** Olive tree canopy locations according to height and canopy depth.

$$Ripening\ index = \frac{\sum(RS \cdot n)}{100} \qquad [1]$$

where, *RS* is the value of each ripening stage for each fruit evaluated, according to Jaen ripening index (Uceda & Frías, 1975) (see Suppl. Table S1 [pdf online]) and *n* is the number of fruits classified in each *RS* from each canopy location and tree.

The analysis of the properties of the fruits and oil was performed at the *Laboratorio Agroalimentario*, Córdoba, Spain. There, the olive samples were pressed, cold-centrifuged and filtered. Fat acidity was determined using acid-base titration according to the official method described in OJ (1991). Oil content (%) was measured in wet samples by nuclear magnetic resonance contrasted with the Shoxlet method. Afterwards, the samples were oven-dried to determine percentage humidity (%). Total polyphenol content was determined with a spectrophotometer using caffeic acid as the reference (Ayton *et al*., 2007).

## Results and discussion

Tree growth between harvest seasons (2011 and 2013) was mainly reflected in an increase in trunk diameter. Canopy volume and tree height also increased but did not show significant differences due to the biennial pruning carried out in an off year (Table 1). Harvesting dates produced differences in the characteristic parameters of olive fruit and oil, as shown in Tables 2 to 4.

### Detached fruit before harvesting

The fruit which had fallen to the ground before harvesting represented a mean value of only 2.6% of tree production, showing similar values to those reported by Tous *et al*. (1995) for this cultivar just before harvesting. Differences between harvesting seasons are due to the percentage of fruits which had a fruit detachment force of less than 3 N. In the 2011/12 harvesting season, this figure was 41.8 ± 14.4% and 34.4 ± 13.6% for the 2013/14 harvesting season (mean ± SD). Fruit fallen to the ground was explained by the percentage of fruits that exhibited fruit detachment force levels under 3 N, as well as by the ratio between fruit detachment force and fruit weight, which was around 2 N/g in both harvesting seasons predicting an adequate fruit removal percentage (Farinelli *et al.*, 2012a). This fruit quantity varied between harvesting seasons, depending on the harvest dates, phytosanitary state of the tree and meteorological conditions (Barranco *et al*., 2010). Normally, farmers harvest the tree before an excessive amount of fruit falls

**Table 1.** Tree harvesting parameters (values are means, standard deviation in parenthesis) for both harvesting seasons

| Harvesting season | Trunk diameter (cm) | Canopy volume ($m^3$) | Tree height (m) | Yield § (kg/tree) | Ripening index |
|---|---|---|---|---|---|
| 2011-12 | 12.97 (0.76) b | 11.69 (2.35) a | 3.18 (0.23) a | 38.38 (4.32) a | 2.85 (0.54) a |
| 2013-14 | 13.61 (0.62) a | 12.56 (2.06) a | 3.26 (0.20) a | 39.78 (5.20) a | 1.63 (0.26) b |

§ Yield calculated including fallen fruits. Between the two tested harvesting seasons, values in the same column followed by the same letter are not significant different at $p \leq 0.05$ based on paired Student's T test.

**Table 2.** Production of olive fruit and oil in each tree canopy location for the two considered harvesting seasons. Values are means; standard deviations in parenthesis

| | Fruit position | Samples per season (No.) | Fruit (%) | | | Oil (%) | | |
|---|---|---|---|---|---|---|---|---|
| | | | 2011-12 | 2013-14 | Mean | 2011-12 | 2013-14 | Mean |
| | Ground | 12 | 3.3 (0.8) | 1.9 (0.5) | 2.6 (1.0) | 3.5 (1.0) | 2.1 (0.5) | 2.8 (1.0) |
| Canopy height [1] | Top | 12 | 14.9 (4.9) c | 19.5 (4.5) c | 17.2 (5.1) c | 16.5 (5.2) c | 20.8 (4.9) c | 18.7 (5.4) c |
| | Middle | 12 | 44.3 (4.4) a | 45.6 (5.8) a | 44.9 (5.1) a | 44.4 (4.2) a | 45.3 (5.6) a | 44.8 (4.9) a |
| | Lower | 12 | 28.2 (5.2) b | 24.1 (5.9) b | 26.1 (5.8) b | 26.9 (4.8) b | 23.3 (5.9) b | 25.1 (5.5) b |
| Canopy depth [2] | Outside | 36 | 87.4 (3.6) a | 89.2 (2.7) a | 88.3 (3.2) a | 87.8 (3.5) a | 89.5 (2.8) a | 88.6 (3.2) a |
| | Inside | 12 | 9.3 (3.6) b | 8.9 (2.6) b | 9.1 (3.1) b | 8.7 (3.5) b | 8.4 (2.7) b | 8.5 (3.1) b |

[1] In these fruit positions, values in the same column followed by the same letter are not significant different at $p \leq 0.05$ based on Duncan's multiple range test. [2] In these fruit positions, values in the same column followed by the same letter are not significant different at $p \leq 0.05$ based on Student's T-test.

**Table 3.** Distribution and characteristics of olive oil parameters according to tree canopy position for both harvesting seasons. Values are means; standard deviations in parenthesis

| | Fruit position | Oil content (% fresh weight) | | Acidity (%) | | Polyphenol content (mg/L) | |
|---|---|---|---|---|---|---|---|
| | | 2011-12 | 2013-14 | 2011-12 | 2013-14 | 2011-12 | 2013-14 |
| | Ground | 26.7 (1.8) | 23.1 (0.1) | 4.1 (0.93) | 4.4 (2.30) | 100.0 (12.9) | 95.9 (2.2) |
| Canopy height [1] | Top | 27.9 (1.1) a | 22.2 (1.3) a | 0.23 (0.06) a | 0.42 (0.19) a | 348.5 (25.3) a | 356.5 (62.4) a |
| | Middle | 25.2 (0.7) b | 20.7 (1.0) ab | 0.27 (0.07) a | 0.51 (0.31) a | 364.5 (29.7) a | 344.7 (107.0) ab |
| | Lower | 24.0 (1.0) c | 20.1 (0.8) b | 0.26 (0.05) a | 0.48 (0.19) a | 292.3 (46.3) b | 282.8 (108.9) b |
| Canopy depth [2] | Outside | 25.7 (1.2) a | 21.0 (1.4) a | 0.25 (0.06) a | 0.47 (0.24) a | 332.4 (47.5) a | 328.0 (98.1) a |
| | Inside | 23.3 (1.1) b | 19.5 (1.6) b | 0.18 (0.06) b | 0.35 (0.15) a | 314.1 (67.0) a | 305.6 (86.7) a |

[1] In these fruit positions, values in the same column followed by the same letter are not significant different at $p \leq 0.05$ based on Duncan's multiple range test. [2] In these fruit positions, values in the same column followed by the same letter are not significant different at $p \leq 0.05$ based on Student's T-test.

**Table 4.** Distribution and characteristics of olive fruit parameters according to tree canopy position

| | Fruit location | Fruit detachment force (cN) [1] | | Fruit detachment force / Fruit fresh weight (cN/g) [1] | | Fruit weight (g per 100 fruits) | | Ripening index [2] | |
|---|---|---|---|---|---|---|---|---|---|
| | | 2011-12 | 2013-14 | 2011-12 | 2013-14 | 2011-12 | 2013-14 | 2011-12 | 2013-14 |
| | Ground | – | – | – | – | 130.2 (12.7) | 128.5 (6.8) | 5.1 (0.3) | 2.5 (0.2) |
| Canopy height [3] | Top | 363 (45) a | 333 (31) ab | 186.6 (23.3) b | 222.6 (19.9) b | 168.6 (12.2) a | 150.8 (16.4) a | 4.3 (0.6) a | 2.1 (0.4) a |
| | Middle | 292 (37) b | 317 (36) b | 194.8 (30.1) b | 236.1 (23.9) b | 151.8 (11.4) b | 135.2 (16.2) b | 2.9 (0.7) b | 1.7 (0.3) b |
| | Lower | 320 (41) b | 340 (18) a | 224.1 (29.5) a | 263.5 (35.1) a | 142.5 (8.7) b | 130.6 (15.9) b | 2.3 (0.6) c | 1.4 (0.4) b |
| Canopy depth [4] | Outside | 315 (26) a | 309 (21) a | 201.8 (31.6) b | 240.7 (31.4) a | 154.3 (15.2) a | 138.9 (18.0) a | 2.6 (0.5) a | 1.5 (0.2) a |
| | Inside | 279 (33) b | 291 (16) b | 274.9 (61.2) a | 230.5 (26.4) a | 134.1 (15.0) b | 135.7 (17.3) a | 2.4 (0.5) a | 1.5 (0.2) a |

[1] Each value for these parameters is the mean value of 20 determinations. [2] Each value for this parameter is the mean value of 100 determinations. [3] In these fruit positions, values in the same column followed by the same letter are not significant different at $p \leq 0.05$ based on Duncan's multiple range test. [4] In these fruit positions, values in the same column followed by the same letter are not significant different at $p \leq 0.05$ based on Student's T-test.

to the ground. The cost of harvesting fruits from the ground is higher than fruit harvested from the tree canopy and in some cases these fruits are not worth collecting. The fruit on the ground presented acidity values from 9 to 21 times higher and polyphenol content values about 3 times lower than the fruit from the canopy (Table 3). Although harvesting fruit from the ground increases the quantity of fruit harvested, there is a decrease in quality, which is why ground fruits are usually harvested and processed separately.

## Fruits from inner canopy position

The fruits from inner canopy position (>0.5 m from the canopy exterior) represented 9.1% of tree production and 8.5% of olive oil production (Table 2). These fruits are relatively difficult to reach with manual harvesting systems and canopy contact systems. This is a particular problem when the canopy volume is high and reduces the efficiency of these harvesting methods (Ferguson *et al*., 2010).

The growth of new shoots on the olive tree provides a potential reproductive site and photosynthetic surface, but flowering, and therefore production, is also influenced by previous bearing (Castillo-Llanque & Rapoport, 2011). In particular, the production of fruits of 'Arbequina' is highly influenced by the most sunlit areas. Accordingly, the interior and lower areas of the tree showed fewer inflorescences per twig than the other locations of the tree (Acebedo *et al*., 2000). Therefore, vase-shaped trees with open centres favour fructification on the inner canopy areas, unlike more intensive hedgerow systems, with low canopy porosity (Connor *et al*., 2009). The lower intercepted radiation inside the canopy played a key role in producing smaller fruits on the inner and lower canopy (134.9 and 136.6 g per 100 fruit, respectively), which also have a lower fat content (21.4% and 22.1%, respectively) than other fruits in the tree canopy (Connor *et al*., 2009). However, these differences between canopy locations and tree orientations can be mitigated as the fruits can attract assimilates from other better-lit areas during development (Proietti *et al*., 2006). Similar differences were reported by Acebedo *et al*. (2000) with respect to the oil content of dry matter according to fruit location. Previous research performed by Pastor Muñoz-Cobo & Humanes Guillén (2010) points out the differences with inner fruits with regard to their size and fat content when located at heights of less than 2 m off the ground. Although reduced fruit weight is one of the factors limiting shaker efficiency (Kouraba *et al*., 2004), the inner fruits presented the lowest mean fruit detachment force values in each harvesting season (279 and 291 cN, respectively), a parameter that facilitates their removal by vibration. However, harvesting efficiency is also dependent on the ratio between fruit detachment force fruit and fresh fruit weight (Farinelli *et al.*, 2012b). Measured values were higher in the 2013/14 harvesting season, and within the canopy, values were significantly higher on lower branches; that, along with vibration transmission, could explain why it is more difficult to detach fruits from lower branches. Inner and outer canopy fruits showed opposite trends in the two years under study. In other fruit crops, such as vase-shaped sweet cherry trees with open centers, the inner fruits are located on high and elongated branches, where the vibration energy is amplified, thus improving the harvest efficiency of the fruits with trunk shaker systems (Du *et al*., 2012). Pastor Muñoz-Cobo & Humanes Guillén (2010) showed that trunk shaker efficiency in fruit removal increased by up to 16% when moving from branches with an incline of 48 degrees to vertical branches. Tree pruning can improve harvest efficiency with trunk shakers; severe pruning is useful in reducing canopy density, increasing the unit weight of the fruits and providing a regular distribution of fruiting shoots (Tombesi *et al*., 2002).

Results showed that fewer fruits were harvested from inside the canopy in high-density orchards and these fruits have a reduced fat content. Consequently, the harvesting of these fruits is not a priority in the design and use of harvesting systems based on canopy shakers or manual equipment. However, fructification inside the canopy is not a limiting factor for trunk shaker efficiency.

## Fruits from outer canopy positions

The acidity values of the fruits from outer canopy positions presented no significant differences compared to inner positions. The mean acidity value was 0.23% for the 2011-13 harvesting season, and it was 0.44% for the 2013-14 harvesting season, almost double than the mean value in the previous harvesting season. These are typical values for fruits with no mechanical damage and which are free from disease or plagues that would otherwise affect their quality (Yousfi *et al.,* 2006). No significant differences in acidity were found between the different canopy areas except in the 2011/12 harvesting season, when acidity values were higher for fruits from outer canopy positions. The ripening index, however, did register significant differences in both years and so we can state that ripening process was not a determinant factor for oil acidity.

There were no significant differences in terms of polyphenol content between fruits from inner and outer canopy positions. However, the two harvesting seasons under study did not produce the same polyphenol pattern and the content varied. As reported by Tovar *et al.* (2002), polyphenol content shows a positive linear correlation with the L-phenylalanine ammonia-lyase activity, which decreases over the course of the ripening process. Polyphenol oxidase activity also increases in riper fruits (Ortega-García *et al.*, 2008). For this reason, the polyphenol content in the 2013/14 harvesting season could be slightly lower than in the 2011/12 harvesting season. However, in the interior of the tree canopy the opposite relationship between polyphenol content and fruit ripening stage was observed for the same harvesting date (Tables 3 and 4).

The fruits from lower canopy positions represented approximately a quarter of tree fruit production (26.1%) and oil content (25.2%). Unlike the fruits inside the canopy, the lower fruits presented a higher fruit detachment force (330 cN). In addition, the position of these fruits on outer pendulous branches, where the vibration must travel a longer distance from the trunk and there is an increase in damping, make fruit removal with trunk shakers difficult (Castro-Garcia *et al.*, 2008) and also presents a problem when using catching frames. The harvest efficiency of these fruits is reduced if the branches make contact with the catching frame and they may even restrict its movement. Shaking technology, whether it is hand-held, tractor-mounted, or self-propelled requires skirt pruning for trunk or branch access (Ferguson, 2006). The reduction of canopy skirts is recommended when using trunk shakers, in order to increase harvesting efficiency. This area, however, contains a large quantity of fruit. Similarly, skirt pruning is important when using straddle harvesters (Suppl. Fig. S1-D [pdf online]). With canopy shaker systems, most of the fruits remaining on the tree after harvest (1.4%) are concentrated on the canopy skirts because they are not accessible to the machine (Ravetti & Robb, 2010).

The outer fruits located at heights of between 1 and 2.2 m from the ground represent almost half of the fruit and oil produced by the tree (44.9% and 44.8%, respectively). The fruits in the middle of the canopy presented a low fruit detachment force (from 292 to 317 cN), exhibiting less fruit retention than the fruits at the top of the tree. The ripening index of the fruits located in the middle was greater than the fruits from the lower canopy but less than fruits from the upper canopy. In super high-density olive orchards (tree distance 3.5 × 1.5 m), the majority of the fruits (>95%) are located between 1.5 and 2.25 m from the ground (Pastor Muñoz-Cobo & Humanes Guillén, 2010); showing intense bud initiation at the higher levels (Gómez-del-Campo *et al.*, 2009). These differences are less marked in high-density olive orchards, where 62% of the fruits are concentrated above a height of 1.5 m, exhibiting an increase in fat content and fruit unit weight as their height on the tree increases (Pastor Muñoz-Cobo & Humanes Guillén, 2010).

The fruits from the upper canopy presented a higher value for fat content as a percentage of total wet matter and higher polyphenol content compared to the lower and middle canopy. However, fruit accessibility and detachment from the middle of the canopy, as well as fruit quantity and quality, make these fruits a priority for any efficient mechanical harvesting system. In fact, the straddle harvester easily removes the fruits from this position, with only 0.7% of the production left on the tree (Ravetti & Robb, 2010).

The fruits from the upper canopy position were characterized by the highest weight and ripening index values, as well as oil and polyphenol content. These fruits represented 17.2% of the fruit on the tree and 18.7% of the oil (close to double the oil from inner canopy fruits). Furthermore, this difference can quadruple in the case of super high-density olive orchards (Acebedo *et al.*, 2000). The fruits from the upper canopy presented a higher fat content as a percentage of total wet content than at other canopy heights, and medium polyphenol content. Even though the harvesting of upper fruits may not be a priority in terms of increasing harvest efficiency, it should be targeted as a way of increasing harvested oil quality, considering that these fruits increase the polyphenol content of the harvest. In studies performed on 'Arbequina' hedgerows, fruit maturity and size were greater in the upper layers while oil content increased by nearly 50% from the lower to upper layers (Gómez-del-Campo *et al.*, 2009).

The position of the upper fruits (between 2.2 and 3.2 m from the ground) makes these fruits difficult to harvest with manual systems. It is also difficult for canopy shakers to reach these fruits due to their upper canopy position and the lack of foliar mass necessary for the shaking to detach the fruit. Canopy shakers are more effective on farms with orchards that have a good level of vegetative development and a high level of production (Ravetti & Robb, 2010). A high fruit detachment force makes fruit detachment even more difficult. However, trunk shakers could remove the fruits borne on the upper canopy, as they are located on high and elongated branches, exhibiting a principal vibratory transmission path from the trunk to the fruit-bearing branch (Du *et al.*, 2012). Finally, annual pruning of the upper canopy is recommended to increase and facilitate the mechanical harvesting efficiency, whether trunk- or canopy-contact technology are used (Ferguson & Castro-Garcia, 2014).

In summary, fruit and oil quality distribution varied according to the position of the fruits in the olive tree canopy, although further research is needed in order to extend the results to other varieties and locations. Fruit quality properties varied to a lesser extent with respect to the tree canopy height, because only polyphenol content showed significant differences. The outer middle and upper tree canopy held more than 60% of the production, which makes these areas a priority for any mechanical harvesting system. Although the fruits from the lower canopy represented close to a quarter of the fruit and oil production, pruning of this area could be recommended due to its low harvest efficiency with all harvesting technologies except hand held. This could be improved with different tree training, lengthened trunk height or, for trees that have already been planted, the lower canopy may be pruned to the extent that it affects the harvester performance. The fruits from an interior canopy position are not an important objective due to their small quantity (>10%) and difficult access. In any case, all oil obtained from different canopy positions achieved the extra virgin olive oil requirements based on acidity. The adaptation of each mechanical harvesting system and tree training are necessary to achieve an efficient and quality harvest.

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