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Suitability of Two Table Olive Cultivars ('Manzanilla de Sevilla' and 'Manzanilla Cacereña') for Mechanical Harvesting in Superhigh-density Hedgerows

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***Abstract*. At a time of increasing demand, the extremely high cost of manual labor required to harvest fruit in table olive groves is limiting the economic survival of the crop in many producing countries. New grove designs and management practices such as superhigh-density (SHD) groves now in use in oil olive production should be explored as an option to facilitate mechanical harvesting in table olives. The feasibility of two table olive cultivars, Manzanilla de Sevilla and Manzanilla Cacereña, to be harvested in a 5-year-old SHD grove (1975 trees/ha) was studied in 2012 when trees of both cultivars formed highly productive continuous hedgerows (≈10,000 and 18,000 kg·ha^{-1}, respectively). The differences between manual and mechanical harvesting using a grape straddle harvester were evaluated taking into consideration harvesting time, efficiency in fruit removal, and fruit quality both before and after processing as Spanish-style green olives. The average harvest time per hectare with a grape straddle harvester was less than 1.7 hours compared with 576 person/hour or more when done manually. Fruit removal efficiency was high in both cases, 98% for mechanical treatment and 100% for hand treatment. Mechanically harvested fruits had a high proportion of bruising damage (greater than 90%) and the severity of the damage was greater in 'Manzanilla de Sevilla' than in 'Manzanilla Cacereña'. After Spanish-style green processing, however, the proportion of bruised fruits was below 3% in each cultivar. The fruit size in both cultivars was suitable for table olive processing and only 7% and 4% of 'Manzanilla de Sevilla' and 'Manzanilla Cacereña' fruits, respectively, were diverted to oil extraction as a result of insufficient size. Small differences were found between processed 'Manzanilla Cacereña' fruits that were manually or mechanically harvested. In contrast, mechanically harvested 'Manzanilla de Sevilla' fruits showed a significantly higher proportion of cutting (18%), a type of damage that may take place during harvesting, and lower firmness and texture than those harvested manually.**

Table olives are deeply rooted in the Mediterranean culture and diet and recent data confirm the expansion of this sector. Worldwide production in 2011–12 was 2,432,500 t with an 82% increase in the last decade; consumption was 2,562,000 t and also increased by 78% over the same period. Spain, Turkey, Egypt, and Syria, in this order, are the major producing countries of table olives, accounting for 61% of the total production, whereas Turkey, Egypt, Spain, and the United States are the major consumers, representing 42% of total consumption. Exportations represent 27% of total production with Spain as the main exporter followed by Argentina and Egypt (International Olive Council, 2013). Large size, high pulp-to-pit ratio, low oil content, and adequate color, shape, and texture in fruits that release the pit easily are usually requested by both the consumer and processing industries (Garrido-Fernandez et al., 1997). Moreover, olives are particularly rich in monounsaturated fatty acid, phenolic compounds, triterpenoids, sugars, and vitamin E (Rallo et al., 2011), and their nutritional quality has been recently rediscovered because there is a close relationship between the consumption of most of these compounds and the lower incidence of several human diseases such as inflammatory processes, some cancers, etc. (Kountouri et al., 2009).

Reducing labor costs in table olive groves has become a priority in many traditional producing countries because fruits are usually harvested by hand, accounting for as much as 69% of the total direct eligible costs. This has led to the removal of a considerable number of olive groves and to the development of mechanical harvesting methods in traditional table olive farms (Ferguson et al., 2010; Rallo et al., 2013a, 2013b). 'Manzanilla de Sevilla' is the leading Spanish table olive cultivar and is grown worldwide (Spain, the United States, Portugal, Israel, Argentina, etc.). In Spain olives are mostly picked at the beginning of ripening for Spanish-style green processing, whereas in the United States, fruits are picked at veraison for black-ripe processing. 'Manzanilla Cacereña' is cultivated in Spain and Portugal, where it is also known as 'Azeiteira', 'Azeitineira', and 'Negrinha' (Barranco et al., 2005). The fruits are slightly smaller than 'Manzanilla de Sevilla' and their texture is also slightly coarser, but once processed, they have a characteristic taste that makes them highly demanded in the table olive market, particularly when black-ripe processed (Garrido-Fernandez et al., 1997).

Mechanical harvesting in current table olive groves is performed mainly by trunk shakers or canopy contact harvesters and has several difficulties, particularly fruit bruising and low fruit removal efficiency (Castro-García et al., 2012; Ferguson et al., 2010). Fruit bruising is the most limiting factor and can affect up to 90% of the olives, depending on the cultivar, thus reducing the quality of the processed fruit (Jiménez et al., 2011). It usually occurs when olives impact each other or on a hard surface (Jiménez-Jiménez et al., 2013; Segovia-Bravo et al., 2011). This damage can be drastically reduced by transporting the fruits in dilute sodium hydroxide solutions, although this requires the appropriate equipment (Rejano et al., 2008). Low fruit removal efficiency is usually related to fruit retention force, something that also depends on cultivar. This force is greater in green than in fully ripe fruits and therefore more energy is required to detach the former (Castro-García et al., 2012; Ferguson et al., 2010). The efficiency of trunk shakers and canopy contact harvesters is not usually greater than 80% and 90%, respectively (Castro-García et al., 2009, 2012). The application of various fruit abscission products has been proposed before mechanical harvesting in table olive groves, but results for their commercial use are not satisfactory (Burns et al., 2008; Zipori et al., 2014).

Ferguson et al. (2010) suggested hedgerows of a limited width and height as the means of increasing mechanical harvesting efficiency and decreasing fruit damage when olives fall to the ground in a table olive grove. Hedgerow groves with high density (≈250 to 500 trees/ha) are common in table olive. SHD

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(≈1500 to 2000 trees/ha) layouts have not been explored yet and, thus, there is no literature concerning the production or harvesting of table olives in SHD groves. This system was developed in Spain in the 1990s and nowadays it has become a viable alternative for olive oil production not only in Spain, but also in new olive production areas (Chile, Australia, South Africa, the United States, etc.) (Connor et al., 2014; Rius and Lacarte, 2010). The groves are designed for full mechanization of harvest by using over-row canopy contact harvesters adapted from grape straddle harvesters, most of which are self-propelled. To remove the fruit, these machines use contact rods that shake the canopy. As they progress, the machines' lateral movement shakes the shoots and smaller branches. Harvesting efficiency is usually high (95%). Mechanical harvesting by grape straddle harvesters usually involves a dramatic decrease in the both labor costs and time used. However, most current cultivars are not suitable for SHD hedgerow cultivation as a result of the high vigor. This hampers the harvester's movement because the most common machines are no more than 3.5 m tall. Early-bearing cultivars with compact trees as well as consistent annual yields are also necessary to rapidly recover the high establishment costs of SHD groves (Connor et al., 2014). Susceptibility to fruit damage may also be an obviously possible limitation to be taken into account with regard to table olive production. Direct contact of the fruit with the rods can cause damage, which seems to increase as firmness decreases during maturation (Camposeo et al., 2013).

Given the need to explore new designs and management for table olive groves to increase mechanical harvesting efficiency and to satisfy demand, the aim of this study was to evaluate the potential of mechanically harvesting two table olive cultivars ('Manzanilla de Sevilla' and 'Manzanilla Cacereña') cultivated in SHD groves using a grape straddle harvester.

Material and Methods

Grove description. The field experiment was carried out in Sept. 2012 in a grove located in Elvas (Portugal) (long. 38°56′ N; lat. 7°02′ W; altitude 201 m) with 5-year-old 'Manzanilla de Sevilla' and 'Manzanilla Cacereña' (*Olea europaea* L.) hedgerows with a space of 3.75 m between rows and 1.35 m within rows (1975 trees/ha) in a north–south orientation. The area is characterized by a Mediterranean climate with an average annual rainfall and reference crop evapotranspiration of 516.4 mm and 1296.5 mm, respectively. Effective soil depth of the grove was 0.6 m. The soil was a loam with pH 7.4. Trees were irrigated from March to October with 280 mm of water. The irrigation system consisted of one drip line per tree row with two 2.43 $L \cdot h^{-1}$ compensating drippers per tree, 0.60 m apart. Trees were fertilized according to foliar analyses to non-limiting nutrient conditions. Weeds were controlled by non-residual herbicides in the tree rows and natural groundcover between them. In winter, the branches growing toward the center of the rows were removed.

Before harvesting, the stem perimeter at 0.30 m, plant height and plant width at 0.80 and 1.70 m, above the ground, were determined in 40 randomly selected trees per cultivar. Three random rows of trees (≈90) per cultivar ('Manzanilla de Sevilla' and 'Manzanilla Cacereña') and per harvesting treatments (hand, in which fruits were picked by hand; and mechanical, in which trees were harvested with a grape straddle harvester) were selected for the trial.

Fruit harvest. Olives were harvested on 13 Sept. once most fruits had reached a ripening index ≈1. This index was determined according to the pigmentation extent of the epicarp and mesocarp of the olive fruits (Beltrán et al., 2008). Harvesting lasted a single day to ensure similar weather conditions for all treatments. Twelve trees per row were picked in the hand treatment, whereas in the mechanical treatment, the olive trees were harvested with a grape straddle harvester for hedgerows (Model VX 7090; CNH Global, Belgium). This model had a maximum harvesting head width of 3.22 m and ground clearance of 2.2 to 2.8 m. In this study, field tests were conducted at 480 beats per minutes and the nominal travel speed was 3.5 $km \cdot h^{-1}$.

The average time of harvest, expressed as $s \cdot kg^{-1}$, s/tree, and $h \cdot ha^{-1}$, was determined in the hand treatment by measuring the time used by five persons to pick all the fruits of four trees on each replication; in the mechanical treatment, it was obtained measuring the time needed by the grape straddle harvester to harvest a row of trees. The efficiency of mechanical harvest, i.e., fruit removal (%), was determined from the total weight of fruits that remained after harvest on 12 random trees per row.

Two samples of 50 kg and 8 kg per experimental unit were randomly selected from the harvested fruits. The first sample was immediately immersed in a 2.5% (w/v) NaOH (lye) solution previously cooled to 18 °C, and it was processed within 24 h in a table olive industrial facility located in Almendralejo (Badajoz), 60 km from the experimental grove. Several subsamples were taken from the second sample to evaluate fruit traits (weight, pulp-to-pit ratio, shape, firmness, color, moisture content, oil content, and bruising damage).

The average fruit weight (g) and the pulp-to-pit ratio were measured from samples of 0.5 kg of fruits. The pulp-to-pit ratio was determined in fresh weight as the difference between fruit and pit weights. Fruit volume (mL) was measured from the volume of water displaced on immersion of 100 fruits in a graduated beaker with water. Fruit shape was calculated from the maximum longitudinal and equatorial diameters (mm) of 50 fruits and expressed as the ratio between both traits. Color was determined on the equatorial zone of 50 fruits (two measurements per fruit), using a Minolta CM-700d (Konica Minolta Inc., Tokyo, Japan) spectrophotometer. The International Commission on Illumination color notation system (L*a*b*) was applied to determine the parameters L*, a*, and b* with L* as the lightness, a* the color axis from green to red, and b* the color axis from blue to yellow. Fruit firmness ($N \cdot cm^{-2}$) was also evaluated on the equatorial zone of the same fruits using a Zwick 3300 hand densimeter (Zwick GmbH & Co., Ulm, Germany). The consistency of each fruit was measured without rupture by pressure on a 5-mm diameter disk; two measurements per fruit were made. Oil content and moisture content (%) were determined using 100 fruits. Fruits were weighed and dried at 105 °C for 48 h, and oil content was estimated by a NMR analyser Minispec NMS100 (Bruker Optik GmbH, Ettlingen, Germany) according to Del Río and Romero (1999).

Bruising incidence (B_I) was determined at 2 and 24 h after harvest in a 100-fruit subsample. Fruits were classified in three categories according to bruising severity on the skin: non-bruised, low damage (less than 25%), and severe damage (25% to 100%) and the following equation was applied:

$$B_I = \frac{1(N_L) + 2(N_S)}{N_0 + N_L + N_S} \qquad (1)$$

with N_0, N_L, and N_S as the number of non-bruised, slightly, and severely bruised fruits, respectively. In addition, bruising damage was estimated by evaluating both the largest bruise area (B_A) and volume (B_V) in one sample of 30 fruits fixed 24 h after harvest in formalin acetic acid [95% ethanol and distilled water (10:5:50:35 v/v/v/v)] according to Berlyn and Miksche (1976). Bruise area (mm^2) and volume (mm^3) were measured according to Lewis et al. (2007). The external B_A was assumed to be elliptical and determined as:

$$B_A = \frac{\pi}{4} W_1 W_2 \qquad (2)$$

where w_1 and w_2 are the length of main axes (major and minor). B_V was calculated by the equation:

$$B_V = \frac{\pi d}{24}\left(3W_1W_2 + 4d^2\right) \qquad (3)$$

where w_1 and w_2 are the length (mm) of the main axes and d is bruise depth (mm), determined in a transversal cut made in the center of the bruised area.

Fruit processing. Fruits were processed in 50-kg capacity fermenters for Spanish-style green olives. Immediately after harvest, they were immersed for ≈7 h in a 2.5% (w/v) solution of sodium hydroxide (lye) cooled to 18 °C at the beginning of the trial. Once at the factory, they were then washed with 3.5 L water for 24 h and transferred to a brine solution (10.5% NaCl), where lactic fermentation took place at room temperature for 8 months. Measurements of salt, pH, titratable acidity, and combined acidity were performed to monitor the process. After processing, a sample of 1 kg was taken to the laboratory for determination of the average fruit color, firmness, and B_I as mentioned previously. We also measured pulp texture ($N \cdot g^{-1}$) in processed fruits with a Kramer shear compression cell with 10 blades coupled to a Texture Analyzer TA.XT.Plus (Stable Microsystems, Godalming, U.K.) with a 50-kg load cell. A force/displacement curve was logged using the system software (Texture Expert). The test speed was set at 200 $mm \cdot min^{-1}$ with an acquisition rate of 250 data points per second. Texture was the mean of 10 replicates, each using four pitted olives. To characterize fruit damage, the incidence (%) of other types of injuries such as cuts, wrinkled, and peeled fruits was also determined. Finally, a sample of 5 kg was analyzed in a MultiScan I-5 olives (MultiScan Technologies, ES) based on a color camera with a stroboscopic lighting system. This automatic device is now in use in table olive factories in many different countries for sorting the fruits (both fresh and dressed) by color, size, and defects such as fruit bruising.

Statistical analysis. Data were subjected to variance analysis to determine the effect of treatments and cultivars. When necessary, to achieve normality and homogenize the variance, data were previously transformed using the arcsin of the square root or Box-Cox power transformations (Box and Cox, 1964). Mean values of bruising incidence were calculated and contingency tables produced. All analyses were performed using StatGraphics Plus 5.1 software package.

Results

Hedgerow characteristics. The 'Manzanilla de Sevilla' trees were 2.8 ± 0.3 m tall, 2.0 ± 0.2 m wide, and had a stem perimeter of 0.2 ± 0.0 m. Corresponding values for 'Manzanilla Cacereña' were 2.4 ± 0.3 m, 1.5 ± 0.2 m, and 0.2 ± 0.0 m, respectively. Significant differences between cultivars were found in tree height.

Fruit yield and fruit traits. In 2012, when the grove was 5 years old, fruit yield was ≈ 10,000 $kg \cdot ha^{-1}$ for 'Manzanilla de Sevilla' and ≈18,000 $kg \cdot ha^{-1}$ for 'Manzanilla Cacereña' (Table 1). According to historical information concerning the commercial grove, the onset of fruit bearing took place 3 years after plantation. The mean fruit yield of both cultivars for the first bearing year was 3000 $kg \cdot ha^{-1}$, increasing to 9500 $kg \cdot ha^{-1}$ the next year.

Fruit weight, pulp-to-pit ratio, volume, shape, moisture, and oil content were not modified by the mechanical treatment. Mean values by cultivar are shown in Table 1. 'Manzanilla de Sevilla' fruits were larger and heavier than those of the 'Manzanilla Cacereña', but no differences were found in the pulp-to-pit ratio. Both longitudinal and equatorial diameters were also greater in 'Manzanilla de Sevilla', although fruit shape was spherical for both cultivars. The oil content, as expressed in fresh and dry weight, was also higher in the 'Manzanilla de Sevilla' fruits compared with those of 'Manzanilla Cacereña' and, as expected, the contrary was found for the moisture content.

Harvesting efficiency. The efficiency of harvesting was studied in terms of the time required to harvest 1 kg fruits ($s \cdot kg^{-1}$), one tree (s/tree) as well as the time to harvest 1 ha ($h \cdot ha^{-1}$). Efficiency was also studied with regard to the percentage of fruit removal (Table 2). The average time needed to harvest a tree was significantly shorter in the mechanical treatment than in the hand treatment. Significant differences were found between cultivars. The 'Manzanilla Cacereña' hedgerows required more time to be harvested, although no more than 3 s were needed by the grape harvester to harvest a single tree. This gave a harvesting time of 1.6 h to harvest a hectare. This contrasts with the 948 person/h needed in the hand treatment. With regard to the percentage of fruit removal, no differences were found between treatments or between cultivars. The grape straddle harvester removed 98% of the fruits, whereas 100% were removed by hand.

Fruit quality after harvesting. Mechanical treatment reduced firmness and color (Table 3). It also increased bruising (Table 4). Fruit firmness between cultivars was not significantly different in hand-picked fruits (97 $N \cdot cm^{-2}$) but after mechanical harvesting, it decreased a greater extent in 'Manzanilla de Sevilla' fruits (85 $N \cdot cm^{-2}$). The latter also showed lower lightness (L*) and b* values (yellowness) and higher a* values (redness). Color, in the case of 'Manzanilla Cacereña' fruits, was almost unaffected, the mechanically harvested fruits only showing a slight increase in redness.

Significant differences in fruit bruising were found between treatments and cultivars (Table 4). Two h after harvesting, hand-picked fruits showed almost 50% of damage in the case of 'Manzanilla de Sevilla' but only 9% in those of 'Manzanilla Cacereña'; in both cases, most fruits were classified as belonging to the low damage category. The mechanical treatment significantly increased damage in a higher proportion of the 'Manzanilla de Sevilla' (100%) compared with the 'Manzanilla Cacereña' (91%). Moreover, most of the 'Manzanilla de Sevilla' fruits showed severe damage, whereas those of 'Manzanilla Cacereña' had mainly suffered slight damage. Results of B_I confirm that the bruising damage, in both fruits from the hand and mechanical treatments, were more severe for 'Manzanilla de Sevilla'. Twenty-four h after harvesting, few differences were observed in B_I. The proportion of hand-picked fruits with bruising damage increased, in particular in 'Manzanilla de Sevilla' (up to 62%), although most fruits still showed low damage.

Measurements of B_A and B_V allow a better description of bruising damage (Fig. 1). Hand-harvested fruits had a B_A of ≈15 mm^2 and a B_V of ≈23 mm^3 in both cultivars studied. Mechanical-harvested significantly increased the mean values of both parameters although in different ways: in 'Manzanilla de Sevilla', fruits B_A and B_V increased by 5 and 11, respectively, whereas in 'Manzanilla Cacereña' fruits, the increases were 3 and 5, respectively.

Fruit quality after processing. After processing, the proportion of bruised fruits was reduced to less than 3% and no severe damage was observed, so B_I was 0 (Table 5). No significant differences were found between treatments or cultivars. Measurements in the MultiScan I-5 of a table olive factory confirmed these observations. In fact, 'Manzanilla de Sevilla' hand treatment samples had more bruised fruit (6.5%) than those from mechanical treatment. In the 'Manzanilla Cacereña', both types of samples showed no more than 0.2% bruised fruits. The MultiScan I-5 also allowed us to resolve the proportion of small weight fruits and thus destined for the olive oil industry: ≈6.9% in 'Manzanilla de Sevilla' and 4% in 'Manzanilla Cacereña'.

Other fruit characteristics after processing were measured (Table 5). The mechanical treatment significantly increased the proportion of fruits with cuts as compared with the hand treatment. Furthermore, the proportion of mechanically harvested fruits with cuts was greater in 'Manzanilla de Sevilla' (18%) than in 'Manzanilla Cacereña' (2%). Wrinkled and peeled fruits were found in processing fruits, and significant differences between cultivars were appreciated. Thus, regardless of treatment, ≈16% of 'Manzanilla de Sevilla' fruits were wrinkled in contrast to 'Manzanilla Cacereña' fruits (0.3% or less), whereas 'Manzanilla Cacereña' had the highest proportion of peeled fruits (59%). Fruit firmness and texture also decreased significantly in the mechanically harvested fruits, but only in 'Manzanilla de Sevilla'. No differences were found between cultivars for this treatment,

Table 1. Fruit yield and fruit traits (weight, pulp-to-pit ratio, volume, longitudinal and equatorial diameter, shape, moisture and oil content) per cultivar.

	Manzanilla de Sevilla	Manzanilla Cacereña
Fruit yield (kg/tree)	4.9 A[z]	8.9 B
Weight (g)	3.6 B	2.9 A
Pulp-to-pit ratio	5.8	6.2
Volume (mL)	3.8 B	3.1 A
Longitudinal diameter (mm)	21.1 B	19.2 A
Equatorial diameter (mm)	18.1 B	16.3 A
Shape	1.2	1.2
Moisture (%)	63.6 A	68.6 B
Oil content (% FW)	11.6 B	6.9 A
Oil content (% DW)	31.9 B	22.0 A

[z]Mean values in the same row followed by different upper case letters indicate significant differences at $P < 0.05$. No letter means nonsignificant effect.
FW = fresh weight; DW = dry weight.

Table 2. Harvesting efficiency: average time used to harvest a kilogram, tree and hectare, and fruit removal, by treatment and cultivar.

	Manzanilla de Sevilla		Manzanilla Cacereña		Cultivar × treatment[z]
	Hand	Mechanical	Hand	Mechanical	
Average time to harvest a:					
Kilogram (s·kg^{-1})	209.5 b[x]	0.4 a	179.3 b	0.4 a	NS
Tree (s/tree)	1050.9 bA	1.9 aA	1728.4 bB	3.0 aB	NS
Hectare (h·ha^{-1})[y]	576.6 bA	1.1 aA	948.2 bB	1.6 aB	NS
Fruit removal (%)	100.0	97.7	100.0	98.0	

[z]Manzanilla de Sevilla and Manzanilla Cacereña; treatment = hand and mechanical.
[y]Person/h in the hand treatment.
[x]Mean values in the same row followed by different lower case letters indicate significant differences in treatments for each cultivar at $P < 0.05$. Mean values in the same row followed by different upper case letters indicate significant differences in cultivars for each treatment at $P < 0.05$. No letter means nonsignificant effect.
NS = nonsignificant.

Table 3. Fruit firmness, lightness (L*), color axis from green to red (a*), and color axis from blue to yellow (b*) by treatment and cultivar.

	Manzanilla de Sevilla		Manzanilla Cacereña		Cultivar × treatment[z]
	Hand	Mechanical	Hand	Mechanical	
Firmness (N·cm^{-2})	96.9 b[y]	84.9 aA	96.8 b	89.6 aB	***
L*	52.8 b	49.9 aA	54.0	55.8 B	**
a*	(–)11.7 a	(–)9.2 bB	(–)11.2 a	(–)10.3 bA	***
b*	37.3 b	33.7 aA	36.1	36.8 B	**

[z]Manzanilla de Sevilla and Manzanilla Cacereña; treatment = hand and mechanical.
[y]Mean values in the same row followed by different lower case letters indicate significant differences in treatments for each cultivar at $P< 0.05$. Mean values in the same row followed by different upper case letters indicate significant differences in cultivars for each treatment at $P < 0.05$. No letter means nonsignificant effect.
and * indicate significant at $P < 0.01$ or 0.001, respectively.

Table 4. Non-bruised fruits, total bruised fruits, bruised fruits with low damage (L), bruised fruits with severe damage (S), and bruising incidence (B_I) 2 and 24 h after harvest.

	Manzanilla de Sevilla		Manzanilla Cacereña		Cultivar × treatment[z]
	Hand	Mechanical	Hand	Mechanical	
2 h after harvest					
Non-bruised fruits (%)	51.0 bA[y]	0.0 aA	91.3 bB	9.0 aB	***
Bruised fruits					
Total (%)	49.0 aB	100.0 bB	8.7 aA	91.0 bA	***
L (%)	46.4 bB	10.8 aA	8.7 aA	75.3 bB	***
S (%)	2.6 a	89.2 bB	0.0 a	15.7 bA	***
Bruising incidence (B_I)	0.5 aB	1.9 bB	0.1 aA	1.1 bA	***
24 h after harvest					
Non-bruised fruits (%)	37.6 bA	0.0 aA	87.3 bB	7.7 aB	***
Bruised fruits					
Total (%)	62.4 aB	100 bB	12.7 aA	91.7 bA	***
L (%)	56.8 bB	9.0 aA	12.3 aA	60.0 bB	***
S (%)	5.6 aB	91.0 bB	0.4 aA	31.7 bA	***
Bruised incidence (B_I)	0.7 aB	1.9 bB	0.1 aA	1.2 bA	***

[z]Manzanilla de Sevilla and Manzanilla Cacereña; treatment = hand and mechanical. Bruising incidence $B_I = [1(N_L) + 2(N_S)]/(N_0 + N_L + N_S)$; N = number of fruits with no damage (N_0), low damage (N_L), and severe damage (N_S).
[y]Mean values in the same row followed by different lower case letters indicate significant differences in treatments for each cultivar at $P < 0.05$. Mean values in the same row followed by different upper case letters indicate significant differences in cultivars for each treatment at $P < 0.05$. No letter means nonsignificant effect.
***Significant at $P < 0.001$.

whereas hand-picked 'Manzanilla Cacereña' fruits had lower texture than hand-picked 'Manzanilla de Sevilla'. Color was almost unmodified in processed fruits. The a* value (redness) increased significantly in the mechanically harvested fruits for both cultivars with 'Manzanilla de Sevilla' fruits having the highest values.

Discussion

The Manzanilla de Sevilla and Manzanilla Cacereña cultivars are grown mainly for use in the table olive industry. Current groves are manually harvested, which dramatically increases total cost. Cultivation in hedgerows of limited width and height has been suggested as a way to increase mechanical harvesting efficiency and decrease fruit damage (Ferguson et al., 2010). To date, there is no literature on the suitability of any table olive cultivar for mechanical harvesting by grape straddle harvesters when grown in SHD groves. Nowadays, such groves are one of the most common designs in new olive groves for oil production, particularly in new production areas (Connor et al., 2014).

In this study, we confirmed that both the 'Manzanilla de Sevilla' and, in particular, 'Manzanilla Cacereña' formed continuous hedgerows 5 years after plantation of suitable dimensions to allow mechanical harvesting by grape straddle harvesters. To enable the machines to move along the hedgerow as well as to avoid the need of severe pruning, tree size must be kept below 2.5 to 3 m in height and 1.5 to 2 m in width. In fact, excessive vigor and unsuitable tree architecture limit the use of many traditional cultivars in SHD olive groves (Rallo et al., 2013a).

'Manzanilla de Sevilla' and, in particular, 'Manzanilla Cacereña' hedgerows were highly productive and their precocity in fruit bearing may be considered acceptable if compared with current Arbequina, Arbosana, and Koroneiki cultivars used in SHD oil production. These cultivars reach full yield only 3 or 4 years after planting, a yield which, on average, is usually greater than 10,000 kg·ha^{-1} (Rallo et al., 2013a). The onset of fruit bearing in 'Manzanilla de Sevilla' and 'Manzanilla Cacereña' hedgerows was 3 years after plantation and fruit yield reached 9500 kg·ha^{-1} in the fourth year after planting even increasing to as much as 18,000 kg·ha^{-1} in the case of 'Manzanilla Cacereña' the next year. Fruit yield in 2013 was higher than 11,000 kg·ha^{-1} for both cultivars (11,500 kg·ha^{-1} for 'Manzanilla de Sevilla' and 13,800 kg·ha^{-1} for 'Manzanilla Cacereña') (Cera, personal communication), confirming the high productivity of these hedgerows. Results from different trials have shown that various cultivars do not appear to be suitable for cultivation in SHD oil production groves either as a result of their excessive vigor or their delayed onset of fruit bearing. Such is the case of 'Leccino' and 'Frantoio', respectively (Camposeo and Godini, 2010). The high, consistent productivity of 'Manzanilla de Sevilla' and 'Manzanilla Cacereña' trees has been found in two comparative cultivar trials carried out in different groves in Badajoz (Spain), one in an SHD arrangement (García et al., 2012; Puebla and González, 2009). The maintenance of the size and the yield will be critical aspects to take into account in the future of any table olive hedgerow. Suitable management of deficit irrigation and pruning, among other practices, will be a definite contribution to controlling hedgerow size. In particular, deficit irrigation strategies should be designed without adversely affecting the size of the fruit, something that has been previously demonstrated as being feasible (Dell'Amico et al., 2012).

The efficiency of mechanical harvesting to remove fruits from 'Manzanilla de Sevilla'

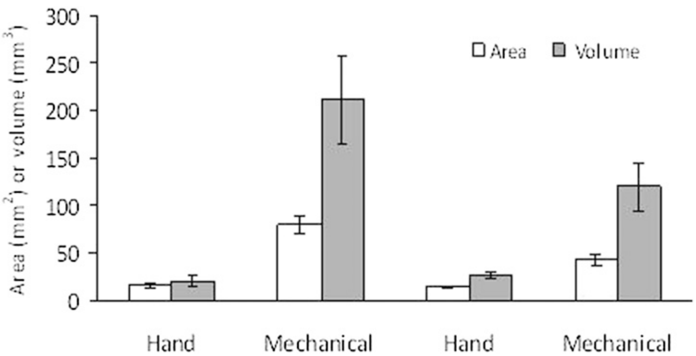

Fig. 1. Bruise area (B_A, mm^2) and bruise volume (B_V, mm^3) by treatment and cultivar. The number of replicates was three per cultivar and per harvesting treatment. Vertical bars represent SD. Different letters indicate significant differences in treatments at $P < 0.05$.

Table 5. Non-bruised fruits, total bruised fruits, bruised fruits with low damage (L), bruised fruits with severe damage (S), and bruising incidence (B_I) and other quality traits (cut, wrinkled, and peeled fruits, firmness, texture, L*, a*, and b*) after Spanish-style green processing.

	Manzanilla de Sevilla		Manzanilla Cacereña		
	Hand	Mechanical	Hand	Mechanical	Cultivar × treatment[z]
Bruising					
Non-bruised fruits (%)	97.3	98.7	99.0	97.3	NS
Bruised fruits					
Total (%)	2.7	1.3	1.0	2.7	NS
L (%)	2.7	1.3	1.0	2.7	NS
S (%)	0.0	0.0	0.0	0.0	NS
Bruising incidence (B_I)	0.0	0.0	0.0	0.0	NS
Cut fruits (%)	0.7 a[y]	17.7 bB	0.0 a	2.0 bA	***
Wrinkled fruits (%)	17.7 B	13.7 B	0.0 A	0.3 A	NS
Peeled fruits (%)	14.0 A	33.0 A	53.0 B	65.3 B	NS
Firmness ($N \cdot cm^{-2}$)	74.8 b	58.8 a	74.4	62.9	NS
Texture ($N \cdot g^{-1}$)	26.4 bB	19.1 a	20.7 A	18.8	NS
L*	48.3	48.5	48.6	48.6	NS
a*	5.8 aB	6.5 bB	4.6 aA	5.2 bA	NS
b*	31.5	31.5	29.0	29.0	NS

[z]Manzanilla de Sevilla and Manzanilla Cacereña; treatment = hand and mechanical. Bruising incidence $B_I = [1(N_L) + 2(N_S)]/(N_0 + N_L + N_S)$; N = number of fruits with no damage (N_0), low damage (N_L), and severe damage (N_S). L* = lightness, a*= color axis from green to red, and b* = color axis from blue to yellow.

[y]Mean values in the same row followed by different lower case letters indicate significant differences in treatments for each cultivar at $P < 0.05$. Mean values in the same row followed by different upper case letters indicate significant differences in cultivars for each treatment at $P < 0.05$. No letter means nonsignificant effect.

NS and *** indicate nonsignificant and significant at $P < 0.001$.

and 'Manzanilla Cacereña' hedgerows, to which fruit loosening agent had not applied before harvest, has also been highlighted in this work (Table 2). The grape straddle harvester removed 98% of the fruits in both cultivars despite the high retention force that usually characterizes ripe green fruits (Ferguson et al., 2010). This could be related to the weight of the fruits (Table 1), much higher than those obtained from the current Arbequina, Arbosana, and Koroneiki cultivars cultivated in SHD for oil production, in agreement with Ferguson et al. (2010) who indicated that fruits over 3 g are more amenable to mechanical harvest. This probably contributed to the very short time—less than 1.7 h—finally required for harvesting 1 ha. Total time would obviously increase if the grape straddle harvester downtime were to be considered, but it would probably not increase to more than 2 h. These results clearly contrast with the 576 person/h or more needed to pick a hectare by hand (Table 2). Time also depended on fruit yield, so it was greater for 'Manzanilla Cacereña'.

With regard to fruit traits, Barranco et al. (2005) reported mean values of 4 to 6 g in the pomological descriptions of both cultivars. Therefore, fruit weights from the 'Manzanilla de Sevilla' hedgerows of this work (4 g) would be considered as normal, whereas those of 'Manzanilla Cacereña' hedgerows (3 g) would be small. Fruits from both cultivars usually have a similar appearance, although the 'Manzanilla Cacereña' fruits are slightly smaller than 'Manzanilla de Sevilla' (Garrido-Fernandez et al., 1997). Moreover, given the inverse relationship usually found between olive fruit weight and fruit yield, the high cropload could negatively influence fruit weight. Nevertheless, more than 93% of the fruits of both cultivars in our trial would have been accepted by the table olive industry on the basis of size, and the rest (less than 7%) would have been destined for the oil industry, as revealed the MultiScan I-5 analysis in processed fruits. These proportions are usual in Spanish table olive factories. The results of oil content must be also taken into account because farmers often divert fruits for oil extraction when table olive market prices are low. Moreover, the quality of oil from both cultivars is highly appreciated (Barranco et al., 2005), so the cultivation of 'Manzanilla de Sevilla' and 'Manzanilla Cacereña' in SHD groves would probably be interesting for both products: table olive and olive oil. In this work the oil content was low probably because the fruits were harvested with ripening index 1. It is usually assumed that, in the case of 'Manzanilla Cacereña', fruits have a low oil content.

The suitability for mechanical harvesting by grape straddle harvesters of 'Manzanilla de Sevilla' and 'Manzanilla Cacereña' trees cultivated in SHD for table olive production was also evidenced by the quality of fruits after processing as Spanish-style green olives, particularly in terms of bruising. Bruising is considered as the major limiting factor for mechanical harvesting in current intensive groves (Jiménez et al., 2011). This is particularly true for 'Manzanilla de Sevilla', the most popular table olive cultivar worldwide because of its productivity and fruit quality. Independent of the cultivar studied here, we have observed no more than 3% of bruised fruits after processing (Table 5) despite the high proportion (greater than 90%) found on unprocessed fruits and the great severity of the damage in 'Manzanilla de Sevilla' fruits (Table 4). MultiScan I-5 analysis also confirmed these observations, which demonstrate the acceptability of the fruits according to the marketing standards in the table olive industry. Laboratory measurements of free acidity and combined acidity (data not shown) indicated, however, that initial immersion of fruits in a lye solution (2.5% w/v sodium hydroxide) was not appropriate in all fruit samples. This solution is needed to eliminate the bitter taste of the fresh fruits, by hydrolysis of the oleuropein, and the lye must penetrate two-thirds of the way through the flesh (Rejano et al., 2008). A lower temperature and concentration of the alkaline solution in which fruits were immediately immersed after harvest for transport to the table olive industry (i.e., 10 °C and 0.3% to 0.4% NaOH, respectively) would probably contribute to better processing, as suggested by other authors (Rejano and Sánchez, 2004). In fact, Rejano et al. (2008) indicated that a resting period of more than 24 h is usually recommended for 'Manzanilla de Sevilla' to avoid fruit peeling, although the transport of mechanically harvested fruits in very low concentrated alkaline solutions is also useful for the same purpose. In any case, our results show the highest damage susceptibility of 'Manzanilla de Sevilla' when harvested by grape straddle harvesters, as it can be deduced by the proportions of fruits with cuts and firmness and texture mean values (Table 5).

Finally, an approximate comparative study of the cost of harvesting per hectare shows the economic significance of our results. Thus, the mechanical harvesting in SHD groves of table olives would cost no more than €400 ha^{-1} in Spain (Rallo et al., 2013), whereas the cost of manual harvesting would probably be €3000 ha^{-1}.

In summary, although results from this work are preliminary (the data refer to 1 year, one type of grape straddle harvester, and a specific machine setting), they show that the table olive cultivars studied are high-yielding and that the tree size does not hamper mechanical harvesting by the grape straddle harvesters when they are cultivated in SHD hedgerow groves. Four-year data of fruit yield evidence the earliness of the first bearing taking place in the third year after plantation and no alternate bearing since then. Moreover, although fruit production is high, the fruit size is appropriate for table olive consumption. The high efficiency of these machines has been confirmed in terms of time to harvest a hectare (less than 2 h) and the high percentage of fruit removal (98%). Industrial processing can reduce fruit bruising to a very low incidence (less than 3%) despite the high percentage of damaged fruits after harvesting, so that for both of the studied cultivars, most fruits meet commercial requirements as Spanish-style green olives. Considering hedgerow characteristics, fruit yield and overall fruit quality after processing with special focus on fruit damage (percentages of bruised, cut, and wrinkled fruits), 'Manzanilla Cacereña' seems to be the cultivar best suited to SHD systems. However, the transportation of the fruit to the factory and the fruit processing industry itself should be correctly adapted to handle straddle-harvested fruits.

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