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RESEARCH ARTICLE

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Evaluation of different mechanical fruit harvesting systems and oil quality in very large size olive trees

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Abstract

In 2006 and 2009, trials were carried out in the Apulia region in Southern Italy to evaluate the possibility of mechanizing olive harvesting in groves of old and very large trees. The trees belonged to the cultivars 'Cellina di Nardò' and 'Ogliarola Salentina'. They were 60-100 years old and 7-9 m tall with a canopy volume of 140-360 m^3. In the first half of November 2006, with a mechanical beater mounted on a tractor plus hand-held pneumatic combs, the harvesting yield was close to 90% of the total olives present in the canopy, and the harvesting working productivity was around 60 kg of harvested olives h^{-1} $worker^{-1}$. With a self-propelled shaker attached to the main branches the harvesting yield was about 73% in 'Cellina di Nardò', and 40% in 'Ogliarola Salentina', while the harvesting working productivities were around 103 and 85 kg of harvested olives $h^{-1}worker^{-1}$, respectively. In the second half of November 2009, in 'Cellina di Nardò', with a mechanical beater mounted on a tractor plus nets on the ground or a catching frame (reversed umbrella) mounted on another tractor, the harvesting yield was about 97%. The working productivity was about 98 kg of harvested olives h^{-1} $worker^{-1}$ with the mechanical beater plus nets and around 133 kg of harvested olives h^{-1} $worker^{-1}$ when the mechanical beater was combined with a reversed umbrella. The oil obtained from the mechanically harvested olives was always of high quality. A basic economic evaluation of the harvesting costs is also reported.

Additional key words: *Olea europaea* L.; mechanical beater; pneumatic combs; branch shaker; harvesting cost.

Introduction

Olive growing is concentrated in the countries around the Mediterranean Basin, where a great part of the groves are traditional. That is, they are characterised by low tree density, old trees, irregular spacing, more than one trunk and/or steep inclines (Jardak, 2006; Metzidakis & Koubouris, 2006; Pinheiro, 2006; Rallo, 2006; Famiani & Gucci, 2011; Sola-Guirado *et al.*, 2014). In Southern Italy, and particularly in the regions of Apulia and Calabria, a large number of olive groves have old and very large sized trees (height > 7 m). In these groves, it is very difficult to harvest the fruit from the trees and so olives are usually harvested by periodically collecting the fruit from the ground (Godini, 2002). This makes the production of extra virgin oil impossible. Moreover, in many cases, because of the historical, landscape and/or monumental importance of these groves and because they are protected by law, they cannot be replaced by young trees (Fig. 1) (Inglese & Calabrò, 2002; Dettori *et al.*, 2012). Trees of large or very large size can also be found in other Italian regions (*i.e.,* Campania and Sicily) and in parts of traditional olive groves in all of the Mediterranean olive producing countries. In these situations, to make olive cultivation sustainable, it is important to upgrade the production,

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Abbreviations used: D (diameter); DF (detachment force); DW (dry weight); FW (fresh weight); H (height); PDO (Protected Designation of Origin).

especially when the varieties and environmental and agronomical conditions are favourable for obtaining typical high quality oil, and achieving a good ratio between quality, *i.e.* price, and production costs. In Southern Italy, in the "Salento" area of the Apulia region, large trees represent most of the cultivated olives (this area produces up to 8-10% of Italian olive oil). However, high quality oils can only be produced if the fruit is harvested from the trees and not from the ground. This potential for high quality and typical oils has resulted in the awarding of the Protected Designation of Origin (PDO) "Terra d'Otranto" mark. The two main olive cultivars of this area are 'Cellina di Nardò' and 'Ogliarola Salentina' (Cimato *et al.*, 2001). To produce oil with the PDO "Terra d'Otranto", at least 60% of the processed olives must belong, alone or combined, to these two cultivars. Apulia is the main Italian region for the production of olive oil (this region produces about 35-40% of the total) and the "Salento" area is located in the southern part. The PDO "Terra d'Otranto" includes most of the olive groves in the "Salento" area.The PDO mark links and guarantees a high quality and typical product to a defined territory. Furthermore, it guarantees that the oils have been produced and packaged in the PDO area and that the agronomic (*i.e.,* cultivars which can be used) and oil quality (*i.e.,* respect of maximum or minimum values for several qualitative parameters) prescriptions have been respected.

To date, very few studies have been carried out on the mechanization of olive harvesting of very large olive trees. Because of this, few data are available on alternatives to harvesting olives from the ground (Giametta G, 1983, 2003; Giametta & Zimbalatti, 1993; Giametta F, 1999; Caricato, 2001; Leone *et al.*, 2008). The aim of the present study was to test and evaluate different kinds of machine-aided systems to harvest fruit from very large olive trees. The evaluation also included the quality of the oil obtained and a basic economic analysis of the costs.

Figure 1. Olive grove in the "Salento" area of the Apulia region, where large trees represent most of the cultivated olives, and are a fundamental and highly characterising component of the landscape, also assuming a monumental importance. The ground was prepared to facilitate harvesting the olives from the ground.

Material and methods

The investigation was carried out in the "Salento" area of the Apulia region in the first half of November 2006 and in the second half of November 2009. Three different mechanical harvesting trials were performed using the following harvesting systems:

— Trial A. In the first half of November 2006, a mechanical beater (Oli-Picker, MipeViviani, Monterriggioni - SI, Italy) mounted on a tractor for harvesting the upper parts of the canopy, plus two hand-held pneumatic combs with telescopic handles of 2.5 m maximum length (Olistar Evolution, Campagnola, Bologna, Italy) to harvest the lower parts of the canopy (beater + combs + nets) (Fig. 2a).

— Trial B. In the first half of November 2006, a self-propelled shaker (Omi-Sud, 88.3 kW, with 3 wheels, Italy + shaking head by SICMA, Curinga - CZ, Italy) attached to the main branches (shaker + nets) (Fig. 2d).

— Trial C. In the second half of November 2009, a mechanical beater (Oli-Picker, MipeViviani, Monterriggioni - SI, Italy) mounted on a tractor for harvesting the entire canopy (beater + nets) (Fig. 2b). The mechanical beater was also used in conjunction with a reversed umbrella mounted on another tractor (beater + reversed umbrella) (Fig. 2c).

In all the olive groves used in the trials, the field practices were as normal for commercial olive orchards in the area made up of very large size trees. Fertilization was based on the supply of nitrogen, potassium and phosphorous as chemical fertilizers. The olive groves of Trials A and B were irrigated (drip irrigation), while that of trial C was rainfed. Treatments against diseases and pests were carried out if necessary. Pruning was executed every 4-5 years. The trials were conducted in the middle of this interval. Further details about age and spacing of the trees and cultivated varieties are given in the description of each trial. The olive orchards of the trials A and B were located in the Veglie (LE) area, whereas the one of the trial C was located in Guagnano (LE) area.

Figure 2. Mechanical beater mounted on a tractor for harvesting: (a) the upper parts of the canopy, plus two hand-held pneumatic combs with handles to harvest the lower parts of the canopy of very large size olive trees used in trial A; (b) the whole canopy plus nets under the tree for collecting the detached olives in Trial C; (c) the whole canopy used in combination with a catching frame (reversed umbrella), mounted on another tractor, for collecting detached olives in Trial C. (d) Self-propelled shaker used in trial B.

Trial A (beater + combs + nets) was carried out in an olive grove consisting of 60-year-old olive trees of the cvs. 'Cellina di Nardò' and 'Ogliarola Salentina', spaced 15 × 15 m apart. The harvesting team consisted of five workers. One of them operated the mechanical beater to harvest olives from the upper parts of the canopy, and two used hand-held pneumatic combs to harvest the olives from the low parts of the canopy, up to a height of 4.0-4.5 m. Two other workers placed two rectangular nets under each tree to be harvested and collected the detached olives and put them in bins.

Trial B (shaker + nets) was carried out in an olive grove consisting of 100-year-old trees of 'Cellina di Nardò' and 'Ogliarola Salentina' cultivars, spaced 15 × 15 m apart. The harvesting team consisted of five workers. One handled the self-propelled shaker that was used to shake the main branches of the trees (usually two main branches per tree), while the other four workers moved two rectangular nets under each tree to be harvested and collected the detached olives and put them in bins.

Trial C was carried out in an olive grove consisting of 70-year-old trees of the cv. 'Cellina di Nardò', spaced 10 m × 10 m apart. The harvesting team consisted of three workers. One operated the mechanical beater to harvest olives from the entire canopy, while the other two workers moved two rectangular nets under each tree to be harvested and collected the detached olives and put them in bins (beater + nets). When harvesting was performed by replacing the nets with a reversed umbrella mounted on a tractor (beater + reversed umbrella), the harvesting team consisted of two workers. One operated the mechanical beater to detach the olives and the other one moved the other tractor with the catching frame in order to intercept and collect the detached olives, which were unloaded into bins when the base of the catching frame was full.

Nine trees were used for each cultivar and trial. Trunk diameter (at 0.5 m from the ground) and height, tree height, and canopy diameter (D) and height (H) were measured for each of the trees harvested. Then canopy volume (V) was calculated as:

$$V = \frac{2}{3}\pi\left(\frac{D}{2}\right)^2 H$$

Before harvesting, olive detachment force (DF) was determined on each tree using a dynamometer (Somfy Tec, Ademva, Cluses Cedex, France). After harvesting, the amount of detached and undetached (the olives remaining in the canopy after harvesting) fruit was determined. The amount of undetached olives was determined by beating the canopy with a pole; if required, a ladder was used to reach the highest portions of the canopy. From each tree, fruit samples were taken to evaluate their characteristics and the stage of ripening, in terms of fruit weight, oil content and skin and flesh pigmentation. Fruit weight both fresh (FW) and dry (DW) was determined on samples of 100 olives tree^{-1}, by weighing them before and after drying to a constant weight in a ventilated oven at 105°C. The fruit DF/FW ratio was calculated. Pigmentation was determined on samples of 50 olives tree^{-1} using a "pigmentation index" that ranged from 0 to 5 points, with 0 for green olives and 5 for olives with superficial pigmentation on 100% of the surface and pigmentation also in the pulp (Camposeo *et al.,* 2013). Oil content was determined using an InfraAlyzer apparatus (SpectraAlyzer Zeutec BRAN+LUEBBE, Rendsburg, Germany) both on fresh and dry weight basis. The time required to execute harvesting was recorded considering three groups of three trees each (three replicates) for each harvesting system.

The percentage of harvested olives was calculated as

$$\textit{Harvesting yield} = \frac{\text{Detached olives}}{\text{Detached olives} + \text{Undeteched olives}} \times 100$$

and the harvest working productivity was also calculated as the amount of harvested olives h^{-1} worker^{-1} and the number of harvested trees h^{-1} worker^{-1}.

Samples of the oil extracted within 24 h from fruit harvest were analysed to determine free acidity, peroxide number, spectrophotometric absorbance in the ultra-violet range, fatty acid composition and sensory characteristics according to the procedures in EEC/Reg. 2568/91.

A basic economical evaluation was done by calculating the cost to harvest 1 kg of olives (detachment of olives, collecting them from the nets and putting them in bins) and the incidence of harvesting cost on each kilogram of oil extracted from the harvested olives with the different harvesting systems. In the area studied, the mechanical beater and trunk shaker are usually rented because of the small size of the farms; hence their cost per hour was considered equal to the price h^{-1} to rent them, which was € 60 and 70 h^{-1}, respectively. Also for the tractor + reversed umbrella a rental cost was considered to be € 40 h^{-1} including the driver. The price paid to rent the machines to the contractor included the use of the harvesting machine and the tractor on which it was mounted, with all the operating expenses, such as fuel and oil, and the driver. The compensation for the other workers that made up the harvesting team was considered equal to € 10 h^{-1}, which is the hourly salary for workers in the area (www.inps.it/bussola). The per hour cost for pneumatic combs was calculated considering: the price to buy the compressor and the pneumatic combs including the tubes, which was € 2800 + € 1200 = € 4000, a lifetime of 7 years for these devices, and a per year use of 200 hours (corresponding to 25 working days). As far as the nets are concerned, their incidence on harvesting cost was calculated considering the price of € 100 to buy each net, a lifetime of 5 years and a per year use of 200 hours (corresponding to 25 working days). For the capital invested to buy the machines, an interest rate of 5% was considered. In Table 1, the cost per hour of the different harvesting systems is reported.

All data are reported as means ± standard error. Data were also analysed statistically using the t-test to compare the means of the two different cultivars (Trial A and B) or machines employed (Trial C).

Results

In Trial A (beater + combs + nets), trees of both cultivars were very large: trunk diameter, tree height and canopy volume were high (Table 2). The yield of olives from each tree, given the large size of the canopy, was medium (Table 2). At harvesting, the fruit characteristics were evaluated according to the classification for the different parameters proposed by Barranco *et al.* (2000). On the basis of this classification, the fruit weight was low, the fruit DF was medium and the fruit DF/FW ratio was high for both cultivars (Table 3). The

Table 1. Hourly cost of the different machine-aided systems/teams utilised in the present work to harvest olives from large trees of the cultivars 'Cellina di Nardò' and 'Ogliarola Salentina', in the Apulia Region (Italy)

Trial	Description of costs	Cost (€ h^{-1})
Trial A		
(beater + combs + nets)	Beater + driver	60.00
	4 workers × 10 € h^{-1}	40.00
	Compressor and pneumatic combs	
	— Depreciation allowance (4000 / 5 years) / 200 h	4.00
	— Interest (4000 × 0.05) /200 h	1.00
	— Fuel and lubricant	2.00
	— General expenses (maintenance, insurance, etc.) (4000 × 0.005) / 200	0.10
	Nets	
	— Depreciation allowance [(4 × 100) / 5 years] / 200 h	0.40
	— Interest (4 × 100 × 0.05) / 200 h	0.10
	Total cost	**107.60**
Trial B		
(shaker + nets)	Shaker + driver	70.00
	4 workers × 10 € h^{-1}	40.00
	Nets	
	— Depreciation allowance [(4 × 100) / 5 years] / 200 h	0.40
	— Interest (4 ×100 × 0.05) / 200 h	0.10
	Total cost	**110.50**
Trial C		
(beater + nets)	Beater + driver	60.00
	2 workers × 10 € h^{-1}	20.00
	Nets	
	— Depreciation allowance [(4 × 100) / 5 years] / 200 h	0.40
	— Interest (4 × 100 × 0.05) / 200 h	0.10
	Total cost	**80.50**
Trial C		
(beater + reversed umbrella)	Beater + driver	60.00
	Tractor with reversed umbrella + driver	40.00
	Total cost	**100.00**

pigmentation index was higher for 'Cellina di Nardò' than for 'Ogliarola Salentina', indicating complete superficial (skin) pigmentation for 'Cellina di Nardò' and incomplete superficial pigmentation for 'Ogliarola Salentina' (Table 3). The oil content, both on FW and DW basis, was low for 'Cellina di Nardò' and medium for 'Ogliarola Salentina'(Table 3). The harvesting yield was close to 90% and the working productivity was around 60 kg of harvested olives h^{-1} $worker^{-1}$ (= 0.6-0.7 trees h^{-1} $worker^{-1}$) for both cultivars (Table 4). The oil obtained from processing the 'Cellina di Nardò' and 'Ogliarola Salentina' olives together had good qualitative characteristics (Tables 5 and 6). The values of the qualitative parameters were within those required for classification of the oil as extra virgin (EEC/Reg. 702/2007, and COI/T.15/NC no 3/Rev. 7 November 2013). They also fell within the standards required to obtain the PDO "Terra d'Otranto" (Tables 5 and 6).

In Trial B (shaker + nets), the harvested trees of both cultivars were also very large (Table 2). The olive yield per tree was medium for 'Cellina di Nardò' and medium-high for 'Ogliarola Salentina' (Table 2). At harvesting time, the fruit weight was low for both the cultivars (Table 3). The fruit DF was medium for 'Cellina di Nardò' and high for 'Ogliarola Salentina', with a consequent higher fruit DF/FW ratio for 'Ogliarola

Table 2. Tree characteristics and yield of large olive trees of the cultivars ‘Cellina di Nardò’ and ‘Ogliarola Salentina’, in the Apulia Region (Italy), harvested with different kinds of machine-aided systems/teams

Trial[1]	Trunk diameter (m)	Trunk height (m)	Distance between canopy and ground (m)	Tree height (m)	Canopy diameter (m)	Canopy volume (m^3)	Yield (kg olives $tree^{-1}$)
Trial A - First half of November (beater + combs + nets)							
Cellina di Nardò	0.6 ± 0.04 a	1.5 ± 0.1 a	0.7 ± 0.1 a	8.2 ± 0.3 a	9.0 ± 0.4 a	318 ± 16.3 a	105.0 ± 7.9 a
Ogliarola Salentina	0.6 ± 0.03 a	1.5 ± 0.1 a	0.7 ± 0.1 a	8.1 ± 0.2 a	8.9 ± 0.4 a	307 ± 12.3 a	98.2 ± 5.4 a
Trial B - First half of November (shaker + nets)							
Cellina di Nardò	0.5 ± 0.02 a	1.6 ± 0.1 a	1.5 ± 0.1 a	8.8 ± 0.4 a	8.8 ± 0.4 a	296 ± 18.2 a	94.1 ± 9.2 b
Ogliarola Salentina	0.6 ± 0.03 a	1.7 ± 0.1 a	1.1 ± 0.1 b	9.4 ± 0.2 a	9.1 ± 0.4 a	360 ± 13.3 a	141.2 ± 5.8 a
Trial C - Second half of November - ‘Cellina di Nardò’							
Beater + nets	0.5 ± 0.03 a	1.6 ± 0.1 a	1.3 ± 0.1 a	7.4 ± 0.3 a	6.7 ± 0.3 a	143 ± 7.1 a	74.2 ± 6.8 a
Beater + reversed umbrella	0.5 ± 0.04 a	1.6 ± 0.1 a	1.2 ± 0.1 a	7.3 ± 0.3 a	6.6 ± 0.3 a	139 ± 5.8 a	77.4 ± 7.4 a

[1] Harvesting time / (machine-aided system) / cultivar.Values are the mean ± standard error; n = 9. For each column and within each trial, means followed by the same letter are not significantly different at $p < 0.05$.

Table 3. Fruit characteristics, at harvesting time, of large olive trees of the cultivars ‘Cellina di Nardò’ and ‘Ogliarola Salentina’, in the Apulia Region (Italy), harvested with different kinds of machine-aided systems/teams. DF = detachment force; FW = fresh weight; DW = dry weight

Trial[1]	Fresh weight (g)	Dry weight (g)	Detachment force (N)	Detachment force/fresh weight ratio (DF/FW) (N g^{-1})	Pigmentation index (0-5)	Oil content (% FW)	Oil content (% DW)
Trial A - First half of November (beater + combs + nets)							
Cellina di Nardò	1.35 ± 0.05 a	0.64 ± 0.04 a	5.6 ± 0.6 a	4.1 ± 0.3 a	3.0 ± 0.1 a	14.3 ± 0.7 b	31.4 ± 1.9 b
Ogliarola Salentina	1.27 ± 0.07 a	0.64 ± 0.05 a	4.8 ± 0.5 a	3.8 ± 0.3 a	2.4 ± 0.2 b	19.0 ± 0.4 a	38.3 ± 1.4 a
Trial B - First half of November (shaker + nets)							
Cellina di Nardò	1.40 ± 0.10 a	0.71 ± 0.03 a	4.6 ± 0.3 b	3.3 ± 0.2 b	3.3 ± 0.2 a	15.2 ± 0.7 b	30.4 ± 1.2 b
Ogliarola Salentina	1.30 ± 0.12 a	0.66 ± 0.03 a	6.0 ± 0.3 a	4.6 ± 0.3 a	2.2 ± 0.1 b	19.4 ± 0.6 a	38.2 ± 1.4 a
Trial C - Second half of November - ‘Cellina di Nardò’							
Beater + nets	1.55 ± 0.06 a	0.65 ± 0.02 a	3.8 ± 0.2 a	2.5 ± 0.2 a	3.3 ± 0.2 a	16.1 ± 0.8 a	38.6 ± 1.3 a
Beater + reversed umbrella	1.63 ± 0.07 a	0.70 ± 0.02 a	3.9 ± 0.2 a	2.4 ± 0.2 a	3.3 ± 0.2 a	16.6 ± 0.7 a	38.8 ± 1.3 a

[1] Harvesting time / (machine-aided system) / cultivar. Values are the mean ± standard error; n = 9. For each column and within each trial, means followed by the same letter are not significantly different at $p < 0.05$.

Salentina’ than for ‘Cellina di Nardò’ (Table 3). The fruit pigmentation index was also higher for ‘Cellina di Nardò’ than for ‘Ogliarola Salentina’ (Table 3).The oil content, both on FW and DW basis, was low for ‘Cellina di Nardò’ and medium for ‘Ogliarola Salentina’ (Table 3). The harvesting yield was greater than 70% for ‘Cellina di Nardò’ and about 40% for ‘Ogliarola Salentina’. The harvesting working productivities were higher than 100 kg of harvested olives h^{-1} $worker^{-1}$ (= 1.6 trees h^{-1} $worker^{-1}$) for ‘Cellina di Nardò’ and about 85 kg of harvested olives h^{-1} $worker^{-1}$ (= 1.5 trees h^{-1} $worker^{-1}$) for ‘Ogliarola Salentina’ (Table 4). The oil obtained from processing the ‘Cellina di Nardò’ and ‘Ogliarola Salentina’ olives together had good

Table 4. Harvesting yield and harvesting working productivity of large olive trees of the cultivars 'Cellina di Nardò' and 'Ogliarola Salentina', in the Apulia Region (Italy), harvested with different kinds of machine-aided systems/teams

Trial[1]	Harvesting yield (%)	Harvesting team (No. of workers)	Harvesting working productivity (kg olives h^{-1} worker^{-1})	Harvesting working productivity (Trees h^{-1} worker^{-1})
Trial A - First half of November (beater + combs + nets)				
Cellina di Nardò	87.2 ± 2.6 a	5	62.0 ± 6.0 a	0.7 ± 0.1 a
Ogliarola Salentina	89.9 ± 2.4 a	5	56.0 ± 4.0 a	0.6 ± 0.1 a
Trial B - First half of November (shaker + nets)				
Cellina di Nardò	72.5 ± 6.0 a	5	103.4 ± 12.4 a	1.6 ± 0.1 a
Ogliarola Salentina	40.4 ± 2.4 b	5	84.7 ± 7.2 a	1.5 ± 0.1 a
Trial C - Second half of November - 'Cellina di Nardò'				
Beater + nets	97.2 ± 3.6 a	3	96.1 ± 6.3 b	1.3 ± 0.1 b
Beater + reversed umbrella	96.8 ± 4.1 a	2	128.8 ± 8.8 a	1.7 ± 0.2 a

[1] Harvesting time / (machine-aided system) / cultivar. Values are the mean ± standard error; n = 9 for harvesting yield; n = 3 for harvesting working productivity. For each column and within each trial, means followed by the same letter are not significantly different at $p < 0.05$.

Table 5. Free fatty acids, peroxide value, spectrophotometer absorbances in ultra-violet (K_{232}, K_{270}, ΔK) and panel test score of the oils extracted from olives of large olive trees of the cultivars 'Cellina di Nardò' and 'Ogliarola Salentina', in the Apulia Region (Italy), harvested with different kinds of machine-aided systems/teams

Trial[1]	Free acidity (%)	Peroxide value (meq O_2 kg^{-1} oil)	K_{232}	K_{270}	ΔK	Panel test score (1-9)
Trial A - First half of November (beater + combs + nets)						
Cellina di Nardò + Ogliarola Salentina	0.39 ± 0.02	5.3 ± 0.4	1.60 ± 0.07	0.120 ± 0.020	0.001 ± 0.001	7.5
Trial B - First half of November (shaker + nets)						
Cellina di Nardò + Ogliarola Salentina	0.41 ± 0.02	7.3 ± 0.7	1.64 ± 0.19	0.130 ± 0.020	0.001 ± 0.001	7.5
Trial C - Second half of November - 'Cellina di Nardò'						
Beater + nets	0.20 ± 0.03 a	8.0 ± 0.5 a	2.06 ± 0.07 a	0.140 ± 0.015 a	0.001 ± 0.001 a	7.3
Beater + reversed umbrella	0.25 ± 0.02 a	7.5 ± 0.5 a	2.02 ± 0.06 a	0.135 ± 0.010 a	0.001 ± 0.001 a	7.3
IOC-TS[2]	≤ 0.80	≤ 20	≤ 2.50	≤ 0.220	≤ 0.01	
PDO "Terra d'Otranto"[3]	≤ 0.65	≤ 14	≤ 2.20	≤ 0.170		

[1] Harvesting time / (machine-aided system) / cultivar. Values are the mean ± standard error; n = 3. For each column and within each trial, means followed by the same letter are not significantly different at $p < 0.05$. [2] International Olive Council (IOC) trade standard (TS) for extra virgin olive oils. [3] Standards required to obtain the Protected Designation of Origin "Terra d'Otranto".

qualitative characteristics (Tables 5 and 6). As with trial A, the values of the qualitative parameters were within those required for classification of the oil as extra virgin olive oil and fell within the standards required to obtain the PDO "Terra d'Otranto" (Tables 5 and 6).

In Trial C (beater + nets and beater + reversed umbrella), the trees were relatively smaller than those of Trials A and B, but still very large (trunk diameter around 0.5 m; tree height > 7 m; canopy volume around 140 m^3), and the yield of olives from each tree was

Table 6. Fatty acid composition of the oils extracted from olives of large olive trees of the cultivars 'Cellina di Nardò' and 'Ogliarola Salentina', in the Apulia Region (Italy), harvested with different kinds of machine-aided systems/teams

Trial[1]	Palmitic (%)	Palmitoleic (%)	Stearic (%)	Oleic (%)	Linoleic (%)	Linolenic (%)	Arachidic (%)
Trial A - First half of November (beater + combs + nets)							
Cellina di Nardò + Ogliarola Salentina	15.10 ± 0.16	1.55 ± 0.02	2.01 ± 0.02	71.00 ± 0.21	8.40 ± 0.21	0.78 ± 0.01	0.40 ± 0.01
Trial B - First half of November (shaker + nets)							
Cellina di Nardò + Ogliarola Salentina	15.20 ± 0.16	1.50 ± 0.02	1.99 ± 0.02	70.90 ± 0.21	8.45± 0.21	0.77 ± 0.01	0.41 ± 0.01
Trial C - Second half of November - 'Cellina di Nardò'							
Beater + nets	14.66 ± 0.14 a	1.47 ± 0.01 a	1.85 ± 0.02 a	72.00 ± 0.21 a	8.32 ± 0.18 a	0.77 ± 0.01 a	0.35 ± 0.01 a
Beater + reversed umbrella	14.68 ± 0.14 a	1.46 ± 0.01 a	1.82 ± 0.03 a	71.80 ± 0.21 a	8.74 ± 0.19 a	0.78 ± 0.01 a	0.32 ± 0.01 a
IOC-TS[2]	7.50 – 20.00	0.30 – 3.50	0.50 – 5.00	55.00 – 83.00	3.50 – 21.00	≤ 1.00	≤ 0.60
PDO "Terra d'Otranto"[3]				≥ 70.00	≤ 13.00	≤ 0.80	

[1] Harvesting time / (machine-aided system) / cultivar. Values are the mean ± standard error; n = 3. For each column and within each trial, means followed by the same letter are not significantly different at $p < 0.05$. [2] International Olive Council (IOC) trade standard (TS) for extra virgin olive oils. [3] Standards required to obtain the Protected Designation of Origin "Terra d'Otranto".

relatively high (Table 2). At harvesting time, the DF was medium-low and fruit weight was low (Table 3). The fruit DF/FW ratio was around 2.5 N g^{-1}. The pigmentation index indicated complete superficial pigmentation of the olives (Table 3). The oil content, both on FW and DW basis, was low (Table 3). The harvesting yield was very high (> 95%) with both the beater + nets and the beater + reversed umbrella (Table 4). The working productivity was around 95 kg of harvested olives h^{-1} $worker^{-1}$ (= about 1.3 trees h^{-1} $worker^{-1}$) with the beater + nets and increased significantly up to about 130 kg of harvested olives h^{-1} $worker^{-1}$ (= about 1.7 trees h^{-1} $worker^{-1}$) with the beater + reversed umbrella (Table 4). The oil had very low values of free acidity, peroxide number and spectrophotometric absorption and a good fatty acid composition and sensory assessment, without differences due to the harvesting system used (Tables 5 and 6). All the values of the qualitative parameters were within those required for classification of the oil as extra virgin olive and fell within the standards required to obtain the PDO "Terra d'Otranto" (Tables 5 and 6).

Basic economic evaluation of harvesting costs

The hourly cost of the different harvesting systems ranged from € 80.50 to 110.50 h^{-1} (Table 1). Dividing the hourly cost of each harvesting team by the amount of olives harvested with the different harvesting systems and the oil obtained from the harvested olives, the cost to harvest 1 kg of olives and the incidence of harvesting cost on each kilogram of oil extracted from the harvested olives were determined (Table 7). The harvesting costs varied from € 0.21 to 0.39 kg^{-1} of olives and the incidence of harvesting cost on each kilogram of oil extracted from the harvested olives with the different harvesting systems ranged from € 1.34 to 2.43 kg^{-1} of oil. The lowest costs to harvest 1 kg of olives were obtained with the shaker (Trial B) and the mechanical beater + nets in the second half of November (Trial C). The lowest incidence of harvesting cost on each kilogram of oil extracted from the harvested olives was obtained with the shaker (Trial B), the mechanical beater + nets in the second half of November (Trial C) and the mechanical beater + pneumatic combs with 'Ogliarola Salentina' (Trial A).

Discussion

The dimensions of the trees clearly indicated their very large size, which resulted comparable to that reported in other investigations carried out in the same region (Giametta, 1999). The fruit weight and oil content recorded for 'Cellina di Nardò'and 'Ogliarola Salentina' were consistent with the characteristic va-

Table 7. Harvesting costs of olives and oils of large olive trees of the cultivars 'Cellina di Nardò' and 'Ogliarola Salentina', in the Apulia Region (Italy), harvested with different kinds of machine-aided systems/teams

Trial[1]	Harvesting team (No. of workers)	Olives harvested by the whole harvesting team[2] (kg h^{-1})	Oil "harvested" by the whole harvesting team[3] (kg h^{-1})	Cost to harvest 1 kg of olives[4] (€ kg^{-1})	Incidence of harvesting on the cost of 1 kg of oil[5] (€ kg^{-1})
Trial A - First half of November (beater + combs + nets)					
Cellina di Nardò	5	310.0	44.3	0.35	2.43
Ogliarola Salentina	5	280.0	53.2	0.38	2.02
Trial B - First half of November (shaker)					
Cellina di Nardò	5	517.0	78.6	0.21	1.41
Ogliarola Salentina	5	423.5	82.2	0.26	1.34
Trial C - Second half of November - 'Cellina di Nardò'					
Beater + nets	3	288.3	46.4	0.28	1.73
Beater + reversed umbrella	2	257.6	42.8	0.39	2.34

[1] Harvesting time / (machine-aided system) / cultivar. [2] Calculated by multiplying the harvesting working productivity reported in Table 4 by the number of workers in each harvesting team (first column of this Table). [3] Calculated by multiplying the amount of olives harvested by each harvesting team (2nd column of this Table) by the olive oil content reported in Table 3. [4] Calculated by dividing the per hour cost of each harvesting system/team, reported in Table 1, by the amount of olives harvested by each team (2nd column of this Table). [5] Calculated by dividing the per hour cost of each harvesting system/team, reported in Table 1, by the amount of oil "harvested" by each team (3rd column of this Table).

lues reported in the literature for these two varieties (Barranco *et al.*, 2000; Cimato *et al.*, 2001; Lombardo *et al.*, 2004).

In the first half of November, when mechanical harvesting of large olive trees was performed using a mechanical beater mounted on a tractor plus two hand-held pneumatic combs, the harvesting yield was close to 90% and the working productivity was 56-62 kg of harvested olives h^{-1} worker^{-1}. The harvesting yield was very good, especially considering the high fruit DF/FW ratio. It was higher than that obtained in other studies on large trees harvested with mechanical beaters in the same region (Giametta, 1999; Caricato, 2001). The higher harvesting yield might be due to the use of hand-held pneumatic combs together with the mechanical beater in the present study. With these small hand-held devices almost all of the olives can be harvested, also in early harvesting when the fruit detachment force is high (Tombesi *et al.*, 1996a; Abdeen *et al.*, 2006; Famiani *et al.*, 2006, 2008).

The harvesting yield with the mechanical beater in the second half of November was very high (about 97%). This is likely the result of the relatively smaller size of the trees with respect to those of Trial A, which made it easier to work the whole canopy. In addition, the fruit DF/FW ratio in the second half of November was lower with respect to the first half (2.4-2.5 *vs* 4.1 N g^{-1}), which made fruit detachment easier. Significant increases in the harvesting yields have also been reported in other studies when this ratio decreased from 3.8-3.9 N g^{-1} (Giametta, 1999) to 2.7 N g^{-1} (Tombesi *et al.*, 1996a), suggesting that this variable, with values around 2.5 N g^{-1}, could be used as an index to establish harvesting time in order to obtain high harvesting yields using mechanical beaters.

In general, the working productivities obtained in the present study with the mechanical beater in combination with pneumatic combs and, especially, when the beater was used alone in the second half of November, were similar or higher than those reported by Giametta & Zimbalatti (1993), Tombesi *et al.* (1996a), Caricato (2001) and Fiorino *et al.* (2006). In Trial C, the higher working productivity values were due to the higher harvesting yield and the shorter time for shaking to detach the olives; both were likely related to the lower fruit DF/FW ratio at that time. A further increase in the working productivity was obtained with the combination of the mechanical beater and the reversed umbrella, which allowed the number of workers on the harvesting team to be reduced to two.

When mechanical harvesting was performed using the self-propelled shaker attached to the main branches, the working productivity of the harvesting team was good (85-103 kg of olives h^{-1} $worker^{-1}$) and comparable to that reported in other studies regarding the use of trunk shakers and nets (Tombesi *et al.*, 1996a,b; Famiani *et al.*, 2006), but lower than that reported by Leone *et al.* (2008) for similar large trees. In this last regard, working productivity as affected by fruit load needs to be taken into account: the higher the load, the greater the working productivity (Famiani *et al.*, 2004), and this can explain the difference with respect to the results of Leone *et al.* (2008). The harvesting yield was relatively high for 'Cellina di Nardò', but low for 'Ogliarola Salentina'. This difference may be due to the high fruit detachment force and DF/FW ratio for the olives of 'Ogliarola Salentina', which were significantly higher than those of 'Cellina di Nardò' (Table 3). This could also contribute to explaining the differences in harvesting yields with respect to other studies concerning 'Ogliarola Salentina' (Panaro *et al.*, 2003). The high fruit detachment force of 'Ogliarola Salentina' in Trial B might be the result of the high fruit load of the trees (Table 2), which can cause slower ripening (Inglese *et al.*, 2011). Thus a major role of the fruit DF/FW ratio is confirmed in terms of choosing the optimal harvesting time to obtain a high efficiency with the use of shakers (Di Vaio *et al.*, 2012; Farinelli *et al.*, 2012a,b). Moreover, further improvements could be obtained by pruning to increase the rigidity of the main and secondary branches, as in large trees high harvesting yields can be obtained with regular, even mechanical, pruning (Dias *et al.*, 2012). It could also be helpful to conduct studies to determine the best point to grasp the main branches with the shaker. Indeed, large size trees are characterised by a large inertial mass due to their big canopy and root system and in these conditions, increase in the height of the attachment point of the clamp may be important in order to improve the transmission of vibrations and, as a result of this, the harvesting efficiency (Horvath & Sitkei, 2001).

The oil qualitative characteristics recorded in all the trials were consistent with the values reported in the literature for the two cultivar considered (Cimato *et al.*, 2001; Lombardo *et al.*, 2004).

In all the groves used in the trials, the results show that the amount of production per hectare (< 12000 kg olives ha^{-1}), the olive oil content on a fresh weight basis (< 20%), and the oil characteristics, such as acidity (< 0.8%), peroxide number (< 14 meq O_2 kg^{-1} oil), spectrophotometric absorptions (K_{232} < 2.20; K_{270} < 0.170), fatty acid composition (oleic acid > 70%; linoleic acid < 13%; linolenic acid < 0.8%) and sensorial characteristics, were within the values (indicated between brackets) prescribed to obtain the PDO "Terra d'Otranto" mark.

Basic economic evaluation of harvesting costs

The cost to harvest 1 kg of olives and 1 kg of oil (Table 7), besides being affected by the hourly cost of the harvesting system/team (Table 1), was greatly affected by the working productivity of the harvesting system/team (Table 4) and, in the case of the oil, by the oil content of the olives (Table 3). This last effect was particularly clear in Trials A and B, where 'Ogliarola Salentina', having a higher oil content, always had a higher cost to harvest 1 kg of olives, but a lower cost "to harvest" 1 kg of oil than 'Cellina di Nardò'. As the working productivity of the harvesting system/team depends greatly on the load of the trees (Famiani *et al.,* 2004), the unit cost to harvest olives/oil can vary due to this factor. Moreover, the working productivity also depends on harvesting time, which affects detachability of the olives, affecting the fruit DF/FW ratio: relatively late harvesting gives higher harvesting yields and working productivities. Indeed, later harvesting with the mechanical beater + nets gave a lower harvesting cost (Trial C - Table 7). The cost to harvest 1 kg of olives with the mechanical beater was essentially similar to that calculated in Portugal when the machine was used on a high number of trees with a good production (Almeida & Peça, 2012).

To harvest most of the olives with the shaker, it is advisable to use the shaker 2-3 times during the whole olive harvesting period. It is interesting to note that, on the basis of the amount of fruit on the trees (in the 2^{nd} and 3^{rd} harvestings the amount of olives on the tree becomes lesser and lesser) and the harvesting yields obtained (normally lower early in the season and higher late in the season), this may cause variability in the unit harvesting costs. In Trial C the relatively higher cost of the combination beater + reversed umbrella with respect to the beater + nets is due to the relatively low cost of manpower; however, the possibility of full mechanization of harvesting is taking on more and more importance since it is becoming constantly more difficult to find manpower; moreover, it allows better working conditions because moving the nets is very tiring.

It is important to note that in the basic evaluation of the costs, the incidence of olives not harvested (percentage left on the trees), which could be considered as an indirect cost, was not included.

A representative team to harvest olives from the ground (2 workers + 2 machines: a harvester and a sorter) on average has a working productivity of about 200 kg h^{-1} $worker^{-1}$ (around 400 kg^{-1} h^{-1} $team^{-1}$) (Giametta, 2003) and an hourly cost of about € 60. This results in a cost of about € 0.15 kg^{-1} of harvested olives, which in turn, considering an oil content ranging from 14 to 20% FW, gives a harvesting cost of € 0.75-1.07 kg^{-1} of oil. The oil obtained from olives harvested from the ground is usually "lamp oil", which is not edible and must be processed industrially to produce olive oil that can be marketed. The price of lamp oil is around € 2 kg^{-1}(average value deriving from our market investigation in the Apulia region), which means a difference of € 0.93-1.25 kg^{-1} between the price and the cost of "harvesting" 1 kg of oil.

By harvesting olives directly from the trees an extra virgin olive oil is obtained, which, at least on the basis of the qualitative parameters that were evaluated, is also eligible for obtaining the PDO "Terra d'Otranto" mark. Therefore, the oil can be sold as extra virgin or PDO, for which the sale prices are, respectively, around € 3.00 kg^{-1} (which can increase up to € 4.00-4.50 kg^{-1}, if the oil is put into 5 L containers and sold directly to consumers) and € 6.00 kg^{-1} (which can increase up to € 10.00-15.00 kg^{-1}, if the oil is bottled and sold directly to consumers) (average values deriving from our market investigation in the Apulia region; President of the "Terra d'Otranto" Consortium, pers. comm.). This means that the difference between the price and the "harvesting" cost can be € 0.57-1.66 kg^{-1} for extra virgin oil and € 3.57-4.66 kg^{-1} for PDO "Terra d'Otranto" oil or higher if the oil is sold directly to consumers. These calculations indicate that mechanization of olive harvesting from the trees, with respect to harvesting from the ground, allowing high quality oil to be obtained, can give opportunities to obtain a greater difference between the price of the oil and the cost "to harvest" it, particularly if the oil is sold as a PDO oil and/or directly to consumers.

The results of the present study indicate that there are varied and good possibilities for the mechanization of olive harvesting to obtain oils of high quality in olive groves that are characterised by particularly large, also centennial, trees. Indeed, relatively good harvesting working productivity values were obtained with all the mechanised systems tested.

The joint use of the mechanical beater with the hand-held pneumatic combs gave harvesting yields close to 90% already in the first half of November, while the mechanical beater gave values around 97% when harvesting was performed in the second half of November. These values must be considered high because the large size of the trees makes working the whole canopy to detach the fruit difficult. The effect of the fruit DF/FW ratio on the harvesting yield is interesting, showing that very high values can be obtained when this ratio reaches values around 2.5 N g^{-1}. This indicates that the ratio could be used as a ripening index to determine the best harvesting time for efficient fruit detachment using mechanical beaters.

The use of a catching frame in combination with the mechanical beater gave an increase in the working productivity, as a result of reducing the manpower requirement (only 2 workers), and full mechanization of both fruit detachment and collection.

With the shaker, considering the high production per tree, the possibility of using this machine 2-3 times during the entire olive harvesting period is advisable in order to harvest most of the fruit directly from the trees. However, this system is discontinuous (2-3 applications to harvest most of the fruit) and implies obtaining oils with different qualitative characteristics in relation to the diverse stage of ripening of the olives at the different harvesting times (Inglese *et al.*, 2011). Moreover, by prolonging the harvesting time, potential losses, such as natural fruit drop, will increase and become significant.

The use of the mechanical beater alone or in conjunction with hand held machines offers the possibility of harvesting the olives in one pass, thus concentrating the harvest in the period in which the oil meets the required qualitative characteristics. Harvesting almost all the olives from these particularly large trees, by using machines at the right time, assumes further importance where the high quality oil can be certified with the Protected Designation of Origin mark.

The basic economic evaluation of harvesting costs indicates that harvesting olives from the trees, with respect to harvesting from the ground, can allow a larger difference between the price and the "harvesting" cost of the oil. In this regard, it might also be considered that harvesting olives from the ground also implies losses due to deterioration of the dropped fruit and damage due to animals and this represents an additional indirect cost not considered in this work.

The proposed harvesting systems/teams gave differences in the costs "to harvest" 1 kg of oil, but it must be taken into account that higher costs can be compensated for by higher prices of the product if a high quality oil is obtained, especially if the olive grower is able to promote his/her product in an efficient way and sell it directly to consumers and/or selected retailers. The value of the oil could also be improved using the size and beauty of the trees and the landscapes they form as positive aspects for promoting the marketing of the oil.

The possibility of using machines to harvest olives and obtain high quality oils from very large sized trees would also make it easier to preserve the historical-agricultural landscapes, with a high social and environmental importance, which have a value that can go far beyond the pure value of the product. This is also important in other countries of the Mediterranean Basin.

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