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Planting density affects vigour and production of 'Arbequina' olive

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Abstract

The hedgerow orchard type is being increasingly used with the olive although not much information is still available about its suitability to this species. The objective of this study was to assess the influence of planting density (312, 416, 625 and 1,250 trees ha^{-1}) on vigour and productive characteristics of 'Arbequina' olive trees planted in 2003. Significant linear regressions have been observed between planting density and tree width, trunk cross section area and canopy volume. Increasing planting density showed positive linear correlation (R^2 = 0.63) with canopy volume per hectare. There was a negative correlation between planting density and production per tree in the five first crops, but it was positive with production per hectare both in olive and olive oil production with coefficients of determination ranging from 0.16 to 0.43 and from 0.28 to 0.46, respectively. A significant linear regression (R^2 = 0.31 and 0.48) was found between planting density and fruit size on two of the studied cropping years. Our results have not allowed establishing any relationship between planting density and fruit oil content. Finally, the studied densities did not affect the oil fatty acid composition. The production increase observed at the highest tried density is linked to the increase in canopy volume per hectare, but these results should be checked at later stages of tree development, as this study covers only until the fifth harvested crop.

Additional key words: fruit and oil traits; *Olea europaea* L; yield.

Resumen

Influencia de la densidad de plantación sobre el comportamiento del olivo 'Arbequina'

El cultivo en seto está siendo cada vez más usado en olivo aunque todavía no hay demasiada información acerca de su idoneidad para esta especie. El objetivo de este estudio fue evaluar el efecto de la densidad de plantación (312, 416, 625 y 1.250 árboles ha^{-1}) sobre las características de vigor y productivas de árboles de 'Arbequina' plantados en 2003. Se han observado regresiones significativas entre la densidad de plantación y la anchura del árbol, el área de su sección de tronco y su volumen de copa. La densidad de plantación ha mostrado una relación lineal positiva (R^2 = 0,63) con el volumen de copa por hectárea. Hubo una correlación negativa entre la densidad de plantación y la producción por árbol de los cinco primeros años, pero fue positiva con la producción por hectárea, tanto de aceituna como de aceite, con coeficientes de determinación que variaron entre 0,16 y 0,43 y entre 0,28 y 0,46, respectivamente. Se encontró una regresión significativa (R^2 = 0,31 y 0,48) entre la densidad de plantación y el tamaño de los frutos en dos de las cosechas estudiadas. Nuestros resultados no han permitido establecer ninguna relación entre la densidad de plantación y el contenido en aceite del fruto. Finalmente, las densidades de plantación empleadas no afectaron a la composición acídica del aceite. El aumento de producción observado a las mayores densidades de plantación está asociado al incremento de volumen de copa por hectárea, pero estos resultados deben ser confirmados con árboles de mayor desarrollo, puesto que este estudio solo llega hasta la quinta cosecha recolectada.

Palabras clave adicionales: características de la fruta y el aceite; *Olea europaea* L.; producción.

Introduction

Since the 60' of the XX century planting density increase has been used in apple (*Malus domestica* Borkh.) and pear (*Pyrus communis* L.), giving rise to early and heavy cropping (Vittrup Christensen, 1979; Sansavini & Musacchi, 2002). It has been also used as a powerful tool to allow for the mechanization of tech-

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nical operations, mainly harvesting and pruning (Policarpo *et al*., 2006). Similarly, the traditional dry-farming olive orchard, with low density, less than 100 trees ha^{-1}, frequent tillage to better conserve water by controlling weeds and manual harvest (Pastor *et al*., 2006), shifted to a new model, with densities going from 200 to 400 trees ha^{-1}, very much used in Spain and other countries nowadays, and later to even 2,000 trees ha^{-1} (Pastor *et al*., 2007). Drip irrigation, mechanical harvest and better fertilization and pest and disease control are already used in the medium-density model, while they are a must in the high-density one (Villalobos *et al*., 2006).

Increasing density up to 200-400 trees ha^{-1} in olive lead to a significant reduction in production costs by using mechanical harvesters such as "shakers" and "knockers" and by high yield (Pastor *et al*., 2007). The use of very high planting densities (1,250-2,500 trees ha^{-1}) has given rise to hedgerow orchards, harvestable by straddle machines, thus reducing production costs even more (Tous *et al*., 2003). 'Arbequina' was the first cultivar used for this new system by its earliness of bearing, just two years after planting (Del Río *et al*., 2005; Tous *et al*., 2005a). The use of an early-bearing cultivar at very high density allows for heavy cropping within a few years after planting (De la Rosa *et al*., 2007; León *et al*., 2007; Pastor *et al*., 2007). Therefore hedgerow system has expanded quickly, up to more than 100,000 ha (Agromillora Catalana S.A., 2007). Very high density hedgerows should optimise tree spacing between and within rows for optimal interception of radiation by the tree canopies (Pastor *et al*., 2007), thus a good control of vigour, either by pruning or by controlled deficit irrigation is compulsory, as new compact cultivars are not tested yet and there are not dwarfing rootstocks (Del Río *et al*., 2005; Tous *et al*., 2005b).

Three high-density trials with 'Arbequina' have been planted before the one reported here, testing four densities from 238 to 888 trees ha^{-1} (Tous *et al*., 2005c), four from 204 to 1,904 trees ha^{-1} (Pastor *et al*., 2007) and 10 from 780 to 2,581 trees ha^{-1} (León *et al*., 2007). Higher densities may allow for higher productions during the first years (Tous *et al*., 2006; León *et al*., 2007, Pastor *et al*., 2007, Freixa *et al*., 2010) but, later on, too much growth could reduce light interception with the subsequent significant olive production decrease (Tombesi, 2006; Pastor *et al*., 2007). Indeed, the importance of properly designing this orchard type (orientation, row height and width, alley width and canopy slope) has been already discussed in order to maximize light interception and, therefore, productivity (Connor, 2006). Another work has discussed the appropriate row spacing in relation to the maximum tree height, a variable to be established by the over-the-row harvester to be used (Vossen, 2007). Two vigorous cultivars have shown not suited to this hedgerow planting system (Larbi *et al*., 2011), although the application of uniconazol, a gibberelin synthesis inhibitor, has been reported to control the canopy size in some others (Avidan *et al*., 2011).

The olive hedgerow system was introduced in Tunisia in 2000, becoming a matter of debate concerning cultivar choice and tree density. Therefore a density trial with 'Arbequina' is being carried out in Tunisia since 2003, where trees are either isolated, as in the medium-density orchards, or they form hedgerows, depending on the density. This work had the objective of studying the influence of four planting densities (from 312 to 1,250 trees ha^{-1}) on 'Arbequina' vigour, fruit production, fruit characteristics and oil acidic composition.

Material and methods

This trial was planted at Takelsa (North-East of Tunisia; 36° 47' N; 10° 37' E) in April 2003. Four densities were tested (312, 416, 625 and 1,250 trees ha^{-1}). 'Arbequina' self-rooted trees of 50 cm tall were planted.

The trial is located in an almost flat, sandy soil, low in organic matter (0.2%), pH 7.8. The mean, maximum and minimum temperatures are 18.4, 23.5 and 13.2°C, respectively. The area average annual rainfall is 500 mm and the irrigation applied during the first five crops reported here ranged between 1,500 and 2,000 m^3 ha^{-1}. The fertilization program was based essentially on N, P and K, the latter being applied since the third year after planting. Since the spring of 2008 three treatments against *Fusicladium oleagineum* (formerly *Spilocaea oleagina)* were applied yearly, at the required times. Herbicide applications were performed as needed to aid in controlling orchard weeds. Training and/or little pruning was done manually as needed, in winter time.

Trees planted at the highest density were trained to a central leader trying to make a hedgerow as soon as possible. All the other were trained to a free vase, maintaining each one like a true tree. The experimental design consisted of four randomised complete blocks with 4 m as distance between rows and 2, 4, 6 and 8 m between trees in the rows. Each block consists of 36 trees and measurements were taken only on trees located in the middle of each density treatment.

Growth traits and production

Tree height and trunk girth at 20 cm above soil level were measured after the fifth recorded crop (December 2009). The trunk cross-section area (TCSA) was then calculated. Canopy volume of trees grown at the highest density (1,250 trees ha^{-1}) was calculated by considering the tree as a parallelepiped and consequently by using the Eq. [1], while for trees grown at 312, 416 and 625 trees ha^{-1} it was figured out by considering the tree as a spherical casquete using the Eq. [2] (Del Rio *et al*., 2005). Canopy volume was determined after the fourth (2008) and the fifth crops (2009).

$$\text{Canopy volume} = L * e * h \qquad [1]$$

where L, e and h are the width, thickness and height of the tree, respectively.

$$\text{Canopy volume} = (\pi/4) * d^2 * hc \qquad [2]$$

where d and hc are the average width of two perpendicular diameters and the height of the tree canopy, respectively.

All the trial trees were harvested separately from the first (2005) to the fifth crops (2009), except those considered as guard trees in each block.

Fruit characteristics

Three fruit samples of 3 kg each were taken from each block and planting density, at a ripening index ranging from 3 to 4 on a scale of 0 to 7 (Ferreira, 1979). The average fruit weight was determined from three samples of 100 fresh fruits each, which were then dried in a forced-air oven at 105°C until reaching a constant weight (Del Rio & Romero, 1999). Dried samples were weighted to determine their moisture content and then their dry matter oil percentages were measured in a nuclear magnetic resonance analyser, model Oxford 4000 (Del Rio & Romero, 1999). These fruit characteristics were determined in the second, fourth and fifth crops.

Oil characteristics

At the first (2005), second (2006) and fourth reported crops (2008) olive oil was extracted from fruit samples (three samples from each block and planting density) using the laboratory oil mill Abencor (MC2, Sevilla, Spain) consisting of a hammer mill, a thermobeater, and a paste centrifuge, according to the method described by Martínez *et al*. (1975). Fatty acid methyl ester (FAME) composition of oils was determined according to EU Regulations (EC, 2002). The methyl esters were prepared by vigorous shaking of a solution of oil in hexane (0.2 g in 3 mL) with 0.4 mL of 2 N methanol potassium and analyzed by gas chromatography (Shimadzu GC-17A) and equipped with a FID detector. A fused silica capillary column (30 m length × 0.32 mm diameter), coated with Carbowax (polyethylene glycol) phase was used. Nitrogen was employed as carrier gas with a flow through the column of 1 mL min^{-1}. The temperatures of the injector and detector were set at 230 and 250°C respectively, whereas the oven temperature was 180°C. An injection volume of 1 μL was used.

Statistical analysis

For all studied characteristics, analysis of variance (ANOVA) and regression analyses were performed to determine the influence of planting density on production characteristics using SPSS (Statistical Package of the Social Sciences) base 18.0 software (Chicago, IL, USA). Pearson correlation (using average values) was also determined to study the relationship between olive production, oil content and vigour and planting densities.

Results

Effect of tree density on vigour characteristics

There were significant linear regressions between planting density and tree width, TCSA and canopy volume (Table 1).Tree canopy volume at 1,250 trees ha^{-1} was only 75% of that at 312 trees ha^{-1}. Canopy volume was negative and significantly related (R^2 = 0.92 and R^2 = 0.94) to planting density in 2008 and 2009, respectively (Fig. 1A). There were positive linear relations (R^2 = 0.98 and R^2 = 0.96) between planting

Table 1. Regression analysis of planting density and vigour characteristics of 'Arbequina' by the 7th year after planting. Data are means of 12 replicates

Planting density (trees ha^{-1})	Tree height (m)	Canopy width (m)	TCSA[1] (cm^2)	Canopy volume (m^3 tree^{-1})	Canopy volume (m^3 ha^{-1})
312	2.71	2.75	81.96	14.90	4,648
416	2.62	2.67	79.35	13.54	5,632
625	2.66	2.59	72.2	12.83	8,018
1,250	2.84	2.19	67.8	11.22	14,025
Significance[2]	NS	S (0.000)	S (0.008)	S (0.009)	S(0.000)
Intercept	2.60	2.95	84.72	15.17	1,472.1
Density	0.00	–0.001	–0.014	–0.003	10.12
R^2	0.018	0.302	0.05	0.070	0.63

[1] TCSA: trunk cross section area. [2] NS, S: non significant and significant at $p < 0.05$, respectively.

density and canopy volume per hectare, respectively, in both years (Fig. 1B).

Effect of tree density on fruit production

Significant linear regressions between density and production per tree were observed only at the third and the fourth harvest (Table 2). The average tree production of the highest density (1,250 trees ha^{-1}) was only 72.7% of that at 312 trees ha^{-1}. Also there was a significant negative linear regression between planting densities and tree production as average of the five reported harvests (Table 2). Also, when using average data, a significant negative correlation was found between planting density and average tree production of the first five harvests (R^2 = 0.92) (Fig. 2). However, there were significant linear regressions between density and production per hectare in all cases. Indeed, increased planting density positively influenced production per hectare, with coefficient of determinations ranging from 0.16 to 0.43 (Table 3). Moreover, good positive correlations were found between planting density and production when using average value for production per hectare (Fig. 3). The average of the first five harvests was 191% higher at 1.250 than at 312 trees ha^{-1}.

Effect of tree density on fruit and oil characteristics and on oil yield

Significant linear regressions between density and fruit weight average were observed in the second and fifth crops but not in the fourth one (Table 4). With regard to dry matter fruit oil content and humidity fruit content, no significant linear regressions were observed between density and both fruit characteristics except for humidity fruit content in the fourth crop. However, significant liner regressions were found between density and oil crop per hectare every of the three studied years (Table 4). Also, when using average data, a significant positive correlation was found between oil crops and planting density (Fig. 4).

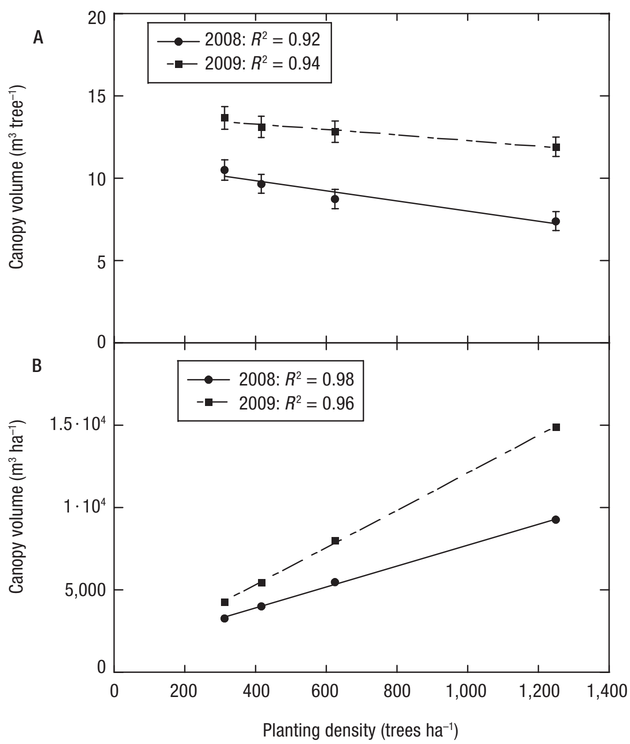

Figure 1. Linear regression trend between canopy volume per tree (A) and canopy volume per hectare (B) and planting density in 2008 and 2009. R^2 values were obtained using Pearson's correlation.

Table 2. Regression analysis of planting density and average olive production per tree of 'Arbequina' from the third to the seventh year after planting and average production per tree after the first five harvests. Data are means of 12 replicates

Planting density (trees ha^{-1})	Years after planting					Average production (kg tree^{-1})
	3	4	5	6	7	
	2005	2006	2007	2008	2009	
312	2.51	8.25	3.36	15.2	7.55	7.59
416	2.24	7.38	3.6	13.5	6.38	6.76
625	2.94	7.47	2.16	12.15	7.42	6.65
1,250	2.06	6.56	2.16	9.40	5.93	5.52
Significance[1]	NS	NS	S (0.016)	S (0.000)	NS	S(0.000)
Intercept	2.71	8.43	3.74	16.27	7.68	7.97
Density	0.000	–0.002	–0.001	–0.006	–0.001	–0.002
R^2	0.011	0.028	0.046	0.15	0.017	0.123

[1] NS, S: non significant and significant at $p < 0.05$, respectively.

No significant linear regressions were found between density and fatty acid composition (palmitic, oleic and linoleic) in three different crops (Table 5).

Discussion

A significant linear decrease of canopy volume, TCSA and canopy width per tree were found with increased planting density. Tous *et al*. (2005c) also show that trees growing at higher densities tend to show lower TCSA and canopy volume than those grown at a normal density (238 trees ha^{-1}). But both trials show a proportional significant increase in canopy volume per hectare with the increase in planting density. Moreover, Pastor *et al*. (2007) have reported that the excessive development shown by the density of 1,904 trees ha^{-1} five years after planting when applied irrigation water was 6,000 m^3 ha^{-1} in an area with similar

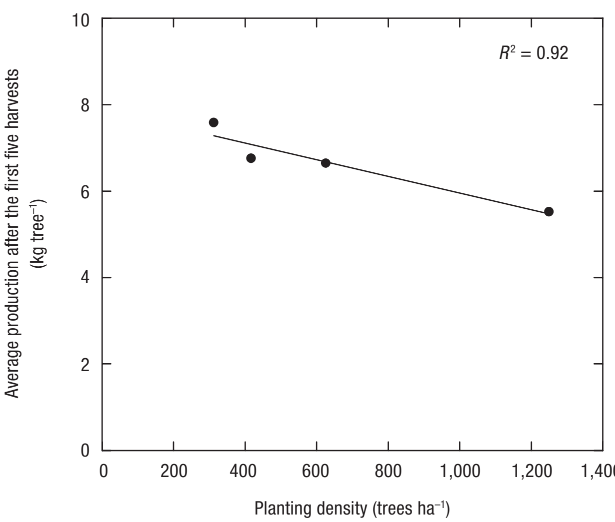

Figure 2. Linear regression trend between average olive production per tree after the first five crops and planting density. R^2 values were obtained using Pearson's correlation.

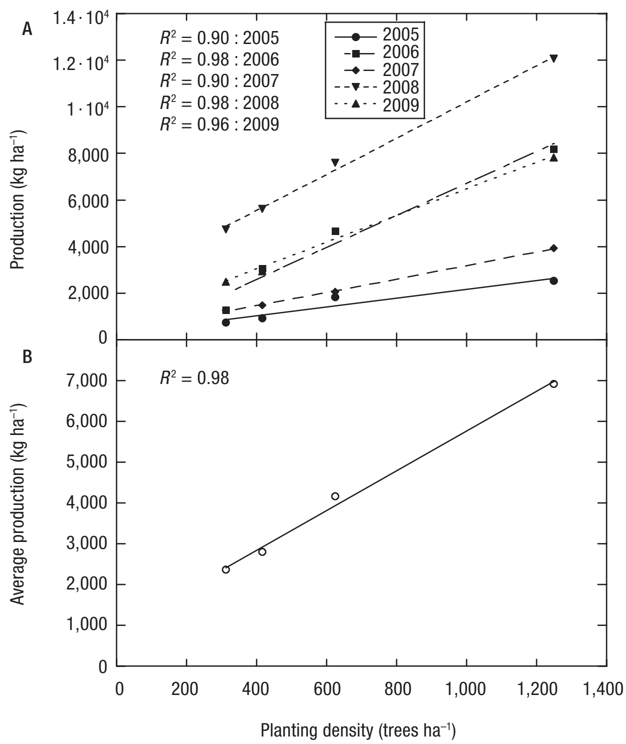

Figure 3. Linear regression trend between planting density and production (kg ha^{-1}) from 2005 to 2009 (A), and average production (kg ha^{-1}) of the first five crops (B). R^2 values were obtained using Pearson's correlation.

Table 3. Regression analysis between planting density and olive production (kg ha^{-1}) of 'Arbequina' from the third to the seventh year after planting and on average production of the first five crops. Data are means of 12 replicates

Planting density (trees ha^{-1})	Years after planting 3	4	5	6	7	Average production (kg ha^{-1})
	2005	2006	2007	2008	2009	
312	749	2,574	1,285	4,742	2,502	2,370
416	932	3,070	1,497	5,616	2,945	2,808
625	1,837	4,669	2,068	7,594	4,637	4,161
1,250	2,537	8,200	3,925	12,062	7,825	6,910
Significance[1]	S (0.00)	S (0.00)	S (0.00)	S (0.00)	S (0.00)	S(0.00)
Intercept	294.6	753.9	569.4	2616.7	699.5	1,003.5
Density	1.9	5.90	1.66	7.4	5.49	4.61
R^2	0.31	0.43	0.16	0.42	0.32	0.54

[1] S: significant at $p < 0.05$.

rainfall than in our experiment obliged to a severe pruning aimed at allowing the use of the over-the-row harvester, the same being needed with that of 816 trees ha^{-1} two years later.

In our case, the canopy volume at 312 trees ha^{-1} is lower than 5,000 m^3 ha^{-1} (Table 1) and still far from the maximum of 12,000 m^3 ha^{-1} determined suitable for good 'Picual' production in the Andalusian environment under irrigation (Pastor *et al.,* 2006). However, in the highest density (1,250 trees ha^{-1}) 'Arbequina' has already attained and even surpassed that maximum canopy volume per hectare just seven years after planting. This confirms that good attention must be paid to pruning the trees growing in the hedgerow model, so that they do not grow excessively, to allow solar radiation reach the lower part of the canopy. This trial will eventually show how long this moderate high-density orchard could be maintained profitably.

The smallest tree width of our hedgerow trees may be the result of so little space among them in the rows. Working with pears Policarpo *et al*. (2006) indicated that canopies are able to perceive the presence of adjacent trees, therefore trying to avoid competition for light by modifying stem length and/or orientation, and ultimately canopy shape. Moreover, our smallest TCSA in the highest density also agree with a work on apple trees grown at high density (Vittrup Christensen, 1979), as leaf area per tree decreases as planting density increases.

At 3 m height and 0.20 of incident daily radiation, adequate illumination is provided at the wall bases with alley widths varying from 2.2 to 3.7 m, depending on

Table 4. Regression analysis between planting density and fruits characteristics and oil production of 'Arbequina'. Data are means of 12 replicates

Planting density (trees ha^{-1})	Fruit weight (g)			Fruit oil content (% dry weight)			Fruit water content (%)			Oil yield (kg ha^{-1})		
	2006	2008	2009	2006	2008	2009	2006	2008	2009	2006	2008	2009
312	2.0	1.5	2.7	53.3	46.7	53.2	59.1	59.2	57.5	561.1	903.5	565.5
416	2.07	1.6	2.5	51.5	47.0	52.8	57.8	60	56.7	667.2	1,064.2	673.2
625	1.68	1.7	2.4	56.0	47.2	54.8	55.9	57.2	55	1,151.5	1,606.8	1,143
1,250	1.7	1.9	2.2	54.4	47.6	51.9	55.6	60.9	59.5	1,980	2,244.9	1,645
Significance[1]	S(0.00)	NS	S(0.00)	NS	NS	NS	S (0.03)	NS	NS	S	S	S
Intercept	2.67	1.42	2.72	52.7	46.5	54.1	59.0	58.2	55.16	87.9	760.5	220.5
Density	0.000	0.00	0.00	0.002	0.001	–0.001	–0.003	0.002	0.003	1.58	1.18	1.2
R^2	0.31	0.06	0.48	0.06	0.03	0.03	0.10	0.08	0.06	0.46	0.32	0.28

[1] NS, S: non significant and significant at $p < 0.05$, respectively.

Table 5. Regression analysis between planting density and 'Arbequina' oil fatty acid composition (oleic, linoleic and palmitic acid) at 2005, 2006 and 2008. Data are means of 12 replicates

Planting density (trees ha^{-1})	Palmitic acid (%)			Oleic acid (%)			Linoleic acid (%)		
	2005	2006	2008	2005	2006	2008	2005	2006	2008
312	18.4	15.9	17.05	60.6	66.5	63.4	14.09	13.9	14.1
416	18.0	17.5	17.46	61.2	63.3	63.5	14.33	14.6	13.5
625	17.9	16.0	17.36	61.7	64.4	62.7	13.9	16.2	14.5
1,250	17.5	16.9	17.91	61.9	64.8	62.2	13.6	14.7	14.7
Significance[1]	NS	NS	NS	NS	NS	NS	NS	NS	NS
Intercept	18.44	16.3	16.93	60.67	64.91	63.81	14.34	14.56	13.59
Density	–0.001	0.00	0.001	0.001	0.000	–0.001	–0.001	0.00	0.001
R^2	0.038	0.026	0.032	0.077	0.004	0.019	0.077	0.012	0.081

[1] NS: non significant at $p < 0.05$.

canopy slope (Connor, 2006). Our alley width was just 1.8 m after the last reported harvest, thus needing to continue pruning laterally afterwards. Vossen (2007) has also explained that for distances of 4 m among rows like in our highest density, tree height should not go above 3 m. Our trees already were 2.84 m-tall and the maximum height compatible with the use of the harvester is 2.75 m, therefore they should be slightly top-pruned, thus loosing canopy height and then crop.

The strong association between tree density and production per hectare taking into account both the annual and average figures indicates that the highest planting density allow for higher productions during the first five crops after planting. Indeed, the highest density multiplies by three the average crop of the five considered years with respect to the smallest one, but it is only 85% higher than that of 625 trees ha^{-1} (Table 3). Pastor *et al*. (2007) have reported that with an irrigation of 6,000 m^3 ha^{-1}, 1,904 trees ha^{-1} was beneficial only during the first three crops, due to the severe "topping" pruning they had to perform after the third harvest because of the trees being almost 5-m-tall, thus avoiding them to be harvested by over-the-row harvester, also leading to a drastic decrease of light interception by the lower part of the canopy.

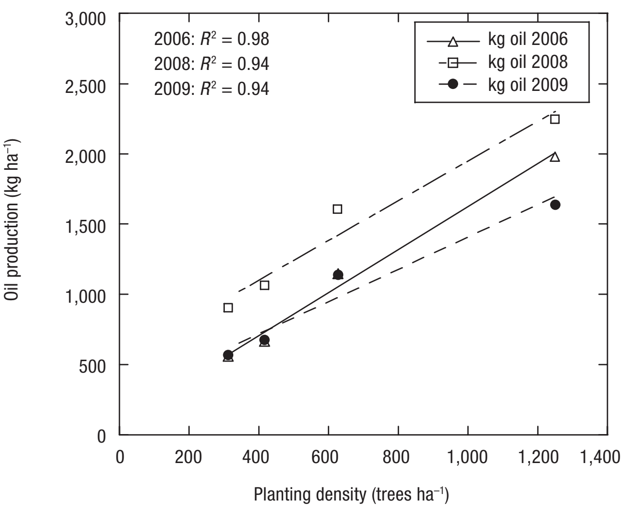

Figure 4. Linear regression trend between oil production (kg ha^{-1}) during 2006, 2008 and 2009 and planting density. R^2 values were obtained using Pearson's correlation.

Working with pear and apple trees other authors have reported that tree density increase results in higher production mainly during the first years after planting (Sansavini & Musacchi, 2002). Others have shown that tree density and production are not linearly related, meaning that a threshold can be found beyond which a further increase in density may not result in greater yield (Corelli & Sansavini, 1989; Weber, 2001; Hampson *et al*., 2002).

Contrary to the results reported by León *et al*. (2007) in olives and Widmer & Krebs (2001) in apple, a significant linear regression were found between fruit size and increased planting density in two of the studied crops. Indeed, a decrease of fruit size was observed in trees grown at higher density. However, the lack of any clear relationship among tree density and fruit oil content is in agreement with previous data showing that planting density did not affect olive oil content (León *et al*., 2007). But the integration of olive production and fruit characteristics leads to estimate the oil production per surface unit, which shows a good positive correlation with tree density (Fig. 4). Our results are in good agreement with previous data for the same cultivar (León *et al*., 2007). Indeed, these authors have shown that oil yields increase linearly with planting density from 780 to 2,500 trees ha^{-1} during the first five harvests. However, Pastor *et al*. (2007) have shown that this tendency was observed only during the first three harvests, indicating that from the fourth one, the highest density start diminishing oil production, probably due to the excessive vegetative growth determined by irrigating with 6,000 m^3 ha^{-1}.

In conclusion, these preliminary results indicate that our highest density, 1,250 trees ha^{-1}, allows for high fruit production during the first years as compared to the other tested densities. The increase of planting density is associated with an increase in canopy volume per hectare. The mutual shading at the highest density does not influence tree production (efficiency and productivity), and oil quality (fatty acids composition). But due to the still relatively young age of the trees (7 years) it is difficult to advise the highest tried density as productivity and canopy development could change with the increase of tree age. Therefore, this study needs to be continued some more years to arrive to final conclusions, also testing the effect of uniconazol, already shown to control canopy size in more vigorous cultivars.

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