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Growth and Yield of Two High-Density Tuono Almond Trees Planted at Two Different Intra-Row Spacings

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Abstract: One of the key techniques for successful almond tree cultivation in newly irrigated areas is increasing planting density. To investigate this, field experiments were carried out over five consecutive growing seasons (2019–2023) to evaluate the effects of two different tree densities on the vegetative growth and productivity of almond trees (*Prunus dulcis*, cv. Tuono) in a semi-arid climate in Southern Italy. The two planting densities tested were 1660 trees per hectare (achieved with 1.5 m intra-row spacing × 4.0 m inter-row spacing) and 833 trees per hectare (3.0 m × 4.0 m spacing). The results showed that significantly lower values of annual shoot length were recorded in both 2020 and 2021, years characterized by late frosts in March and April. However, with the exception of the first year (2019), when the plants had not yet been influenced by the different planting densities, the annual shoot length was significantly higher in the lowest planting density compared to the highest one in the following years. Additionally, higher annual trunk growth values were recorded at the lower planting density compared to the higher density. By the end of the five seasons, trees at the lower density showed a cumulative trunk growth of 177 mm, whereas those at the higher density reached only 137 mm. No significant effect of the two different tree planting densities on overall fruit development, specifically length, width, and thickness, was observed. As the trees matured, kernel yield per tree increased under both planting densities. However, significantly higher individual tree yields were recorded in the lower-density configuration, reaching 2.70 kg per tree by the end of five seasons, compared to 1.68 kg per tree in the high-density arrangement. In contrast, kernel yield per hectare was greater in the densely planted configuration, achieving 2.81 t ha^{-1}, whereas the lower-density planting resulted in a yield of 2.25 t ha^{-1} by the end of the same period. Furthermore, no significant differences were observed between the two tree planting densities in terms of the percentage of hull per fruit, kernel per nut, or the occurrence of double seeds. Similarly, morphological traits of the nuts and kernels, such as weight, length, width, and thickness, remained unaffected. However, slightly higher kernel weights were noted at the lower planting density.

Keywords: plant density; almond; shoot; trunk and fruit growth; kernel yield and fruit characteristics

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1. Introduction

The almond (*Prunus amygdalus* (L.) Batsch = *P. dulcis* (Mill.)) is widely cultivated in Mediterranean countries, and Italy ranks seventh among the world's largest almond producers, with 53,386 hectares cultivated and a total production of 79,092 tons in 2024 [1,2]. The majority of almond cultivation in Italy is concentrated in the southern regions, particularly in Sicily (54,377 tons from 32,965 hectares) and Puglia (18,290 tons from 20,320 hectares) [2].

The almond is one of the world's leading tree nut crops and has experienced the most significant growth in production over the past decade [3]. Today, this crop has evolved from traditional orchards characterized by low planting intensity (up to a maximum of about 3–400 trees/ha) to intensive orchards and, more recently, to medium-high density (MHD; about 300 to 1000 trees/ha) and super-high density (SHD; more than 2000 trees/ha) [4]. These intensive almond orchards facilitate the complete mechanization of orchard management operations [5]. New cultivars resistant to specific climatic conditions, rootstocks, and specific technologies have contributed to the development of almond cultivation technology [6]. For these modern cultivation systems, which are designed to allow for the full mechanization of orchard management operations [5], Rootpac® 20, a rootstock (*P. besseyi* × *P. cerasifera*) developed by the Agromillora breeding program [7], is the most commonly used rootstock for grafting almond trees [8]. It is characterized by low vigor and a compact, upright growth habit in the grafted plants. Furthermore, it appears to be tolerant of calcareous soils and poor drainage, and is moderately resistant to *Meloidogyne* spp. [9]. In Italy, modern high-density almond cultivation systems have been developing in irrigated areas for about 10 years, following trends observed in other countries around the world. Currently, approximately 1500 hectares are cultivated using intensive methods, with 80% of this area concentrated in the Puglia region [10]. A significant portion of the newly planted almond acreage is dedicated to the Lauranne® Avijor cultivar (48% of the total) and the Guara-Tuono cultivars (39% of the total) [11].

The main objective of these new systems is to achieve early and consistent yields, high fruit quality, and low production costs [12]. The concept of maximizing almond yield is relatively simple in theory: capture as much sunlight as possible per hectare of land. Naturally, the sooner the orchard achieves full canopy cover, the sooner it will reach its maximum yield potential [13]. The amount of light intercepted, together with water and mineral elements absorbed by the roots, is, in fact, one of the main factors determining the productivity of a plant [14]. According to previous studies, the establishment of new growing systems can significantly impact light distribution and interception within the canopy [15,16], which are crucial factors regulating photosynthesis, carbohydrate accumulation, and ultimately determining the final yield of almonds [17,18]. Efficient canopies that optimize light interception and distribution can be achieved by increasing planting density [19], which promotes a more uniform spatial arrangement of foliage and enhances the overall leaf area index (LAI). Moreover, a north–south row orientation allows for better distribution of photosynthetically active radiation (PAR) throughout the entire canopy compared to an east–west orientation [8,15,16].

High-density systems can be established to achieve early bearing and high yields using continuous mechanical harvesting systems [20]. In almonds, these high-density systems typically begin production in the third year and reach maximum productivity after 6 to 7 years [21]. However, the effects of different planting densities on vegetative growth and yield can vary depending on tree variety, rootstock, and climate [22–25] In particular, different cultivars exhibit variations in tree height, canopy thickness, and various architectural traits such as trunk and shoot parameters [26]. Since the introduction of these new cropping systems for almond cultivation is relatively recent, there are currently very few published studies [23,27,28] that have examined the impact of different planting densities on vegetative parameters and yield, in an effort to promote more efficient and sustainable orchard management.

Due to the growing interest of farmers in almond cultivation—particularly under medium-high density (MHD) and super-high density (SHD) orchard systems—this study aims to evaluate the effects of two different planting densities, 1660 trees per hectare (achieved with 1.5 m intra-row spacing x 4.0 m inter-row spacing) and 833 trees per hectare

(3.0 m × 4.0 m spacing), on the vegetative growth, yield, and fruit quality of the Tuono almond variety.

2. Materials and Methods

2.1. Site and Orchard

A 5-year study was conducted in an irrigated almond orchard from 2019 to 2023, corresponding to the 3rd, 4th, 5th, 6th, and 7th years after planting, to evaluate the performance of two planting densities: 1660 trees per hectare (achieved with 1.5 m intra-row spacing × 4.0 m inter-row spacing) and 833 trees per hectare (3.0 m × 4.0 m spacing.) The orchard is located in the Foggia countryside (Puglia, southern Italy: 41° 27′ 08″ N, 15° 31′ 56″ E, 54 m a.s.l.). Cv. 'Tuono' almond trees, an important self-compatible hard-shelled cultivar native to Puglia, were grafted onto Rootpak 20® hybrid (*Prunus besseyi* × *Prunus cerasifera* L.-H. Bailey and Ehr) rootstock. The trees were planted in March 2017 and trained in a vase shape with three production axes, oriented in rows from north to south. The first production was obtained in 2019.

The soil has a silty-clay texture and is classified as a vertisol of alluvial origin, with a depth of 1.20 m (Typic Chromoxerert, fine, thermic, according to the USDA Soil Taxonomy [29]). The physical and chemical properties of the soil were described in a previous study conducted on the same site by Tarantino et al. (2024) [11].

2.2. Cultural Practices

Orchards followed standard regional practices. Drip lines (2 L h^{-1} drippers, 40 cm apart) were installed 50 cm above ground along tree rows, delivering an average of 3000 m^3 ha^{-1} of water per season. Manual pruning was done in the first two years; mechanical topping, hedging, and trimming were used after harvest in later years. Fertigation supplied 100 kg/ha N, 60 kg/ha P, and 80 kg/ha K annually. Fungal diseases were managed in autumn–winter with copper-based products, in line with the Integrated Production Regulations of the Puglia Region [30].

2.3. Experimental Design

The research was planned as a randomized block design with three replicates for each of the two planting densities: 1660 trees per hectare (1.5 × 4.0 m) and 833 trees per hectare (3 × 4 m). Each treatment block, representing one planting density, consisted of 15 trees arranged in three adjacent rows. Three centrally positioned almond trees were selected as sample trees for measurement, and the remaining trees were used as guard trees.

2.4. Climate

The study site, located in a semi-arid zone with an accentuated thermomediterranean climate [31] experiences winter lows below 0 °C and summer highs above 40 °C. Rainfall averages 559 mm annually, mostly in winter [32]. Daily temperature and precipitation data were recorded by the nearest Syngenta meteorological station during each experimental year [33].

In Table 1, which reports monthly temperatures and precipitation over the five experimental years, some differences between years can be observed.

Annual precipitation was lower in 2021 (461.7 mm) compared to the other years (values ranging from 524.1 mm to 627.8 mm).

The highest annual mean temperature was recorded in 2023 (18.0 °C). In comparison, lower values were observed in 2019 and 2022 (17.0 °C), 2021 (16.5 °C), and 2020 (16.3 °C). Frosts were recorded during the almond flowering and fruit-setting periods on 24 and 25 March 2020 (−0.24 °C and −1.43 °C, respectively), and on 8, 9, and 10 April 2021

(−0.6 °C, −2.6 °C, and −0.9 °C, respectively) (Table 2). More favorable temperature trends for almond cultivation were observed in 2019, 2022, and 2023 (Table 2).

Table 1. Monthly mean maximum and minimum temperatures (Tmax, Tmin) and total precipitation (P) for the 2019, 2020 2021 2022, and 2023 years.

Month	YEAR														
	2019			2020			2021			2022			2023		
	Tmax (°C)	Tmin (°C)	P (mm)	Tmax (°C)	Tmin (°C)	P (mm)	Tmax (°C)	Tmin (°C)	P (mm)	Tmax (°C)	Tmin (°C)	P (mm)	Tmax (°C)	Tmin (°C)	P (mm)
Jan	10.6	1.6	61.0	10.5	1.6	3.6	12.2	2.4	58.2	13.3	1.7	23.8	12.7	3.4	112.8
Feb	14.6	2.6	21.2	14.6	2.9	51.0	15.5	3.4	35.2	15.5	3.0	60.2	13.7	1.8	12.0
Mar	18.6	4.5	32.0	15.6	2.1	83.0	15.4	3.4	57.8	17.2	4.1	28.2	19.1	4.6	75.2
Apr	20.6	8.2	40.3	18.8	6.1	48.9	19.9	4.7	40.4	19.6	6.3	20.8	19.6	6.6	66.2
May	21.3	10.2	86.7	27.5	14.7	25.8	26.5	10.8	26.0	28.5	12.7	22.2	24.0	11.9	73.6
Jun	33.2	17.5	9.2	28.8	17.7	19.7	33.2	15.9	8.6	33.9	18.6	51.3	31.1	16.0	84.0
Jul	33.7	19.5	30.0	31.0	21.2	20.4	35.4	19.3	100.8	34.7	19.0	49.8	37.9	19,9	3.2
Aug	34.8	20.3	5.7	31.5	21.8	40.0	34.9	19.4	29.2	32.3	19.1	20.0	34.9	18.4	28.4
Sept	29.5	16.8	3.8	22.2	17.4	38.5	29.5	15.4	19.4	28.0	15.5	84.8	30.6	17.4	17.6
Oct	25.5	11.5	29.2	25.5	9.7	44.6	21.2	10.9	70.2	25.0	12.2	27.2	27.4	14.3	25.6
Nov	19.3	9.4	112.6	19.3	7.7	68.6	17.2	10.8	135.4	17.9	8.6	91.2	19.6	7.8	72.0
Dec	14.7	5.0	30.0	14.7	5.2	83.0	13.7	4.8	46.6	15.9	5.6	44.6	16.1	5.0	21.0
Mean	23.4	10.6		21.7	10.9		22.9	10.1		23.5	10.5		23.9	12.2	
Total			461.7			527.1			627.8			524.1			566.0

Table 2. Daily minimum temperatures (Tmin) on frost days: 24–25 March 2020 and 8–10 April 2021.

Year			
2020		2021	
Date	Tmin (°C)	Date	Tmin (°C)
March 24	−0.2	April 8	−0.6
March 25	−1.4	April 9	−2.6
		April 10	−0.9
Mean	−0.8	Mean	−1.4

2.5. Plant Measurements

2.5.1. Vegetative Development

Shoot length (SL) and trunk diameter (TD) were measured at the beginning (February) and end (September) of each of five seasons on three central plants per treated plot. SL was measured in centimeters on two well-lit, one-year-old shoots from opposite sides (east and west) of each plant using a tape. TD was measured in millimeters at a marked point 50 cm above ground using a digital vernier caliper. Annual shoot growth (ASG) and trunk growth (ATG) were calculated as the difference between the February and September measurements each year.

2.5.2. Development of Fruits

In 2023, the development of retained fruits was monitored by measuring the length, width, and thickness of 10 whole fruits from the fruit set stage to maturity on each of two selected branches in the east and west directions of the three trees mentioned above. Thus, approximately 20 fruits per tree (180 per treatment block) were monitored every fortnight throughout the season.

2.5.3. Harvesting, Fruit Collection, and Yield

Each year, almond fruits for each treatment were hand-harvested at the commercial maturity stage (85 BBCH stage [34]) during the last 10 days of September. The fresh weight of the almond fruits per tree was measured.

Production results were reported as kernel yields in kilograms per tree (kg tree^{-1}) and tonnes per hectare (t ha^{-1}), with the latter estimated based on the planting densities described in Section 2.3. The reported kernel production values were adjusted to a standard moisture content of 10%, estimated after sun-drying the nuts for 5 days.

Production results were reported as kernel yields, in kg/tree and in t/ha. The latter was estimated considering the planting densities indicated in Section 2.3.

Samples of 2 kg of almonds with hulls were taken from each replicate, stored in plastic bags, and transported to the laboratory. Each fruit in the samples was separated from the hull, and the nuts were left to dry in the sun for 5 days, reducing the humidity to about 10% of their weight. The results were expressed as kernel dry yield (as a percentage of kernel per nut) and double seeds (percentage of nuts with two kernels).

Furthermore, 10 fruits were randomly collected from each replication to measure the principal dimensions (length, width, and thickness) of the nuts and kernel (see Figure 1) [35]. A digital caliper with an accuracy of 0.01 mm was used for all measurements. Nut and kernel mass were measured with an electronic balance with a sensitivity of 0.001 g.

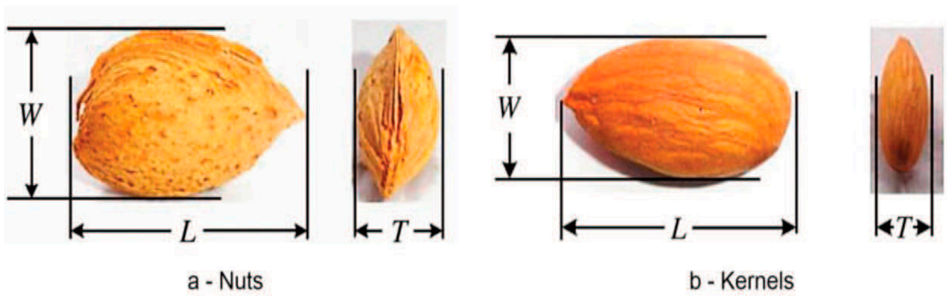

Figure 1. Almond size parameters: L = length; W = width; T = thickness [35].

2.6. Statistical Analysis

The results were evaluated with one-way ANOVA using JMP® software version 8 (SAS Institute Inc., Cary, NC, USA) and average values were compared with the Tukey test. Standard deviations (SDs) were calculated using Excel software in the Office 2007® suite (Microsoft Corporation, Redmond, WA, USA). Percentage values were transformed to arcsine prior to analysis of variance. Furthermore, to relate the different vegetative and fruiting parameters, correlation analysis was carried out using the Pearson correlation coefficient.

3. Results

3.1. Shoot and Trunk Development

The vegetative growth of Tuono plants was influenced both by climatic conditions that occurred over the years and by the two different planting densities (833 and 1660 trees ha^{-1}).

In general, as shown in Figure 2, a noticeable differencce for annual shoot length was noted between years and planting densities. Significant low values (ranging from 11.5 to 25.8 cm) were recorded in both 2020 and 2021, characterized by late frosts in March and April, which indicate the susceptibility of almond trees to climatic conditions. Higher values (between 50.1 and 59.2 mm) were instead observed under normal climatic conditions in 2019, 2022, and 2023 in both planting densities. Furthermore, with the exception of the first year (2019), when the plants had not yet been influenced by the different planting densities, in 2020, 2021, 2022, and 2023, the annual shoot length was significantly higher (on average 20.2, 25.8, 48.4, and 52.4 cm, respectively) in the lowest planting density (833 trees ha^{-1}) than in the highest planting density (1660 trees ha^{-1}), where the lengths were 11.5, 15.3, 39.1, and 40.7 cm, respectively (Figure 2).

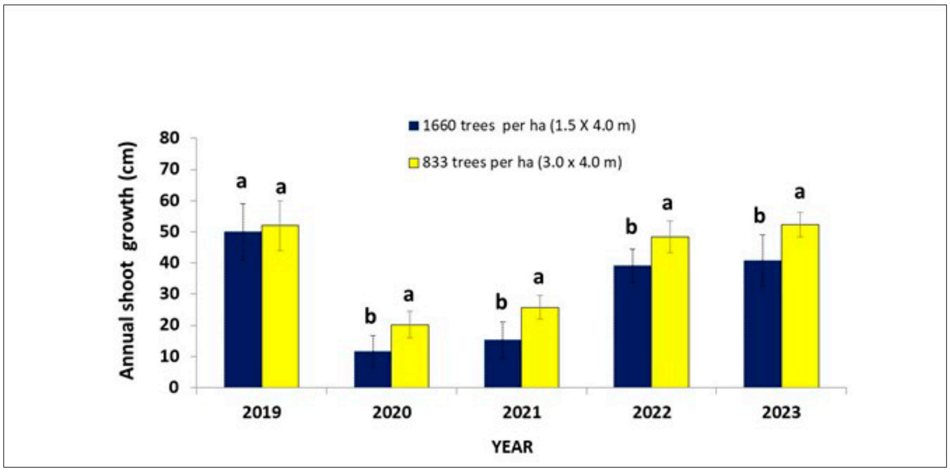

Figure 2. Annual shoot growth in two planting densities. The data are average value ± SD in five subsequent years (2019–2023). Different lowercase letters in the years indicate significant differences according to Tukey's test ($p < 0.05$).

Annual trunk growth (Figure 3) showed significant differences between the two planting densities only in the years 2019, 2022, and 2023, which were characterized by normal climate conditions. Higher growth values (ranging from 28.9 to 34.4 mm) were recorded at the lower planting density (633 trees ha^{-1}) compared to those (ranging from 21.3 to 22.3 mm) at the higher density (1660 trees ha^{-1}). However, even in the frost-prone years of 2020 and 2021, the increases recorded at the lower planting density (633 trees ha^{-1}), although not significantly different, were higher (25.3 and 22.1 mm, respectively) than those recorded at the higher density (1660 trees ha^{-1}) (19.2 and 16.7 mm, respectively).

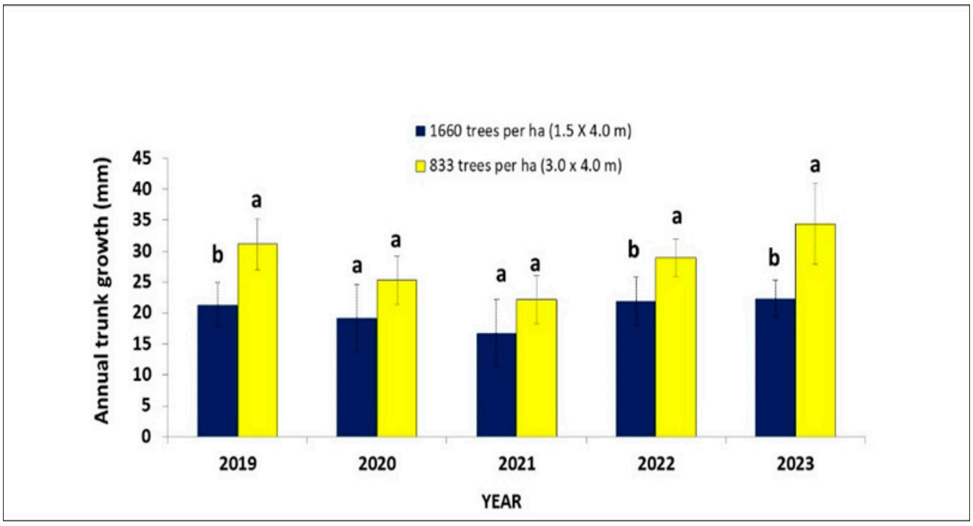

Figure 3. Annual trunk growth in two planting densities. The data are average value ± SD in five subsequent years (2019–2023). Different lowercase letters in the planting densities indicate significant differences according to Tukey's test ($p < 0.05$).

The cumulative tree trunk growth (CTG) (Figure 4) in the lower planting density (833 trees per hectare) exhibited a greater growth rate over time compared to that in the higher density (1660 trees per hectare). At the end of the five seasons, the CTG was higher in the lower plant density, reaching 177 mm of growth, compared to the higher density, which had a cumulative growth of 137 mm. This difference in CGT was statistically significant, indicating that the lower planting density allowed for better overall growth of the trees.

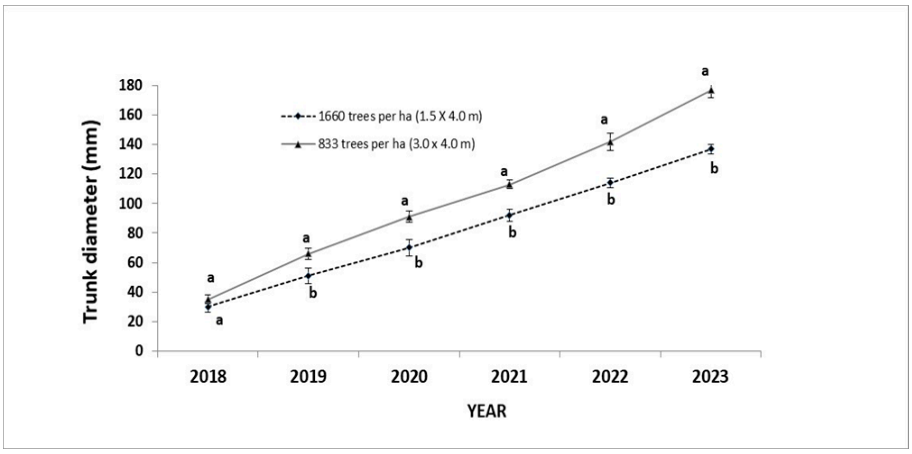

Figure 4. Trunk cumulative diameter for two planting densities (1660 and 833 tree ha^{-1}) from 2018 to 2023. The data are average value ± SD. Different lowercase letters in the two planting densities in each year indicate significant differences according to Tukey's test ($p < 0.05$).

3.2. Fruit Growth

No significant effect of the two different tree planting densities on whole fruit development in almonds was observed. Therefore, in Figure 5, the average fruit size development values (length, width, and thickness) for two different planting densities are presented, showing two main phases. The first phase, immediately after fruit set, is characterized by rapid growth, reaching the maximum size (approximately 50 mm in length, 40 mm in width, and 35 mm in thickness) after about 55–65 days. The second phase, occurring during stone hardening, shows that the fruit size remaines relatively stable. Therefore, the fruit (including the seed) completes its growth during the period from March to April and stabilizes in the following months.

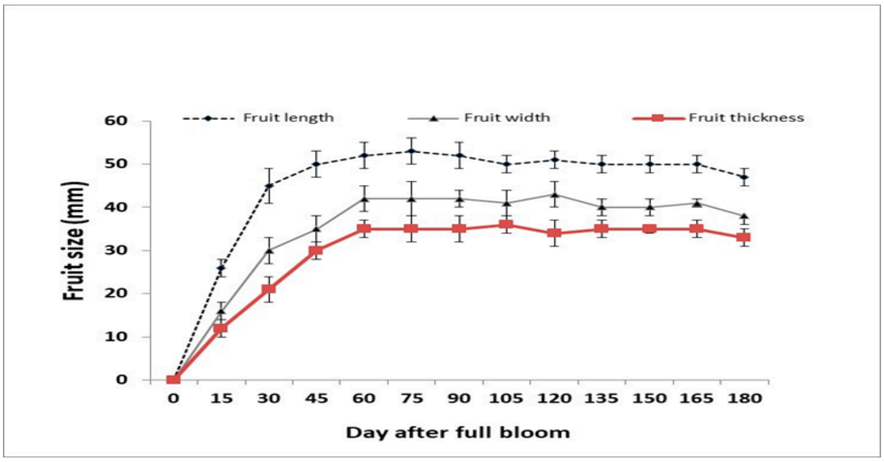

Figure 5. Development of length, width, and thickness of fruit in almond cv. Tuono.

3.3. Kernel Yield

The data in Figure 6 show how almond kernel yield per tree (expressed in kg) was influenced by two treatments (1660 and 833 trees per hectare) over five experimental years. In both 2020 and 2021, when spring frosts occurred, there were very low increases in production as the trees matured. The yield per tree remained between 0.30 and 0.50 kg for both treatments. Subsequently, the yield increased, with differences observed between the two planting densities as the trees aged. In both 2022 and 2023, significantly higher kernel yields per tree were recorded (1.75 kg and 2.70 kg per tree, respectively) in the sparse planting (833 trees per hectare) compared to the denser planting (1660 trees per hectare), which yielded 1.24 kg and 1.68 kg per tree, respectively.

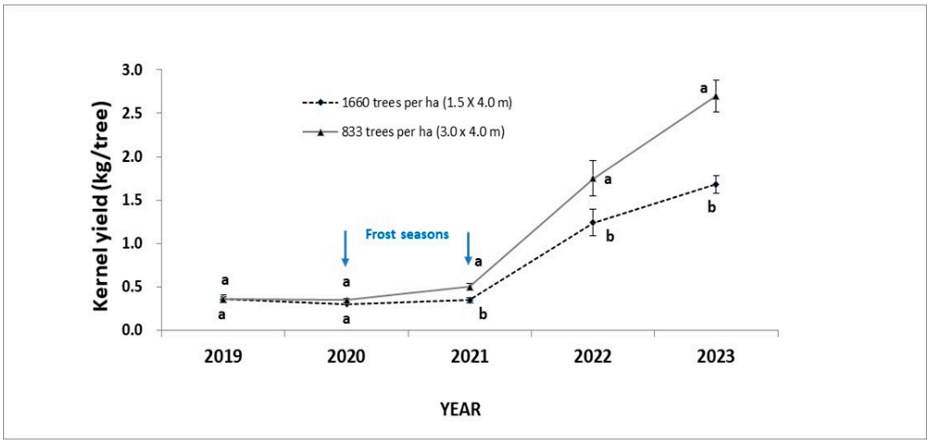

Figure 6. Evolution of kernel yield per tree of almond trees over 5 years (2019 to 2023) as influenced by planting densities (1660 and 833 trees ha^{-1}). The data are presented as average value ± SD. Different lowercase letters in each year for the two planting densities indicate significant differences at $p \leq 0.05$, according to the Tukey test.

The kernel yield per hectare (expressed in tons) over the 5-year period from 2018 to 2023 (Figure 7), unlike the yield per tree, showed higher values in the dense planting (1660 trees ha^{-1}) than in the lower density planting (833 trees ha^{-1}). In particular, the yield under the lowest planting density ranged from 0.60 t ha^{-1} in 2018 to 0.50 t ha^{-1}, 0.52 t ha^{-1}, 2.05 t ha^{-1}, and 2.81 t ha^{-1} in the following years. In comparison, under dense planting, the yield ranged from 0.30 t ha^{-1} in 2018 to 0.29 t ha^{-1}, 0.42 t ha^{-1}, 1.46 t ha^{-1}, and 2.25 t ha^{-1} in the subsequent years.

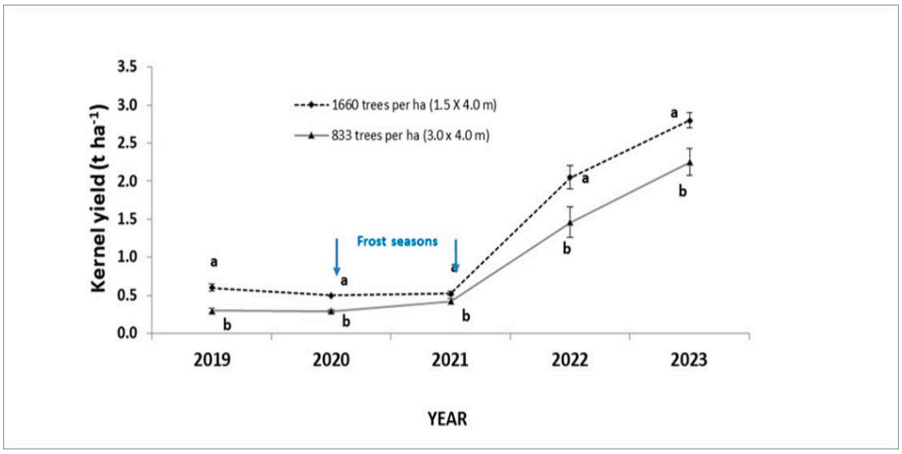

Figure 7. Evolution of kernel yield per hectare of almond trees over 5 years (2019–2023) as influenced by planting densities (1660 and 833 tree ha^{-1}). The data are average value ± SD. Different lowercase letters in each year for the two planting densities were significantly different at $p \leq 0.05$, according to the Tukey test.

3.4. Yield-Related Variables

The fruit quality parameters presented in Table 3 did not show statistically significant differences between the years or the planting density treatments. The mean percentage values for hull per fruit, kernel per nut, and double seeds over 5 years ranged from 46.7% to 50.3%, 30.1% to 32.1%, and 6.9% to 10.3%, respectively.

Table 3. Fruit quality parameters of almond over 5 years (2019–2023) as influenced by planting densities (1660 and 833 tree ha^{-1}).

Parameter	Planting Density (tree ha^{-1})	Year 2019	2020	2021	2022	2023
Hull per fruit (% of total fresh weight)	1660	48.9 ± 3.4	47.8± 3.0	46.7 ± 3.0	48.9 ± 2.9	50.1 ± 3.0
	833	50.3 ± 3.0	47.6 ± 4.1	49.1 ± 3.3	47.9 ± 2.2	48.4 ± 3.4
Shelling: kernel per nut dry (%)	1660	30.1 ± 0.9	31.3 ± 0.8	30.7 ± 0.9	31.3 ± 0.8	30.3 ± 0.8
	833	31.0 ± 0.8	32.1 ± 0.7	30. 2 ± 0.8	31.4 ± 0.9	31.3 ± 0.7
Double seeds (%)	1660	6.9 ± 3.5	8.1 ± 2.9	10.3 ± 2.5	10.1 ± 2.9	9.8 ± 2.9
	833	6.8 ± 2.9	9.0 ± 3.2	10.0 ± 2.9	9.3 ± 3.0	9.7 ± 2.7

The data are average value ± SD of the two planting densities (1660 and 833 tree ha^{-1}) in each year.

3.5. Nut and Kernel Morphological Traits

The morphological characteristics of the nuts, such as weight, length, width, and thickness, reported in Table 4, showed no statistical differences between planting densities or years, with average values ranging from 5.4 to 7.4 g for weight, 33.1 to 43.9 mm for length, 27.1 to 33.9 mm for width, and 17.4 to 24.6 mm for thickness, respectively.

Table 4. Morphological characteristics of almond nuts planted at two different densities (1660 and 833 tree ha^{-1}) in five consecutive years (2019–2023).

Parameter	Planting Density (tree ha^{-1})	Year 2019	2020	2021	2022	2023
Nut dry weight (g nut^{-1})	1660	6.8 ± 0.8	5.4 ± 0.7	5.8 ± 0.6	7.0 ± 0.6	6.8 ± 0.8
	833	6.7 ± 0.6	5.7 ± 0.6	6.0 ± 0.7	7.4 ± 0.8	6.9 ± 0.8
Nut length (mm)	1660	41.6 ± 2.0	33.1 ± 2.3	34.0 ± 2.3	42.0 ± 2.2	43.1 ± 2.0
	833	42.5 ± 2.0	42.5 ± 2.0	34.5 ± 2.2	43.1 ± 2.0	43.9 ± 1.9
Nut width (mm)	1660	32.0 ± 1.4	27.1 ± 1.4	28.2 ± 2.3	33.1 ± 1.4	33.7 ± 1.5
	833	32.3 ± 1.4	27.9 ± 1.5	29.0 ± 1.4	33.9 ± 1.5	34.1 ± 1.4
Nut thickness (mm)	1660	22.5 ± 0.8	18.4 ± 0.5	18.0 ± 0.9	23.9 ± 0.7	23.2 ± 0.8
	833	22.7 ± 0.7	18.5 ± 0.8	18.2 ± 0.8	23.8 ± 0.8	23.6 ± 0.9

The data are average ± SD of the two planting densities (1660 and 833 tree ha^{-1}) in each year.

Similar to nuts, the weight, length, width, and thickness of the kernels (Table 5) showed no statistical differences between years or planting densities, with average values ranging from 1.5 to 2.1 g for weight, 24.3 to 30.7 mm for length, 15.9 to 17.7 mm for width, and 7.3 to 8.9 mm for thickness. Furthermore, although there were no significant differences in kernel weight, slightly higher values were observed at the lowest planting density, where the weight ranged from 1.6 to 2.1 g. In comparison, the highest planting density showed kernel weights ranging from 1.5 to 1.9 g.

Table 5. Morphologic traits of almond kernel planted at two different densities (1660 and 833 tree ha^{-1}) over five consecutive years (2019–2023).

Parameter	Planting Density	Year				
	(tree ha^{-1})	2019	2020	2021	2022	2023
Kernel dry weight (g kernel^{-1})	1660	1.6 ± 0.3	1.7 ± 0.3	1.5 ± 0.2	1.8 ± 0.3	1.9 ± 0.4
	833	1.6 ± 0.2	1.8 ± 0.3	1.8 ± 0.3	2.0 ± 0.2	2.1 ± 0.3
Kernel length (mm)	1660	26.6 ± 2.4	26.3 ± 1.9	24.3 ± 2.3	29.7 ± 1.9	30.0 ± 2.0
	833	26.5 ± 2.4	25.9 ± 1.9	25.7 ± 1.7	29.9 ± 1.8	30.7 ± 1.9
Kernel width (mm)	1660	15.9 ± 1.5	16.6 ± 1.2	15.9 ± 1.1	17.1 ± 1.2	16.9 ± 1.2
	833	15.9 ± 1.3	16.5 ± 1.5	16.0 ± 1.3	18.1 ± 1.4	17.7 ± 1.5
Kernel thickness (mm)	1660	7.3 ± 1.5	8.1 ± 0.6	8.5 ± 0.6	8.7 ± 0.6	8.4 ± 0.5
	833	7.3 ± 1.0	7.3 ± 1.5	8.5 ± 0.6	9.3 ± 0.7	8.9 ± 0.6

The data are average ± SD of the two planting densities in each year.

3.6. Correlation Analysis

The correlation matrix relating the different vegetative and fruiting parameters is presented in Table 6. The results show that annual shoot length exhibited a moderately positive correlation with annual trunk growth (r = 0.49). Cumulative trunk diameter over the years showed a positive correlation with both kernel yield per hectare and kernel yield per tree (r = 0.54 and r = 0.69, respectively). Therefore, vegetative growth parameters are affected by year-to-year interaction. In contrast, both annual vegetative growth and annual trunk growth showed no significant correlation with cumulative trunk diameter or kernel yield, either per tree or per hectare. As expected, kernel yield per tree had a strong positive linear correlation with kernel yield per hectare (r = 0.89).

Table 6. Pearson correlation coefficient (r) among vegetative growth and productive parameters for the two planting densities of almond.

Parameter	Annual Shoot Length	Cumulative Trunk Diameter	Annual Trunk Growth	Kernel Yield per Hectare	Kernel Yield per Tree
Annual shoot length	1.00				
Cumulative trunk diameter	0.25 ns	1.00			
Annual trunk growth	0.49 *	0.23 ns	1.00		
Kernel yield per hectare	0.20 ns	0.54 *	0.26 ns	1.00	
Kernel yield per tree	0.32 ns	0.69 *	0.35 ns	0.89 **	1.00

Correlation significant at the 0.05 level (*p*-value 0.05); *: correlation significant at the 0.01 level (*p*-value 0.01); **: ns: not significant.

4. Discussion

This study aimed to evaluate the influence of two different inter-row tree spacings (4 × 1.5 m and 4 × 3.0 m, resulting in 1660 and 833 trees per hectare, respectively) of almond, cv. Tuono, on the vegetative growth and reproductive behavior of trees. Field experiments were conducted over five consecutive seasons (2019–2023), corresponding to the 3rd, 4th, 5th, 6th, and 7th year after planting.

4.1. Vegetative Growth

Overall, results showed that planting density has a clear impact on the tree growth. A positive increase was recorded in both shoot length (an average of 21.9%) and trunk diameter (an average of 39.8%) over the years in trees with the lowest intra-row spacing (3.0 × 4.0 m), compared to those with higher intra-row spacing (1.5 × 4.0 m). This means that tree growth is inversely correlated with the number of trees per hectare. These results align with those obtained in previous studies [13,20]. This suggests that lower planting densities may provide more favourable conditions for better growth, potentially due to factors such as reduced competition for resources like light, water, and nutrients. The increase in vegetative shoot growth can result in more buds that will support future production [11].

4.2. Fruit Development

Concerning the fruit development, immediately after fruit set, the fruit underwent a phase of rapid growth, reaching its maximum size (50 mm in length, 40 mm in width, and 30 mm in thickness) after about 45–50 days. Following this initial rapid growth, the fruit remained relatively stable in size. These results are consistent with the stage of development of almond fruit described in previous research [36–40].

4.3. Yield

The annual yield of almonds is known to be highly influenced by adverse weather events, especially during the post-setting and early fruit growth phases [41] In our trial, both 2020 and 2021 were characterized by spring frosts, and no significant increases in production were observed as the trees matured. During these years, the yield per tree remained between 0.30 and 0.50 kg for both treatments. In the 7th year after planting, the yield reached 2.70 kg per tree in the low-density planting and 1.69 kg per tree in the high-density planting. It is noted that by the 7th year after planting the trees in this study had not yet reached the peak production levels reported in previous research [28]. This may be due to irregular weather events, particularly unseasonal frosts that occurred during the years in question, which could have affected the growth and fruiting cycles of the almond trees. These conditions may have slowed the growth process and delayed full canopy development, preventing the trees from reaching maximum yield within the expected time frame.

However, overall, the kernel weight per tree increased significantly by 28.8% in the lower row spacing compared to the higher row spacing. These findings align with the results reported by Kumar et al. [23,42]. This increase is likely due to the greater availability of space, which facilitated enhanced nutrient uptake and translocation from the soil to the aboveground parts of the plant. As a result, the trees in the lower row spacing exhibited increased branch length, supporting a higher number of fruits per individual tree. In contrast, kernel yield per hectare increased significantly by 27.6% with higher tree density compared to lower density. Similar findings are in accordance with those reported by previous studies [23,28,42,43]. This increase is attributed to the higher number of trees per unit area, although they are smaller.

4.4. Correlation Analysis Between Vegetative Growth and Yield

Significant variation in vegetative and productive traits was observed across planting densities and years, largely due to seasonal frost events. Annual shoot length positively correlated with annual trunk growth, while cumulative trunk diameter was positively associated with kernel yield per tree and per hectare. Almond yield related to tree size was also reported by Hill et al. [44]. However, no correlation was found between annual vegetative growth and either cumulative trunk growth or kernel yield. Similarly, cumulative trunk diameter showed no correlation with annual trunk growth or kernel yield, likely due to high interannual variability.

Therefore, this study highlights the complexity of the relationship between tree growth and fruiting, with climatic conditions, particularly frost, being major influencing factors that introduce variability into the expected patterns of growth and fruit production in almond trees. Similar conclusions were also made by Mosie et al. [45].

4.5. Fruit Characteristics

The fruit incidence characteristics, such as hull, shelling, and double seed percentages, showed no statistical differences either between the years or across plant density treatments. These traits are primarily determined by genotype, but environmental factors also play a role [46–49]. Our hull percentage data (on average 44.9%) are consistent with data previously reported in the literature (EPA, 1995) [50] as is the percentage of shelling (on average 30.1%), which falls within the 30–40% range reported in previous research [8,36,41,51–54]. In contrast, our data regarding the percentages of double seeds (on average 7.6%) are lower than those obtained for the same Tuono cultivar (between 15% and 31%) by other authors [8,46–49,51]. Indeed, as for the incidence of each single part of the fruit, they are primarily determined by genotype but also by environmental factors [46–49]. Therefore, in this regard, our data show distinctive and commercially interesting agronomic characteristics.

Regarding the morphological traits of nuts and kernels, such as weight, length, width, and thickness, no statistical differences were observed between planting density treatments and years.

Only for kernel weight, although it showed no significant differences, were slightly higher values observed at the lowest planting density (ranging from 1.5 to 1.9 g) compared to the highest planting density (ranging from 1.6 to 2.1 g). Our results are in contrast with those of Kumar [23], who reported that for all the abovementioned traits significantly higher values were recorded at lower plant densities.

In this trial, the average values for the nuts ranged from 5.4 to 7.4 g for weight, 33.1 to 43.9 mm for length, 27.1 to 33.9 mm for width, and 18.4 to 23.9 mm for thickness. For the kernels, the average values ranged from 1.5 to 2.1 g for weight, 24.3 to 30.7 mm for length, 15.0 to 18.1 mm for width, and 7.3 to 9.3 mm for thickness. These results are notably superior to those reported for the same Tuono cultivar in other studies [8,55–58]. In those studies, the nuts ranged from 3 to 4 g in weight, 28 to 34 mm in length, 21 to 23 mm in width, and 15 to 20 mm in thickness, while the kernels ranged from 1.2 to 1.4 g in weight, 23.4 to 23.9 mm in length, 12.2 to 14.9 mm in width, and 6.3 to 7.2 mm in thickness. Therefore, our data demonstrate distinctive and commercially interesting agronomic characteristics.

5. Conclusions

In this study, two different planting densities in Tuono almond orchards were compared under similar culture conditions over a 5-year period (2019–2023): 1660 trees per hectare (achieved with 1.5 m intra-row spacing × 4.0 m inter-row spacing) and 833 trees per hectare (3.0 m × 4.0 m spacing).

The results show that the almond fruit growth after fruit set follows a rapid growth phase followed by size stability, with similar development observed across both planting density systems.

On the other hand, planting density significantly impacted both vegetative and productive parameters of almond trees.

In irrigated areas with semi-arid climates, such as the one where the trials were conducted, the yield per hectare increased with a higher planting density of 1660 trees per hectare compared to a lower density of 866 trees per hectare. This increase is attributed to the greater number of trees per unit area. Although the individual trees at the higher density are smaller than those at the lower density, their overall performance is better.

Although the high-density orchard of 1660 plants per hectare produced higher yields during the 3- to 7-year age range in our experiment, the long-term consequences remain uncertain. Extending the observation period beyond 7 years would provide more comprehensive insights into tree development and the timing of peak yield. Long-term research is essential to evaluate the effects of tree age—especially in mature orchards—as well as to better understand factors such as canopy development and disease management. These insights will be critical for enhancing almond production in a more sustainable and efficient manner.

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