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Yield and fruit quality of avocado grown at different planting densities in Colombia

Abstract – The objective of this work was to determine the effect of planting densities on the yield and quality of 'Hass' avocado (*Persea americana*) in the department of Antioquia, Colombia. The experimental design was randomized complete blocks with three replicates. The treatments were six plant densities (204, 278, 333, 400, 625, and 816 trees per hectare) with five harvest seasons, and each experimental unit consisted of six nine-year-old trees. The highest fruit yield is obtained at 333 and 400 trees per hectare. The main harvest represents 70% (18 Mg ha^{-1}) of the annual production, whereas the secondary (*mitaca*) harvest represents 30% (5.25 Mg ha^{-1}). Yield per tree and number of avocado fruits per tree are negatively affected by the increase in planting densities. In addition, fruit quality parameters show better results at intermediate planting densities of 333 and 400 trees per hectare, with the highest ratios of mesocarp and the lowest of seed, both in fresh and dry weight.

Index terms: *Persea americana*, planting system, tree spacing, yield potential.

Produção e qualidade de fruto de abacateiro cultivado a diferentes densidades de plantio na Colômbia

Resumo – O objetivo deste trabalho foi determinar o efeito de densidades de plantio na produção e na qualidade do abacateiro 'Hass' (*Persea americana*) no departamento de Antioquia, Colômbia. O delineamento experimental foi de blocos ao acaso, com três repetições. Os tratamentos foram seis densidades de plantio (204, 278, 333, 400, 625 e 816 árvores por hectare) com cinco colheitas, e cada unidade experimental consistiu em seis árvores com nove anos de idade. O maior rendimento é obtido às densidades de 333 e 400 árvores por hectare. A colheita principal representa 70% (18 Mg ha^{-1}) da produção anual, enquanto a colheita secundária (*mitaca*) representa 30% (5.25 Mg ha^{-1}). A produção por árvore e o número de frutos de abacate por árvore é afetado negativamente pelo aumento das densidades de plantio. Além disso, os parâmetros de qualidade dos frutos apresentam melhores resultados nas densidades de plantio intermediárias de 333 e 400 árvores por hectare, com as maiores proporções de mesocarpo e a menor de sementes, tanto em massa fresca quanto em seca.

Termos para indexação: *Persea americana*, sistema de plantio, espaçamento entre árvores, potencial de rendimento.

Lucas Esteban Cano-Gallego[1 ✉],
Sara Isabel Bedoya-Ramírez[2],
Jorge Alonso Bernal-Estrada[1],
Carlos Felipe Barrera-Sánchez[3] and
Oscar de Jesús Córdoba-Gaona[3]

[1] Centro de Investigación La Selva, Km 7, vía Rionegro-Las Palmas, Sector Llanogrande, Rionegro, Antioquia, Colombia. E-mail: lcanog@agrosavia.co, jbernal@agrosavia.co

[2] Avofruit S.A.S, Carrera 33, nº 7-29, Edificio Bianco, Medellín, Colombia. E-mail: sbedoya@cartama.com

[3] Universidad Nacional de Colombia, Facultad de Ciencias Agrarias, Carrera 65, nº 59A-110, Bloque 11-117-10, Medellín, Colombia. E-mail: cfbarreras@unal.edu.co, ojcordobag@unal.edu.co

✉ Corresponding author

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Introduction

According to Food and Agriculture Organization of the United Nations (FAO, 2021), the production of avocado (*Persea americana*

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Mill.) worldwide was 7,179,689 tons in 2019, with the main producing countries being Mexico, Dominican Republic, Peru, and Colombia, representing 32, 9.2, 7.5, and 7.5% of the total; however, considering the 726,660 ha of harvested area, Mexico and Colombia stood out covering 29.7 and 8.7%, respectively. In the last decae, from 2009 to 2019, Colombia increased its planted area from 19,225 to 63,534 ha and its production from 189,029 to 535,021 tons, representing respective increases of 229 and 183% (FAO, 2021).

Avocado can be grown successfully from the tropics to the subtropics, at a latitude of 35°, up to a height of 15 to 18 m (Menzel & Le Lagadec, 2014). According to the same authors, trees typically thrive in commercial orchards, which are traditionally planted at a spacing of 7.0x7.0 or 10x10 m, with 204 or 100 trees per hectare. Yield per unit, however, is low during the first years after planting, increasing until trees begin to shade each other and decreasing after approximately five to ten years, which explains the great interest in using high-density plantings to increase productivity and yield especially in the early life of orchards (Menzel & Le Lagadec, 2014).

A closer spacing by controlling tree size allows of higher initial yields per planted area (Köhne & Kremer-Köhne, 1991), with a consequent net return due to the higher number of plants per hectare (Ladaniya et al., 2020). Menzel & Le Lagadec (2014) and Reddy (2022) added that, at high densities, maximum land use is possible, showing potential for a higher yield than traditional planting systems, particularly during the first years of production. When comparing avocado yield in high- and standard-density systems, with 800 and 400 trees per hectare, respectively, Köhne & Kremer-Köhne (1991) found that, although yield per tree was similar (43.5 kg), fruit production doubled in the first three years of harvest at the higher density (34.4 vs 17.6 Mg ha^{-1}).

In the case of Colombia, most modern avocado orchards are planted with 159 and 416 trees per hectare, in a 9.0×7.0 and 6.0×4.0 m design, respectively, determined according to topography, cultivar, pruning systems, and training (Estrada & Díez, 2020). However, recently, orchards have been established at high densities, which, due to the intensive use of pruning practices, has led to a severe incidence of pests and diseases and to cost overruns in labor (Estrada & Díez, 2020). This shows the importance of identifying and defining cultivation practices for different avocado tree densities.

In addition, avocado production in the country is still low, with an average yield of 8.42 Mg ha^{-1}, below the global average of 9.88 Mg ha^{-1} (FAO, 2021), which can be attributed to the existing high genetic and agroecological variability, resulting in heterogeneous production systems and, consequently, in heterogenous fruit (Carvalho et al., 2014). Therefore, it is necessary to develop strategies to increase yield per area in a sustainable way considering the events that occur throughout plant reproductive development in Colombia (Rebolledo & Romero, 2011).

The objective of this work was to determine the effect of planting densities on the yield and quality of 'Hass' avocado in the department of Antioquia, Colombia.

Materials and Methods

The research was carried out in two nine-year-old commercial orchards of cultivar Hass avocado grafted onto Creole rootstocks during three consecutive years, from 2019 to 2021. Both orchards were located in the Antioquia department of Colombia: one in the municipality of Rionegro (06°5'56.8"N, 075°26'21.9"W, at 2,200 above mean sea level) and the other in the municipality of El Peñol (06°11'28.4"N, 075°14'34.4"W, at 2,100 above mean sea level).

The climatic variables recorded through the Watchdog 2000 portable meteorological station (Spectrum Technologies, Aurora, IL, USA) are presented in Figure 1. The climate of the region is Cw, subtropical dry winter, according to Köppen-Geiger's classification (Belda et al., 2014). Throughout the three study years, in the municipalities of El Peñol and Rionegro, the average minimum temperatures were 15 and 13°C, the average maximum temperatures were 23 and 24°C, and the average annual precipitation was 2,236 and 1,367 mm.

The soil of the experimental area is representative of the region, being classified as an Andosol according to World Reference Base for soils of FAO (Delmelle et al., 2015).

The experimental design was a randomized complete block with three replicates. The treatments consisted of the six following planting densities: 7.0x7.0 m, with 204 trees per hectare; 6.0x6.0 m, with 278 trees per hectare; 6.0x5.0 m, with 333 trees per hectare; 5.0x5.0 m, with 400 trees per hectare; 4.0x4.0 m ,with 625 trees per hectare; and 3.5x3.5 m, with 816 trees per hectare. Each experimental unit consisted of six trees.

Five harvest seasons were carried out from 2019 to 2021: three main harvests in December–January of 2019, 2020, and 2021, with flowering in February–March of the previous year; and two secondary (known as *mitaca* or *traviesa*) harvests in June–July of 2020 and 2021, with flowering in August-September of the previous year.

After each harvest (main and *mitaca*), the soil was analyzed for fertility from 2019 to 2021 (Table 1). For this, subsamples were taken below the canopy of the trees at a depth of 0–30 cm. The subsamples were mixed to obtain a composite sample for the chemical analysis of: pH; organic matter; P, K, Ca, Al, Mg, S, Fe, Mn, Zn, Cu, and B contents; cation exchange capacity (CEC); and electrical conductivity (EC).

All commercial-sized fruit (including those for industrial processing) were harvested, counted, weighed, and, then, blended to obtain the average yield for each plot, estimated as the weighted sum of the total fruit harvested per tree at each harvest time and for each treatment. Yield per hectare was adjusted for plant density and yield per tree. In each experimental year, the following data were recorded for each tree: height; rootstock height, considered as the distance from the root collar to the graft union; trunk diameter at 5.0 cm above (TDA) and below (TDB) the graft; graft union; canopy height, considered as the difference between tree height and canopy base; north-south longitude within the planting furrow; and east-west longitude of the canopy between planting furrows. From these data, canopy volume was determined for each tree using the equation for an irregular ellipsoid: [$V = (\pi \times x \times y \times z)/ 6$)] (Wilkie et al., 2019). Volume per area corresponded to the ratio between canopy

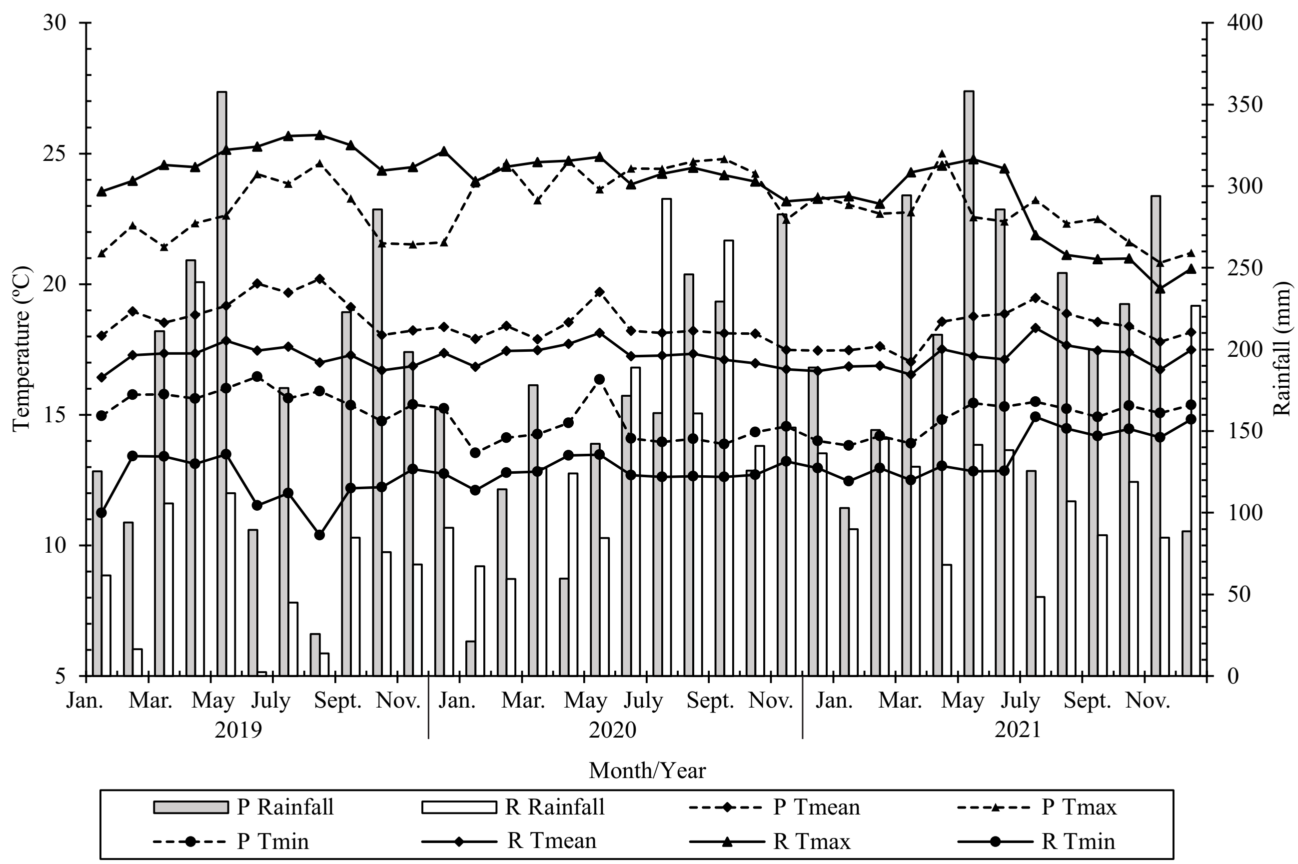

Figure 1. Monthly maximum (Tmax), minimum (Tmin), and mean (Tmean) temperatures, as well as monthly rainfall, from 1/1/2019 to 31/12/2021, in the municipalities of Peñol (P) and Rionegro (R), in the department of Antioquia, Colombia.

volume and number of trees per hectare for each planting density.

To determine the average fruit parameters per treatment, 25 fruit per tree (150 fruit per treatment in six trees) were randomly selected to obtain fresh fruit weight (g), longitudinal and equatorial diameters (cm), and epicarp, mesocarp, and seed fresh and dry matter ratios (%). Subsequently, the epicarp, mesocarp, and seed were weighed. Then, each of the tissues was dried in an oven with forced-air circulation, at 60°C, for 72 hours or until a constant weight was reached, in order to determine the dry weight of the epicarp, mesocarp, seed, and fruit.

The statistical analysis was performed using the agricolae package in the R software (R CORE TEAM, 2021). The results were developed through a two-way analysis of variance for two factors: planting stand (204, 278, 333, 400, 625, and 816 trees per hectare) and harvest (main harvest in 2019, 2020, and 2021, and *mitaca* harvest in 2020 and 2021). Differences between means were evaluated through the analysis of variance, followed by Tukey's honestly significant difference test for mean comparison, with a probability higher than 95%. For the evaluation of soil fertility, a principal component analysis was performed using the same statistical package.

Results and Discussion

The chemical variables of the soil where the avocado trees were established, presented in Table 1, were subjected to principal component analysis considering different plant densities (Figure 2 A) and harvest seasons (Figure 2 B). At the plant density of 333 trees per hectare, the soil presented the highest pH and the lowest contents of organic matter, S, Fe, EC, B, and K, whereas, at the plant density of 625 trees per hectare, it showed an inverse behavior. At the plant density of 916 trees per hectare, the soil had the highest CEC and Ca and Mg contents. Despite these differences, the soil presented similar chemical attributes during the three years of evaluation.

Avocado fruit yield varied significantly between plant densities and harvest times. The highest yield of 19 Mg ha^{-1} occurred at the densities of 333 and 400 trees per hectare, while the lowest ones of 6.0 and 8.0 Mg ha^{-1} were observed at the low densities of 204 and 278 trees per hectare, respectively. Comparatively, the high densities of 625 and 816 trees per hectare produced average yields from 12 to 13 Mg ha^{-1} (Figure 3 A). Also for 'Hass' avocado, Stassen et al. (1999) reported higher yields of 13.60 and 9.60 Mg ha^{-1} at the high densities of 1,666 and 600 trees per hectare, respectively, 43 months after planting. In citrus crops at high densities, Ladaniya et al. (2020) found that, although fruit yield per plant was low, it was more than two fold that of the control per area.

Regarding the harvest factor in the three study years, the highest fruit yield was obtained in the main harvest, with a mean of 18 Mg ha^{-1}, compared with that of 5.25 Mg ha^{-1} in the *mitaca* harvest, representing 70 and 30%

Table 1. Soil fertility analysis of the plots for each of the evaluated plant densities and harvests of 'Hass' avocado (*Persea americana*) in the municipalities of Peñol and Rionegro, in the department of Antioquia, Colombia.

Plant density (trees per hectare)	pH H_2O	EC (dS m^{-1})	OM (%)	P	S	CEC	Ca	Al	Mg	K	Fe	Cu	Mn	Zn	B
				----(mg kg^{-1})----		-------------------(cmol$_c$ kg^{-1})-------------------					--------------------(mg kg^{-1})--------------------				
204	5.2	1.61	20.3	101	63.2	15.16	10.9	0.77	1.94	1.11	103.7	5.62	21.5	73.36	1.57
278	5.2	1.34	17.5	55.9	75.32	8.90	5.59	0.75	1.25	0.85	138.6	8.29	10.7	51.02	1.98
333	5.9	1.03	10.2	78.7	33.46	16.66	13.4	0.00	2.18	0.93	124.2	5.36	11.8	46.94	2.10
400	5.4	1.33	20.8	112	50.13	17.18	13.3	0.38	2.15	0.95	109.7	6.04	26.1	75.68	1.42
625	5.2	1.73	21.5	96.4	119.8	13.05	7.15	1.21	2.28	1.72	573.8	12.04	14.6	103.1	5.23
816	5.8	0.98	19.1	141	45.51	17.14	12.3	0.00	3.33	1.40	114.4	4.73	7.57	127.5	2.55
Year + harvest(1)															
2019P	5.3	1.54	19.8	73.5	84.71	14.87	10.3	0.63	2.06	1.48	246.7	6.31	8.3	89.09	2.82
2020M	5.5	1.36	17.0	66.8	59.39	13.45	9.37	0.55	1.83	1.13	152.1	5.85	26.1	53.12	4.26
2020P	5.4	1.40	14.6	84.4	53.56	15.05	11.1	0.57	2.02	1.03	164.6	8.74	22.6	66.18	2.20
2021M	5,7	0.86	17.7	85.6	46.3	1356	10.1	0.24	2.33	0.69	143.6	6.42	16.2	73.17	1.10
2021P	5.6	1.12	18.9	226	38.26	16.10	11.7	0.39	2.95	0.85	158.1	9.16	17.6	97.55	1.31

(1)P, main harvest; and M, secondary (*mitaca*) harvest. EC, electrical conductivity; OM, organic matter; and CEC, cation exchange capacity.

of the annual production, respectively (Figure 3 B). For yield per tree, the treatments of 333 and 400 trees per hectare presented the highest fruit production of 57.5 and 49.5 kg per tree, respectively. For yield per area, the low densities showed an intermediate mean fruit production of 38.8 and 21.3 kg per tree, whereas

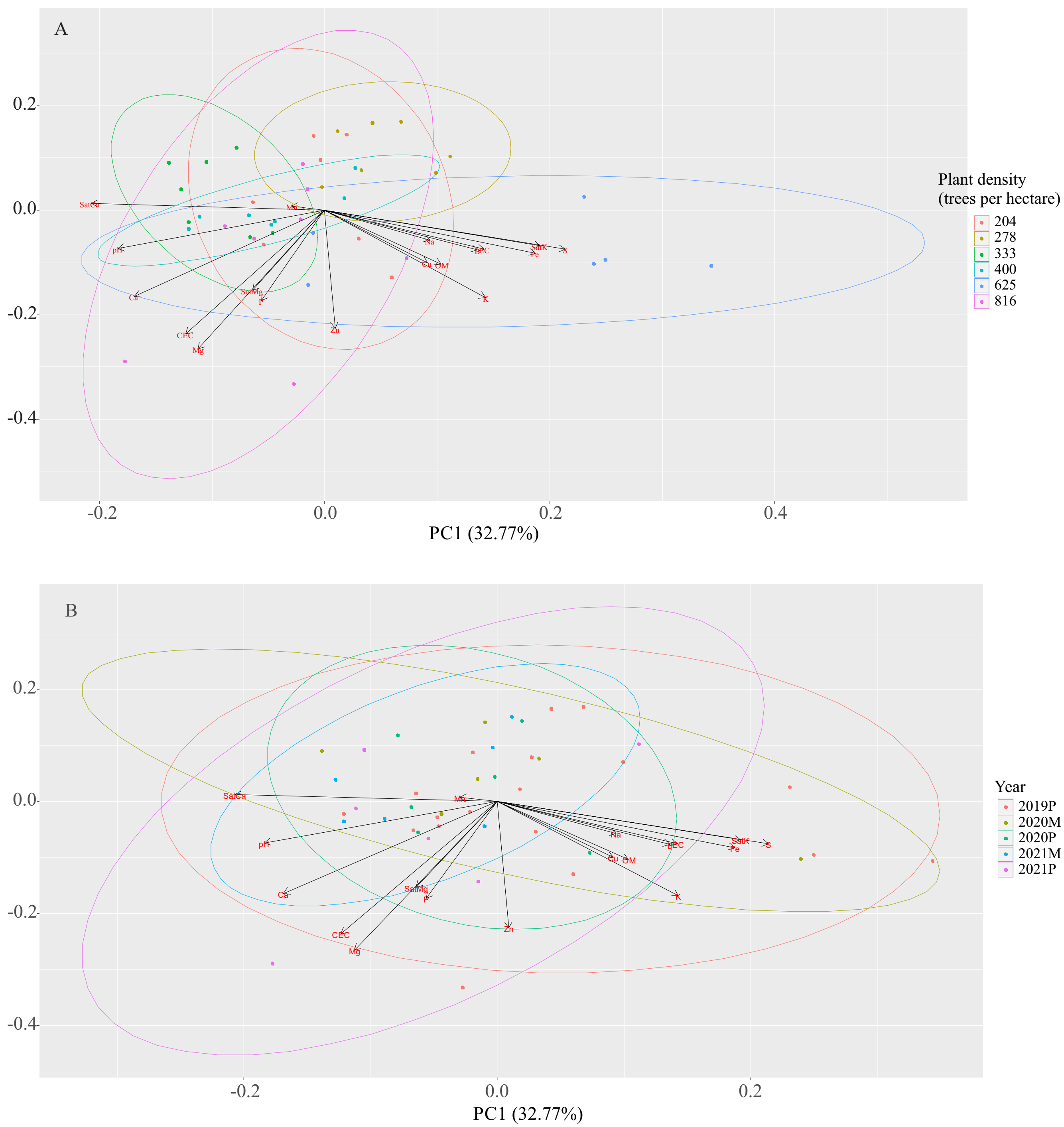

Figure 2. Principal component analysis for chemical soil variables as a function of six plant densities (A) and five harvests (B) of 'Hass' avocado (*Persea americana*). Mean values correspond to five chemical soil analyses (harvests) over three years (2019–2021) in the municipalities of Peñol and Rionegro, in the department of Antioquia, Colombia. P, main harvest; and M, secondary (*mitaca*) harvest.

the high densities had the lowest yields per tree of 17.9 and 6.3 kg per tree (Figure 3 C). For 'Bacon' avocado on 'Mexicola' rootstock in Chile, Razeto et al. (1992) observed that yield per hectare increased to 69.9 Mg ha^{-1} until the seventh year at a high-planting density of 1,250 trees per hectare, reaching only 24.4 and 43.5 Mg ha^{-1} at the low and intermediate densities of 277 and 600 trees per hectare, respectively. In the

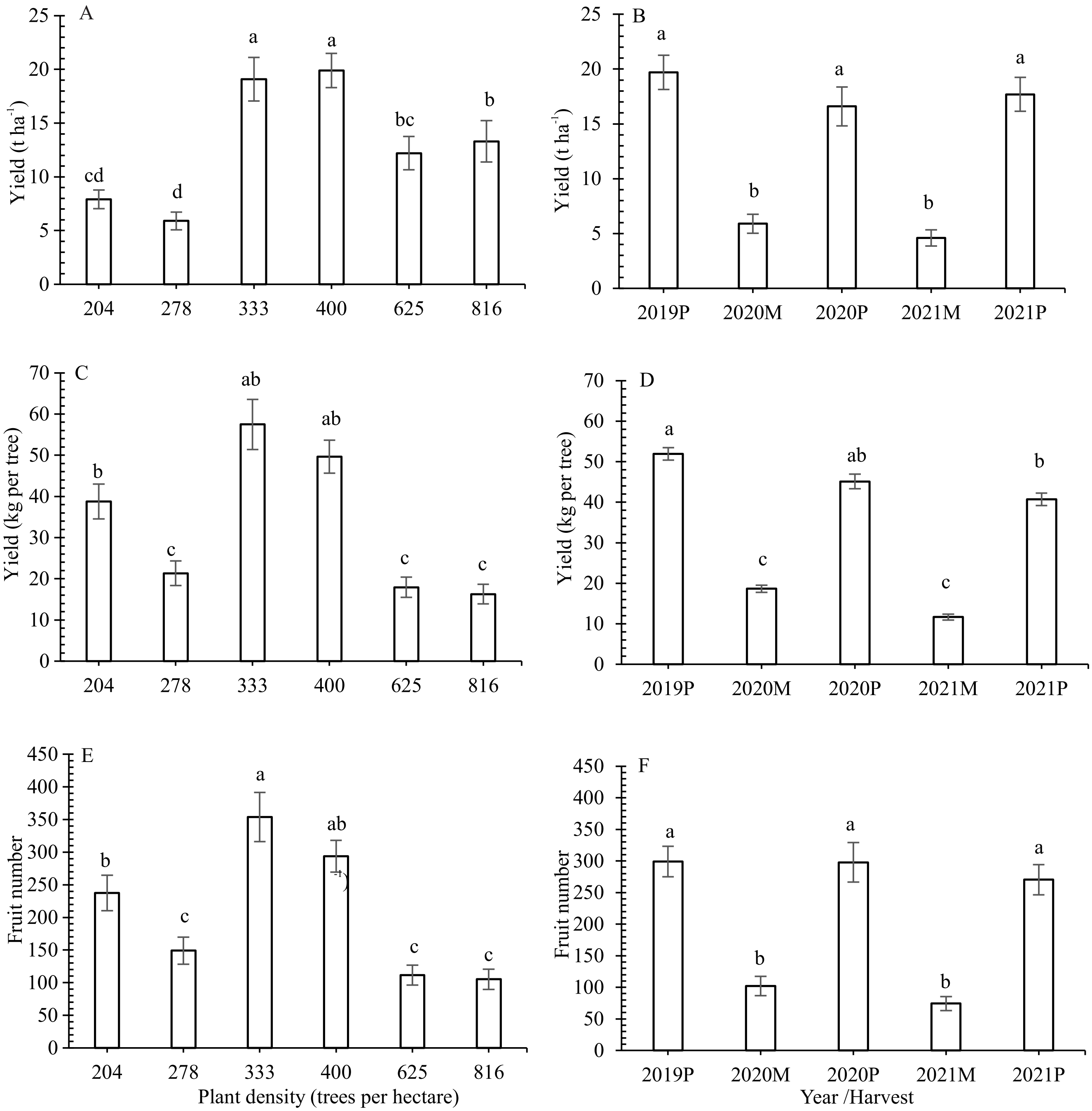

Figure 3. Mean values of fruit yield (A), fruit yield per tree (C), and fruit number per tree (E) for each plant density, as well as fruit yield (B), fruit yield per tree (D), and fruit number per tree (F) for each harvest year of 'Hass' avocado (*Persea americana*) in the municipalities of Peñol and Rionegro, in the department of Antioquia, Colombia. Means followed by equal letters do not differ by Tukey's honestly significant difference test, at 5% probability. Error bars indicate the standard error. P, main harvest; and M, secondary (*mitaca*) harvest.

present study, yield per tree and yield per area showed a similar behavior similar. The main harvest produced, on average, 45.9 kg per tree, which was three times the value of 15.2 kg per tree in the *mitaca* harvest (Figure 3 D).

The behavior of number of fruits per tree was similar to that of yield per tree. The intermediate densities of 333 and 400 trees produced, on average, 323 fruits per tree, the low densities of 204 and 278 trees per hectare produced 193 fruits per tree, and the high densities of 625 and 816 trees per hectare produced 108 fruits per tree (Figure 3 E). This shows that the harvest factor behaved similarly to the yield factor, with a higher average number of 289 fruits in the main harvest compared with that of 88 fruits in the *mitaca* harvest (Figure 3 F).

According to the obtained results, 200 more fruits were produced per tree in the main harvest, which is considered an "on" year, characterized by intense flowering, a high fruit-set percentage, and a high yield, differently from the *mitaca* harvest, with low flowering, a low fruit-set percentage, and a low yield, behaving as an "off" year (Garner & Lovatt, 2016) with a higher shoot growth due to the decreased inflorescence from one production cycle to the next (Rebolledo & Romero 2011; Salazar-García et al., 2016). Therefore, under tropical conditions, the avocado productive cycle involves a high harvest load in the "on" year and a low one in the following cycle in the "off" year (Garner & Lovatt, 2016), which are represented by the main harvest in December-January and the secondary (*mitaca*) harvest in June-July, depending on water availability and dry season.

All tree canopy growth variables were statistically significant for planting densities and harvest times (Table 2). In general, the lowest values for these variables were obtained at the high densities of 625 and 816 trees per hectare, whereas the low and intermediate densities did not differ regarding tree growth during the three years of evaluation. Canopy volume and canopy volume per area showed an inverse behavior with the increase in number of plants per hectare, as follows: the first tended to decrease with increasing densities, going from 84 to 42.2 m^3 per tree, whereas the second increased with the increase of planted trees, varying in 100% between 207 and 816 trees per hectare (Table 2).

The canopy volumes of 28,000 and 36,000 m^3 per hectare were associated with the highest yields achieved at the densities of 333 and 400 trees per hectare, respectively, coinciding with the values obtained in the study of Wilkie et al. (2019), who reported an increase in yield per hectare up to approximately

Table 2. Effect of plant density and harvests on shoot growth of 'Hass' avocado (*Persea americana*) trees in the municipalities of Peñol and Rionegro, in the department wof Antioquia, Colombia[(1)].

Plant density[(2)]	Factor[(3)]									
	H (m)	RH (cm)	TDA (cm)	TDB (cm)	GU (cm)	CH (m)	NS (m)	EW (m)	TCV (m^3)	CVA (m^3 ha^{-1})
p-value[(4)]	8.94e-16	1.93e-11	< 2e-16	< 2e-16	< 2e-16	< 2e-16	<2e-16	< 2e-16	< 2e-16	< 2e-16
204 trees per hectare	4.28cd	0.24ab	23.2a	25.01a	28.33ab	4.01cd	6.30a	6.1a	84.0b	17,135c
278 trees per hectare	4.81b	0.21cd	23.9a	25.18a	28.83ab	4.72b	5.8ab	5.6b	84.0b	23,357b
333 trees per hectare	5.41a	0.20d	23.9a	23.76a	28.47ab	5.22a	6.2a	6.2a	109.8a	36,554a
400 trees per hectare	4.65bc	0.23bc	23.3a	25.07a	29.60ab	4.40bc	5.6bc	5.4bc	71.4bc	28,569b
625 trees per hectare	4.68bc	0.25ab	22.6a	24.39a	27.39b	4.40b	5.1c	5.1c	63.9c	39,964a
816 trees per hectare	4.11d	0.26a	17.0b	17.96b	20.84c	3.84d	4.4d	4.5d	42.2d	34,460a
Year + harvest[(5)]/ p-value[(4)]	< 2e-16	0.00011	0.0061	< 2e-16	0.00006	< 2e-16	0.1298	0.000039	5.91e-12	4.44e-11
2019P	5.56a	0.21b	21.4b	13.25b	26.31c	5.35a	5.7a	5.6ab	93.5a	37,042a
2020M	4.38b	0.25a	21.9ab	26.46a	26.77bc	4.18b	5.7a	5.3bc	69.0bc	26,718b
2020P	4.39b	0.23a	22.5ab	26.90a	27.56ab	4.20b	5.7a	5.8a	78.0b	30,093b
2021M	4.29b	0.24a	23.2a	27.63a	28.33a	4.04b	5.4a	5.3c	63.0c	26,173b
Mean	4.66	0.23	22.3	23.56	27.27	4.44	5.6	5.5	75.9	30,006

[(1)]Means followed by equal letters, in the columns, do not differ by Tukey's honestly significant difference test, at 5% probability. [(2)]Plant density values are means of five measurements over three years (2019–2021). [(3)]H, tree height; RH, rootstock height; TDA, trunk diameter at 5.0 cm below graft union; TDB, trunk diameter at 5.0 cm above graft union; GU, graft union; CH, canopy height; NS, north-south longitude; EW, east-west longitude; TCV, tree canopy volume; and CVA, canopy volume per area. [(4)]p-values less than 0.05 show significant differences for the analysis of variance. [(5)]P, main harvest; and M, secondary (*mitaca*) harvest.

80–84% total light interception and 30,000–35,000 m^3 canopy volume. These authors documented the relationship between canopy volume per area, total light interception by trees, and yield per hectare for 'Hass' avocado trees grown in low-density planting systems. They found that the total light interception of the orchard increased with canopy volume, but that light interception per canopy volume of each tree decreased as canopy volume per area increased.

Regarding avocado fruit quality, Wilkie et al. (2019) did not observe shading effects on fruit growth and final size when light interception increased. However, in an apple (*Malus* × *domestica* Borkh.) orchard, Lordan et al. (2018) concluded that differences in fruit quality were likely due to the poorer light distribution at higher plant densities. For acid lime (*Citrus aurantifolia* Swingle) at low densities, Ladaniya et al. (2020) observed that plants did not make the best use of the resources available for their growth due to their low canopy volume during the first years after planting. In this sense, Lordan et al. (2018) highlighted the importance of determining the right combination between cultivar and plant density to obtain the best light distribution within the canopy and, consequently, the highest yield and fruit quality. This shows the need of developing approaches for an optimal planning to increase production while incorporating sustainability metrics (González-Estudillo et al., 2017).

Mokria et al. (2022) concluded that avocado production is often compromised depending on cropping density and canopy size. At high densities, due to canopy volume, trees tend to crowd despite efforts to control shoot growth by pruning or applying growth regulators (Menzel & Le Lagadec, 2014). At these densities, crowding occurs one or two years earlier than at traditional densities, showing the need for tree-shape manipulation (Köhne, 1988), as well as for the removal of alternate trees in avocado orchards (Köhne, 1988; Köhne & Kremer-Köhne, 1992). Despite this, when comparing tree stands, high planting densities show financial advantages as long as the individual tree produces enough fruit to cover the costs with it before its removal (Köhne & Kremer-Köhne, 1992). In addition, at high densities, individual trees produce more biomass than at low and intermediate ones (Farooq et al., 2019).

These results are an indicative that the success of high-planting density depends on the use of methods to control shoot growth and maximize light interception as trees begin to fruit (Menzel & Le Lagadec, 2014). Ramírez-Gil et al. (2021) highlighted that management practices, such as pruning, are adopted to avoid the incidence of postharvest diseases and disorders in high-density plantings.

Rootstock height, TDA, TDB, and graft union increased over the three experimental years. Canopy trunk diameter showed the highest increase of 14 cm, which is noticeable when compared with that of 3.0 cm in graft diameter. Tree height, canopy height, north-south longitude, and east-west longitude showed a constant behavior, which depends on the management of the avocado tree canopy through pruning to maintain an adequate distance between trees at each planting density (Table 2).

Trunk diameter was wider at the lower planting density, as also observed for 'Rocha' avocado by Pasa et al. (2015). Tun et al. (2018) and Smith & Samach (2013) concluded that higher planting densities significantly affect tree growth since the resources for tree and crown development are directed to fruit and not vegetative growth. In addition, root growth may be suppressed at higher densities due to the closer spacing, leading to a greater competition for soil resources (Pasa et al., 2015), which affects stand development (Farooq et al., 2019).

Avocado fruit variables varied in response to planting densities and harvest times (Table 3). For planting densities, the highest equatorial/longitudinal diameter ratio was observed for fruit harvested from trees planted at the intermediate densities of 333 and 400 trees per hectare, contrasting with low and high densities, which presented lower values. A high ratio indicated more elongated fruit, whereas a low one indicated more circular fruit. Therefore, the low and high densities tended to produce rounder fruit, while the intermediate ones produced more elongated pear-shaped fruit, which is characteristic of the Hass cultivar. Fruit weight did not vary consistently across plant densities, with the highest values found at 204, 400, and 625 trees per hectare, being 7.0% higher than those obtained at 278, 333, and 816 trees per hectare. Moreover, dry matter accumulation at harvest, which averaged 26%, was not significantly affected by plant density.

Regarding harvest times, fruit-associated variables showed the highest values in the main harvest in 2019, in the *mitaca* harvest in 2020, and in the main harvest in 2020, when compared with the *mitaca* harvest in 2021 and the main harvest in 2021 (Table 3). Although yield was not significantly affected in the main harvest, the fruits produced in 2021 showed the lowest dry matter accumulation in the epicarp, mesocarp, and seed tissues. Fruit dry matter was also not significantly affected, with a mean value of 26% across the five harvests.

The highest proportions of pulp and the lowest seed fresh weight/dry weight ratio were obtained at the densities of 333 and 400 trees (Table 3), which resulted in 69.9 and 68.2% mesocarp fresh matter, 63.3 and 62.5% mesocarp dry matter, 13.9 and 14.5% seed fresh weight, and 21.8 and 23.4% seed dry weight. Salazar-García et al. (2016), evaluating the quality of 'Hass' avocado fruit produced in three regions of Mexico, found values of 64.65 and 69.83% for mesocarp fresh weight, 58.88% for mesocarp dry weight, 12.28 and 16.16% for seed fresh weight, and 18.87 and 24.91% for

Table 3. Effect of plant density and harvests on 'Hass' avocado (*Persea americana*) in the municipalities of Peñol and Rionegro, in the department of Antioquia, Colombia[(1)].

Plant density[(2)]	Factor[(3)]					
	ED (cm)	LD (cm)	ED/LD	EpFW (g)	MeFW (g)	SeFW (g)
p-value[(4)]	< 2e-16	< 2e-16	< 2e-16	1.74e-10	< 2e-16	< 2e-16
204 trees per hectare	6.45ab	8.12b	1.26c	31.32a (17.8%)	114.17b (64.7%)	29.71ab (16.9%)
278 trees per hectare	6.22c	7.52d	1.21d	29.29ab (18.7%)	97.4 d (62.2%)	27.62bc (17.6%)
333 trees per hectare	6.18c	8.26ab	1.34a	26.00c (15.9%)	114.08b (69.9%)	22.64c (13.9%)
400 trees per hectare	6.43b	8.45a	1.32b	29.59a (16.5%)	122.64a (68.2%)	26.13c (14.5%)
625 trees per hectare	6.57a	7.78c	1.18d	30.06a (16.6%)	115.70ab (63.8%)	31.63a (17.4%)
816 trees per hectare	6.28c	7.85c	1.25c	27.08bc (16.4%)	106.13c (64.2%)	29.16b (17.6%)
Year + harvest[(5)]/p-value[(4)]	1.2e-12	2.16e-10	8.11e-07	< 2e-16	2.23e-11	< 2e-16
2019	6.34b	8.00b	1.26ab	30.49b (17.3%)	113.35b (64.5%)	30.88a (17.6%)
2020M	6.56a	8.19ab	1.25ab	34.21a (18.8%)	116.91ab (64.3%)	29.97ab (16.5%)
2020P	6.55a	8.26a	1.26ab	30.95b (17.1%)	125.15a (69.0%)	27.91bc (15.4%)
2021M	6.26b	7.80c	1.25b	25.21c (15.7%)	107.98c (67.4%)	24.48d (15.3%)
2021P	6.32b	8.07ab	1.28a	28.71b (17.0%)	107.98c (64.1%)	27.44c (16.3%)
Mean	6.41	8.06	1.26	29.91	114.27	28.14
Plant density[(2)]	FFW (g)	EpDW (g)	MeDW (g)	SeDW (g)	FDW (g)	DMC (%)
p-value[(4)]	< 2e-16	< 2e-16	< 2e-16	< 2e-16	1.58e-12	0.3033
204 trees per hectare	176.32a	7.17a (15.5%)	26.11bc (56.6%)	12.89ab (27.9%)	46.16a	27.05a
278 trees per hectare	156.71b	5.66cd (14.3%)	22.84d (57.5%)	11.19cd (28.2%)	39.68c	25.11a
333 trees per hectare	163.22b	5.44d (12.9%	27.60ab (63.3%)	9.20e (21.8%)	42.23bc	25.75a
400 trees per hectare	179.75a	6.59b (14.1%	29.22a (62.5%)	10.97d (23.4%)	46.78a	26.46a
625 trees per hectare	181.47a	6.41b (13.8%	26.34bc (56.5%)	13.84a (29.7%)	46.59a	25.56a
816 trees per hectare	165.33b	5.95c (13.6%)	25.37c (58.1%)	12.36bc (28.3%)	43.68ab	26.51a
Year + harvest[(5)]/p-value[(4)]	6.5e-13	< 2e-16	< 2e-16	< 2e-16	< 2e-16	0.0484
2019P	175.78a	6.95a (14.5%)	26.92b (56.2%)	14.05a (29.3%)	47.92a	27.22a
2020M	181.90a	7.28a (14.8%)	28.92ab (58.8%)	13.01ab (26.4%)	49.21a	26.92a
2020P	181.38a	6.07a (12.5%)	31.19a (64.1%)	11.43bc (23.5%)	48.70a	26.50a
2021M	160.18c	5.65a (14.2%)	24.69c (61.9%)	9.55d (23.9%)	39.89b	25.24a
2021P	168.47b	5.79a (13.8%)	24.77c (59.0%)	11.42c (27.2%)	41.98b	25.50a
Mean	173.54	6.35	27.30	11.89	45.54	26.28

[(1)]Means followed by equal letters, in the columns, do not differ by Tukey's honestly significant difference test, at 5% probability. [(2)]Plant density values are means of five measurements over three years (2019–2021). [(3)]ED, equatorial diameter; LD, longitudinal diameter; EpFW, epicarp fresh weight; MeFW, mesocarp fresh weight; SeFW, seed fresh weight; FFW, fruit fresh weight; EpDW, epicarp fresh weight; MeDW, mesocarp fresh weight; SeDW, seed dry weight; FDW, fruit dry weight; and DMC, dry matter content. [(4)]p-values less than 0.05 show significant differences for the analysis of variance. [(5)]P, main harvest; and M, secondary (*mitaca*) harvest. The values between parentheses correspond to the percentage contribution of each fruit tissue organ contributes to the total fruit weight.

seed dry weight. According to Abbott (1999), for most fruits, a higher proportion of mesocarp indicates a higher fruit quality according to consumer preferences and expectations. The obtained results are an indictive that the production of uniform and high-quality fruit is critical for a successful planting system, confirming the need for more detailed studies of the factors required for a sustainable production (Ramírez-Gil et al., 2018).

Conclusions

1. The highest fruit yield of 'Hass' avocado (*Persea americana*) is obtained at the intermediate plant densities of 333 and 400 trees per hectare, since increased densities negatively affect yield per tree and number of avocado fruits per tree.
2. The highest fruit yield of 18 Mg ha^{-1} is obtained in the main harvest and the lowest of 5.25 Mg ha^{-1}, in the *mitaca* harvest, representing 70 and 30% of the annual production, respectively.
3. Fruit quality parameters show better values at the plant densities of 333 and 400 trees per hectare, which result in the highest proportions of mesocarp and the lowest seed fresh weight/dry weight ratio.

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References

ABBOTT, J.A. Quality measurement of fruits and vegetables. **Postharvest Biology and Technology**, v.15, p.207-225, 1999. DOI: https://doi.org/10.1016/S0925-5214(98)00086-6.

BELDA, M.; HOLTANOVÁ, E.; HALENKA, T.; KALVOVÁ, J. Climate classification revisited: from Köppen to Trewartha. **Climate Research**, v.59, p.1-13, 2014. DOI: https://doi.org/10.3354/cr01204.

CARVALHO, C.P.; VELÁSQUEZ, M.A.; VAN ROOYEN, Z. Determination of the minimum dry matter index for the optimum harvest of 'Hass' avocado fruits in Colombia. **Agronomía Colombiana**, v.32, p.399-406, 2014. DOI: https://doi.org/10.15446/agron.colomb.v32n3.46031.

DELMELLE, P.; OPFERGELT, S.; CORNELIS, J.-T.; PING, C.-L. Volcanic soils. In: SIGURDSSON, H. (Ed.). **The Encyclopedia of volcanoes**. 2nd ed. Amsterdam: Elsevier, 2015. p.1253-1264. DOI: https://doi.org/10.1016/b978-0-12-385938-9.00072-9.

ESTRADA, J.A.B.; DÍEZ, C.A.D. (Comp.). **Actualización tecnológica y buenas prácticas agrícolas (BPA) en el cultivo de aguacate**. 2.ed. Mosquera: AGROSAVIA, 2020. DOI: https://doi.org/10.21930/agrosavia.manual.7403831.

FAO. Food and Agriculture Organization of the United Nations. **Faostat**. Avalaible at: <http://www.faostat.fao.org/>. Accessed on: Apr. 8 2021.

FAROOQ, T.H.; WU, W.; TIGABU, M.; MA, X.; HE, Z.; RASHID, M.H.U.; GILANI, M.M.; WU, P. Growth, biomass production and root development of Chinese fir in relation to initial planting density. **Forests**, v.10, art.236, 2019. DOI: https://doi.org/10.3390/f10030236.

GARNER, L.C.; LOVATT, C.J. Physiological factors affecting flower and fruit abscission of 'Hass' avocado. **Scientia Horticulturae**, v.199, p.32-40, 2016. DOI: https://doi.org/10.1016/j.scienta.2015.12.009.

GONZÁLEZ-ESTUDILLO, J.C.; GONZÁLEZ-CAMPOS, J.B.; NÁPOLES-RIVERA, F.; PONCE-ORTEGA, J.M.; EL-HALWAGI, M.M. Optimal planning for sustainable production of avocado in Mexico. **Process Integration and Optimization for Sustainability**, v.1, p.109-120, 2017. DOI: https://doi.org/10.1007/s41660-017-0008-z.

KÖHNE, J.S. Methods of increasing avocado fruit production. **South African Avocado Growers’ Association Yearbook**, v.11, p.53-55, 1988.

KÖHNE, J.S.; KREMER-KÖHNE, S. Avocado high density planting – a progress report. **South African Avocado Growers’ Association Yearbook**, v.14, p.42-43, 1991.

KÖHNE, J.S.; KREMER-KÖHNE, S. Yield advantages and control of vegetative growth in a high-density avocado orchard treated with paclobutrazol. In: WORLD AVOCADO CONGRESS, 2., 1991, Orange. **Proceedings**. Riverside: University of California, 1992. p.233-235.

LADANIYA, M.S.; MARATHE, R.A.; DAS, A.K.; RAO, C.N.; HUCHCHE, A.D.; SHIRGURE, P.S.; MURKUTE, A.A. High density planting studies in acid lime (*Citrus aurantifolia* Swingle). **Scientia Horticulturae**, v.261, art.108935, 2020. DOI: https://doi.org/10.1016/j.scienta.2019.108935.

LORDAN, J.; FRANCESCATTO, P.; DOMINGUEZ, L.I.; ROBINSON, T.L. Long-term effects of tree density and tree shape on apple orchard performance, a 20 year study – Part 1, agronomic analysis. **Scientia Horticulturae**, v.238, p.303-317, 2018. DOI: https://doi.org/10.1016/j.scienta.2018.04.033.

MENZEL, C.M.; Le LAGADEC, M.D. Increasing the productivity of avocado orchards using high-density plantings:

a review. **Scientia Horticulturae**, v.177, p.21-36, 2014. DOI: https://doi.org/10.1016/j.scienta.2014.07.013.

MOKRIA, M.; GEBREKIRSTOS, A.; SAID, H.; HADGU, K.; HAGAZI, N.; DUBALE, W.; BRÄUNING, A. Fruit weight and yield estimation models for five avocado cultivars in Ethiopia. **Environmental Research Communications**, v.4, art.075013, 2022. DOI: https://doi.org/10.1088/2515-7620/ac81a4.

PASA, M. da S.; FACHINELLO, J.C.; ROSA JÚNIOR, H.F. da; DE FRANCESCHI, É.; SCHMITZ, J.D.; SOUZA, A.L.K. de. Performance of 'Rocha' and 'Santa Maria' pears as affected by planting density. **Pesquisa Agropecuária Brasileira**, v.50, p.126-131, 2015. DOI: https://doi.org/10.1590/S0100-204X2015000200004.

R CORE TEAM. **R**: a language and environment for statistical computing. Vienna: R Foundation for Statistical Computing, 2013.

RAMÍREZ-GIL, J.G.; HENAO-ROJAS, J.C.; MORALES-OSORIO, J.G. Postharvest diseases and disorders in avocado cv. Hass and their relationship to preharvest management practices. **Heliyon**, v.7, e05905, 2021. DOI: https://doi.org/10.1016/j.heliyon.2021.e05905.

RAMÍREZ-GIL, J.G.; MORALES, J.G.; PETERSON, A.T. Potential geography and productivity of “Hass” avocado crops in Colombia estimated by ecological niche modeling. **Scientia Horticulturae**, v.237, p.287-295, 2018. DOI: https://doi.org/10.1016/j.scienta.2018.04.021.

RAZETO, B.; LONGUEIRA, J.; FICHET, T. Close planting of avocado. In: WORLD AVOCADO CONGRESS, 2., 1991, Orange. **Proceedings**. Riverside: University of California, 1992. p.273-279.

REBOLLEDO, A.; ROMERO, M.A. Avances en investigación sobre el comportamiento productivo del aguacate (*Persea americana* Mill.) bajo condiciones subtropicales. **Ciencia & Tecnología Agropecuaria**, v.12, p.113-120, 2011. DOI: https://doi.org/10.21930/rcta.vol12_num2_art:220.

REDDY, I.V.S. Ultra high density planting of mango in Telangana: prospects and problems. **The Pharma Innovation Journal**, v.11, p.73-77, 2022.

SALAZAR-GARCÍA, S.; MEDINA-CARRILLO, R.E.; ÁLVAREZ-BRAVO, A. Evaluación inicial de algunos aspectos de calidad del fruto de aguacate 'Hass' producido en tres regiones de México. **Revista Mexicana de Ciencias Agrícolas**, v.7, p.277-289, 2016. DOI: https://doi.org/10.29312/remexca.v7i2.343.

SMITH, H.M.; SAMACH, A. Constraints to obtaining consistent annual yields in perennial tree crops. I: Heavy fruit load dominates over vegetative growth. **Plant Science**, v.207, p.158-167, 2013. DOI: https://doi.org/10.1016/j.plantsci.2013.02.014.

STASSEN, P.J.C.; SNIJDER, B.; DONKIN, D.J. Results with spacing, tree training and orchard maintenance in young avocado orchards. **Revista Chapingo Serie Horticultura**, v.5, p.159-164, 1999.

TUN, T.N.; GUO, J.; FANG, S.; TIAN, Y. Planting spacing affects canopy structure, biomass production and stem roundness in poplar plantations. **Scandinavian Journal of Forest Research**, v.33, p.464-474, 2018. DOI: https://doi.org/10.1080/02827581.2018.1457711.

WILKIE, J.D.; CONWAY, J.; GRIFFIN, J.; TOEGEL, H. Relationships between canopy size, light interception and productivity in conventional avocado planting systems. **Journal of Horticultural Science and Biotechnology**, v.94, p.481-487, 2019. DOI: https://doi.org/10.1080/14620316.2018.1544469.