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Original Research

Optimizing Planting Densities of Avocado on the Basis of Long-Term Canopy Growth and Development at Melkassa, Ethiopia

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Abstract

There is a controversy regarding the spacing requirements of avocado varieties, different experts recommend varying planting densities for different varieties in different avocado growing countries, including Ethiopia. Each avocado variety has its own canopy stature, thus there is no spacing that fits all varieties. The canopy growth of different avocado varieties was recorded annually from a replicated plot of well-established trees, assuming that the tree canopy reached a maximum growth during the long-term experiment at Melkassa Research Centre. Measurements were made from six trees replicated three times. The data were averaged per plot and per replications. The results showed that each variety reached maximum canopy diameter that occupied its own area with adequate distance between trees and rows. Hass and Nabal grew to a maximum canopy diameter of 4.30 m, while Ettinger has grown to a maximum diameter of 5.50m; Fuerte and Bacon attained 5.0 m canopy diameter; Pinkerton developed to a maximum diameter of 3.10m. This suggests that with addition of small workspace the optimum spacing for Ettenger could be 5mx5m (400 trees/ha); Fuerte and Bacon at 5.0m x 5.50m (363 trees/ha); Hass and Nabal at 4.30m x 4.80m and Pinkerton at maximum of 3.50m x 3.50m (816 trees /ha). This spacing could give a high tree population per ha and allow enough work space between trees with sufficient light penetration. Accordingly, these spacings provide higher tree population density per ha and could be used for new avocado plantations in the Melkassa area and other similar environment.

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INTRODUCTION

Avocado fruit has emerged as a new multipurpose agricultural commodity in Ethiopia (Mekonnen *et al*., 2024; MoA, 2020), where 11,337,925.00 ha of land is highly suitable in the country, with nearly 6,687,381.00 ha of land (58.9%) is found in Oromia (Mekonnen *et al*., 2024). This study further identified that nearly 19,237,194.00 ha of land is moderately suitable for avocado production in Ethiopia, where nearly 10,001,475.00 ha (51.99%) is found in Oromia (*Ibid*).

All crop varieties, such as avocado fruits, have different stature and canopy development at a particular location, requiring different intera- and inter-row spacing (Crane *et al*., 2013; Lahav and Lavi, 2013; Schaffer *et al*., 2013; Wolstenholme, 2013). However, since the registration of six avocado varieties in Ethiopia in 2008 (MoA, 2008), six meter by six meter spacing was recommended for all varieties irrespective of the canopy growth and development (MoA, 2018) and through the long-time period, It is learned that there is a high variation in the avocado canopy development for each variety indicating, there should be different spacing for each avocado variety at a given location such as Melkassa area. On the other hand, due to land scarcity and early break-even point, there is a trend of high planting density of fruit trees where high numbers of trees are planted at much higher densities (Schaffer *et al*., 2013; Whiley *et al*., 2013). Thus, plant spacing such as avocado plant, is a highly debated topic. Higher planting densities result in higher yields in the early years of planting, but can also lead to more canopy management problems in later years (Téliz-Ortíz *et al*., 2003). There is no agreement on the planting density of avocado variety, even at a particular production area and every commercial grower adopts his/ her planting densities for a particular variety in all avocado growing (Whiley *et al*., 2013). This leads to a disagreement on the spacing required for avocado fruit and varieties and has evolved into a controversy on the spacing requirements of commercial avocado varieties in many countries, including Ethiopia.

All perennial fruit crops occupy large spaces for decades. Different experts and commercial growers recommend different planting densities for avocado varieties in Ethiopia and there is no common spacing agreed upon for each avocado variety. For instance, under good management avocado fruit is expected to have an expected lifespan of more than 50 years. Continuing decline in the availability of cultivable land, depleting natural resources, impact of climate change, rising energy and land costs together with increasing demand have pushed to the concept of high-density planting; and most of the fruit

growers in many countries including Ethiopia are looking for ways to increase yield and economic benefit of fruits in their orchards through high density planting (www.thepacker.com/markets/shipping/high-density-planting-technique-helps-boost-yields; and www.lynwoodavocado.co.nz/high-density-plantings).

The fruit tree spacing varies with types of fruit crops and varieties (canopy nature), environmental conditions and with intended subsequent management practices (Schaffer *et al*., 2012; Edossa *et al*., 2024). The tree height and diameter should allow sunlight to pass over the top of the tree and shine light on the lower canopy of the next tree. Thus, avocado varieties have their own stature, so there is no one size spacing fits all varieties of avocado. Some varieties have a spreading growth habit, whereas others have either upright growth or medium growth habits. Thus, establishing optimum spacing for avocado varieties based on scientific evidence requires estimation of maximum growth of canopy diameter for each commercial variety, an important factor which determines the yield of an orchard. Appropriate spacing depends on the tree canopy radius, which intern is dependent on the varietal characteristics. The investigation on long-term annual growth and development of each variety at a particular place would give trends and reaches a maximum growth in diameter which then by constant growth. Thus, long-term canopy growth measurements for a particular fruit crop and variety would give an estimation of the maximum spacing required at a particular place. Therefore, the objectives of this paper were: to determine possible planting densities (spacing) and maximum canopy growth and development trend of commercial avocado varieties of each commercial avocado varieties based on their long-term canopy growth and development measurements at Melkassa.

MATERIALS AND METHODS

Description of the study areas

Melkassa Agricultural Research Centre (MARC) is located at a latitude of 8°24'N, a longitude of 39°21'E and an altitude of 1550 meters above sea level. It has a bimodal pattern in seasonal rain distribution, which is from mid-February to mid-May and from June to September (1987-2017). The annual long -term average rainfall at Melkassa is 827 mm/ annum of precipitation, which is concentrated in July and August (Figure 1). With an annual long-term mean temperature of 21.6°C, of the temperature is highest in May to June and lowest in November to December (Figure 1). May is the warmest month, with an average temperature of 31.2°C, while December is the coldest, averaging 11°C respectively.

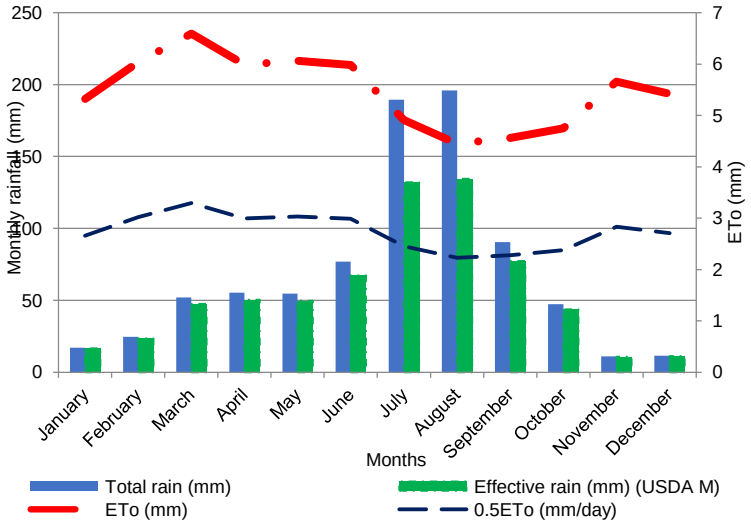
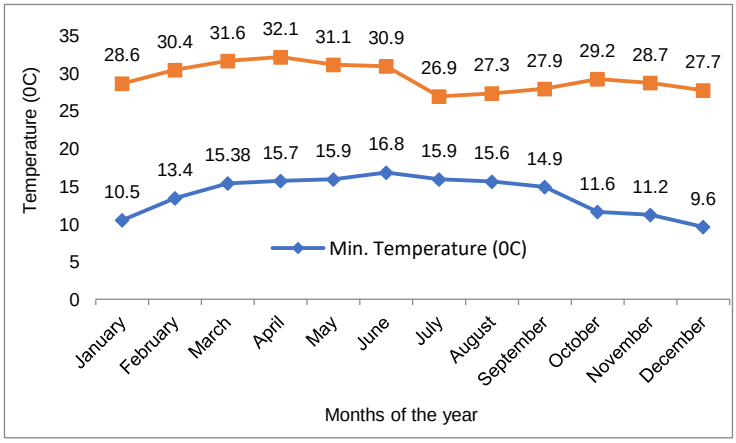


Figure 1: Mean long-term monthly total and effective rainfall with daily reference evapotranspiration (ETo) at Melkassa

Figure 2: Long-term mean maximum and mean minimum



temperatures at Melkassa (1987-2017)

Description of avocado varieties

Six commercial avocado varieties, namely Hass, Ettinger, Fuerte, Bacon, Nabal and Pinkerton were established at Melkassa in 2002 (1995 EC) at the spacing of 6m x 6m. Varieties were planted in three replications and each replication contains six avocado trees. Varieties were evaluated over the years and were released in 2008 (MoA, 2008); however, their growth and development characteristics were recorded for additional years. The orchard was irrigated by furrows throughout its life except during the rainy season, which lasts from late June to mid-September.

Data collection

Data on the tree architectural characteristics such as canopy diameter, canopy radius, plant height, canopy volume and canopy cover were collected from registered avocado varieties (MoA, 2008) as described below. The averages of six trees with three replications were calculated.

Canopy diameter: Average of two diameter measurements of south to north tip and from east to west growth tips were measured at the broadest diameter using a meter at the end of each harvest. The average of these measurements was taken for the canopy diameter.

Canopy radius: Half of the canopy diameter was taken as a canopy radius for each tree measured after harvest annually**.**

Plant height: Tree height was measured from the ground level to the tip of the tree height using labelled pole at the end of each harvest annually.

Canopy volume: Canopy volume was calculated yearly using the formula for the volume of a standard ellipsoid (4/3π HW1W2), where H is the height and W is the width of the tree (*Mickelbart et al., 2012;* Mulugeta *et al*., 2022). All measurements were made using meter at the end of each harvest from each tree.

Canopy cover: Tree canopy cover, is also known as canopy coverage or crown cover, estimated in percentage, is defined as the proportion of the tree covered by the vertical projection of the tree crowns (Jennings *et al*. 1999). Each data points were collected once the tree reached maximum yield after 8th years after transplanting and continued measuring at every year after harvest.

Data analysis

Data were recorded yearly after harvest and these data were analyzed yearly using descriptive statistics.

RESULTS AND DISCUSSION

Canopy diameter

The long-term measurement result showed that the maximum canopy diameter of avocado varieties at Melkassa varied with varieties. It indicated that Pinkerton had the smallest canopy diameter (3.2m) whereas Fuerte showed the widest canopy diameter (5.0m) (Table 1). This means that different planting densities are needed for each avocado variety since they were originally planted at a 6m x 6m spacing. The Pinkerton variety should have been planted with much closer spacing.

Table 1: Mean canopy diameter of avocado varieties spaced at 6m x 6m at different ages after transplanting at Melkassa

Years after transplanting	Average canopy diameter of avocado variety (m)					
	Bacon	Ettinger	Fuerte	Hass	Nabal	Pinkerton
8	4.51	4.35	4.88	4.29	4.74	3.04
10	4.49	4.55	5.09	4.54	4.70	3.16
12	4.58	4.37	5.18	4.45	5.31	3.16
14	4.90	4.37	4.97	4.23	4.71	3.04

Avocado tree size and vigour dictate the orchard planting density; planting distance usually depends on the growth habit of each avocado variety. For instance, Fuerte which exhibited a large and spreading growth habit requires wider spacing while Hass had an upright and narrower diameter that requires narrow spacing. With the original 6m x 6m spacing, all avocado varieties did not cover all spaces allowed for tree architecture. The long-term study showed that large spaces between rows and plants left uncovered by the tree architecture confirmed the possibility of increasing avocado plant population by narrowing the spacing between plants and rows, or by narrowing distances within a row while keeping wider distances between rows.

Based on the tree growth measurements conducted at Teppi, all commercial avocado varieties tended to grow taller at Teppi than at Melkassa (Shamil, 2023). However, there was similar growth of canopy diameter for most varieties at Teppi and Melkassa (Shamil, 2023). There is no avocado variety at Teppi that surpassed 4.5m in canopy diameter, indicating that the spacing required for all avocado varieties should be less than 5m.

Canopy radius

The development of tree canopy radius is a critical factor for determining spacing. The canopy of one tree cannot touch the canopy of the nearby trees at the normal planting density. Based on the long-term measurements, the Fuerte avocado variety had the widest radius (2.5 m), whereas Pinkerton had the narrowest radius (1.5m) (Table 2). Each tree of all varieties was allowed to grow at a radius of 3 m spaces; however, each variety showed a variable radius of branch growth characteristic without any pruning.

Table 2: Mean canopy radius of commercial avocado varieties planted at 6m x 6m at different ages after transplanting at Melkassa

Years after transplanting	Average canopy radius of avocado varieties (m)					
	Bacon	Ettinger	Fuerte	Hass	Nabal	Pinkerton
8	2.26	2.18	2.44	2.15	2.37	1.52
10	2.25	2.28	2.54	2.27	2.35	1.58
12	2.29	2.19	2.59	2.23	2.66	1.58
14	2.45	2.19	2.48	2.12	2.36	1.52

It is clearly shown from the long-term data that the radius of each avocado variety remained nearly constant after the age of 8th years after transplanting. This indicates that the radius spacing provided for each variety and each tree (3 m) was not used by each variety and each tree, which required the possibility of narrowing the spaces provided for each tree branch growth.

Tree height

The long-term avocado variety tree stature measurements showed that Bacon was the tallest variety, whereas Pinkerton was the shortest in all the years (Table 3). This indicates that where the trees are short, it is possible to increase the density as each tree cannot shade much on each other

T**able 3:** Mean plant height of commercial avocado varieties planted at 6m x 6m at different ages after transplanting at Melkassa

Years after transplanting	Average plant height of avocado varieties (m)					
	Bacon	Ettinger	Fuerte	Hass	Nabal	Pinkerton
8	4.21	3.12	3.03	2.92	3.08	2.08
10	4.46	3.30	3.15	3.18	3.60	2.22
12	4.67	3.46	3.65	3.23	3.67	2.40
14	4.91	4.02	3.60	3.48	3.87	2.63

Similar tree heights were recorded for Ettinger (3.15m), Fuerte (3.05m) and Hass (2.9m) varieties. Although the tree height in all avocado varieties looks like it was increasing (Table 3), it showed a lack of pruning aimed at controlling tree height for easy harvesting. Pruning in avocado is managed for the distribution of light in the tree; maintaining the height of the trees between 3.5 and 4.0m (which also helps to balance the above and below ground portions of the tree), and to facilitate the agronomic and phytosanitary practices in the farm.

Avocado trees are usually pruned aiming at establishing a central leader, keeping the trees not taller than 5m. Water suckers (upright growth) usually aris from any parts of the avocado tree and growers should remove these water suckers at all the times.

Canopy volume

The estimation of canopy cover showed that Bacon had the highest canopy cover, followed by Fuerte and Nabal, which had very similar canopy covers; and Pinkerton had the smallest canopy cover (Table 4).

Table 4: Mean canopy volume of avocado varieties at different ages after transplanting at Melkassa`

Average plant canopy volume of avocado varieties (m^3)						
Years after transplanting	**Bacon**	**Ettinger**	**Fuerte**	**Hass**	**Nabal**	**Pinkerton**
8	44.36	30.58	37.38	29.93	35.85	9.95
10	46.48	35.39	42.11	39.95	41.20	11.48
12	50.75	34.13	50.74	33.13	53.61	12.41
14	61.07	39.77	45.88	31.95	44.48	12.78

Similar to average plant height, canopy volumes tended to increase over the years. However, this indicates that as the tree increases in height, there is difficulty in harvesting and other management practices, such as spraying. Thus, there should be a strategy to regularly control tree height in avocado orchards.

Canopy cover

Canopy cover of trees normally represents the fraction of the soil surface that is shaded by vegetation (Allen *et al*., 1998). The canopy cover is an important measurement for the determination of the daily irrigation area per hectare, Irrigation covers the canopy cover and it increases with age. Avocado trees cover a small portion of land during the first year, and canopy cover increases with age until it reaches a constant.

Bacon and Fuerte avocado varieties had the highest canopy cover of 0.66 and 0.68, at the age of 14 years, whereas Ettinger and Hass had medium canopy covers of 0.53 and 0.49, respectively. Pinkerton had the lowest canopy cover (0.25), where more than 70% of the surface was not covered by the canopy (Table 5). In this avocado row plantation, it requires irrigating only the ratio of canopy cover, but not the total area of the plantations.

Table 5: Mean canopy cover of avocado varieties at different ages after transplanting at Melkassa

Years after transplanting	**Average canopy cover ratio of avocado varieties**					
	Bacon	**Ettinger**	**Fuerte**	**Hass**	**Nabal**	**Pinkerton**
8	0.56	0.52	0.66	0.55	0.62	0.26
10	0.56	0.57	0.71	0.57	0.61	0.27
12	0.58	0.53	0.74	0.55	0.78	0.27
14	0.66	0.53	0.68	0.49	0.61	0.25

Varietal productivity of commercial avocado types was studied in different parts of Ethiopia, from North to South and East to West, such as Bore, Guji Zone, South Oromia (Aschalew *et al.,* 2021); in the North Raya Azebo, Tigray Region (Haile *et al*., 2022); and in West Yeki (Teppi), South West Ethiopia (Shamil, 2023). They found variable results of canopy growth and development among varieties due to variation in ages, climate and soil types. Conclusive results were not obtained; thus, spacing would be determined for a particular variety, location, age of the plantations, and management practices.

Varietal planting density options and increasing planting density scenarios

Orchard geometry, layout and spacing depend on the slope of the area and other aspects such as whether it is north or east-facing, the soil type, the thinning practices followed, and access for the machinery.

The results from long-term actual avocado canopy diameter development, area covered by each tree and estimated tree population of avocado varieties after the age of 14 years at Melkassa indicated that the original spacing provided for each variety, 6m x 6m with 277 trees/ha, was very wide and no variety reached a diameter of 6m x 6m. The future avocado tree planting around the Melkassa area and similar environments should use narrower spacing with higher tree populations per ha (Table 6).

Table 6: Maximum actual canopy diameter development, area covered by each tree and estimated tree population of avocado varieties at the age of 14 years at Melkassa

Variety	**Canopy diameter (m)**	**Area covered by the tree (m^2)**	**Potential tree population per ha**
Hass	4.30	18.49	541
Ettinger	4.50	20.25	494
Fuerte	5.00	25.00	400
Bacon	5.00	25.00	400
Nabal	4.30	18.49	541
Pinkerton	3.10	9.61	1041

Avocado orchard planting density depends upon the slopes of the area and management practices. It is usually planted in a rectangular system; there would be a tree row in which the trees could be closer to each other and a work row that would separate the tree rows from each other. The work row is required to optimize the utilization of sunlight by the leaf canopy.

Scenario I. Single row spacing

The distance between the tree rows (stem to stem) or the work row must be wide enough for farm implements such as sprayers, picking trailers and mechanical pruning equipment to be used. Based on the average maximum tree diameter attained by each avocado variety with an addition of 0.5m workspace either between single rows or between two rows, new avocado plantations could be established as indicated in Table 7. Both Hass and Ettinger could be spaced at 5m x 5m or 4.5m x 5m, whereas Pinkerton could be spaced at a maximum of 3.5m x 3.5m. This spacing could give high tree population per ha with the corresponding fruit yield.

Table 7: Average actual canopy diameter, estimated work space, area required for one avocado tree and tree population at Melkassa area

Variety	**Average canopy diameter (m)**	**Work space (m)**	**Spacing including work space (m)**	**Estimated area required for one tree (m^2)**	**Estimated tree population (No. of tree/ ha)**
Hass	4.30	0.50	4.30 x 4.80	20.64	484.49
Ettinger	4.50	0.50	4.50 x 5.00	22.50	444.44
Fuerte	5.00	0.50	5.0 x 5.50	27.50	363.63
Bacon	5.00	0.50	5.0 x 5.50	27.50	363.63
Nabal	4.30	0.50	4.30 x 4.80	20.64	441.69
Pinkerton	3.10	0.50	3.10 x 3.60	11.16	896.05

The research conducted in South Africa demonstrated that the height of the avocado trees should be about 80% of the spacing. This height allows sunlight to pass over the top of the tree and shine light on the lower canopy of the next tree. This arrangement tends to keep leaves on the trees down to the ground, which in turn grants growers to keep the fruits low in the tree and pick without using ladders. However, for varieties like Fuerte with a spreading type of growth, a wider spacing should be provided, whereas for varieties such as Pinkerton with dense growth type, narrow spacing should be used (Table 8). The standard spacing for grafted Hass avocado in Kenya is 5m by 5m (www.richfarmkenya.com). With this spacing, 400 avocado trees could be planted on one ha of land. Many researchers have determined that the optimal spacing for avocado trees within a row is typically between 3m to 5m, with a minimum space of 5m between rows. In South Africa, numerous avocado farms adhere to a standard planting density of 5m x 5m, allowing for 400 trees to be planted per hectare. This information is sourced from www.freshelaexporters.com/avocado/farming/south-africa

Table 8: Mean annual yield and estimated potential yield of avocado varieties at Melkassa

Variety	Spaced at 6m x 6m		Estimated potential yield at narrow spacing		
	Actual yield* (q/ha)	Estimated actual yield (q/tree)	If the trees are spaced at	Population per ha	Estimated potential yield (q/ha)
Hass	223	0.98	4.30x4.80	485	475.8
Ettinger	342	1.51	4.50x5.00	444	669.3
Fuerte	257	1.13	5.0x5.50	364	410.9
Bacon	228	1.00	5.0x5.50	364	364.5
Nabal	200	0.88	4.30x4.80	442	390.0
Pinkerton	240	1.06	3.10x3.60	896	947.1

*Sources: MoA, (2008)

Looking for dwarf varieties is slowly gaining acceptance among avocado farmers in South Africa and many other avocado-producing countries. Growing dwarf avocado varieties has various economic benefits. Dwarf avocado trees grow slowly and require less pruning. Small branches are removed to be used as mulch. In addition, the dwarf size makes harvesting easy with less labor and machinery. Spraying dwarf avocado trees against insect pests or diseases is easier and more cost-effective. Moreover, dwarf avocado trees require less chemical fertilizer and save labor and fertilizer costs. Furthermore, growing dwarf avocado is a form of high-density planting since 550 trees could be planted on one hectare.

Scenario II: Narrow spacing between plants and wider spacing between rows

Avocado trees could be planted with a double row planting system where maximum spacing is used within a row and between two rows. For instance, 4.30 m is used within a row of Hass variety and at the same time, 4.30m could be used between plants in a row and 4.80m is used as workspace for two rows (Table 8). In this case higher number of trees could be accommodated for each variety per hectare.

Scenario III: High-density planting

With rising input costs and limited resources such as land and water, most of the avocado farmers in many countries are looking for strategies to increase yield in their orchards (Hofshi, 1996; www.lynwoodavocado.co.nz/high-density-plantings). Some of them have started practicing innovative agricultural techniques such as high-density planting and planting dwarf varieties. High-density planting in avocado farms involves controlling the size of the trees by thinning, especially for avocado trees that grow vigorously, removing alternate trees to avoid crowding; practicing regular pruning; and using Paclobutrazol, which is used as a plant growth regulator and allows closer tree spacing and higher initial yields per hectare. The spacing from one tree to another and from one row to another row is **5m** x **2m: t**his implies that nearly **800** trees of avocado can be planted on one hectare in South Africa (*Anon*.).

Although high-density planting is more expensive to maintain the plants, the harvests start to profit after five years. However, with standard density planting, the avocado farm starts to be profitable after six years (Hofshi, 1996; Francis, 1994; and Faber, 1991). Avocado growers in most countries consider high-density plantings since they give more profitable incomes as compared to the normal planting density (Hofshi, 1996; Francis, 1994; Faber, 1991). High-density planting increases the profitability of avocado production given there is suitable land for high-density orchard development and proper canopy development.

There are numerous advantages of high-density planting (www.lynwoodavocado.co.nz/high-density-plantings). Full production occurs earlier when an entire canopy is attained. Production will commence in year three and full productivity will be achieved in year five or six, with good shelter results in better quality fruit and higher fruit yield. Moreover, small trees will serve as self-mulch, which allows roots to grow into the mulch layer and results in healthy trees and more efficient nutrient uptake. Furthermore, regular pruning improves tree health since shoot to root ratio is kept in balance. Fruit size will be improved as the trees are healthier with a strong, efficient canopy and root system, **less pest and disease damage,** more effective fungicide application **and b**etter spray penetration, **and** less fruit staining as trees maintain a strong, vigorous canopy (https://www.lynwoodavocado.co.nz/high-density-plantings).

CONCLUSION

This long-term information assisted the growers in redesigning intra- and inter-row spacing for each avocado variety to maximise plant population density and establish appropriate high planting geometry from the beginning of orchard/plantation establishment. The long-term data demonstrated that avocado canopy growth and development for each variety would help to determine spacing, while after 14 production years, there is a variation where there is a space not yet covered by the canopy of avocado trees. Each avocado variety had shown varied growth and development characteristics that would lead to implementing specific spacing for each variety. According to the maximum tree canopy development results in the area, it was suggested that Hass and Ettenger varieties could be spaced at 5m x 5m or 4.5m x 5m, Fuerte and Bacon at 5m x 5.5m, Nabal at 4.30m x 4.80m, and Pinkerton could be planted at a maximum of 3.50 m x 3.50m spacing. Extra spaces should not be left between rows and plants, as the average landholding by the smallholders is tiny. Avocado growers can use either single row spacing or double row spacing with narrow spacing between plants within a row and wider spacing between rows, where enough workspace can be provided between two rows and accommodate a higher number of avocado trees per unit area. In conclusion. There has been a trend to use higher planting densities (narrower spacing) by all avocado growers by practicing pruning and tree growth control practices in many countries. Therefore, these results confirmed that narrower and different spacing requirements of avocado varieties for new avocado growers with further canopy management on specific management practices, such

as plant nutrition, pruning, irrigation, and other field management practices required for high-density planting, is crucial for the long-term sustainability of the orchard and the plantation.

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Conflicts of Interest

The author declares that there is no conflicts of interest

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