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Experimental determination of the optimum oil palm planting density in Western Africa☆

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Abstract – This article follows on from two articles published in 2014 and 2018 on the same trial conducted in an oil palm plantation in Nigeria which was aimed at assessing a range of different planting distances between oil palms (7.5 to 9.5 m) in an equilateral triangle design. The climate in the region is very stable, with two seasons and an average 2000 mm of rainfall per year. The soil is of the desaturated ferralitic type, sandy on the surface, deep, and without coarse elements. After continually monitoring the experimental palms for 16 years, there is now enough hindsight to propose an optimum planting density for oil palms in Western Africa. A plateau has been reached at between 143 and 160 palms per hectare for Pobè C1001F material in the aforementioned pedoclimatic context.

Keywords: oil palm / planting density / spacing / thinning / yield

Résumé – **Détermination expérimentale de la densité de plantation optimale du palmier a huile en Afrique de l'Ouest.** Cet article fait suite à deux articles publiés en 2014 et en 2018 sur la même expérience conduite dans une palmeraie au Nigéria, ayant pour but de tester différentes distances de plantation entre palmiers (7,5 à 9,5 m) dans un dispositif en triangle équilatéral. Le climat de la zone est très stable, à deux saisons et une moyenne de 2000 mm de précipitations par an. Le sol est du type ferrallitique désaturé, sableux en surface, profond et sans éléments grossiers. Après un suivi continu des palmiers expérimentaux pendant 16 ans, nous avons maintenant suffisamment de recul pour proposer une densité de plantation optimale en Afrique de l'Ouest. Nous avons atteint un plateau s'étendant de 143 à 160 palmiers à l'hectare pour le matériel végétal Pobè C1001F dans le contexte pédoclimatique décrit ci-dessus.

Mots clés : palmier à huile / densité de plantation / écartement / éclaircissage / rendement

1 Introduction

In two previously published articles (Bonneau *et al.*, 2014, 2018), we discussed how planting density affects oil palm yields. The spacing between oil palms is considered as a major contributor to yield under planting designs following equilateral triangle as used in monocultures (Prévot *et al.*, 1955; Smith, 1972). We have monitored the trial over four more seasons (from year 13 to year 16 after planting) and we are up to speed for most of the variables measured, be it for growth or yields. We now have enough hindsight to propose an optimum planting density for D $\times$ P oil palms along a full economic cycle (20 to 25 years) in Western Africa.

☆ Contribution to the Topical Issue "Palm and palm oil / Palmier et huile de palme".

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2 Material and methods

2.1 Location, soil and climate

The Presco-plc oil palm estate is located at Obaretin near Benin City, Edo State, Nigeria. The terrain of the region is flat, over a vast sedimentary formation called the Continental Terminal. The very uniform soils are of the ferralitic type: they are deep, very sandy on the surface, with a gradual increase in clay content in line with depth, without any coarse elements. There are two seasons: a dry season from November to April (the driest months being December and January) and a wet season from May to October, providing an average annual rainfall of 2069 mm (Fig. 1). Rainfall is well distributed, and a moderate water deficit occurs (Fig. 2). The planting density experiment was set up in a second-generation plantation established in July 2005, on previous oil palm cover that had

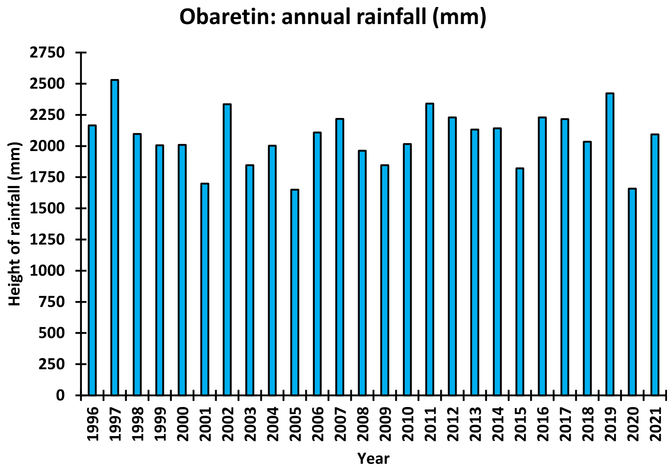


Fig. 1. Obaretin: annual rainfall (mm).

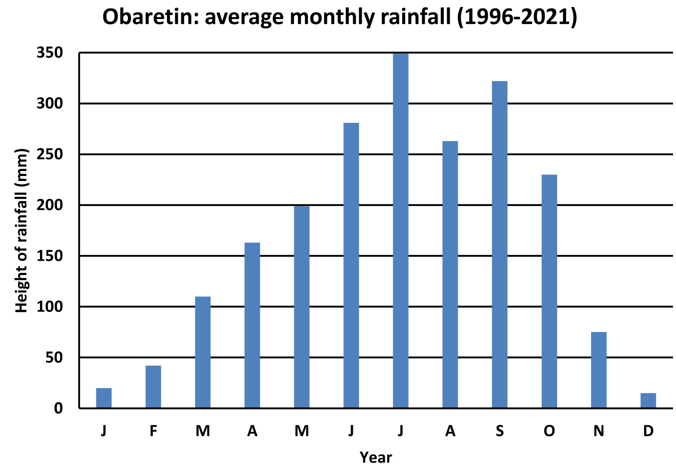


Fig. 2. Presco: Obaretin plantation. Monthly rainfall pattern.

Table 1. Treatment description.

Treatment	Initial planting density (number of palms per hectare)	Distance between palms (in m)	Management of planting density
D 1	128	9.5	Fixed
D 2	143	9	Fixed
D 3	160	8.5	Fixed
D 4	180	8	Fixed
D 5	180	8	Thinned ([1])
D 6	205	7.5	Fixed

[1] By eliminating every 7th palm at 8 years (one central palm per hexagon). At eight years (July 2013) the density went from 180 down to 154 p/ha.

occupied the plot for 25 years. The stems of the felled old palms were pushed to the edge of the experimental plot.

2.2 Planting material

The planting material used since 2002 by the Presco Company is of Pobè C1001F type, which belongs to the Deli × La Mé Group. This variety is widely used throughout the world, providing a high CPO (Crude Palm Oil) yield with a very high oil extraction rate and a slow growth rate. In addition, this genotype has been bred for its resistance to *Fusarium* wilt, a fungal disease widely present in Africa. As this planting material showed a high level of resistance to the disease, it accounts now for more than half of the oil palm seeds sold in the African official market and it is expected to remain one of the most widely sold materials for the next 10 to 20 years (Durand-Gasselin, 2021).

2.3 Statistical design

Our statistical design is a randomized complete block with four replicates of six treatments as described in Table 1 and illustrated in Figure 3. Each of the 24 unit plots comprises 72 palms planted in 9 rows of 8 palms with a double border,

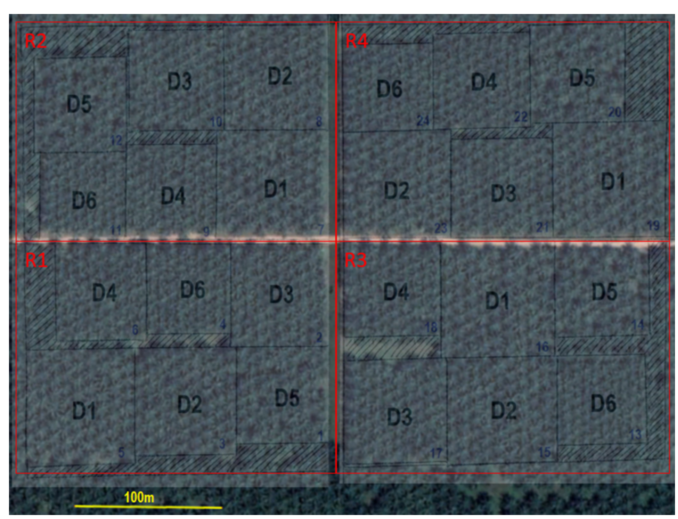


Fig. 3. Presco: Obaretin plantation. Density trial layout in the field. The hatched surfaces represent the zones of in filling at 143 p/ha.

i.e., 20 useful central palms (5 rows of 4). Where necessary, any gaps between the studied plots have been filled with neutral palms. The total area of the trial was 12.7 hectares. The experimental palms were planted in an equilateral triangle design.

Table 2A. Fertilization per palm on young palms (in g of fertilizer per palm).

Date	Type of fertilizer			
	Compound	KCl	Kieserite	Borax
July 2005	500	x	x	x
September 2005	500	x	x	x
April 2006	500	x	x	x
September 2006	500	x	x	x
March 2007	1000	x	x	x
June 2007	1000	x	x	x
September 2007	1000	x	x	x
March 2008	2000	x	x	x
October 2008	x	x	500	x
May 2009	x	2000	x	x
June 2009	x	x	500	x
July 2010	x	x	x	50

NB: 12-12-17-2 compound

Table 2B. Fertilization per hectare from the age of 4 years (in kg of fertilizer per hectare).

Date	Type of fertilizer			
	KCl	EFB	Urea	Kieserite
24 to 28 May 2010	286	x	x	x
29 to 30 June 2011	357.5	x	x	x
24 April to 16 May 2012	x	12 200	x	x
22 to 23 May 2012	286	x	x	x
26 April to 24 May 2013	x	35 000	x	x
30 to 31 May 2013	286	x	x	x
16 April to 14 May 2014	x	35 000	x	x
26 to 27 May 2014	357.5	x	x	x
1 to 21 May 2015	x	35 000	x	x
21 to 22 May 2015	286	x	x	x
16 Mar. to 15 April 2016	x	35 000	x	x
21 to 22 April 2016	x	x	x	286
12 to 13 May 2016	286	x	x	x
19 to 20 May 2016	x	x	286	x
29 Mar. to 26 April 2017	x	35 000	x	x
25 to 26 April 2017	x	x	x	286
12 to 13 October 2017	143	x	x	x
2 to 30 April 2018	x	35 000	x	x
22 to 23 May 2018	214.5	x	x	x
7 March to 5 April 2019	x	35 000	x	x
14 to 15 May 2019	214.5	x	x	x
19 March to 21 April 2020	x	35 000	x	x
19 to 20 May 2020	214.5	x	x	x
12 March to 13 April 2021	x	35 000	x	x
2 to 3 June 2021	143	x	x	x

NB: EFB = Empty Fruit Bunch

2.4 Fertilization regime

The study palms received uniform fertilization regime per palm for the first four years, then uniform fertilization per unit area from the fifth year onwards (Tabs. 2A and 2B). The aim was to adjust the fertilizer input so that mineral fertilization is never a limiting factor. Annual leaf analyses have been used to continuously monitor the mineral nutrition status of the palms and to adjust the fertilization regime accordingly. Table 3 describes changes in nutrition data for the whole experiment from year 13 up to year 16 based on leaf contents for the main nutrients.

Table 3. Leaf contents are expressed as a weight percentage of dry matter.

Treatment	Leaf N contents				Leaf P contents			
	2017	2018	2019	2020	2017	2018	2019	2020
D 1	2.69 ab	2.90 a	2.75	2.87	0.166 a	0.178 a	0.171 a	0.172
D 2	2.67 ab	2.92 a	2.81	2.83	0.160 a	0.178 a	0.170 a	0.171
D 3	2.71 a	2.89 ab	2.75	2.80	0.161 a	0.178 a	0.168 ab	0.164
D 4	2.71 a	2.87 ab	2.75	2.80	0.156 ab	0.174 ab	0.167 ab	0.165
D 5	2.59 ab	2.81 ab	2.67	2.78	0.157 ab	0.175 ab	0.165 ab	0.167
D 6	2.52 b	2.72 b	2.65	2.64	0.150 b	0.169 b	0.161 b	0.159
Mean	2.65	2.85	2.73	2.79	0.158	0.175	0.167	0.166

Treatment	Leaf K contents				Leaf Mg contents			
	2017	2018	2019	2020	2017	2018	2019	2020
D 1	0.952	0.943	0.948	1.04	0.239	0.247	0.239	0.250
D 2	1.03	0.960	1.01	1.06	0.211	0.228	0.222	0.240
D 3	1.01	0.994	1.03	1.10	0.223	0.247	0.235	0.238
D 4	0.938	1.00	1.03	1.09	0.224	0.243	0.235	0.259
D 5	1.05	0.980	1.05	1.10	0.243	0.260	0.255	0.260
D 6	1.01	1.03	1.07	1.15	0.244	0.250	0.248	0.244
Mean	0.998	0.985	1.02	1.09	0.231	0.246	0.239	0.248

Treatment	Leaf C1 contents			
	2017	2018	2019	2020
D 1	0.650	0.572	0.572	0.579
D 2	0.667	0.571	0.556	0.570
D 3	0.649	0.583	0.567	0.598
D 4	0.635	0.591	0.587	0.625
D 5	0.651	0.576	0.585	0.595
D 6	0.690	0.620	0.607	0.606
Mean	0.657	0.586	0.579	0.595

2.5 Trial management

All the replanted palms have grown satisfactorily, and the reasons for the replacements had nothing to do with the planting density: all the treatments have been similarly affected by replacements. It was possible to incorporate many of the replanted palms planted in 2006 and 2007 into the population of useful original palms after they caught up with the adjacent useful palms for growth and yield. The replanted palms that could not be incorporated into the list of useful palms for growth and yield calculations have nonetheless played a large part in the role attributed to them by filling the gaps, thus ensuring the continuity of the canopy and root system in accordance with the protocol density of each unit plot.

2.6 Measured variables

Three types of variables were monitored during the third part of this experiment, namely growth, yield, and climate (monthly rainfall).

For the growth variables:

– Frond length was measured each year from the base of the petiole to the tip of the rachis, by adding together the linear segments.
– The projection on the ground of frond 33 was also evaluated each year, from the base of the stem (thus excluding the radius of the stem) to the tip of the ground projection of the frond. As frond 33 is in quite a horizontal position, its tip is considered as giving the span of the oil palm foliage, which can be viewed as a sphere. This foliage span variable was used to calculate the frond overlap rate in the canopy.
– Stem height was measured each year from the ground to the petiole base of frond 33.
– The LAI (Leaf Area Index) was evaluated in 2017 (Tailliez *et al.*, 1992; Claus 2017).

For the yield variables:

– During each harvesting round (every 10 days), the number of ripe bunches per palm and the individual bunch weights were recorded. Four variables were then analysed on a yearly basis, namely the bunch number per palm, average bunch weight, total bunch weight per palm and total bunch weight per hectare.

Table 4. Changes in frond length (m).

	Age of palms in years								
Treatment	8	9	10	11	12	13	14	15	16
D 1	5.69 c	5.87 c	6.11 c	6.52 c	6.51 b	6.39 b	6.42 c	6.76 d	6.42 c
D 2	5.73 c	5.93 bc	6.19 bc	6.75 bc	6.67 ab	6.54 ab	6.61 bc	6.83 cd	6.61 bc
D 3	5.89 bc	6.12 abc	6.38 abc	6.87 abc	6.72 ab	6.64 ab	6.66 bc	6.98 bc	6.70 bc
D 4	6.04 ab	6.18 ab	6.57 ab	7.08 ab	6.75 ab	6.71 ab	6.86 ab	7.18 b	6.92 b
D 5	6.04 ab	6.19 ab	6.39 abc	6.86 abc	6.68 ab	6.64 ab	6.71 b	7.00 bc	6.80 b
D 6	6.13 a	6.28 a	6.74 a	7.26 a	6.81 a	6.90 a	7.04 a	7.44 a	7.33 a
Mean	5.92	6.10	6.40	6.89	6.69	6.64	6.72	7.03	6.80

a,b,c... = classification of the treatments according to the Tukey test at 5%.

Table 5. Changes in stem height (m).

	Age of palms in years								
Treatment	8	9	10	11	12	13	14	15	16
D 1	1.38	1.76	2.21	2.44	2.82	3.15	3.52 b	3.94	4.35 b
D 2	1.40	1.75	2.23	2.57	2.89	3.28	3.74 ab	4.06	4.52 ab
D 3	1.42	1.78	2.22	2.57	2.90	3.31	3.77 ab	4.08	4.56 ab
D 4	1.48	1.86	2.34	2.67	3.05	3.39	3.95 a	4.25	4.66 ab
D 5	1.38	1.74	2.23	2.61	2.96	3.35	3.75 ab	4.10	4.56 ab
D 6	1.45	1.84	2.28	2.62	3.09	3.48	3.93 a	4.32	4.87 a
Mean	1.42	1.79	2.25	2.58	2.95	3.33	3.78	4.12	4.59

3 Results

Table 3 shows trends in leaf contents for five nutrients (N, P, K, Mg and Cl) over the last four seasons. Nutrition has remained good and uniform, apart from a decreasing gradient in line with planting density for N and P, though without any consequences for yields, as within a non-limiting content range.

Tables 4–6 show the trends evidenced for three growth variables, namely: stem height, frond length and length of vertical frond projection on the ground. Etiolation of the palms has become significant over the latest seasons between the lowest planting density and the highest. At sixteen years, there is a height difference of 52 cm between D1 (435 cm) and D6 (487 cm). The average frond length stabilized at slightly under 7 m right from the eleventh year after planting. There is an increasing "frond length" gradient in line with planting density which is also logically found for the "length of foliage projection on the ground" variable.

Tables 7–10 show trends recorded for yields over the last nine seasons. The linear gradient for the annual yield reduction in line with planting density has been confirmed year after year and is logically found for the cumulative yields per palm. For annual yields per hectare, the high densities were still in pole position in the eighth year, but a switchover occurred in the ninth year, when the low densities took the lead and remained there, with the difference proving significant in years fourteen and sixteen. This switchover has logically led to a levelling off of cumulative yields per hectare, with density D3 moving into the lead and remaining there since year thirteen.

4 Discussion

Thinning was found not to be relevant under our experimental conditions (starting with 180 p/ha, thinning at 8 years by removing every 7th palm, leaving 154 p/ha). In fact, as found in the rows of treatments D4 and D5, in Tables 7–10, the individual yields of the remaining palms increased (Tab. 7) after thinning, but not enough to compensate for the loss of 1 out of 7 palms (Tab. 10): at 8 years, the cumulative yields per hectare in treatment D5 were 95% those of D4; at 16 years, they were 97%. Eight years after thinning, density D5 had still not caught up with density D4, and even if it did so before the end of the oil palm cycle, it would be too late to be a profitable operation.

For yields, three different strategies were used to achieve the same goal, namely calculate the optimum density at 20–25 years in an equilateral triangle design at a fixed density.

Firstly, Figure 4 shows the optimum density trends calculated yearly as a function of yield over time. Optimum densities were high (between 155 and 199) up to 11 years, and then fell to around 143 and below from year 12 onwards. It is therefore highly likely that they will remain at the level 143, or even eventually below it.

Secondly, Figure 5 shows trends in the optimum density as a function of cumulated yield over time. It is a curve with a rapid descent levelling off towards an asymptote. Out of several possible types of mathematical fitting, two proved to be the most realistic.

Table 6. Changes in the distance from the stem of the projection on the ground of the tip of frond 33 (m).

	Age of palms in years								
Treatment	8	9	10	11	12	13	14	15	16
D 1	4.86 b	5.08	5.54	5.48 b	5.89 b	5.88 b	5.99 b	6.05 c	6.04 c
D 2	4.94 b	5.20	5.63	5.57 ab	5.96 ab	5.92 ab	6.18 ab	6.31 abc	6.18 bc
D 3	5.05 ab	5.25	5.71	5.72 ab	6.14 ab	6.09 ab	6.22 ab	6.28 bc	6.32 bc
D 4	5.16 a	5.37	5.79	5.87 a	6.05 ab	6.25 ab	6.23 ab	6.42 ab	6.53 ab
D 5	5.19 a	5.29	5.73	5.78 ab	6.05 ab	5.99 ab	6.27 ab	6.27 bc	6.32 bc
D 6	5.22 a	5.42	5.85	5.90 a	6.22 a	6.40 a	6.47 a	6.57 a	6.80 a
Mean	5.07	5.27	5.71	5.72	6.05	6.09	6.23	6.32	6.36

Table 7. Changes in annual yield per palm in kg of bunches.

	Year of planting								
Treatment	8	9	10	11	12	13	14	15	16
D 1	110.2 ab	125.1 a	135.9 a	132.6 a	148.8 a	129.3 a	135.7 a	153.6 a	150.6 a
D 2	114.4 a	117.9 a	122.9 a	125.3 ab	140.9 a	116.3 a	127.5 ab	121.7 b	131.5 b
D 3	109.9 ab	112.0 ab	122.0 a	125.3 ab	122.0 ab	99.2 ab	116.3 ab	122.8 ab	122.6 bc
D 4	98.9 bc	83.6 cd	106.4 ab	102.7 bc	103.2 bc	82.9 bc	84.1 cd	102.9 bc	94.3 d
D 5	93.2 c	97.5 bc	112.4 ab	114.8 abc	109.2 bc	99.6 ab	107.8 bc	112.2 b	115.5 c
D 6	91.2 c	76.4 d	91.2 b	88.5 c	90.7 bc	57.3 c	65.1 d	78.4 c	81.5 d
Mean	103.0	102.1	115.1	114.9	119.2	97.4	106.1	115.3	116.0

a,b, c... = classification of the treatments according to the Tukey test at 5%.

Table 8. Changes in cumulative yield per palm in kg of bunches.

	Year of planting								
Treatment	8	9	10	11	12	13	14	15	16
D 1	326	451 a	587 a	719 a	868 a	998 a	1133 a	1287 a	1437 a
D 2	320	438 ab	561 ab	686 ab	827 a	943 ab	1071 ab	1192 ab	1324 ab
D 3	318	430 ab	552 ab	677 abc	799 ab	899 bc	1015 bc	1138 bc	1260 bc
D 4	301	385 bc	491 bc	594 cd	697 cd	780 de	864 d	967 d	1061 d
D 5	286	384 bc	496 bc	611 bcd	720 bc	820 cd	927 cd	1040 cd	1155 cd
D 6	285	361 c	452 c	541 d	632 d	689 e	754 e	832 e	914 e
Mean	306	408	523	638	757	855	961	1076	1192

Table 9. Changes in annual yield per unit area in tons of bunches per hectare.

	Year of planting								
Treatment	8	9	10	11	12	13	14	15	16
D 1	14.11 b	16.01	17.40	16.97	19.05	16.55	17.37 ab	19.66	19.27 a
D 2	16.36 ab	16.86	17.58	17.91	20.05	16.63	18.23 a	17.40	18.81 ab
D 3	17.59 a	17.92	19.52	20.05	19.53	15.87	18.61 a	19.64	19.61 a
D 4	17.80 a	15.04	19.16	18.49	18.57	14.92	15.14 ab	18.51	16.98 bc
D 5	16.78 a	15.01	17.32	17.68	16.82	15.33	16.60 ab	17.28	17.79 abc
D 6	18.69 a	15.66	18.69	18.13	18.59	11.75	13.34 b	16.08	16.71 c
Mean	16.89	16.08	18.28	18.21	18.79	15.17	16.55	18.10	18.20

Table 10. Changes in cumulative yield per unit area in tons of bunches per hectare.

Treatment	Year of planting								
	8	9	10	11	12	13	14	15	16
D 1	42 d	58 c	75 b	92 b	111 b	128 b	145	165	184
D 2	46 cd	63 bc	80 ab	98 ab	118 ab	135 ab	153	170	189
D 3	51 bc	69 ab	88 a	108 a	128 a	144 a	162	182	202
D 4	54 ab	69 ab	88 a	107 ab	125 a	140 ab	155	174	191
D 5	52 bc	67 ab	84 ab	102 ab	118 ab	134 ab	150	168	185
D 6	58 a	74 a	93 a	111 a	129 a	141 ab	155	171	187
Mean	50	67	85	103	122	137	153	172	190

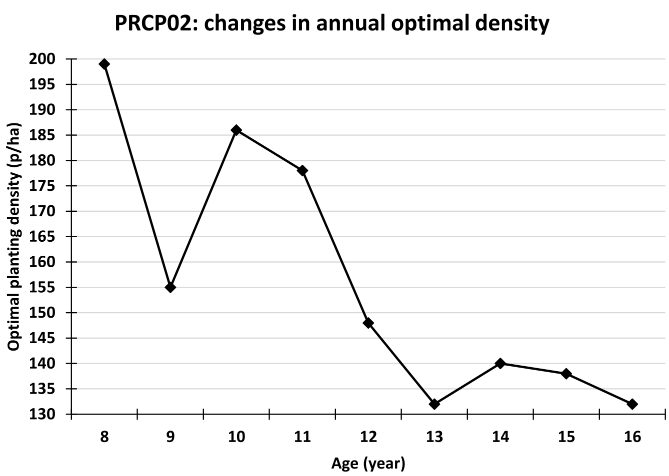


Fig. 4. Values of the yearly optimal densities as a function of yield.

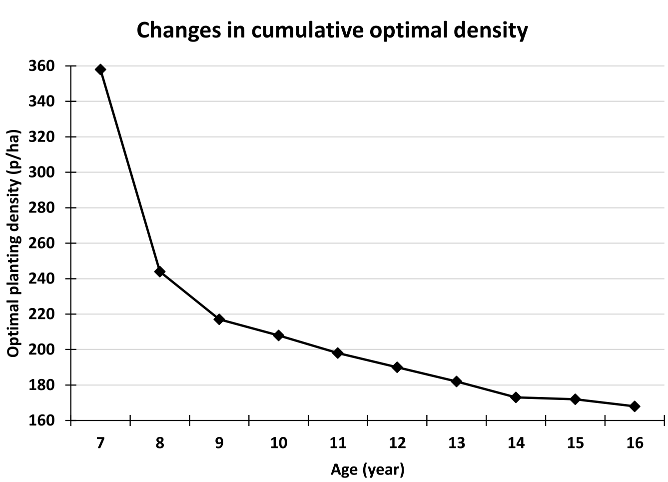


Fig. 5. Values of the optimal densities as a function of cumulated yield.

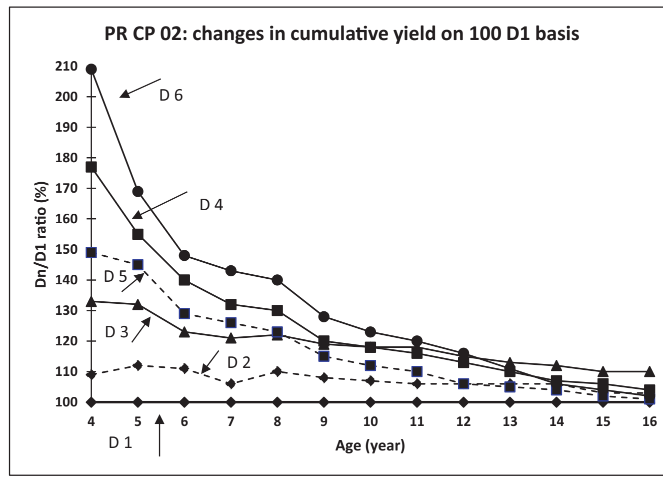
The logistic model of equation

$$y = a/(1 + b * e\exp(-c * x))$$

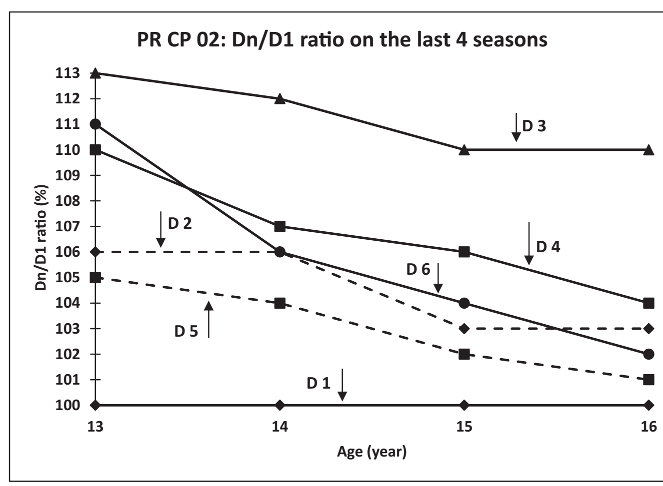
The saturation growth model of equation

$$y = a * x/(x - b)$$

where a, b and c being positive coefficients.



(a)



(b)

Fig. 6. PR CP 02: Changes in cumulative yield on 100 D1 basis.

The better of the two (saturation growth, because the calculated figures in the 20–25 year range are more realistic) gave a calculated optimum density of 147 p/ha at 20 years and 138 p/ha at 25 years.

Thirdly, Figure 6 shows the Dn/D1 ratio trend for each of the studied densities over time. Extension of the curve for each using the saturation growth model gives the following

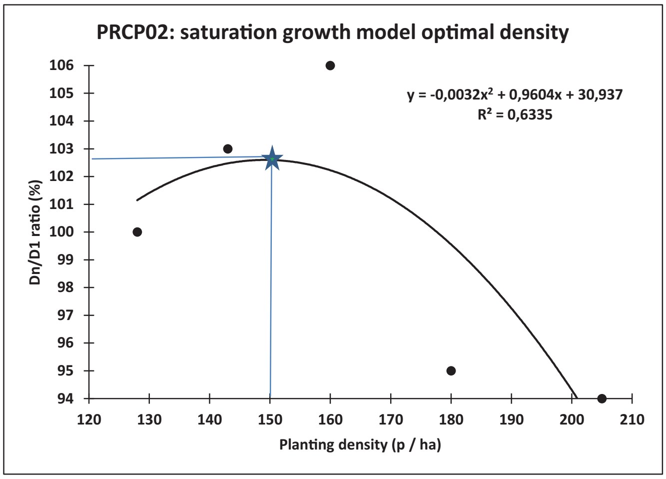
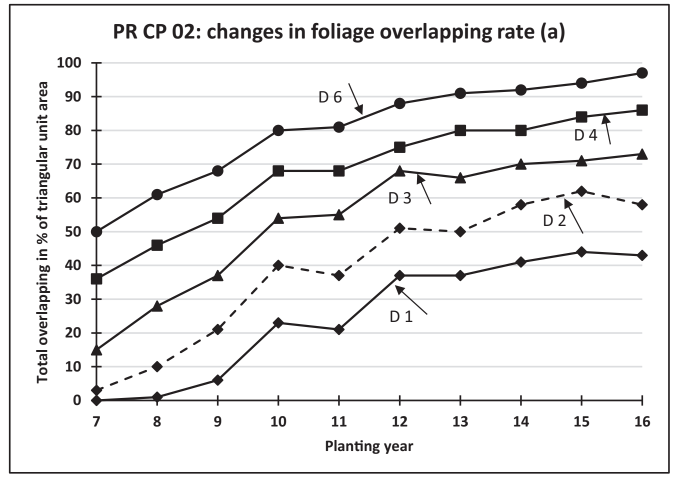


Fig. 7. Optimal density: quadratic adjustment.



(a)

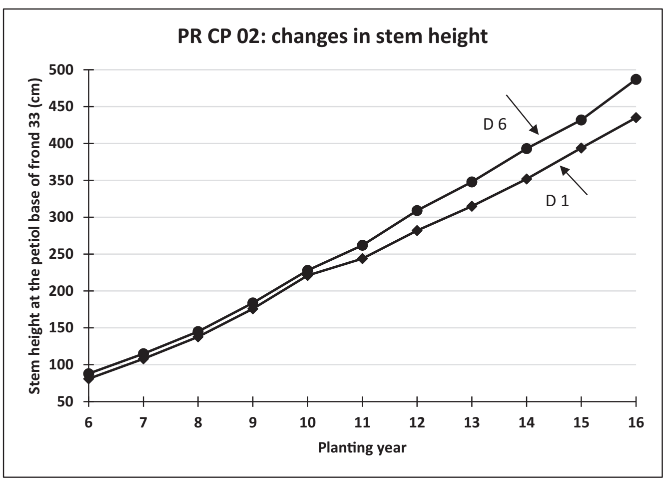
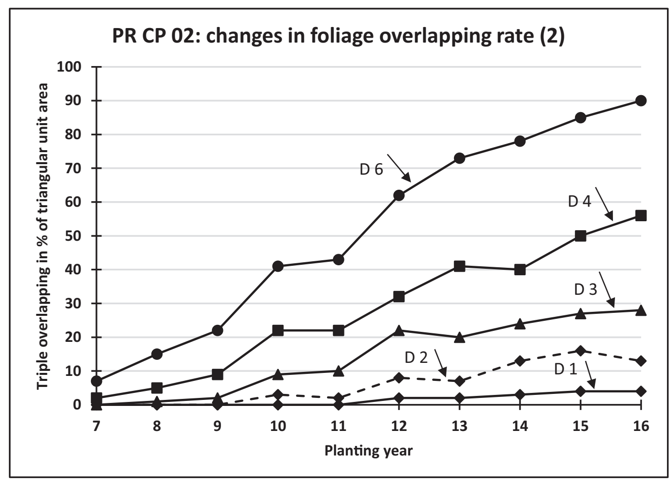


Fig. 8. PR CP 02: Changes in stem height.



(b)

Fig. 10. (a, b) PR CP 02: Changes in foliage overlapping rate.

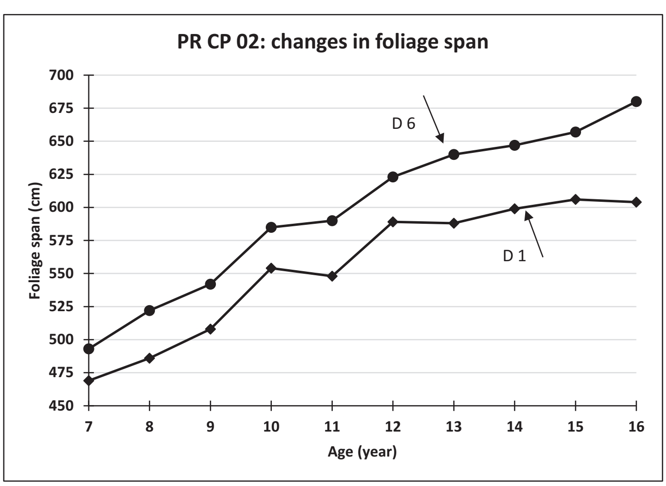


Fig. 9. PR CP 02: Changes in foliage span.

Table 11. Leaf Area Index at 12 year (source: Claus, 2017).

Treatment	D.	F.A.	N.F.	L.A.I.
D 1	128	7.22	35.1	3.24
D 2	143	6.93	35.5	3.52
D 3	160	7.30	34.2	3.99
D 4	180	7.41	33.6	4.47
D 5	154	7.56	33.1	3.85
D 6	205	7.43	31.6	4.81

D.: Planting density as number of palms per hectare; F.A.: Foliar area in m^2; N.F.: Number of fronds per palm; L.A.I.: Leaf Area Index as (D × FA × NF / 10 000).

asymptotic values: 94 for D6, 95 for D4, 106 for D3 and 103 for D2. These values were used to produce a quadratic graph from which the optimum density was drawn, namely 150 p/ha (Fig. 7).

The three methods were found to be compatible and they generated values fluctuating around an optimum density plateau of between 138 and 160 p/ha within the 20 to 25-year age range.

For oil palm growth, we were able to calculate that with a vertical growth rate of 37 cm per year for the stem, it would take 1000/37 = 27 years, *i.e.*, 30 years when adding the 3 years of growth during the young age before stem emergence, to reach the maximum height (10 m) for bunch accessibility to harvesters using harvesting poles. Etiolation was found to be real (Fig. 8), but only occurring significantly at either end of the density scale.

The maximum frond length stabilized at almost 7 m from the 12th year of planting, with a length gradient increasing in line with planting density. We put forward the hypothesis that leaf area increases in line with planting density, in order to increase radiative interception in a highly competitive environment for incident radiation capture.

The same gradient is found for oil palm foliage span, measured by the projection on the ground of the length of a horizontal frond, ranging from 6 to 6.5 m. Figure 9 shows trends for the two extreme densities. A Weibull fit gave final foliage bulk values of between 6.17 m for density D1 and 6.89 m for density D6. These foliage bulk values are used to calculate the foliage overlap rate in the triangle formed by three palms. Figure 10 shows overlap trends over time: by the foliage of two palms or more (Fig. 10a) and by the foliage of three palms only (Fig. 10b). A virtually linear increasing gradient is logically found for the overlap rate in line with the planting density. The differences are clearer for the overlap by the foliage of three palms (Fig. 10b): from 4% (D1) to 90% (D6). The optimum planting density corresponds to a foliage overlap rate of 60 to 70%, or roughly two thirds of the canopy consists of foliage of at least two palms. This corresponds to a Leaf Area Index of 3.5 to 4 within a Leaf Area Index range of 3.24 (D1) to 4.81 (D6) measured at 12 years (Tab. 11).

5 Conclusion

The purpose of this study was to determine the optimum planting density for C1001F material planted in the coastal zone of Western Africa on desaturated ferralitic sandy soil under a two-seasons climate, over an economic life span of 20 to 25 years.

The major outcome of the present study is an optimum density plateau ranging between 143 and 160 p/ha.

Under such conditions generating a broad optimum density plateau, what criteria should be used to choose the better planting density? Is it better to plant at the lowest density or the highest density of the plateau, or rather in the middle as a trade-off?

When taking the economic life span into account, with the longest possible access to bunches for harvesting, preference will be given to the lowest density in the plateau to benefit from a slow vertical growth rate. The palms will take longer to reach a stem height placing bunches beyond the reach of harvesting poles. Even so, we found etiolation to be significant between the two extreme densities at 16 years, and to be limited between density D2 (452 cm) and density D3 (456 cm), *i.e.*, only + 4 cm. Consequently, this factor will not play a large role in deciding between 143 and 160 p/ha.

If the phytosanitary aspect is considered, in zones where lethal diseases are rife, the recommendation is to plant at the highest plateau density, in order to allow for a degree of cumulative mortality over 20 years. At the end of the cycle, there will be gaps in the canopy, but the remaining density will stay within the plateau. This argument, while not insubstantial, is not of paramount importance with C1001F material in Western Africa. Indeed, it has proved to be highly tolerant to vascular wilt (no dead palms over the 16 years of the trial), and tolerant of *Ganoderma* (only 2 deaths/1000 over the 16 years of the trial). The causes of death in this trial have been: termite and grass cutter attacks in the young age, sporadic *Oryctes* attacks, but those are rarely lethal (they usually result in some temporary deformation of the crown) and toppling of the crowns of adult palms of unknown origin, which affected some palms twice in sixteen years. Such toppling also leads to crown deformation, which can sometimes be lethal, but most of the palms right themselves after a while. It is assumed that toppling was caused by strong gusts of wind at the end of the dry season, at a time when palms are at their most fragile. It is worth noting that lightning, a random but frequent phenomenon that can kill one or more palms in one go, spared the palms throughout the life of the trial. Mortality has therefore remained low over the sixteen years. Consequently, this factor will not play a paramount role either under the local experimental conditions.

Herbaceous ground cover diminishes in line with planting density. We found in the experiment that the middle of the interrow remained abundantly grass and heliophilic weeds covered in the lowest density and that cover decreased as the planting density increased, with hardly any cover on the ground at the highest density. This is therefore an advantage at high densities: less competition between oil palm roots and weed roots for water and nutrients, along with less outlay for weed control. However, given that the interrow is occupied anyway by a creeping legume that dominates herbaceous weeds, at least during the immature years, this argument carries less weight. The largest weeding costs are those incurred to clean the weeded circles around the oil palms to limit loose fruit losses from ripe bunches. This is a variable cost, which is discussed below.

The economic factor is the most important (Surre, 1955). If emphasis is on the return on investment, then planting should be at the highest density (160 as it happens), since the optimum density curves show that the 160 p/ha density remains better than the 143 p/ha density up to 16 years and will probably remain so for another few years. On the other hand, if emphasis is on long-term productivity (up to the end of the economic life span in this case), planting should be at the lowest density of the plateau (143 p/ha). Indeed, for the same cumulative yield, variable costs such as harvesting, weeded circle cleaning and fertilizer application per palm is greater when there are more palms per hectare. In our case, it results into an increase in variable costs of 160/143 = 12% when switching from 143 to 160 p/ha.

As a trade-off, a choice can be made to plant at an intermediate density between 143 and 160, such as 151 p/ha, corresponding to an 8.75 m equilateral triangle planting design.

6 Perspectives

We have published a series of three successive articles covering a 16-year period of continuous control and monitoring of an oil palm planting density field experiment. It results in proposing a plateau of optimal planting density of a specific material grown in a specific pedoclimatic context.

We demonstrate that planting density is an important production factor, as important as other more famous production factors like: the material, the fertilization or the crop protection against pests and diseases.

We see indeed that the spacing between the palms has a significant effect on the utilization of natural resources, especially the radiative resource, which in turn has a significant impact on the cumulative yield of the palms during a 20 to 25-year economic life cycle.

Planting at the best possible density is therefore an important factor with significant positive consequences in the optimization of the yield, so not to be underestimated by the planters and the agronomists.

The experimental data on the optimization of the planting density are not as numerous as the data on the other aforementioned production factors, because field experiments on planting density with their long-to-come return on investment require a lot of patience and are therefore less attractive.

We would suggest that the oil palm seed producers include this planting density parameter when they promote their material. Mentioning for instance that a certain material has a certain yield potential but also specifying the conditions to reach this potential yield particularly the planting density.

It is also important to note that the conclusions drawn from this trial apply to monoculture plantations with a regular and consistent spacing distance between palms in an equilateral triangle design, established at planting time. Indeed, alternative plantation design systems can be relevant in cases where oil palm is combined with other crops (intercropping) or land uses (following the contour lines along terraces in hilly areas for instance). Intercropping is one such option and would appear to be most efficient at low density planting as it results in higher production per palm, slower stem growth and shorter foliage span which would give more space and resources for other crops, although intercropping is much more practiced with coconut palm (Bonneau *et al.*, 1999; Mialet *et al.*, 2001) than with oil palm. Indeed, due to the higher economic value of palm oil, intercropping is rarely practiced in industrial estates but its income and output diversification might be an interesting option for smallholders.

Similarly, the thinning treatment, while not economically viable in terms of cumulative oil palm yield, can have other benefits considering that the felled trees can provide some income (for example from palm wine tapping, a common practice in Africa). Additionally, the space left by the reduction of the initial density can be used for intercropping or cattle grazing.

Such perspectives are particularly relevant for smallholder plantations, which represent a large share of the oil palm planting area and production output in western Africa. Additional studies and field experiments should further evaluate the socio-economic and agro-ecological challenges and opportunities offered by intercropping systems at reduced oil palm planting density. The results from this trial can provide valuable insights to design and optimize them.

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