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High Robusta coffee plant density is associated with better yield potential at mixed responses for growth robustness, pests and diseases: which way for a farmer?

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Abstract

Plant density in Robusta coffee is an unresolved issue in low volume producing countries especially when compared with leading producers. In this study, we aimed to compare the response of Robusta coffee to pest incidence, disease severity, growth and yield potential in two contrasting spacing regimes. Two spacing regimes of 3mx3m and 3mx1m were evaluated for selected parameters in a randomized complete block design with three replications. There was a highly significant difference in pest incidence between the spacing regimes ($p<0.01$) for all the pests except scales ($p=0.126$). The black coffee trig borer incidence was higher under close spacing of 3mx1m than for 3mx3m with a mean difference of 13.2%. There was no significant association between spacing regime and leaf rust disease incidence while the association was significant for red blister disease ($\chi 2=33.56$, df=1, $p<0.001$). Significant difference in growth response between spacing regimes ($p<0.05$) were also obtained for change in canopy height (dCAH), number of primaries, number of stems and leaf size. For instance, dCAH was higher under 3mx1m spacing than for 3mx3m spacing. A significant difference in yield potential existed between the spacing regimes ($p<0.05$) for average yield per tree and average yield per hectare (aYH). Close spacing produced a higher aYH (5.82 t cc/ha) than wide spacing (4.80 t cc/ha). Whereas yield potential is high at high tree densities, associated prevalence of biotic constraints calls for supportive stress management package for farmers.

Keywords: Recommended spacing; Robusta coffee productivity; plant population; Black coffee trig borer incidence; Disease severity.

Abbreviations: BCTB_Black coffee trig borer; CBB_Coffee berry borer; CLR_Coffee leaf rust; FAO_Food and Agriculture Organization of the United Nations; GoU_Government of Uganda; kg cc/ha_kilograms of clean coffee per tree.

Introduction

Coffee (*Coffea* spp.) is the main traditional cash crop in Uganda, and it's the major source of export revenue, contributing over 20% of the country's foreign exchange earnings. However, the productivity of coffee in Uganda is still very low estimated, at an average of 0.53 t ha^{-1}/yr, compared to an average of 1.51 t/ha and 2.44 t/ha by Brazil and Vietnam, respectively; the leading producers of the crop (FAO, 2018). In 2016, the top five coffee producing countries worldwide included Brazil, Vietnam, Colombia, Indonesia and Ethiopia at 50.3, 24.3, 12.4, 10.7 and 7.8 million 60-kg bags, respectively; while Uganda was in the 10th position with 3.4 million 60-kg bags (FAO, 2018). Uganda also has the lowest area under coffee production when compared to the 5 top producing countries (Brazil, 1.99 m ha; Vietnam, 0.60 m ha; Colombia, 0.87 m ha; Indonesia, 1.23 m ha; Ethiopia, 0.70 m ha; Uganda, 0.38 m ha).

Further, Uganda's coffee productivity (production per unit area; yield) is lower than that of top producers apart from Indonesia (0.52 t/ha). The apparent reason for the current low coffee production in Uganda is the low area under coffee cultivation (FAO, 2018), among other constraints (biotic and abiotic) (Olal et al., 2019; Kagezi et al., 2018a; Bukomeko *et al*., 2017; Paulo et al., 2010). However, the Government of Uganda (GoU) and its partners have recently embarked on increasing the area under coffee cultivation through distribution of seedlings to farmers. The current low yields are partly attributable to inappropriate agronomic practices (Olal et al., 2018; Kagezi et al., 2018b). Findings by Anim-Kwapong *et al.* (2010) revealed that the highest yield (1289.5 kg/ha) of clean coffee were obtained from the highest planting density of 2667 trees/ha of Robusta coffee clones after 5 years in Ghana. However, the clones had a relatively compact growth habit, that is, smaller stem diameter and shorter internode length (Anim-Kwapong et al., 2010; Sakai et al., 2013; Salamanca-Jimenez et al., 2017). Further, an impact of tree system (multiple or single) is indispensable but a systematic investigation into such a claim is yet to be carried out. In the case of the on-going on-farm trials whose preliminary results this report highlights, we aimed to compare on-farm performance of Robusta coffee under two contrasting spacing regimes. Specifically, the second data collection was aimed at comparing the: pest incidence and damage, disease incidence and severity, and growth response and yield potential under two contrasting spacing regimes of Uganda 3mx3m and Brazil's 3mx1m. The information generated will be used by researchers, policy makers and extension workers when recommending to farmers the best-bet spacing of coffee for maximum productivity.

Results

Pest incidence

There was a significant association between RMB infestation and spacing ($\chi2=11.82$, df=1, p=0.001). Widely spaced coffee fields were recorded with a higher RMB incidence than the closely spaced field (Fig. 1). Further, there was a significant interaction between month and spacing for incidence of LM (Table 3) but non-significant for BCTB, SKL, TC, LEB, CM, Scales, BM and CBB. There was also a significant difference in incidence of pests between months for BCTB (p<0.001) (Fig. 2), LM (p<0.001), LEB (p<0.001) and CBB (p<0.05). Overall, BCTB incidence increased from 11.1% in June 2018 to17.6% in October 2018. Incidence of LM increased from 10.5% in June 2018 to 17.6%. There was a reduction in LEB incidence from 5.4% in June 2018 to 1.9% in October 2018. The CBB incidence increased from 2.7% in June 2018 to 5.1% in October 2018.

There was a highly significant difference in pest incidence between the spacing regimes (p<0.01) for all the pests except Scales (p=0.126) (Table 2). The BCTB incidence was higher under close spacing of 3mx1m than for 3mx3m with a mean difference of 13.2% (Tables 1, 4 and 6). Similarly, LEB incidence was higher under 3mx1m spacing than for wide widely spaced coffee, by a margin of 3.7%. However, incidence of LM, SKL, TC, BM and CBB was higher under 3mx3m (wide spacing) than in closely spaced coffee; with CM's incidence being higher by 30.9% when compared to closely spaced coffee (Fig. 3).

Disease incidence and severity

No symptoms of BES were observed. There was no significant association of spacing and LRD incidence while it was significant for RBD ($\chi2=33.56$, df=1, p<0.001). The incidences for RBD was lower under closely spaced coffee than with widely spaced (3mx3m) coffee fields. Similarly, there was no significant difference in severity of LRD between spacing regimes (p>0.05). The difference in RBD between spacing regimes was very highly significant (p<0.001). There was a lower RBD severity (1.0; no symptoms) under close spacing (3mx1m) compared to widely spaced (3mx3m) coffee whose mean severity was 1.6.

Growth response and yield

Growth response

There was a significant difference in growth response between spacing regimes (p<0.05) for canopy height (dCAH) (Table 6), number of primaries (dNOP), number of stems (aNOS), leaf blade length (aLBL) and leaf blade width (aLBW). The dCAH was higher under 3mx1m spacing (Field 1) than for 3mx3m spacing (Table 7). Specifically, dCAH for closely coffee fields was higher by 7.91 cm and 11.84 cm when compared to widely spaced fields 2 and 3, respectively (Table 9). The dNOP for 3mx1m and 3mx3m spacing was 0 and 5, respectively. The aNOS was lower for close spacing at 2 stems/tree than wide spacing at 3 stems/tree. Similarly, dCAD was lower under close spacing than wide spacing. Further, longer leaves (24.4 cm) were obtained under wide spacing as compared to close spacing (23.6 cm) (Table 8). Conversely, wider leaves were obtained under close spacing (10.4 cm) compared to wide spacing (9.9 cm).

The mean difference (d) between the close spacing field (Field 1) and any wide spacing field (Field 2 and Field 3) was positive and significant for canopy height (d=11.84 cm, p=0.040) (Table 9), internode length on primary (d=0.57, p=0.037) and leaf blade width (d=0.475, p=0.040). However, d was negative and significant for stem girth (d=-0.23, p=0.045), number of primaries (d=-6.32, p=0.003), number of stems (d=-1.74, p<0.001), and leaf blade length (d=-1.37, p=0.002).

Green bean yield potential

There was a significant difference in yield potential between spacing regimes (p<0.05) for average yield per tree (aYT) and average yield per hectare (aYH) (Table 6). Specifically, aYH was higher under close spacing (3mx1m) at 5.82 t cc/ha (Table 8) than wide spacing at 4.80 t cc/ha (3mx3m). The aYT was however, higher under wide spacing at 2.31 kg cc/tree than close spacing which generated 1.75 kg cc/tree. Similarly, higher number of berries per tree was observed under wide spacing at 6,934 berries per tree than close spacing which produced 5,241 berries per tree.

The mean difference (d) for yield-related parameters between the close spacing field (Field 1) and any wide spacing field (Field 2 and Field 3) was higher and but non-significant for number of clusters per sample primary (Field 1 minus Field 2: d=1.17 berries/cluster, p=0.230) (Table 9) and yield potential per hectare (Field 1 minus Field 2: d=0.84, p=0.189; Field 1 minus Field 3: d=0.34, p=0.609). However, d was negative and significant for number of active bearing primaries (Field 1 minus Field 2: d=-11.31, p<0.001), number of berries per cluster (Field 1 minus Field 2: d=-7.52, p=0.001; Field 1 minus Field 3: d=-9.60, p<0.001), number of berries per tree (Field 1 minus Field 3: d=-2712.85, p=0.003) and yield per tree (Field 1 minus Field 3: d=-0.90 kg cc/tree, p=0.003).

Discussion

Effect of spacing on pest incidence

Pest incidence varied with spacing with some pests exhibiting a higher incidence under close spacing (3mx1m) than wide spacing (3mx3m), and vice-versa. High RMB presence was associated with 3mx3m compared to 3mx1m. It is notable that the 3mx1m plantation was younger than 3mx3m fields. RMBs are more incident when plants are stressed. The 3mx3m fields consisting old plants are most probably more stressed than recently established plantations. Further, RMBs require time to spread from one field to another; implying that relatively young plantations (for 3mx1m) had not yet experienced high RMB populations (Mani et al., 2016). It is thus likely that as plants of closely spaced coffee mature, nutrient deficiency may set in if appropriate supplementation is not done; as RMB populations also rise; the incidence and damage by the pest can surpass that under wide spacing. Also, close spacing is highly likely to facilitate plant-to-plant RMB spread (Mani et al., 2016). Incidence of black coffee trig borer (BCTB) and leaf eating beetles (LEB) increased over time, and it was always higher under closely spaced plants. Generally, highly shaded agro-systems such as coffee encourage BCTB infestation (Bukomeko et al., 2017; Kagezi et al., 2014). Basing on the analogy by Kagezi et al. (2014), Kagezi et al. (2013) and Hultman et al. (2016), close spacing is thus suggested to have created bushy conditions which increase proximity to BCTB and LEB infested coffee plants. Notable is that both BCTB and LEB are coleopterans (Kagezi et al., 2013, 2014; Mani et al., 2016), and they can readily fly over short ranges which are created with close spacing.

Table 1. Mean comparison for incidence of different coffee pests recorded over time, fields and spacing regimes.

Month	Field	Spacing	BCTB	LM	SKL	TC	LEB	CM	Scales	BM	CBB
Jun-18	Field 1	3mx1m	20.1	10.9	1.5	2.5	8.5	13.5	0.0	7.5	0.1
	Field 2	3mx3m	10.4	11.7	1.9	3.0	2.0	46.7	0.6	16.7	7.6
	Field 3	3mx3m	2.8	8.9	16.5	19.0	5.8	38.1	0.7	7.6	0.4
		3mx1m	20.1	10.9	1.5	2.5	8.5	13.5	0.0	7.5	0.1
	Mean	3mx3m	6.6	10.3	9.2	11.0	3.9	42.4	0.6	12.2	4.0
		Mean	11.1	10.5	6.6	8.2	5.4	32.8	0.4	10.6	2.7
Oct-18	Field 1	3mx1m	25.8	10.8	0.9	3.0	3.6	7.7	0.2	1.2	0.8
	Field 2	3mx3m	19.8	15.0	3.4	4.1	1.4	41.7	0.2	16.2	13.0
	Field 3	3mx3m	7.0	27.3	13.2	14.2	0.7	40.0	0.9	5.7	1.3
		3mx1m	25.8	10.8	0.9	3.0	3.6	7.7	0.2	1.2	0.8
	Mean	3mx3m	13.5	21.1	8.2	9.1	1.0	40.8	0.5	11.1	7.3
		Mean	17.6	17.6	5.7	7.0	1.9	29.8	0.4	7.7	5.1
Mean	Field 1	3mx1m	22.9	10.8	1.2	2.8	6.0	10.7	0.1	4.4	0.4
	Field 2	3mx3m	15.1	13.4	2.7	3.5	1.7	44.2	0.4	16.5	10.3
	Field 3	3mx3m	4.8	17.9	14.9	16.7	3.3	39.0	0.8	6.7	0.8
		3mx1m	22.9	10.8	1.2	2.8	6.0	10.7	0.1	4.4	0.4
	Mean	3mx3m	10.0	15.6	8.7	10.0	2.5	41.6	0.6	11.6	5.6
		Mean	14.4	14.0	6.2	7.6	3.6	31.3	0.4	9.2	3.9

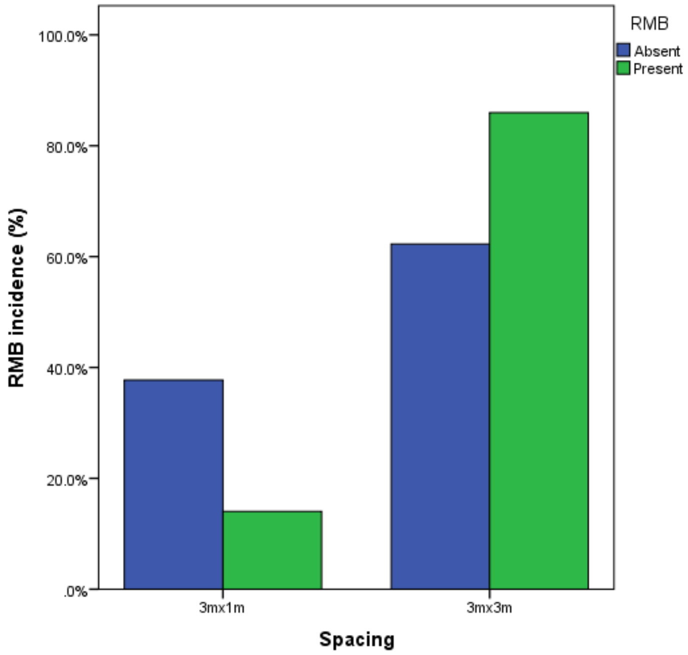

Fig 1. Relative frequency of root mealy bug under contrasting spacing regimes in Robusta coffee

Table 2. Significance of mean difference (MD) in pest incidence between two contrasting spacing regimes

Pest	Assumption on variances	Levene's test for equality of variances		*t*-test for equality of mean pest incidence for spacing regimes						
		F	*p*	*t*	d.f	*p* (2-tailed)	MD	S.E.D	95% CI for MD	
									LL	UL
BCTB	Non-equal variances			9.791	199.83	0.000	12.92	1.319	10.32	15.52
LM	Equal variances	18.16	0.000	-3.024	320	0.003	-4.82	1.593	-7.95	-1.68
SKL	Equal variances	112.50	0.000	-6.679	320	0.000	-7.51	1.124	-9.72	-5.30
TC	Equal variances	72.62	0.000	-6.494	320	0.000	-7.26	1.117	-9.45	-5.06
LEB	Equal variances	14.50	0.000	3.634	317	0.000	3.50	0.963	1.60	5.39
CM	Equal variances	42.65	0.000	-8.864	319	0.000	-30.97	3.494	-37.84	-24.09
Scales	Equal variances	9.45	0.002	-1.535	320	0.126	-0.47	0.305	-1.07	0.13
BM	Equal variances	29.21	0.000	-4.551	320	0.000	-7.26	1.596	-10.40	-4.12
CBB	Equal variances	69.81	0.000	-4.890	319	0.000	-5.17	1.056	-7.24	-3.09

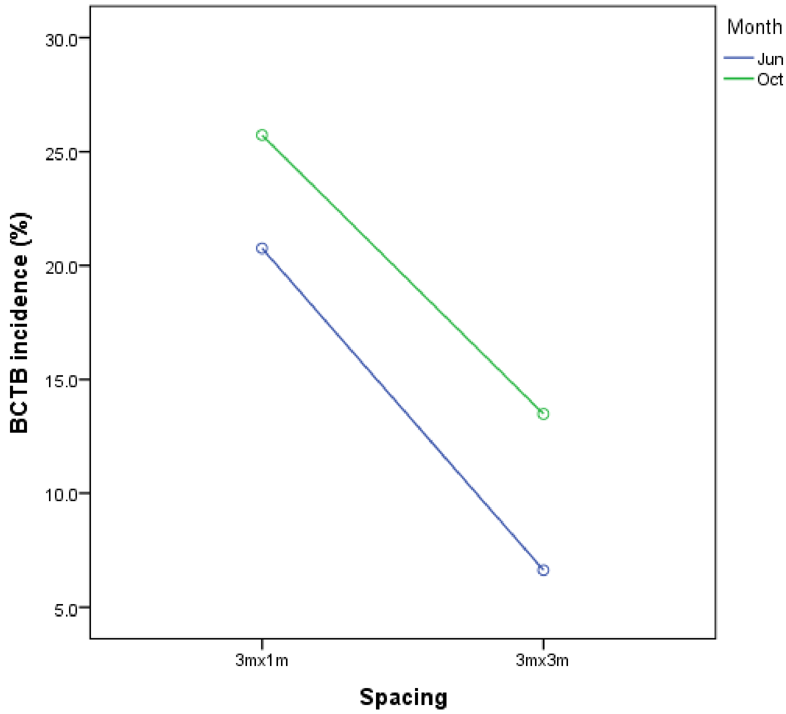

Fig 2. Variation in BCTB incidence at contrasting spacing regimes over time.

Table 3. Degrees of freedom (d.f) and mean squares for mean incidence of different coffee pests measured at two contrasting spacing regimes

Source	d.f	BCTB	LM	SKL	TC	LEB	CM	Scales	BM	CBB
Month (M)	1	3425.7***	4063.2***	67.2	103.4	953.2***	706.2	0.0	672.1	452.3*
Spacing (S)	1	11919.9***	1688.8***	4043.1***	3772.8***	895.0***	68405.2***	15.7	3770.5***	1920.3***
M x S	1	24.3	2102.6***	2.9	105.0	68.2	322.0	1.7	480.3	117.1
Error	318	108.4	163.8	91.1	89.5	62.4	872.9	6.7	180.3	78.3

*,**, *** significance at 5%, 2.5 and 1% level; BCTB, black coffee trig borer; LM, leaf miners; SKL, skeletonizers; TC, tailed caterpillars; LEB, leaf eating beetles; CM, canopy mealy bugs; Scales, canopy scales; BM, coffee berry moth; CBB, coffee berry borer.

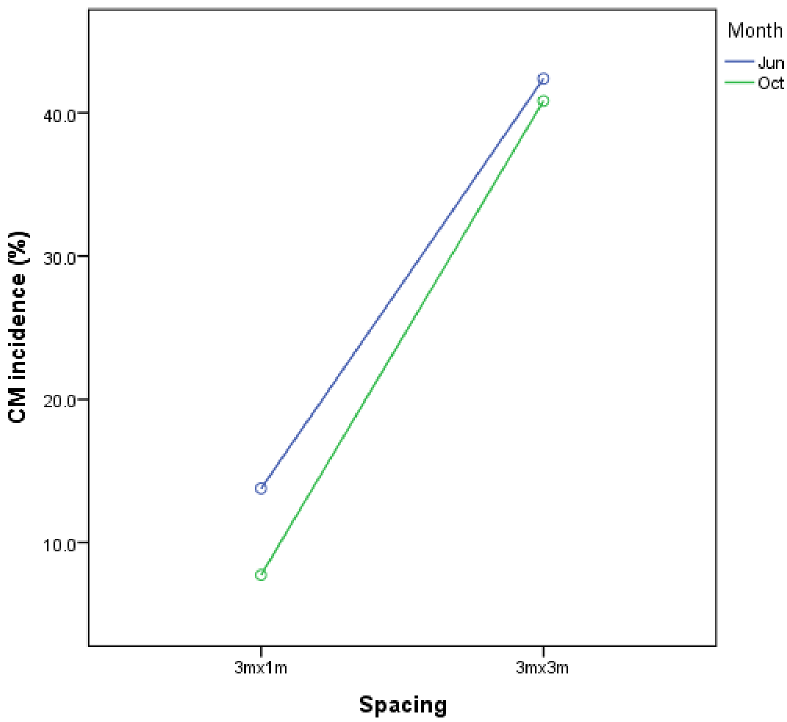

Fig 3. Variation in CM incidence at contrasting spacing regimes over time.

Table 4. Mean incidence of coffee pests under two contrasting spacing regimes over time.

Pest	Month	Spacing	% incidence	Std. error	95% CI Lower limit	Upper limit
BCTB	Jun	3mx1m	20.8	1.48	17.85	23.67
		3mx3m	6.6	1.00	4.65	8.60
	Oct	3mx1m	25.7	1.43	22.91	28.55
		3mx3m	13.5	1.01	11.49	15.48
LM	Jun	3mx1m	10.2	1.81	6.61	13.72
		3mx3m	10.3	1.23	7.89	12.72
	Oct	3mx1m	10.9	1.75	7.45	14.35
		3mx3m	21.1	1.24	18.62	23.50
SKL	Jun	3mx1m	1.6	1.36	-1.09	4.27
		3mx3m	9.2	0.93	7.40	11.04
	Oct	3mx1m	0.9	1.32	-1.69	3.51
		3mx3m	8.2	0.93	6.36	10.04
TC	Jun	3mx1m	2.6	1.35	-0.04	5.26
		3mx3m	11.0	0.92	9.19	12.80
	Oct	3mx1m	2.9	1.31	0.34	5.49
		3mx3m	9.1	0.93	7.26	10.90
LEB	Jun	3mx1m	8.6	1.12	6.39	10.79
		3mx3m	3.9	0.76	2.41	5.41
	Oct	3mx1m	3.7	1.09	1.57	5.84
		3mx3m	1.0	0.77	-0.47	2.55
CM	Jun	3mx1m	13.8	4.20	5.51	22.05
		3mx3m	42.4	2.86	36.77	48.02
	Oct	3mx1m	7.7	4.08	-0.30	15.77
		3mx3m	40.8	2.89	35.17	46.53
Scales	Jun	3mx1m	0.0	0.37	-0.73	0.73
		3mx3m	0.6	0.25	0.13	1.12
	Oct	3mx1m	0.2	0.36	-0.50	0.92
		3mx3m	0.5	0.25	0.02	1.02
BM	Jun	3mx1m	7.6	1.91	3.86	11.38
		3mx3m	12.2	1.30	9.62	14.74
	Oct	3mx1m	1.1	1.86	-2.59	4.71
		3mx3m	11.1	1.31	8.47	13.64
CBB	Jun	3mx1m	0.1	1.26	-2.38	2.57
		3mx3m	4.0	0.86	2.31	5.68
	Oct	3mx1m	0.7	1.22	-1.75	3.06
		3mx3m	7.3	0.86	5.56	8.96

Table 5. Mean difference in pest incidence at two contrasting spacing regimes.

Pest	I	J	d (I-J)	s.e	95% CI for d LL	UL
BCTB	3mx3m	3mx1m	-13.2***	1.25	-15.65	-10.72
LM	3mx3m	3mx1m	5.2***	1.53	2.14	8.17
SKL	3mx3m	3mx1m	7.5***	1.15	5.19	9.73
TC	3mx3m	3mx1m	7.3***	1.14	5.03	9.52
LEB	3mx3m	3mx1m	-3.7***	0.95	-5.54	-1.81
CM	3mx3m	3mx1m	30.9***	3.57	23.85	37.88
Scales	3mx3m	3mx1m	0.5	0.31	-0.15	1.08
BM	3mx3m	3mx1m	7.3***	1.62	4.09	10.47
CBB	3mx3m	3mx1m	5.3***	1.07	3.15	7.35

*,**, *** significant difference d at 5%, 2.5 and 1% level; d, mean difference in incidence of a pest under 3mx3m (I) versus 3mx1m (J) spacing regime; CI, confidence interval; LL, lower limit; UL, upper limit; BCTB, black coffee trig borer; LM, leaf miners; SKL, skeletonizers; TC, tailed caterpillars; LEB, leaf eating beetles; CM, canopy mealy bugs; Scales, canopy scales; BM, coffee berry moth; CBB, coffee berry borer.

Table 6. Significance of mean difference (MD) in growth and yield response between two contrasting spacing regimes.

Variable	Assumption on variances	Levene's test for variances		t-test for Equality of Means					95% CI for MD	
		F	p	t	d.f	p (2-tailed)	MD	s.e.d	LL	UL
dPH	Equal variances	18.09	0.000	-0.84	140	0.402	-3.27	3.894	-10.97	4.43
dSTG	Non-equal variances			-1.92	93	0.058	-0.19	0.100	-0.39	0.01
dCAD	Equal variances	13.83	0.000	-1.92	140	0.057	-20.32	10.600	-41.27	0.64
dCAH	Equal variances	6.30	0.013	2.38	140	0.018	10.08	4.229	1.72	18.44
dLLP	Non-equal variances			0.87	113	0.387	2.85	3.280	-3.65	9.34
dNOP	Non-equal variances			-2.73	93	0.008	-4.73	1.732	-8.17	-1.29
aNOS	Equal variances	25.88	0.000	-8.04	140	0.000	-1.31	0.163	-1.63	-0.99
dNAB	Non-equal variances			-4.82	128	0.000	-7.97	1.653	-11.25	-4.70
dNCP	Non-equal variances			-1.19	114	0.237	-0.92	0.776	-2.46	0.62
dNBC	Non-equal variances			-5.87	96	0.000	-10.52	1.794	-14.09	-6.96
dNIS	Non-equal variances			-1.12	106	0.267	-0.92	0.821	-2.54	0.71
dILS	Non-equal variances			1.76	115	0.082	0.41	0.235	-0.05	0.88
dNIP	Non-equal variances			0.88	105	0.380	0.62	0.700	-0.77	2.00
dILP	Non-equal variances			0.31	127	0.755	0.06	0.203	-0.34	0.46
aLBL	Non-equal variances			-2.56	121	0.012	-0.84	0.326	-1.48	-0.19
aLBW	Non-equal variances			2.55	93	0.012	0.49	0.191	0.11	0.87
aNBT	Equal variances	10.08	0.002	-2.54	144	0.012	-1693	667.452	-3012.51	-373.97
aYT	Equal variances	10.08	0.002	-2.54	144	0.012	-0.56	0.222	-1.00	-0.12
aYH	Non-equal variances			2.08	110	0.040	1.02	0.491	0.05	2.00

Table 7. Mean comparison for growth response and yield potential measured over spacing regimes (part 1 of 2).

Field	Spacing	dPH	dSTG	dCAD	dCAH	dLLP	dNOP	aNOS	dNAB	dNCP	dNBC
Field 1	3mx1m	24.4	0.2	19.4	21.0	8.3	0	2	2	-2	-9
Field 2	3mx3m	31.4	0.4	44.3	11.3	8.2	7	4	13	-2	1
Field 3	3mx3m	23.6	0.3	34.5	10.4	2.3	3	3	7	0	3
Mean	3mx1m	24.4	0.2	19.4	21.0	8.3	0	2	2	-2	-9
	3mx3m	27.7	0.4	39.7	10.9	5.4	5	3	10	-1	2
	Mean	26.5	0.3	32.4	14.5	6.5	3	3	7	-1	-2

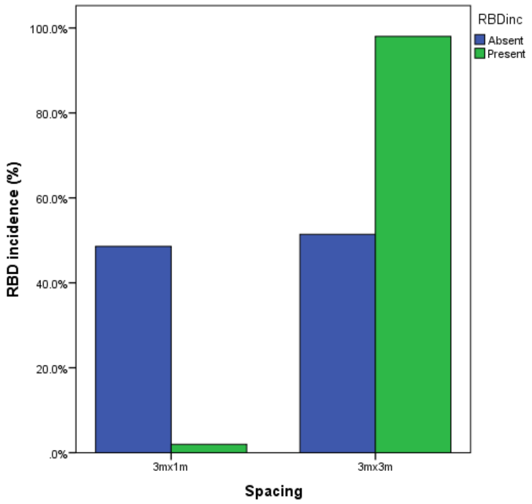

Fig 4. Variation in incidence of red blister disease under contrasting spacing regimes/

Table 8. Mean comparison for growth response and yield potential measured over spacing regimes (part 1 of 2).

Field	Spacing	dNIS	dILS	dNIP	dILP	aLBL	aLBW	aNBT	aYT	aYH
Field 1	3mx1m	5	0.1	1	0.2	23.6	10.4	5241	1.75	5.82
Field 2	3mx3m	7	-0.2	-1	0.6	24.1	9.9	6156	2.05	4.34
Field 3	3mx3m	5	-0.3	1	-0.3	24.7	9.9	7799	2.60	5.32
Mean	3mx1m	5	0.1	1	0.2	23.6	10.4	5241	1.75	5.82
	3mx3m	6	-0.3	0	0.2	24.4	9.9	6934	2.31	4.80
	Mean	5	-0.1	0	0.2	24.1	10.1	6343	2.11	5.16

Table 9. Pair-wise comparison of growth and yield parameters under contrasting Robusta coffee fields for spacing.

Variable	Field *i*	Field *j*	Mean difference(d) d=*i-j*	S.e	95% confidence interval	
					Lower limit	Upper limit
dPH	Field 1	Field 2	-8.36	5.079	-18.41	1.70
		Field 3	0.50	5.289	-9.97	10.98
dSTG	Field 1	Field 2	-0.23*	0.113	-0.45	-0.01
		Field 3	-0.02	0.118	-0.25	0.21
dCAD	Field 1	Field 2	-27.17	13.815	-54.53	0.18
		Field 3	-10.50	14.386	-38.99	17.98
dCAH	Field 1	Field 2	7.91	5.465	-2.92	18.73
		Field 3	11.84*	5.691	0.57	23.11
dLLP	Field 1	Field 2	1.56	4.426	-7.21	10.32
		Field 3	7.56	4.609	-1.56	16.69
dNOP	Field 1	Field 2	-6.32*	2.063	-10.40	-2.23
		Field 3	-1.21	2.148	-5.47	3.04
aNOS	Field 1	Field 2	-1.74*	0.188	-2.11	-1.37
		Field 3	-0.78*	0.195	-1.17	-0.40
dNAB	Field 1	Field 2	-11.31*	2.145	-15.56	-7.06
		Field 3	-3.97	2.234	-8.39	0.46
dNCP	Field 1	Field 2	1.17	0.974	-0.75	3.10
		Field 3	-1.83	1.014	-3.83	0.18
dNBC	Field 1	Field 2	-7.52*	2.115	-11.71	-3.33
		Field 3	-9.60*	2.202	-13.96	-5.24
dNIS	Field 1	Field 2	-1.71	1.020	-3.73	0.31
		Field 3	-0.03	1.062	-2.14	2.07
dILS	Field 1	Field 2	0.19	0.280	-0.36	0.75
		Field 3	0.23	0.292	-0.35	0.81
dNIP	Field 1	Field 2	1.26	0.827	-0.38	2.90
		Field 3	-0.03	0.861	-1.73	1.68
dILP	Field 1	Field 2	-0.29	0.260	-0.80	0.23
		Field 3	0.57*	0.270	0.03	1.11
aLBL	Field 1	Field 2	-0.80	0.423	-1.64	0.03
		Field 3	-1.37*	0.440	-2.24	-0.50
aLBW	Field 1	Field 2	0.19	0.219	-0.25	0.62
		Field 3	0.475*	0.228	0.02	0.93
aNBT	Field 1	Field 2	-1585.86	865.985	-3300.74	129.03
		Field 3	-2712.85*	901.753	-4498.56	-927.13
aYT	Field 1	Field 2	-0.53	0.289	-1.10	0.04
		Field 3	-0.90*	0.301	-1.50	-0.31
aYH	Field 1	Field 2	0.84	0.640	-0.42	2.11
		Field 3	0.34	0.666	-0.98	1.66

*The mean difference is significant at 95% confidence level.

Field 1, 3mx1m spacing; Field 2, 3mx3m spacing; Field 3, 3mx3m spacing; d, change in value of a parameter (October 2018 measurement minus June 2018 measurement); a, average value of a parameter ($average = \frac{October\ 2018\ measurement + June\ 2018\ measurement}{2}$); dPH, change in plant height (cm); dSTG, change in stem girth (cm); dCAD, change in canopy diameter (cm); dCAH, change in canopy height (cm); dLLP, change in length of longest primary (cm); dNOP, change in number of primaries per sample stem; aNOS, average number of stems per plant; dNAB, change in number of active bearing primaries per sample stem; dNCP, change in number of clusters per sample primary; dNBC, change in number of berries per sample cluster; dNIS, change in number of internodes on sample stem; dILS, change in internode length on stem (cm); dNIP, change in number of internodes on sample primary; dILP, change in internode length on primary (cm); aLBL, average leaf blade length (cm); aLBW, average leaf blade width (cm); aNBT, average number of berries per tree; aYT, average yield potential per tree (kg/tree); aYH, average yield potential per hectare (tons cc/ha)

Table 10. Description of growth and yield parameters measured from the Robusta coffee spacing trial.

No	Code	Name	Unit of measure	Description of procedure
1	PH	Plant height	cm	Distance between ground level close to the plant and the tip of terminal growing point of coffee tree, measured using a builder's tape
2	STG	Stem girth	cm	Diameter of stem is taken midway the plant height, using a Vernier caliper
3	CAD	Canopy diameter	cm	The distance between the tips of a pair of longest primaries taken in the direction of widest separation between the measured tree and neighboring trees of coffee
4	CAH	Canopy height	cm	Distance from start of canopy to the tip of terminal growing point of coffee tree, measured using a builder's tape
5	LLP	Length of longest primary	cm	The distance from the stem to the tip of longest primary
6	NOP	Number of primaries	count	Counting all the primaries on a sample stem
7	NOS	Number of stems	count	Counting all the stems on a coffee tree
8	NAB	Number of active bearing primaries	count	Counting all the primaries containing a cherry, berry or pinheads on a sample stem
9	NCP	Number of clusters per primary	count	Counting all the clusters on the sample primary
10	NBC	Number of berries per cluster	count	Counting all the berries on a sample cluster of a sample primary
11	NIS	Number of internodes per stem	count	Counting all the internodes on stem
12	ILS	Internode length per stem	cm	Distance between two internodes on sample stem, obtained by dividing plant height by number of internodes on stem
13	NIP	Number of internodes per primary	count	Counting all internodes on longest primary
14	ILP	Internode length on primary	cm	Distance between two internodes on sample primary, obtained by dividing length of longest primary by number of internodes on primary
15	LBL	Leaf length (cm)	cm	Distance between point of attachment of leaf blade on leaf stalk and the apex of the leaf, measured using a foot ruler
16	LBW	Leaf width (cm)	cm	Distance between the extremes of a widest part of the leaf blade, measured using a foot ruler
17	NBT	Number berries per tree	count	Multiplying the number of active bearing primaries, number of clusters per primary, and number of berries per cluster
18	NBH	Number of berries per hectare	count	Multiplying the number of active bearing primaries, number of clusters per primary, number of berries per cluster, and number of coffee plants in a hectare. Plant population = 10,000/spacing
19	YT	Estimated yield per tree	kg cc/tree	Multiplying number of berries per tree with weight of coffee green. It is assumed that 1 kg of cherries contains about 600 cherries; and that 1 kg of clean coffee (cc) can be obtained from 5 kg of cherries. The yield per tree is recorded in kg cc/tree.
20	YH	Estimated yield per ha	tons cc/ha	Multiplying number of berries per hectare with weight of coffee green. It is assumed that 1 kg of cherries contains about 600 cherries; and that 1 kg of clean coffee (cc) can be obtained from 5 kg of cherries. The yield per hectare is recorded in tons cc/ha.

thus, infesting new plants. Subject to further investigation, close spacing could be a remedy for LM, SKL, TC, BM and CBB whose incidence was lower under wide spacing than with close spacing.

Effect of spacing on disease incidence and damage

Absence of symptoms for some diseases (like BES and RBD) under close spacing is attributable to absence of source of inoculums as the plantation was relatively young. The RBD severity being higher under wide spacing than close spacing fields is attributable to accumulated inoculums (Waller et al., 2007) for RBD as the field had been bearing for over 10 years. LRD equally affected both closely spaced and widely spaced coffee fields. This trend of symptom expression requires to be monitored across seasons (wet and dry seasons). In the current study, data was collected in a rainy period of June and October 2018.

Effect of spacing on growth response

Competition among plants drives their relative response for specific growth parameters under contrasting spacing regimes (Anim-Kwapong et al., 2010; Bell et al., 1995; Canell, 1985; DaMatta et al., 2007). Under high plant density (close spacing), plants tend to compete for sunlight as facilitated by hormonal distribution. As a consequence, abnormal elongation of stems under close spacing arises (Kiup, 2017; Maddonni and Martínez-Bercovich, 2014; Rakocevic et al., 2018); as witnessed with high canopy height and relatively low increase in STG. Conversely, widely spaced coffee plants can access radiation from all directions with minimum competition; accounting for higher increase in lateral growth (high increase in CAD) than close spacing. The high increase in CAD is also explained by the high likelihood for multiple stems per plant whose growth habit ultimately widens the coffee tree canopy (DaMatta et al., 2007; Anim-Kwapong et al., 2010). To corroborate the view on CAD changes, this study documented a higher number of stems per plant under wide spacing than close spacing. Similar to the trend on CAD and CAH, LBL was higher under close spacing while LBW was higher under wide spacing. It is suggested that close spacing creates a lot of competition among Robusta coffee trees which compromises on their robustness attributes (Sakai et al., 2013; Salamanca-Jimenez). However, a follow-up detailed study under complete control of planting dates and blocking for variation management is necessary for solid recommendations.

Effect of spacing on yield potential

High aYT under wide spacing did not translate into better aYH. The highest yield potential was obtained under close spacing. The observation suggests that as plant density increases, yield increases as earlier suggested by Anim-Kwapong et al. (2010) and Paulo et al. (2010). It is imperative that in-depth analysis of relationships among pest incidence, disease incidence and severity, growth response and yield in coffee is conducted. So far, BCTB incidence is shown to be higher under close spacing than wide spacing yet this study also suggests that better yield is achievable as plant density is increased. Unless the pests and diseases whose incidence and severity increases with plant density are sustainably managed (Bell et al., 1995; Canell, 1985; DaMatta et al., 2007; Paulo et al., 2010), the apparent yield increase under high plant densities may not be realized by farmers.

Materials and methods

Plant materials

Clonal cuttings of coffee wilt disease resistant (CWD-r) Robusta coffee varieties were used. The planting materials, a composite of seven CWD-r varieties were obtained from National Coffee Research Institute (NaCORI). NaCORI is a semi-autonomous public research institute mandated to conduct research on coffee and cocoa in Uganda under policy guidance of Ministry of Agriculture, Animal Industry and Fisheries through National Agricultural Research Organisation (www.naro.go.ug).

Study site

This study was imposed in July 2017 on already established farmer's Robusta coffee fields at Bunjako Island, Buwama sub-county in Mpigi district. The Island lies at an altitude of 1138 m.a.s.l and latitude/longitude of 00.2778/ 32.134444 decimal degrees (00° 10' 10" N / 32° 08' 04" E degrees, minutes and seconds). Mpigi district experiences a bi-modal rainfall pattern with first rains occurring between March and May and second rains coming between September and November with an average rainfall amount of *1320 mm* though in many areas around the Lake zone (including Bunjako Island) it is between 1750mm and 2000mm (www.mpigi.go.ug/about/geographical-features).

Experimental design

Three fields were selected to constitute the experiment namely Field 1, Field 2 and Field 3 containing coffee plants spaced at 3mx1m, 3mx3m and 3mx3m, respectively. Field 1 is located near the lake (Bunjako Island) and it is a coffee system. Field 2 is also located near the lake at Bunjako Island but it is a coffee-agroforestry system. Field 3 is located some 3 km away from the lake (host farmer's home); the field is a coffee-banana-agroforestry system). Coffee trees in Field 1 were about 3 years old, trees in Field 2 were about 13 years old but had been stumped and the rejuvenated trees were about 3 years old. Coffee trees in Field 3 were about 8 years old. Two replicates were sampled in the field where coffee trees are spaced at 3mx1m, each replicate having 3 plots of 9 coffee trees each and a total of 54 trees. In fields 2 and 3 where coffee trees are spaced at 3mx3m, there is 1 plot in a block (replicate) and 18 coffee plants were sampled from the plot for three blocks, giving a total of 54 coffee plants per field.

Data collection

Pests' incidence

The selected coffee trees were assessed for root mealybugs (RMB), black coffee twig borers (BCTB), leaf miners (LM), leaf skeletonizers (SKL), leaf eating beetles (LEB), canopy scales (Scales), canopy mealybugs (CM), tailed caterpillars (TC), berry moths (BM), and berry borer (CBB). Trees were assessed for presence or absence of RMB basing on either evidence of ant activity and/or whitish powdery-like materials around the collar region. For BCTB, the total number of primary branches and those infested by BCTB on the sample stem were counted and percentage of infested primary branches(twigs) was computed (infested/total) x 100). To assess LM, SKL, (iii) TC and LEB, the bearing head of the coffee tree was divided into three imaginary sections – upper, middle and lower. One primary branch with berries was randomly selected from each section, from which coffee leaves, berry clusters and berries were sampled for assessment. The total number of leaves as well as those damaged by LM, SKL, TC, and LEB was recorded. The number of coffee clusters as well as those infested with CMB, Scales, and BM sampled twig were also recorded. From a middle cluster of the twig, the number of berries and those infested with CBB were also recorded.

Diseases incidence and severity

Incidence (presence or absence) and severity (scale of 1-5, where 1=no disease and 5=>50% of leaves infected) were scored for coffee leaf rust (LRD) (fungal causal agent, *Hemileia vastatrix*), red blister disease (*Cercospora coffeicola*) (RBD) and brown eye spot (*C. coffeicola*) (BES).

Vegetative growth response

Thirteen growth response variables were measured per coffee tree (Table 1). These variables include plant height, stem girth, canopy diameter, canopy height, length of primary, number of primaries, number of stems per tree, number of internodes per stem, internode length per stem, number of internodes per primary, internode length on primary, leaf blade length and leaf blade width.

Yield potential

Seven yield-related variables were measured per tree (Table 10). The variables include number of active bearing primaries, number of clusters per primary, number of berries per cluster, number of berries per tree, number of berries per hectare, yield potential per tree and yield potential per hectare.

Data analysis

The RMB was recorded as a binary variable (1 for presence, 0 for absence) and a chi-square test was carried out in order to ascertain if pest incidence is associated with spacing regime at a significance level of 5% ($p<0.05$). For rest of pests scored, an independent samples two-tailed *t*-test at $p<0.05$ preceded by Levene's F-test for equality of variances at $p<0.05$ and comparison for mean pest incidence was conducted using IBM SPSS Statistics v21. This *t*-test enabled comparison of mean pest incidence under the contrasting spacing regimes; 3mx1m and 3mx3m, irrespective of month of data collection and age (field) of coffee plantation.

In order to ascertain if there is a temporal (month of data collection) effect on observed differences in pest incidence between spacing regimes, an analysis of variance (ANOVA) for unbalanced treatment structure was conducted using the following general linear model:

$$y_{ijk} = \mu + M_i + S_j + MS_k + e_{ijk}$$

Where; y_{ijk} is any observed pest incidence, µ is grand mean for pest incidence, M_i is the i^{th} month of data collection, S_j is the j^{th} spacing regime, MS_k is the k^{th}month by spacing interaction, and e_{ijk} is random error. The decision on significant differences in pest incidence across months and spacing regimes was made at 95% confidence level.

Disease incidence

Like for pest incidence, the *t*-test at $p<0.05$ preceded by Levene's F-test for equality of variances at $\alpha = 5\%$ and comparison for mean disease incidence was conducted to compare of mean disease incidence under the two spacing regimes.

The *t*-test was followed by ANOVA (F-test) at $p<0.05$ for unbalanced treatment structure in order to ascertain for interactive effects of time (month of data collection) and spacing on incidence of coffee diseases using a similar model:

$$y_{ijk} = \mu + M_i + S_j + MS_k + e_{ijk}$$

where y_{ijk} is any observed disease incidence, µ is grand mean for disease incidence, M_i is the i^{th} month of data collection, S_j is the j^{th} spacing regime, MS_k is the k^{th} month by spacing interaction, and e_{ijk} is random error. The decision on significant differences in disease incidence across months and spacing regimes was made at 95% confidence level.

Growth response and yield potential

Growth was measured as a change (d) in each of the parameters detailed in Table 1 from June 2018 to October 2018. The number of stems per tree (NOS), leaf blade length (LBL) and leaf blade with (LBW) were expressed as average (a) of the June 2018 and October 2018 records, hence aNOS, aLBL and aLBW, respectively.

For each of June 2018 and October 2018, yield potential per tree (kg cc/tree) and yield per hectare (tons cc/ha) were estimated using number of active bearing primaries (NAB), number of clusters per primary (NCP), number of berries per cluster (NBC), cherry weight and shrinkage factor (SF) from cherries to green or clean coffee (cc) as follows:

$$NBT = NAB * NCP * NBC$$
$$NBH = NAB * NCP * NBC * plant\ population$$
$$YT = NBT * cherry\ weight/SF = (NBT/600)/5.$$
$$YH = YT * plant\ population$$

NBT, NBH, YT and YH stand for number of berries per coffee tree, number of berries per hectare, yield potential per tree (kg cc/tree) and yield potential per hectare (t cc/ha), respectively. It was assumed that 1 kg of cherries contains about 600 cherries and that 1 kg of clean coffee (cc) can be obtained from 5 kg of cherries (hence shrinkage ratio of 5:1). The plant population is given by:

$Plant\ population\ (trees/ha) = 10{,}000/(spacing)$; hence $10{,}000/(3 * 1)$ and $10{,}000/(3 * 3)$ for 3mx1m and 3mx3m spacing, respectively.

After obtaining yield-related traits for June and October, average values were calculated as follows:

$$aNBT = \frac{NBT\ for\ October + NBT\ for\ June}{2}$$
$$aYT = \frac{YT\ for\ October + YT\ for\ June}{2}$$
$$aYH = \frac{YH\ for\ October + YH\ for\ June}{2}$$

An independent samples two-tailed *t*-test at $p<0.05$ preceded by Levene's F-test for equality of variances at $p<0.05$ and comparison for mean pest incidence was then conducted using IBM SPSS Statistics v21. This *t*-test enabled comparison of growth and yield response under the contrasting spacing regimes; 3mx1m and 3mx3m. This was followed by a Bonferroni test for pair-wise comparison in growth response and yield across fields. The differences between any two fields for a parameter were declared significant at 95% confidence level.

Conclusion

Plant density has a significant effect on pest incidence, disease incidence and severity, growth response and yield of Robusta coffee. The plant density effect also has temporal dimensions. As plant stress increases under close spacing, pest problems such as RMB and BCTB also increase. Similarly, high yield potential per tree triggers plant stress due to increase in soil water and nutrient harvesting, resulting in disease challenges especially RBD. The growth robustness in Robusta coffee cannot be fully expressed under close spacing though this notion requires further optimization. It is our view that whereas yield potential is high at high tree densities, a detailed longitudinal analysis on the achievability of this apparent yield potential amidst pest, disease and abiotic constraints is conducted as basis for solid recommendation to farmers.

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Conflict of interest

The authors have no conflict of interest to declare.

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