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EFFECT OF PLANT DENSITY ON THE YIELD OF SORGHUM–COWPEA AND PEARL MILLET–COWPEA INTERCROPS IN NORTHERN NIGERIA

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SUMMARY

Three alternate-row intercrop experiments of sorghum (*Sorghum bicolor*)–cowpea (*Vigna unguiculata*) and/or millet (*Pennisetum glaucum*)–cowpea were grown at plant densities of 20 000 to 80 000 plants ha^{-1} at two locations in northern Nigeria between 1990 and 1992 to examine relations between yield and plant density. These relations were examined using the reciprocals of yield per plant to determine effects of environment, species and genotype on the theoretical maximum yield and optimum plant density. The intercrops were dominated by cereals, and cowpea biomass (BY) and seed yield (SY) were <10% of cereal BY and SY. Cowpea yields decreased as cereal plant density (D) increased, whereas cereal and total intercrop yields increased asymptotically with increasing D. Biomass yield of all intercrops responded to increasing D in a similar manner and the theoretical maximum intercrop BY was 12 290 kg ha^{-1} in all experiments. The response of SY to D varied among intercrops and was greatest and least with early and late maturing cereals respectively. The optimum D required to produce 90% maximum intercrop BY and SY varied between 15 600 and 30 000 plants ha^{-1}, and 0 (no response to D) and 120 000 plants ha^{-1} respectively, and was higher for sorghum than for millet intercrops. The implications of these responses for agronomic management and germplasm improvement of cereal–cowpea intercrops are discussed.

INTRODUCTION

The most commonly grown crops of the northern Sudan and Sahel savannas of West Africa are the cereals, millet (*Pennisetum glaucum*) and sorghum (*Sorghum bicolor*), and the legumes, cowpea (*Vigna unguiculata*) and groundnut (*Arachis hypogaea*), with millet and cowpeas being more prevalent in drier areas (Kowal and Kassam, 1978). Rainfall in the Sudanian and Sahelian savannas is monomodal and ranges from 800 to <400 mm (Kowal and Knabe, 1971). Cereals and legumes are usually intercropped, with cereals being planted with the first rains and legumes when the rains become established and the first weeding is carried out (Norman, 1978; Mortimore *et al.*, 1997). In northern Nigeria seed yields are low, <300 kg ha^{-1} for legume and about 1000 kg ha^{-1} for cereal (Norman, 1978; Harris, 1996; Mortimore *et al.*, 1997), due to a combination of low and inconsistent plant population densities (5000–10 000 stands ha^{-1}), low fertility and fertilizer

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use, and variable rainfall (Ntare, 1989; 1990; Ntare *et al.*, 1989; 1993; Harris, 1996; Mortimore *et al.*, 1997). Biotic constraints are also important, particularly *Striga*. Although individual cropping systems vary considerably, at least in the north of Nigeria these systems are predominantly alternate-row intercrops.

In intercropping systems farmers have a number of management options available to them to try and maximize productivity of the system (Ofori and Stern, 1987a; b; Fukai and Trenbath, 1993). For example, farmers can choose to plant different species or varieties of cereal or legume in order to alter the complementarity of the components (Rao and Singh, 1990), for example, early or late flowering cereals or legumes, legumes with an erect or prostrate growth habit (Ntare, 1989; 1990) or tall or dwarf cereals (Reddy *et al.*, 1990; Odo, 1991). Farmers can also manipulate the total plant population density of the intercrop or manipulate the plant density of the components of the intercrop, that is, the cereal or legume (Ofori and Stern, 1987b; Ntare *et al.*, 1989). The effects of total intercrop plant density, and component plant densities, of contrasting cereal–cowpea intercrops have not been studied in the northern Sudan savanna.

Relations between dry matter yields, both biomass (BY) and seed (SY), and plant density (D) can be analysed by regressing the reciprocal of BY and SY per plant on plant density (Willey and Heath, 1969; Craufurd, 1996)

$$1/\mathrm{BY} \text{ or } 1/\mathrm{SY} = a + b^*\mathrm{D} \qquad (1)$$

where a and b are constants. The value of the slope, b, gives an indication of the plasticity of a particular species or genotype in relation to D, while the value $1/b$ gives the asymptotic or theoretical maximum yield per unit area in a given environment. The value $1/a$ gives the theoretical yield per plant in a competition-free environment. Since yield per unit area is the product of yield per plant × D, then Equation 1 can be inverted and multiplied

$$\mathrm{BY} \text{ or } \mathrm{SY} = \mathrm{D}/a + b^*\mathrm{D} \qquad (2)$$

to describe the asymptotic relationship between yield and plant density, and hence the optimum value for D. These equations, and the parameters b, $1/b$ and the optimum D, provide a theoretical framework with which to assess density, environmental and genotypic effects on intercrop productivity.

The objective of this study was (a) to examine the effect of plant density, environment (site, year), cereal species (millet, early and late sorghum) and morphologically and phenologically different cowpea genotypes on component and total intercrop yields in northern Nigeria; and (b) to examine how yield–density relations of cereal–cowpea were affected by environment, cereal species and cowpea genotype using Equations 1 and 2.

EXPERIMENTAL DETAILS

Three experiments were carried out between 1990 and 1992 at the IITA Research Farm at Minjibir, 40 km north-east of Kano (lat 12°08′N, long 08°32′E, 500 m asl) and at the Kano State Agricultural and Rural Development Authority farm at Malam Madori, 24 km north-west of Hadeija (lat 12°27′, long 10°04′, 460 m asl). Minjibir is in the northern Sudan savanna and has an average (1961–90) annual rainfall of 690 mm. Soils at Minjibir are classified as typic Ustipsamments and are loamy sands. Soil samples collected before planting in 1990 and 1992 had about 2 g kg^{-1} organic carbon, 0.2–0.3 g kg^{-1} total N and 4–10 mg kg^{-1} Bray P. Malam Madori is in the Sahel savanna and has an average (1979–91) annual rainfall of 381 mm. Soils at Malam Madori are classified as sands and samples collected before planting in 1992 had 2 g kg^{-1} organic carbon, 0.2–0.3 g kg^{-1} total N and 20–30 mg kg^{-1} Bray P.

The three experiments were all intercrops of either sorghum–cowpea and/or millet–cowpea and the varieties used and sowing dates are given in Table 1. All these experiments were plant population density experiments in which plant density was varied from approximately 20 000 to 80 000 plants ha^{-1} by varying the between- and within-row spacing (Table 1) in an additive manner. In all experiments cereals and cowpea were planted in alternate rows and cowpea was planted about 7 d after the cereal.

In all experiments land was first harrowed and then ridged. Experiments were sown by hand and stands were thinned to three plants per stand for cereals and two per stand for cowpea at 7–15 d after sowing (DAS). Plots were hand weeded as necessary and cowpea flower and pod pests controlled by prophylactic spraying from the budding stage onwards. There were no disease problems. Time of 50% flowering and maturity (black layer formation in cereals, 90% leaf senescence in cowpea) was recorded and the number of stands per plot and plants per stand counted at flowering. At maturity total above-ground BY and SY were determined from the net plot area. Harvest index (HI) was calculated as the ratio of SY to BY.

Minjibir 1990

This was a multi-factorial experiment with two contrasting sorghum varieties (KSV4 and KSV8), two contrasting cowpea varieties (Dan Wuri and Kanannado), two fertilizer levels (zero and 50:30:30 kg ha^{-1} N, P and K respectively), three row spacings (1.0, 1.5 or 2.0 m), and for sorghum two within-row spacings (0.5 or 1.0 m) (Table 1). The within-row spacing for cowpea was 0.5 m for Dan Wuri and 1.0 m for Kanannado. The experiment was replicated twice. Plot size was 48 m^2 and the net plot area was 18–24 m^2, depending on row-spacing.

Minjibir 1992

This was a multi-factorial experiment with two cereal species (millet variety Ex-Bornu and sorghum variety Gaya Early), four contrasting cowpea varieties (IT84S-2246, grain type; IT86D-715, grain type; Dan Illan-prostrate, grain type very similar to Dan Wuri; and Kanannado, fodder type), three row-spacing treatments (0.75, 1.5 or 3.0 m), and for cowpea two within-row spacing treatments (0.5 or 1.0 m) (Table 1). The within-row spacing for cereals was 1.0 m. The

Table 1. Details of species and variety, between and within row spacing and sowing date in three intercropping experiments conducted in northern Nigeria between 1990 and 1992.

Experiment	Species	Variety	Days to flower	Habit	Row spacing (m) Between	Within	Number plants m^{-2}	Sowing date
Minjibir 1990	Sorghum	KSV4	65–70	Dwarf	1.0; 1.5; 2.0	0.5; 1.0	2.1–4.9	9 July
		KSV8	90–100	Tall			2.3–6.0	
	Cowpea	Dan Wuri	45–50	Prostrate	1.0; 1.5; 2.0	0.5	1.3–2.6	13 July
		Kanannado	90–100	Prostrate		1.0	1.6–1.1	
Minjibir 1992	Sorghum	Gaya Early	65–70	Tall	0.75; 1.5; 3.0	1.0	1.1–4.1	12 July
	Millet	Ex-Bornu	45–50	Tall				
	Cowpea	IT84S-2246	45–50	Erect				
		IT86D-715	45–50	Semi-prostrate	0.75; 1.5; 3.0	0.5; 1.0	0.7–2.6	18 July
		Dan Illan	45–50	Prostrate				
		Kanannado	90–100	Prostrate				
Malam Madori 1992	Millet	Ex-Bornu	45–50	Tall	0.75; 1.5; 3.0	1.0	1.1–4.5	29 June
	Cowpea	IT84S-2246	45–50	Erect				
		IT86D-715	45–50	Semi-prostrate	0.75; 1.5; 3.0	0.5; 1.0	0.7–3.8	7 July
		Dan Illan	45–50	Prostrate				
		Kanannado	90–100	Prostrate				

experiment was replicated three times. Plot size was 75 and 125 m^2 for 0.75 or 1.5 m and 3.0 m row spacing treatments respectively, and the net plot area 26 and 42 m^2 respectively.

Malam Madori 1992

The experiment at Malam Madori was identical to that of Minjibir 1992, but only millet–cowpea was planted since Malam Madori is considered too dry for sorghum.

Weather data

Daily rainfall, minimum and maximum temperature, relative humidity (RH), solar radiation and windspeed were recorded using automatic weather stations (Campbell Scientific) at each location and Penman potential evaporation was calculated from these daily values.

Data analysis

An ANOVA was carried out on days from sowing to flowering and maturity, BY, SY and HI for total intercrop yield, and for the cereal and legume components separately, for each experiment to examine effects of plant density and variety and interactions between them.

Yield–density relations (Equation 1) were examined by fitting and comparing linear regressions using procedures in Genstat (Genstat 5 Committee, 1987) to test whether the responsiveness of the different intercrops to plant density was different. The critical plant density (D_{crit}) required to produce 90% of the theoretical maximum yield (Y_{max}) was estimated from the parameters a and b in Equation 1 as

$$D_{crit} = (a*0.90*Y_{max})/(b*0.90*Y_{max}) \quad (3)$$

The figure of 90% for Y_{max} was chosen because in an asymptotic relationship the gain in productivity from increasing D near the asymptote would be uneconomic, that is, the cost of seed would be more than the value of the resultant yield increase.

RESULTS

Minjibir 1990

Total rainfall during the growing season at Minjibir in 1990 was 491 mm, 30% below the long-term (1961–90) average of 695 mm (Table 2). The rains started late, on 12 July (day of the year = 193), and ended on 14 September (257), giving a rainy season duration of 64 d. The length of the growing season, defined as the period from the start of the rains until soil moisture was exhausted (estimated using a water-balance equation, and confirmed from neutron probe measurements in other experiments at the same site) was 90 d. There was no drought during the growing season at Minjibir and the most notable feature of the weather

Table 2. Total rainfall and potential evapotranspiration (PET), and mean minimum and maximum temperature and radiation for decadal periods during the growing season at Minjibir in 1990 and 1992, and at Malam Madori in 1992 in Nigeria.

Period	Rainfall (mm)	PET (mm)	Temperature (°C) Minimum	Temperature (°C) Maximum	Radiation (MJ m^{-2})
			Minjibir 1990		
182–191	31.0	50.4	23.0	33.3	23.4
192–201	94.8	40.7	22.1	30.3	19.3
202–211	46.4	45.2	31.0	22.4	20.4
212–221	33.6	36.8	20.2	27.9	16.7
222–231	147.0	37.3	22.2	30.9	18.8
232–241	52.8	38.6	22.4	32.0	19.8
242–251	55.4	43.4	22.5	32.4	20.7
252–261	30.0	43.0	22.5	32.5	19.8
262–271	0.2	47.1	22.6	34.5	20.0
272–281	0.0	49.7	21.8	35.3	20.3
282–291	0.0	51.7	20.9	35.5	20.0
292–301	0.0	61.0	16.9	35.8	23.2
Total or mean	491.2	544.9	21.5	31.9	20.2
			Minjibir 1992		
182–191	49.5	51.7	22.4	32.2	19.7
192–201	48.8	49.3	22.5	31.5	20.2
202–211	35.8	46.4	22.4	31.2	19.8
212–221	76.5	43.3	22.0	31.1	19.3
222–231	69.6	38.1	21.8	30.3	16.9
232–241	125.2	35.5	21.4	30.2	16.7
242–251	74.4	44.2	21.5	31.6	19.6
252–261	74.2	48.6	21.4	32.5	20.0
262–271	0.0	58.5	22.7	35.2	21.8
272–281	0.0	68.9	20.2	35.9	22.1
282–291	0.0	73.4	20.8	37.2	21.9
292–301	0.0	90.2	16.3	35.8	22.2
Total or mean	554.0	648.1	21.3	32.9	20.0
			Malam Madori 1992		
172–181	35.7	69.1	24.1	35.4	21.2
182–191	54.9	59.6	23.1	34.0	20.4
192–201	31.5	53.8	23.6	33.2	21.5
202–211	83.0	49.1	22.6	31.9	22.7
212–221	3.6	52.4	23.4	33.2	21.7
222–231	78.7	39.9	22.5	31.1	19.7
232–241	178.3	36.8	21.6	30.4	18.8
242–251	12.2	48.6	22.5	32.1	22.8
252–261	30.2	45.8	22.0	33.1	21.9
262–271	0.0	59.1	22.3	36.4	22.8
272–281	0.0	73.7	19.9	36.9	23.3
282–291	0.0	64.7	21.7	37.0	22.0
292–301	0.0	88.4	17.6	37.2	22.6
Total or mean	508.1	741.0	22.0	34.0	21.6

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was a rainfall event of 93 mm on 19 August (231). Minimum and maximum temperatures averaged 21.5 and 31.9 °C respectively, with maximum temperature increasing towards the end of the growing season. Values of solar radiation remained high throughout the season.

The average total intercrop BY and SY was 8140 and 1201 kg ha^{-1} respectively. There were significant effects of sorghum variety ($p < 0.001$), plant density ($p < 0.001$), fertilizer application ($p < 0.05$), and interactions between sorghum variety and density ($p < 0.01$), cowpea variety and density ($p < 0.05$) and sorghum and cowpea variety ($p < 0.05$), on intercrop BY and SY, and in general for sorghum and cowpea yields as well. The addition of fertilizer increased BY and SY of sorghum by about 20%, with no effect on cowpea yield, and therefore data were averaged across fertilizer treatments.

Sorghum variety KSV8, which flowered 95 DAS and about 25 d later than KSV4, produced significantly more BY ($p < 0.001$), but significantly less SY ($p < 0.001$), than KSV4 (Table 3). Plant density had no effect on the date of flowering. Although KSV8 flowered at the end of the growing season, it nevertheless produced between 800 and 1000 kg ha^{-1} SY. However, HI was only 0.12. Seed yield in KSV4, and BY and SY in KSV8, were both lower when sorghum was intercropped with the late flowering, prostrate cowpea variety Kanannado compared with the early flowering variety Dan Wuri. These differences in SY were associated with variation in BY and not in HI. However, BY and SY of cowpea were very low, about 10% of values for sorghum. The late-flowering cowpea variety Kanannado, which flowered at the end of the growing season like KSV8, dried-off before any pods or seeds were produced. However Kanannado, like KSV8, had a higher BY than the earlier-flowering cowpea variety Dan Wuri. Furthermore, BY of Kanannado was significantly ($p < 0.001$) greater when grown with the early sorghum KSV4 – a mirror image of the effect of cowpea on sorghum.

There was a strong linear relationship between BY and plant density in KSV4 and KSV8, although in KSV8 the relationship could be asymptotic (Fig. 1a). There was no significant difference in the linear responsiveness of the two

Table 3. Days to 50% flowering, biomass (BY) and seed (SY) yield of sorghum varieties KSV4 and KSV8 intercropped with cowpea varieties Dan Wuri and Kanannado at Minjibir, Nigeria in 1990.

		Sorghum			Cowpea		
Sorghum	Cowpea	Days to 50% flowering	BY (kg ha^{-1})	SY (kg ha^{-1})	Days to 50% flowering	BY (kg ha^{-1})	SY (kg ha^{-1})
KSV4	Dan Wuri	69	6000	1204	47	810	130
	Kanannado	69	6600	1432	97	1110	0
KSV8	Dan Wuri	95	8750	1082	47	745	102
	Kanannado	96	7650	818	97	791	0
S.e.d. (1, 47 d.f.)		0.4	629.0	142.1	0.3	88.9	11.9

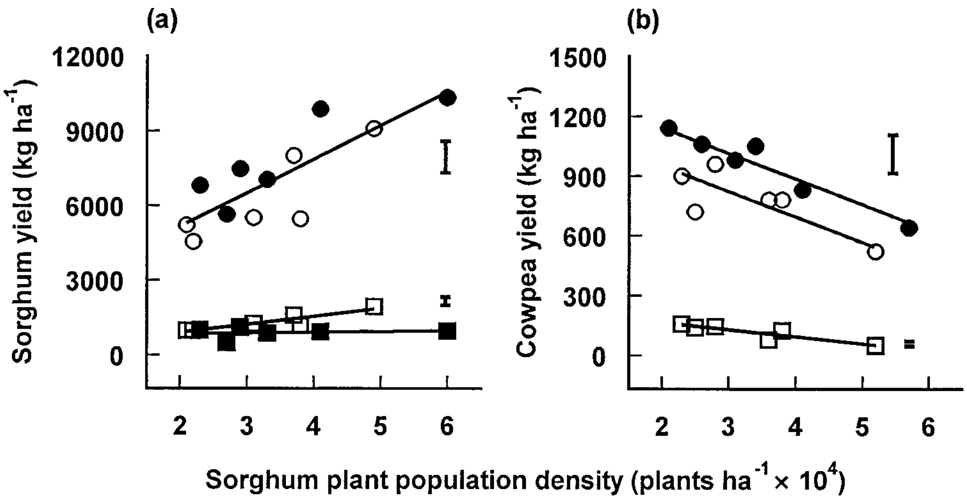

Fig. 1. Relationship between (a) sorghum biomass (●○) and seed (■□) yield and sorghum plant population density in sorghum variety KSV4 (open symbols) and KSV8 (closed symbols), and (b) cowpea biomass (●○) and seed (□) yield and sorghum plant population density in cowpea variety Dan Wuri (open symbols) and Kanannado (closed symbols), grown at Minjibir in Nigeria in 1990. Bars are s.e.d. between means. Fitted lines: (a) ○● Y = 2460(1080) + 0.13(0.03)X, $r^2 = 0.63$; ■ Y = 791(289) + 0.003(0.008)X, $r^2 = 0.32$; □ Y = 250(300) + 0.032(0.009)X, $r^2 = 0.82$; (b) ○ Y = 1209(72) – 0.013(0.002)X, $r^2 = 0.82$; ● Y = 1404(416) – 0.013(0.002)X, $r^2 = 0.82$; □ Y = 250(300) + 0.004(0.009)X, $r^2 = 0.84$.

genotypes to plant density and mean BY increased from 5160 kg ha^{-1} at 20 000 plants ha^{-1} to 9210 kg ha^{-1} at 50 000 plants ha^{-1}. In contrast to BY, there was a significant ($p < 0.001$) difference between KSV4 and KSV8 in the responsiveness of SY to plant density (Fig. 1a). Seed yield in the early variety KSV4 increased with increasing plant density from 897 kg ha^{-1} at 20 000 plants ha^{-1} to 1860 kg ha^{-1} at 50 000 plants ha^{-1}. Harvest index in KSV4, therefore, was not affected by plant density and was constant at about 0.20. In contrast, in the late flowering KSV8, SY did not respond to plant density, and was about 790 kg ha^{-1} over the range 20 000 to 60 000 plants ha^{-1}. Harvest index in KSV8 also varied with plant density ($p < 0.05$), declining from about 0.15 at 20 000 plants ha^{-1} to 0.09 at 60 000 plants ha^{-1}.

In contrast to sorghum, there was not a strong positive relationship between BY and SY (Dan Wuri only), and plant density in cowpea, and BY and SY were greatest at the lowest cowpea (and sorghum) plant densities (not presented), suggesting that cowpea yields were determined primarily by competition from sorghum. To test this hypothesis, cowpea BY and SY were plotted against sorghum plant density, revealing a negative relationship between yield and sorghum plant density (Fig. 1b). There was no difference in the responsiveness of BY in Dan Wuri or Kanannado to plant density, with BY decreasing by a mean of 129 kg ha^{-1} per 10 000 plants ha^{-1}. However, intercepts were significantly ($p < 0.01$) different and BY was higher in Kanannado (1404 kg ha^{-1}) than Dan

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Wuri (1209 kg ha^{-1}). Seed yield in Dan Wuri was also affected by sorghum plant density, decreasing by 35 kg ha^{-1} per 10 000 plants ha^{-1}.

Minjibir 1992

The total rainfall during the season at Minjibir in 1992 was 554 mm, 20% below the long-term average (Table 2). The rains also started late in 1992, on 12 July (194) and ended on 21 September (265), giving a rainy season duration of 71 d. The length of the growing season was 98 d. As in 1990, once the rains started there was no drought during the rainy season. Minimum and maximum temperatures, and radiation were similar to Minjibir in 1990.

There were no significant interactions between sorghum or millet and cowpea varieties for total intercrop BY and SY, or when millet and sorghum intercrops were analysed separately. There were highly significant ($p < 0.001$) effects of plant density on cereal BY and SY, but no plant density by cereal interactions. Cowpea BY and SY was not affected by plant density, but there was a cowpea variety by density interaction ($p < 0.05$) for BY.

Millet and sorghum BY and SY were similar in this experiment, 5300–5600 and 1400 kg ha^{-1} respectively despite the fact that sorghum had a longer crop duration (110 d) than millet (75 d) and matured shortly after the end of the growing season. Cowpea BY and SY were again < 10% of the cereal yield at 580 and 110 kg ha^{-1} respectively. Cowpea BY and SY were 15–20% higher with sorghum than with millet, but not significantly.

There were significant differences ($p < 0.001$) between cowpea varieties in BY and SY and these were strongly related to their time of maturity (Fig. 2). Thus BY increased from 330 kg ha^{-1} in IT84S-2246 to 870 kg ha^{-1} in Kanannado as maturity was delayed from 67 to 99 d. In contrast, SY, which only varied from 73

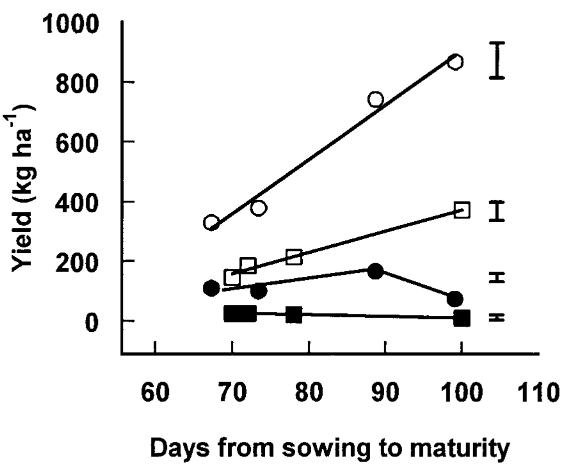

Fig. 2. Relationship between biomass (○●) and seed (□■) yield, and days from sowing to maturity, among four varieties of cowpea grown at Minjibir (open symbols) and Malam Madori (closed symbols) in Nigeria in 1992. Bars are s.e.d. between means. Fitted lines: ○ $Y = -919(156) + 18.2(1.88)X$, $r^2 = 0.98$; □ $Y = -349(42) + 7.2(0.52)X$, $r^2 = 0.99$; ■ $Y = 61(3.5) - 0.5(0.04)X$, $r^2 = 0.99$; ● line fitted by eye.

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to 165 kg ha^{-1}, was highest in Dan Illan which matured after 89 d, that is, shortly before the end of the growing season, and lowest in Kanannado which only started flowering at the end of the growing season.

There was a good asymptotic relationship between cereal BY and SY and plant density (Fig. 3a). Biomass yield increased from about 3900 kg ha^{-1} at 10 000 plants ha^{-1} to 6900 kg ha^{-1} at 40 000 plants ha^{-1} and SY from 930 kg ha^{-1} to 1900 kg ha^{-1} over the same range of plant density. Plant density therefore had no effect on HI which was about 0.25.

Cowpea BY and SY were also affected by plant density ($p < 0.05$) and there was a strong variety by density interaction ($p < 0.01$) for BY (Fig. 3b). Both the erect, early-flowering IT84S-2246 and the prostrate, early-flowering Dan Illan exhibited a quadratic response to plant density, with maximum BYs of 430 and 730 kg ha^{-1} respectively occurring between 25 000 and 30 000 plants ha^{-1}. In contrast, in the late-flowering, prostrate Kanannado BY was linearly and negatively related to cereal plant density, BY decreasing from 1247 kg ha^{-1} at 10 000 plants ha^{-1} to 581 kg ha^{-1} at 40 000 plants ha^{-1}. There was no interaction between plant density and variety for SY, with a mean SY of about 100 kg ha^{-1} at all plant densities.

Malam Madori 1992

Total rainfall at Malam Madori in 1992 was 508 mm, about 35% above the average (1979–91) of 381 mm. The rains started on 28 June (180) and ended on 11 September (255) giving a rainy season duration of 75 d. Malam Madori has

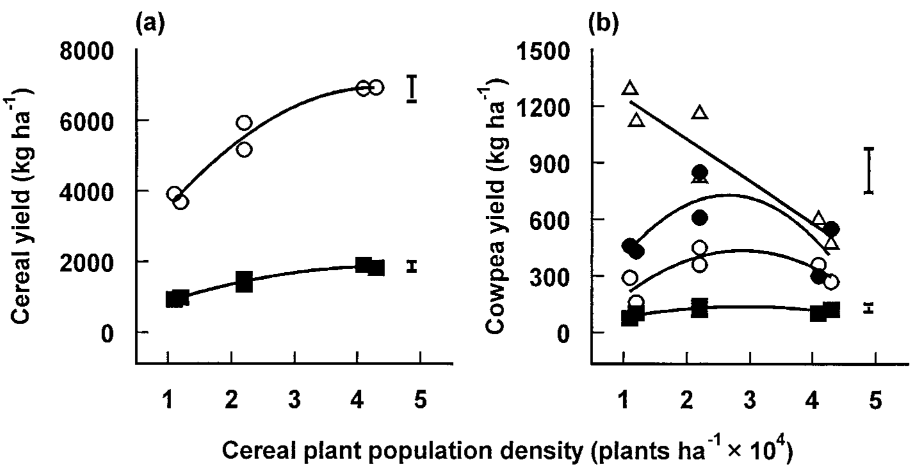

Fig. 3. Relationship between (a) cereal biomass (○) and seed (■) yield and millet plant population density, and (b) cowpea biomass in varieties Kanannado (△), Dan Illan (●) and IT84S-2246 (○) and mean seed (■) yield and millet plant population density at Minjibir in Nigeria in 1992. Bars are s.e.d. between means. Fitted lines: (a) ○ $Y = 1136(920) + 0.27(0.08)X - 3.1 \times 10^{-6}(1.4 \times 10^{-6})X^2$, $r^2 = 0.96$; ■ $Y = 214(199) + 0.07(0.02)X - 8.1 \times 10^{-7}(3.2 \times 10^{-7})X^2$, $r^2 = 0.98$; (b) △ $Y = 1469(122) - 222(43)X$, $r^2 = 0.87$; ○ $Y = -138(196) + 0.04(0.017)X - 6.9 \times 10^{-7}(3.1 \times 10^{-7})X^2$, $r^2 = 0.51$; ● $Y = -117(436) + 0.06(0.030)X - 1.2 \times 10^{-6}(6.9 \times 10^{-7})X^2$, $r^2 = 0.64$; ■ $Y = 6(43) + 0.009(0.003)X - 1.5 \times 10^{-7}(6.8 \times 10^{-8})X^2$, $r^2 = 0.67$.

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deeper soils (> 1.5 m) than at Minjibir, but the length of the growing season was similar to that at Minjibir, about 102 d, because of the higher temperature and evaporative demand at Malam Madori (Table 1). Also, in contrast to Minjibir in 1990 and 1992, there was a drought between 25 July and 9 August during which only 6.5 mm of rain fell.

Average BY and SY at Malam Madori were 7090 and 1920 kg ha^{-1} respectively, 18–29% greater than at Minjibir in the same year. There were significant ($p < 0.001$) effects of plant density on intercrop SY, and on millet BY and SY, but no interactions between plant density and cowpea variety. There were significant effects of plant density on cowpea BY ($p < 0.01$), and significant differences between cowpea varieties in BY ($p < 0.001$) and SY ($p < 0.05$), but again no interactions between variety and density.

There was a strong relationship between BY and time to maturity among cowpea varieties, as at Minjibir in 1992, and BY increased from 156 to 372 kg ha^{-1} as maturity was delayed from 70 to 100 d (Fig. 2). SY was also related to maturity, but negatively, and SY decreased by 0.5 kg ha^{-1} d^{-1} as maturity was delayed. Although the growing seasons in 1992 at Minjibir and Malam Madori were similar (Table 2), cowpea yields at Malam Madori were nonetheless <50% of those at Minjibir.

There was a strong asymptotic relationship between millet BY and SY and plant density (Fig. 4a). Biomass yield increased from about 4300 kg ha^{-1} at 10 000 plants ha^{-1} to 9600 kg ha^{-1} at 40 000 plants ha^{-1} and SY from 1250 to 2340 kg ha^{-1} over the same range of plant density. Harvest index was not affected by plant density, averaging 0.28.

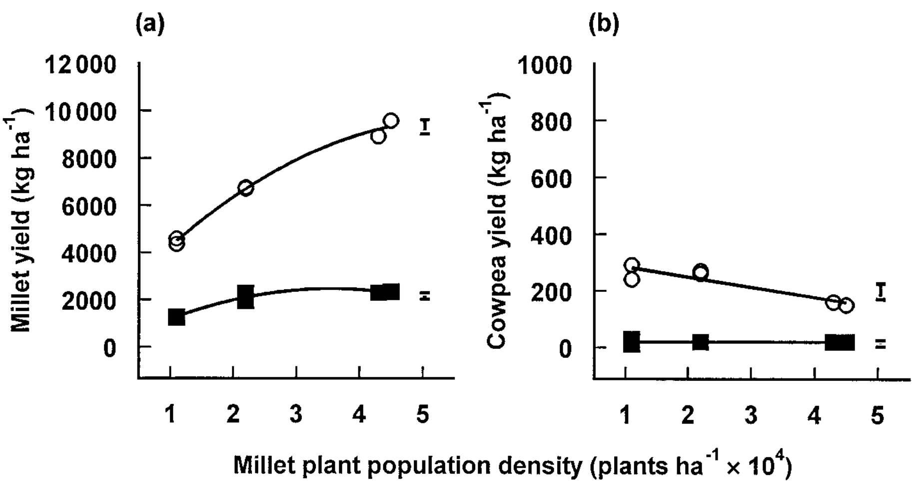

Fig. 4. Relationship between (a) millet biomass (○) and seed (■) yield and millet plant population density, and (b) cowpea biomass (○) and seed (■) yield and millet plant population density at Malam Madori in Nigeria in 1992. Bars are s.e.d. between means. Fitted lines: (a) ○ $Y = 1670(568) + 0.28(0.05)X - 2.5 \times 10^{-6}(8.7 \times 10^{-7})X^2$, $r^2 = 0.99$; ■ $Y = -37(337) + 0.14(0.029)X - 1.9 \times 10^{-6}(5.1 \times 10^{-7})X^2$, $r^2 = 0.95$; (b) ○ $Y = 320(24) - 0.003(0.0008)X$, $r^2 = 0.83$; ■ $Y = 0(2) + 0.002(0.006)X$, $r^2 = 0.0$.

In contrast to Minjibir in 1990 and 1992 there was no interaction between cowpea variety and plant density for BY, and cowpea BY decreased from about 270 kg ha^{-1} at 10 000–20 000 plants ha^{-1} to 150 kg ha^{-1} at 45 000 plants ha^{-1}. Cowpea SY, which was only 20 kg ha^{-1}, was not affected by plant density. The lower yields and lack of interactions at Malam Madori compared with Minjibir in the same year were probably due to the higher BY of, and hence greater competition from millet at Malam Madori.

Intercrop yield–plant density relations

The relationship between the total (cereal + cowpea) productivity of the intercrop and total (cereal + cowpea) plant density was examined using Equations 1 to 3, and the results are summarized in Table 4 and Fig. 5. Intercrop yields from Minjibir 1990 were separated into those with sorghum variety KSV4 or KSV8, and Minjibir 1992 was separated into intercrops with either millet or sorghum. Intercrops with different cowpea varieties were not compared, since there were no effects or interactions with cowpea variety on total intercrop yield.

There were strong linear relations (r^2 = 0.76–0.93) between the reciprocal of intercrop BY and SY per plant and plant density (Equation 1, not presented). For BY, there was no significant difference in the slope, but there was a significant difference ($p < 0.001$) in the intercept of the relationship of 1/BY on plant density between intercrops. Therefore the theoretical maximum BY per hectare (that is, 1/slope) was the same in all intercrops, 12 290 kg ha^{-1}, while the theoretical maximum BY per plant (that is, 1/intercept) ranged from 252 to 424 g (Table 4). In contrast, for SY there was a significant difference in both the intercept ($p < 0.001$) and slope ($p < 0.05$) of the relationship between 1/SY per plant and plant density, largely because of the different response to plant density of KSV4 and KSV8 at Minjibir 1990 (Fig. 1a). Thus KSV4 had a low maximum SY per plant (41 g) but was very responsive to plant density, with a maximum theoretical SY of 9230 kg ha^{-1}. KSV8, on the other hand, was unresponsive to plant density

Table 4. Theoretical maximum biomass (BY) and seed (SY) yield per plant and per hectare, and the plant population density required to produce 90% of the maximum theoretical BY and SY, of intercrops of sorghum–cowpea or millet–cowpea grown in northern Nigeria between 1990 and 1992.

	Maximum yield per plant (g)		Maximum yield per hectare (kg)		Plant density required to produce 90% maximum yield (plants ha^{-1})	
Intercrop	BY	SY	BY	SY	BY	SY
Minjibir 1990 KSV4	252	41	12 290	9230	30 000	120 000
Minjibir 1990 KSV8		0		1000		0
Minjibir 1992 sorghum	305	82		2830	22 100	31 000
Minjibir 1992 millet	325	87			20 900	30 000
Malam Madori 1992 millet	424	157			15 600	16 000

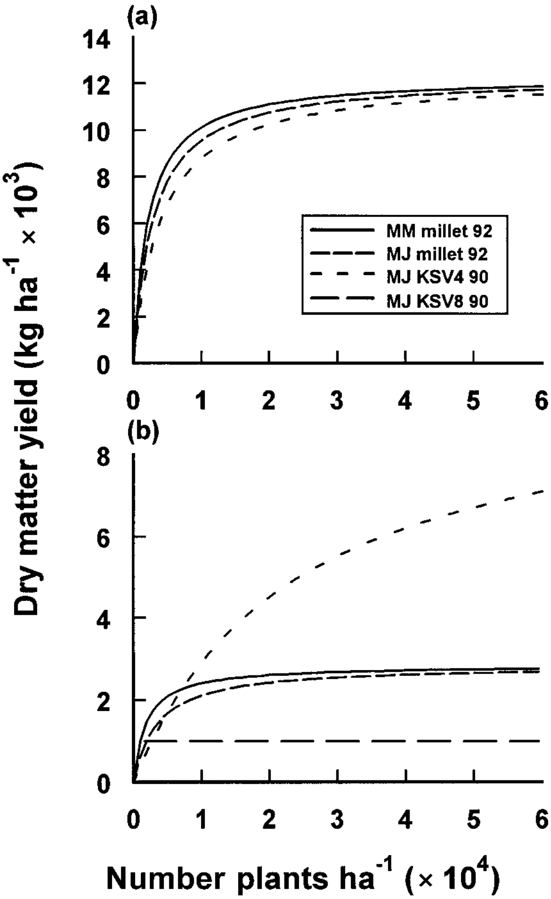

Fig. 5. Predicted asymptotic (a) biomass and (b) seed yield–plant density relationships for intercrops of cereal–cowpea grown in Nigeria in 1990 and 1992. Note: in (a) KSV4 and KSV8 at Minjibir in 1990 shown by single line (MJ KSV4 90); and in (a) and (b) sorghum and millet at Minjibir in 1992 shown as a single line (MJ millet 92).

and had a maximum theoretical SY of 1000 kg ha^{-1} (Table 4). In the remaining intercrops, maximum SY per plant varied from 82 to 157 g ($p < 0.001$) while the theoretical maximum SY was the same, 2830 kg ha^{-1}.

Yield–density curves produced using Equation 2 (Fig. 5) show clearly how similar the response of BY to plant density was in the different intercrops. Nonetheless, because of differences in plant size, the plant density required to produce 90% of the maximum BY (Equation 3) ranged from 15 600 plants ha^{-1} at Malam Madori in 1992 to 30 000 plants ha^{-1} at Minjibir 1990, with sorghum requiring higher plant densities to achieve 90% maximum BY than millet. In contrast to BY, the yield–density curves for SY were markedly different between intercrops, with KSV4 being highly responsive to plant density and KSV8 being completely unresponsive, as discussed above. However, the response of SY in 1992 at Minjibir (millet and Gaya Early sorghum) and Malam Madori was very similar, and these three intercrops required 16 000 to 31 000 plants ha^{-1} to achieve 90% maximum SY, compared with 120 000 plants ha^{-1} in KSV4.

DISCUSSION

The three environments of Minjibir in 1990 and 1992 and Malam Madori in 1992 were very similar, with 500 to 550 mm rainfall and a growing season length of about 100 d. Rainfall at Minjibir was below the long-term average, in line with recent trends, while rainfall at Malam Madori was 40% above normal. Given the similarity in season length, temperature and radiation, it is perhaps not surprising that average intercrop BY and SY with millet or early maturing sorghum (KSV4 and Gaya Early) was similar, between 5450 and 7090 kg ha^{-1}, and 1315 and 1920 kg ha^{-1} respectively. The higher than expected yields at Malam Madori may also have been due to the timely sowing immediately after the first rains and higher P-status. These yields are typical of yields for cowpea–cereal intercrops in the northern Sudan savanna. For example, Mortimore *et al.* (1997) recorded total intercrop SY and BY of 1458 (s.d. 523) and 7124 (s.d. 756) kg ha^{-1} respectively, from 14 different cropping systems with millet, sorghum, cowpea or groundnut in and around Minjibir in 1991.

The intercrops were dominated by the earlier sown cereal, and cowpea BY and SY were $<10\%$ of the cereal component. Several other studies have shown that the legume component of intercrops can be severely disadvantaged by late sowing relative to the cereal (Ofori and Stern, 1987b; Ntare and Williams, 1992), and that cowpea yields are reduced as the plant density of the dominant cereal increases (Tariah and Wahua, 1985). However, there is scope for farmers to increase cowpea production by intercropping complementary cereal and cowpea varieties in terms of crop duration and growth habit (Table 3; Fig. 3). For example, early-flowering varieties of cowpea have some capacity to escape competition (Fig. 3b) from cereals by virtue of their rapid development and small plant size, do not compete with the cereal (Ntare, 1989), and can therefore be intercropped at much higher plant densities (Blade *et al.*, 1997). Other more radical changes to the system, such as simultaneous planting or different row and spatial arrangements (Blade *et al.*, 1997), may also allow cowpea productivity to be increased without reducing cereal yields. It is also worth noting that although cowpea was only a minor part of the intercrop in terms of seed yield, farmers do not regard cowpea yields of $<10\%$ of the cereal component as a sign of failure (Mortimore *et al.*, 1997), since cowpea is valued primarily as a source of fodder.

The BY of all intercrops showed the same asymptotic response to D over the range 10 000 to 60 000 plants ha^{-1}, irrespective of environment, cereal species, or cereal and cowpea crop duration or morphology. Similarly, the SY of all intercrops in 1992 also exhibited an asymptotic response to D. Therefore, the use of reciprocals of yield per plant to describe these responses is appropriate. However, in 1990 SY of the dwarf, early-flowering KSV4 exhibited a linear response to D, while the tall, late-flowering KSV8 exhibited no response to D over the range studied, for reasons outlined below.

In general, early-flowering plants of sorghum, such as KSV4, require higher plant densities for maximum SY because of small plant size (Goldsworthy, 1970). Studies by ICRISAT at Bagauda have shown that the optimum plant density for sole crops of early-flowering, improved varieties of sorghum is $>100\,000$ plants ha^{-1} (ICRISAT Sahelian Centre, 1994). Therefore it is likely that the range of densities used (20 000 to 60 000 plants ha^{-1}) was not high enough to detect the asymptote in KSV4, although the predicted optimum density of 120 000 plants ha^{-1} seems reasonable when compared with ICRISAT data. In contrast, in KSV8 SY was constant at about 800 to 1000 kg ha^{-1} over the range 20 000 to 80 000 plants ha^{-1}. KSV8 flowered about 30 d after the rains had ended in 1990, and the entire seed-filling phase therefore occurred when soil moisture in the profile was exhausted. Therefore, in KSV8 SY was limited to <1000 kg ha^{-1} by drought at all densities. Nonetheless, these late-flowering sorghums show a remarkable ability to produce some seed even under drought conditions (Flower, 1996).

The theoretical maximum intercrop BY was the same at Minjibir in 1990 and 1992, and Malam Madori in 1992, 12 290 kg ha^{-1}, confirming the similarity of the three environments in the particular years in question. Similarly, the theoretical maximum SY was 2830 kg ha^{-1} at Minjibir and Malam Madori in 1992. Thus millet, and early- and late-maturing sorghum intercrops, had the same theoretical yield at an appropriate plant density in these experiments. This was to be expected, given that the theoretical maximum yield is primarily a function of plant morphology and assimilation pathway, both millet and sorghum are C4 cereals with similar canopy architecture and, as noted previously, cowpeas had little effect on total intercrop productivity. However, the years and locations in question were very similar in terms of growing season length, and in different circumstances the response to D and the theoretical maximum yields would be expected to vary, that is, much smaller theoretical maximum yields and lower optimum densities in drier or less favourable environments (Rees, 1986; Craufurd, 1996).

The optimum plant density for intercrops at Minjibir in 1990 with KSV8 and intercrops grown in 1992 at Minjibir and Malam Madori ranged from 15 600 to 30 000 plants ha^{-1} for BY and from 16 000 to 31 000 plants ha^{-1} for SY, the similar optima for BY and SY reflecting the lack of effect of D on harvest index. The asymptotic response to D was very marked in these intercrops, and yields of 50% of the maximum required plant densities of only 2500 to 5000 plants ha^{-1}. Therefore, at even quite low plant densities, whether by design or from poor establishment, moderate yield levels can be obtained in these short-season, low-fertility environments. Clearly, intercropping experiments conducted at plant densities above these optima would also not be representative of these environments. The optimum plant density was higher for sorghum than for millet, reflecting the smaller plant size in the non-tillering, though generally later-flowering cereal (Goldsworthy, 1970) and recommendations for intercropping short-statured, early-flowering sorghums need to take account of this. These optimum values would appear to be close to those already practised by farmers in the northern Sudan savanna, that is, 18 000 to 30 000 plants or 6000 to 10 000 stands ha^{-1} (Mortimore *et al*., 1997; Ntare *et al*., 1989). As noted previously, however, rainfall at Malam Madori in 1992 was 40% above the average and in drier years ($<$400 mm) the optimum plant density at Malam Madori would certainly be lower (compare Rees, 1986).

In conclusion, the response to plant density was asymptotic for BY and SY in most intercrops and therefore the reciprocals of yield per plant, and derived parameters, can be used as a robust analytical tool to examine the effects of environment, species and genotype on intercrop response to plant density. Environment, cereal species and cowpea or sorghum genotype had no effect on the response of intercrop BY to plant density; SY, however, was affected by whether the cereal was early- or late-maturing. There was a strong response to plant density with maximum intercrop yields achieved at low to moderate plant densities of 15 000 to 30 000 plants ha^{-1}. The intercrops were dominated by the cereals, and variation in cowpea morphology or crop duration had no effect on the response to plant density, and only small effects on cereal productivity. This observation, and the considerable plasticity in the response to plant density, suggest that there may be opportunities for increasing cowpea and system productivity by manipulating cowpea morphology and density and also intercrop spatial arrangement.

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REFERENCES

Blade, S. F., Shetty, S. V. R., Terao, T. & Singh, B. B. (1997). Recent developments in cowpea cropping systems research. In *Advances in Cowpea Research*, 114–128 (Eds B. B. Singh, D. R. Mohan Raj, K. E. Dashiell & L. E. N. Jackai). Ibadan, Nigeria: IITA and JIRCAS.

Craufurd, P. Q. (1996). Effect of plant population density on dry matter partitioning and yield in a short-duration cultivar of cowpea (*Vigna unguiculata*) grown in the tropics. *Journal of Agricultural Science*, Cambridge 127:89–96.

Flower, D. J. (1996). Physiological and morphological features determining the performance of the sorghum landraces of northern Nigeria. *Experimental Agriculture* 32:129–141.

Fukai, S. & Trenbath, B. R. (1993). Processes determining intercrop productivity and yields of component crops. *Field Crops Research* 34:247–271.

Genstat 5 Committee (1987). *Genstat 5 Reference Manual*. Oxford: Clarendon Press.

Goldsworthy, P. R. (1970). The growth and yield of tall and short sorghums in Nigeria. *Journal of Agricultural Science*, Cambridge 75:109–122.

Harris, F. (1996). *Intensification of Agriculture in Semi-Arid Areas: Lessons from the Kano Close-Settled Zone, Nigeria. IIED Gatekeeper Series No. 59*. London: International Institute for Environment and Development.

ICRISAT Sahelian Centre (1994). *ICRISAT West African Programs Annual Report 1993*, pp. 61–62. Niamey, Niger: ICRISAT.

Kowal, J. M. & Kassam, A. H. (1978). *Agricultural Ecology of Savanna: A Study of West Africa*. Oxford: Clarendon Press.

Kowal, J. M. & Knabe, D. T. (1972). *An Agroclimatological Atlas of the Northern States of Nigeria*. Zaria, Nigeria: Ahmadu Bello University Press.

Mortimore, M. J., Singh, B. B., Harris, F. & Blade, S. (1997). Cowpea in traditional cropping systems. In *Advances in Cowpea Research*, 99–113 (Eds B. B. Singh, D. R. Mohan Raj, K. E. Dashiell & L. E. N. Jackai). Ibadan, Nigeria: IITA and JIRCAS.

Norman, D. W. (1978). Farming systems and problems of improving them. In *Agricultural Ecology of Savanna: A Study of West Africa*, 318–347 (Eds J. M. Kowal & A. H. Kassam). Oxford: Clarendon Press.

Ntare, B. R. (1989). Evaluation of cowpea cultivars for intercropping with pearl millet in the Sahelian zone of West Africa. *Field Crops Research* 20:31–40.

Ntare, B. R. (1990). Intercropping morphologically different cowpeas with pearl millet in a short season environment in the Sahel. *Experimental Agriculture* 26:41–47.

Ntare, B. R. & Williams, J. H. (1992). Response of cowpea cultivars to planting pattern and date of sowing in intercrops with pearl millet in Niger. *Experimental Agriculture* 28:41–48.

Ntare, B. R., Serafini, P. G. & Fussell, L. K. (1989). Recent developments in pearl millet/cowpea cropping systems for low-rainfall areas of the Sudano-Sahelian zone of West Africa. In *Soil, Crop, and Water Management Systems for Rainfed Agriculture in the Sudano-Sahelian Zone*, 277–289 (Eds C. Renard, R. J. van den Beldt & J. F. Parr). Niamey, Niger: ICRISAT.

Ntare, B. R., Williams, J. H. & Bationo, A. (1993). Physiological determinants of cowpea seed yield as affected by phosphorus fertilizer and sowing dates in intercrop with millet. *Field Crops Research* 35:151–158.

Odo, P. E. (1991). Evaluation of short and tall sorghum varieties in mixtures with cowpea in the Sudan savanna of Nigeria: land equivalent ratio, grain yield and system productivity index. *Experimental Agriculture* 27:435–441.

Ofori, F. & Stern, W. R. (1987a). Cereal–legume intercropping systems. *Advances in Agronomy* 41:41–90.

Ofori, F. & Stern, W. R. (1987b). Relative sowing time and density of component crops in a maize/cowpea intercrop system. *Experimental Agriculture* 23:41–52.

Rao, M. R. & Singh, M. (1990). Productivity and risk evaluation in contrasting intercropping systems. *Field Crops Research* 23:279–293.

Reddy, K. C., van der Ploeg, J. & Maga, I. (1990). Genotypes effects in millet/cowpea intercropping in the semi-arid tropics of Niger. *Experimental Agriculture* 26:387–396.

Rees, D. J. (1986). Crop growth, development and yield in semi-arid conditions in Botswana. II. The effects of intercropping *Sorghum bicolor* with *Vigna unguiculata*. *Experimental Agriculture* 22:169–177.

Tariah, N. M. & Wahua, T. A. T. (1985). Effects of component populations on yields and land equivalent ratios of intercropped maize and cowpea. *Field Crops Research* 12:81–89.

Willey, R. W. & Heath, S. B. (1969). The quantitative relationships between plant population and crop yield. *Advances in Agronomy* 21:281–321.