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Yam tuber and maize grain yield response to cropping system intensification in south-west Nigeria

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ABSTRACT

Four factorial trials were conducted with yam (*Dioscorea rotundata* Poir.) at Ibadan, Nigeria from 2013 to 2015, investigating effects of (1) tillage (2) fertilizer (3) intercropping (4) yam plant densities. Yam tuber yields varied between years (2013: 16.44 Mg ha⁻¹; 2014: 10.08 Mg ha⁻¹; 2015 26.61 Mg ha⁻¹). In 2013 neither tillage nor fertilizer affected tuber yields. In 2014 tillage increased yields (+25.4%, $P < 0.0001$), fertilizer reduced yield (–10.5%; $P = 0.0046$). In 2015 tillage increased tuber yields by 8.1% (ns), fertilizer application increased yield (+17.5%, $P = 0.0017$). Across the years, tuber yields increased ($P < 0.01$) with increasing yam density with a constant increase in 2013 up to the highest density, yet yields leveled out above 14,815 plants ha⁻¹ in 2014 and 2015. Intercropping with maize (66,667 plants ha⁻¹) reduced tuber yield by 42.62% in 2013, 44.52% in 2014 and 30.68% in 2015 ($P < 0.01$ all years) across all yam densities. Maize grain yield was higher in sole crop in 2 years. Fertilizer increased yields in all years ($P < 0.0001$). Maize yield had no response to the yam densities. Ridging had a negative effect on grain yield in 2015 (–0.3 Mg ha⁻¹, $P = 0.0002$). Increasing plant density appears a safe measure to increase yam yields.

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Plant density; intercropping; fertilizer; yam (*Dioscorea rotundata*); maize (*Zea mays*)

Introduction

Yam (*Dioscorea spp*) tubers are a major starchy staple food to at least 60 million people in West and Central Africa (Ravi et al. 1996; Sotomayor-Ramirez et al. 2003; Suja et al. 2003). The crop is widely cultivated in the tropics of West Africa, Asia, Central and South America and it plays a vital role in food security and improvement of livelihoods (IITA 2012). Yam is the third most important global source of carbohydrate after cereals and cassava (Wheatley et al. 1995). Increased yam production in Africa is achieved dominantly through expansion of the cultivated area, yet with marginal improvement in productivity (Nakasone et al. 2006). Despite its importance in the economy and peoples' lives, the crop faces a number of constraints that significantly reduces its contribution to rural development, income generation and provision of affordable food. Progressively declining yam yields and loss of soil fertility, lack of improved varieties, increased pest and disease problems and backward farming technology are the major constraints of small holder farmers (Carsky et al. 2010).

There is little information on the best spacing or plant population for yam. Orkwor and Asadu (1998) however, reported a recommended plant population of 10,000 plants ha⁻¹ (1 × 1m) for yam but it has been reported that higher plant population up to 20,000 plants ha⁻¹ is associated with higher tuber yield and reduced tuber size (Igwilu 1994). Plant response to plant population varies from species to species and is highly dependent on conditions such as soil characteristics, biotic

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elements, climatic conditions of the site and fertility (Ogbonna et al. 2005). Further investigations are required on the appropriate planting densities to produce marketable yams.

Nigeria is the largest producer of yam in Africa accounting for an average annual production of 28.6 million tones. Nigeria's maize production is about 6.3 million tones (FAO 2010). Intercropping yam with maize is believed to be productive and compatible mainly because maize is a short season crop (3–4 months) while yams are long duration (7–12 months) crops (Ibeawuchi and Ofoh 2003).

The general effects of crop density on the yield of sole crops are well known (Harper 1977). However, this information is of little value in predicting the optimum densities of the component crops in intercrops. Yam and maize are major food crops contributing to rural and regional economies (Agboola 2000). Over 50% of the yam (*Dioscorea* spp.) and 75% of the maize grown in Nigeria are produced in intercropping systems (Okigbo and Greenland 1976).

The yam/maize intercrop provides an example of the presence of the competition gap, within the period each crop makes maximum demands on the growth factors (soil-moisture, soil nutrients, light etc.) resulting in higher total yields than the sole crops (Okigbo and Greenland 1976). Intercropping has been shown to have several advantages such as better utilization of environmental factors, greater yield of food, increasing the return per unit area and insurance against crop failure (Silwana and Lucas 2002). However, in many African smallholder intercropping systems, associated crops are often planted at densities much lower than their usual sole crop density (Ibeawuchi 2007). While such systems would still reduce the risk of exposing farmers to crop failure they may not attain higher yields compared with high (or recommended) density sole crops. Here we compare yam sole crops with a yam/maize intercrop seeded at maize densities close to maize sole crop densities to ensure each crop has the preconditions for maximum resource use and yield formation.

Rising population pressure and increased demand on land for food production have made soil fertility maintenance through prolonged fallows an untenable proposition. The yam growing area is not suitable for intensive livestock systems, excluding soil fertility maintenance through manure. Thus fertilizer application needs to be investigated as a potential alternative. The addition of inorganic fertilizer (mostly NPK) to improve tuber yields, produced highly erratic result and remains unreliable (IITA 2003; O'Sullivan and Ernest 2008). The reasons for the variability of tuber yield responses to mineral fertilizer application have not been fully investigated. Fertilizer effects may rely on other factors such as plant density, tillage and the overall cropping system. This study investigated fertilizer effects in combination with the other factors that farmers can manipulate.

Tillage practices profoundly affect soil physical properties. It is essential to select a tillage practice that sustains the soil physical properties required for successful crop growth (Jabro et al. 2009). Yam is usually grown on mounds requiring intensive tillage and thus a lot of labor. Mounds can only be made manually, limiting yam production to relatively small fields and causing high production costs. Ridges can be perceived as long mounds and they can be tied by tractors thus enabling soil preparation on larger fields, in shorter time and potentially at lower costs. Kang and Wilson (1981) reported higher yam yields in mounds than on flat land yet yield differences were small at a comparably low yield level reaching 11.3 Mg ha^{-1} . However, the actual requirement to form mounds or ridges has not been shown to be an essential precondition for high yam yields.

There is limited and contradictory information on the best tillage, fertilizer, intercropping and plant density for yam and there have not been any structured trials assessing if any of these factors, all modifiable by farmers, interact in a synergistic manner. The objectives of this study were: (a) to determine the optimum yam plant density; (b) to determine the effect of ridging versus planting in flat soil on yam tuber yield; (c) to determine yam tuber yield response to fertilizer application; (d) to determine yam tuber yield response to intercropping with maize and (e) to determine if any of these factors have positive interactions on yam and maize yields.

Materials and methods

Site and soil properties

Field experiments were conducted for 3 years at the experimental station of the International Institute of Tropical Agriculture, (7°31' N and 3°54' E) south western Nigeria in the 2013, 2014 and 2015 cropping seasons. Nigeria has a tropical climate with bimodal rainfall patterns (long rainfall from March to July and short rainfall from August to November, with a long dry season from November to March). The meteorological data for the years 2013, 2014 and 2015 were obtained from the GIS unit of IITA, Ibadan Nigeria (Figure 1).

The trial sites had been under abandoned *Leucaena leucocephala* and *Gliricidia sepium* agroforestry systems for around 12 years. The dominant tree at clearing was *L. leucocephala*. Clearing was conducted by manual slashing of understorey growth, felling the trees and removing all tree stumps to allow tillage. Boles and branches > 5 cm diameter, were removed from the sites and the remaining biomass was burned. Soil samples were collected at depths of 0–10 cm and 10–20 cm from three different spots in each plot (top, middle and bottom). Samples were dried at 65°C, then passed through a 2 mm sieve. Soil pH was determined in a water suspension at a 1:1 soil/water ratio. Exchangeable Ca^{2+} , Mg^{2+} , K^{+} and available P were extracted by the Mehlich-3 procedure (Mehlich 1984). The cations were determined by atomic absorption spectrophotometry and phosphorus was determined colorimetrically using the Technicon AAll Auto-analyser. Organic C was determined by chromic acid digestion and spectrophotometric procedure (Heanes 1984). Total N was determined using the Kjeldahl method for digestion and colorimetric determination on Technicon AAll Autoanalyser (Bremner and Mulvaney 1982). Soil properties are presented in Table 1. Soils were Alfisols and Entisols.

Trial structure

The experiment was conducted as a fully orthogonal 4 factorial nested design. The factors were (1) tillage at 2 levels:ridged versus land retained flat; (2) fertilizer at 2 levels: nil versus 60, 12, 75 in kg N, P and K ha^{-1} K; (3) cropping system at 2 levels yam/maize intercropping with maize variety 'TZLcomp.3DTF2' versus sole yam; (4) yam planting density at 6 levels: 10,025, 13,333, 14,814, 16,667, 19,047, 22,222 plants ha^{-1} , nested within each plot. All plots had 7 rows (2 border rows and 5 net plot rows) at 0.75m distance between rows (on flat soil) and ridges. The different yam planting densities were established by varying the distances between yam plants along the rows and ridges, whereby the distance of 1.33 m \times 0.75 m = 10,025 plants ha^{-1} ; 1 m \times 0.75 m = 13,333 plants ha^{-1} ; 0.9 m \times 0.75 m = 14,814 plants ha^{-1} ; 0.8 m \times 0.75 m = 16,667 plants ha^{-1} ; 0.7 m \times 0.75 m = 19,047 plants ha^{-1} and 0.6 m \times 0.75 m = 22,222 plants ha^{-1} . Each yam density section consisted of 4 yam plants per row (20 net plot plants) except the lowest density (10,025 ha^{-1}) which had 3 plants per row (15 net plot plants). Yam density treatments (nested in main plots) were not separated by border

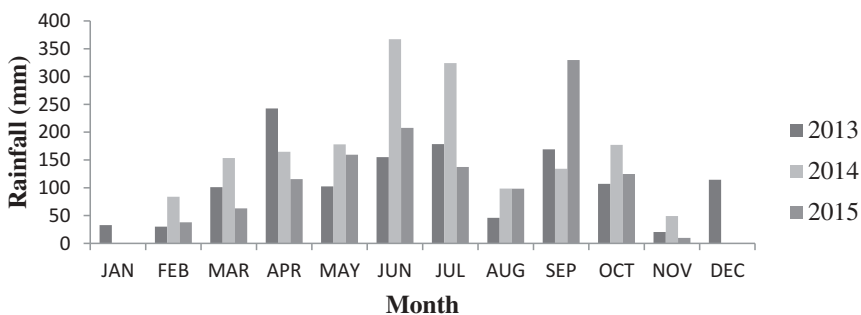


Figure 1. Rain fall (mm per month) over three growing seasons at IITA Ibadan, Nigeria.

Table 1. Soil chemical properties of the trial sites at IITA Ibadan, Nigeria.

Soil Properties	2013	2014	2015
	0–10cm	0–10cm	0–10cm
pH	6.29	6.70	7.21
Organic carbon (%)	0.85	1.38	1.02
Nitrogen (%)	0.11	0.12	0.09
Phosphorus (mg kg ⁻¹)	39.39	24.38	14.34
Calcium (cmol[+] kg ⁻¹)	2.97	2.98	2.10
Magnesium (cmol[+] kg ⁻¹)	0.84	0.42	0.71
Potassium (cmol[+] kg ⁻¹)	0.33	0.33	0.28
	10–20cm	10–20cm	10–20cm
pH	6.30	6.90	6.99
Organic carbon (%)	0.64	1.08	0.90
Nitrogen (%)	0.09	0.13	0.08
Phosphorus (mg kg ⁻¹)	28.40	14.04	11.70
Calcium (cmol[+] kg ⁻¹)	2.03	2.52	2.06
Magnesium (cmol[+] kg ⁻¹)	0.71	0.23	0.68
Potassium (cmol[+] kg ⁻¹)	0.27	0.29	0.27

plants or open spaces. The maize target density was 66,667 plants ha⁻¹ seeded at 0.75 m × 0.2 m. The maize variety 'TZLcomp.3DTF2' had a growing period of 90–100 days to maturity.

Planting material

Yam (*Dioscorea rotundata*) planting material was produced from the main land-race used in Oyo State, Nigeria, using medium sized tubers of around 800–1000 g fresh mass by cutting 'sets' of approximately 150 g. Each set was weighed to ensure a range of 150 ± 10 g. Sets lighter than 140 g were discarded sets heavier than 160 g were cut to stay within the mass limit. Yam sets were treated with the fungicide Z-Force, (active ingredient Mancozeb 80%; family: ethylene bisidithiocarbamate (EBDC)) and the insecticide Cypermethrin (Alpha cypermethrin) by immersing the yam pieces into the solution for 5 min. After treatment, the seed tuber pieces were spread on a plastic sheet to dry and were planted the next day. The yam sets were planted in a shallow hole of approximately 10 cm depth and covered with soil. Maize was seeded at that same time as the yam sets. Maize seeds were spaced 0.2 m apart in a single row exactly between the yam rows on flat soil and in the middle of the slope on one side of each ridge on ridged soil. Maize seeding density remained constant within rows.

Crop husbandry

The yams were planted on 2 May 2013, on 4–11 June 2014 and on 6 May 2015. The yams were staked with bamboo poles reaching 2.5 m height above the soil surface and nylon string was suspended from the poles to the 4 yams next to each pole. The strings were fixed to the soil with bamboo pegs. Weeding was done by hand hoes within 1 week before each fertilizer application and whenever deemed necessary after visual inspection of the fields. The first fertilizer application was a dose of 200 kg ha⁻¹ NPK 15:15:15 at 5 weeks after planting (WAP) equivalent to 30 kg ha⁻¹ N, 12 kg ha⁻¹ P and 25 kg ha⁻¹ K. The second application was a dressing of 65 kg ha⁻¹ of urea equivalent to 30 kg ha⁻¹ N at 7 WAP. The third application was a dressing of 100 kg ha⁻¹ KCl, equivalent to 50 kg ha⁻¹ K at 18 WAP. Fertilizer was applied by banding along the crest of the ridge in ridged soil and between the yam and the maize row on flat soil. Fertilizers were applied in furrows about 3–6 cm deep.

Crop harvests

The maize was harvested at 3 months after seeding (MAS) in the center rows of each yam density subplot. The yams were harvested 7 months after planting (MAP) by manually digging out the tubers of every individual yam plant and placing all tubers of one plant in one bucket, labeled with the position

within the plot and the yam density treatment. Harvested yam tubers were separated into those of commercial or consumable quality (hereafter called good tubers) versus tubers deemed unsuitable for marketing or consumption (hereafter called bad tubers). Both size (approximately <50 g) and sanitary status were considered when separating unsuitable tubers. Tubers either too small to serve as food or seed yam or affected by rot were declared unsuitable for marketing.

The numbers of good and bad tubers per plant were recorded and the tuber mass of good and bad tubers was determined on a 1 g resolution balance. Tubers from plants within the same yam density section were collected into one crate. Once all tubers of a density section of a main plot had been weighed, a sub-sample of three tubers was taken and tubers were sliced to obtain top, middle and bottom end tissue for dry matter determination. Between 200 and 500 g fresh yam tuber tissue were weighed and dried to constant mass at 80°C.

Land equivalent ratios

The land equivalent ratio was calculated for the dry tuber yield of yam and dry grain yield of maize for all three growing seasons and for the four systems used. LER was determined according to the equation below as stated by Mead and Willey (1980) .

$$\text{LER} = L_{\text{Yam}} + L_{\text{Maize}} = I_{\text{Yam}}/S_{\text{Yam}} + I_{\text{Maize}}/S_{\text{Maize}}$$

L_{Yam} and L_{Maize} = LER of individual crops

I_{Yam} and I_{Maize} = Individual crop yield in intercropping systems

S_{Yam} and S_{Maize} = Yield as sole crop

Revenue

Because yam is traded as fresh tubers and maize is marketed as dry grain and due to the differences in prices per kg, the overall revenue (gross income) of the crops was calculated. In each year traders in Bodija market of Ibadan were asked for the current prices of yam tubers and of maize after the respective harvests. In an attempt to estimate farm gate prices, in 2013 traders were invited to make offers for the yams and offers were recorded. As trading in the local markets is not by mass but by volume for maize and by tuber of specific size, the quoted prices for particular quantities of maize and yam were determined by weighing the maize and the yam and converted to prices per kg. Price offers for yam and market retail prices did not correlate and thus the offered prices were not used to estimate the farm gate revenue. Realistic farm gate prices are difficult to obtain and depend on the distance from farm to market, the quality of the roads and other factors thus are highly variable with location. To assess the crops value and revenue potential, an index was formed to compare the relative revenue generated by the different treatments. The retail prices per kg of fresh yam tubers and dry maize grain were multiplied by the yields to attain the total value of the crops. The largest value in a year was set as 100 and all others were normalized against the maximum.

Data analysis

Plant count and crop yield data were analyzed untransformed using the GLM procedure in SAS 9.2 software (SAS 2008). The analyses were conducted on the complete data set including all factors. Percent data and proportions were arc sin of the square root transformed and analyzed using the GLM procedure. Means were separated using SAS procedures LS means and pairwise comparison. Percent and proportion data were re-transformed for presentation using the p values from pairwise comparison to separate the means.

Results

Soil chemical properties

The chemical properties of soil at the experimental site (Table 1) revealed that the soil properties of the sites cropped in 2013 were better than in 2015 and that in 2014 soil properties were for most parameter better than in both other years.

Meteorological conditions

The average maximum temperature was 33.58°C in 2013, 36.58°C in 2014 and 34°C in 2015. Total annual rainfall for the years 2013, 2014 and 2015 were 1299.6 mm, 1730.8 mm, 1283.8 mm, respectively (Figure 1). The distribution pattern of the rainfall for 3 years was consistently bimodal with the heaviest rainfall in July in 2013, June in 2014 and September in 2015. Total rainfall during the yam growing season was 893 mm in 2013, 1494 mm in 2014 and 1200 mm in 2015.

Yam plant survival until harvest

Yam sprouting and survival until harvest was different in all years. The p diff values for the different factors are in Table 2. The attained plant densities at harvest were highest in 2015 and lowest in 2014 (Figure 2). In 2013, across all target densities, 72.6% of yams reached harvest. In 2014 the survival was 65.6% and in 2015 it attained 93.7%. Survival rates in 2013 ranged from 70.3 to 74.6% and in 2015 from 91.6 to 94.8%, without an effect of the target density. Yet, in 2014 the survival rate was significantly lower at the two highest target densities (58.1%) compared with all lower target densities (70.8%). Intercropping had a significant negative effect on survival rates across all years with the largest difference found in 2014 and the smallest in 2015 (Table 3).

*Effect of yam plant density on fresh tuber yield of *Dioscorea rotundata**

Across the years, the fresh tuber yields increased with increasing plant density ($P < 0.01$). However, only in 2013 was the increase continuous up to the highest plant density. In 2014 and 2015 yields peaked at 14,815 and 16,667 and leveled out at higher densities (Figure 3).

*Effect of intercropping on yam tuber yield of *Dioscorea rotundata**

Intercropping yam with maize led to significant fresh and dry tuber yield reductions in all years and across plant densities (Figure 4). In 2013, the fresh tuber yield loss was 42.62% or 8.9 Mg ha⁻¹; in 2014 the loss was 44.52% or 5.80 Mg ha⁻¹; in 2015 the loss was 30.68% yet due to the high yield level the absolute loss was 7.07 Mg ha⁻¹.

Effect of tillage and fertilizer on yam tuber yield

Yam grown on intensively tilled and ridged soil did not produce significantly higher tuber yields than in flat soil in 2013 ($P < 0.139$) and 2015 ($P < 0.192$) (Table 4). However, in 2014, yam tuber yields were

Table 2. Statistics output table (p diff values) for the percentage yam plant survival until harvest.

Factors	2013	2014	2015
Tillage	ns	<.0001	ns
Density	ns	<.0001	ns
System	<.0001	<.0001	0.0060
Tillage×Fertilizer	0.0494	ns	0.0042
System×Fertilizer	ns	0.0044	ns

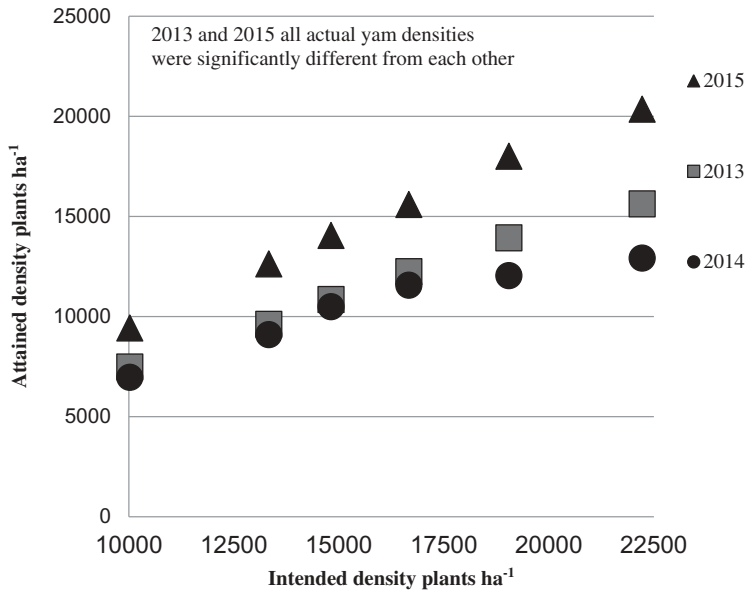


Figure 2. Yam density attained at harvest as a function of the intended target density.

Table 3. Yam plant survival (%) until harvest in sole yam and yam/maize intercrop at IITA, Ibadan, Nigeria. Means across planting densities, tillage and fertilizer.

	2013	2014	2015	Mean
Yam sole crop	73.4	72.6	94.6	79.7
Yam/maize intercrop	66.6	57.1	92.8	71.7
Difference	6.8	15.5	1.8	8.6
P diff	0.0001	0.0001	0.0442	

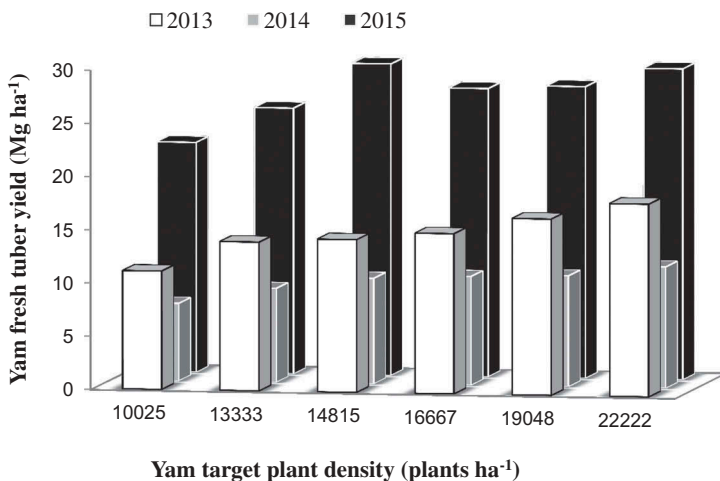


Figure 3. Yam fresh tuber yield (Mg ha⁻¹) as a function of yam planting density.

significantly higher after intensive tillage ($P < 0.01$) than on flat soil. Fertilizer application had no significant effect in 2013 (+1.8% tuber yield), a negative yield response in 2014 by -10.5% ($P = 0.0046$) and a positive yield response of +17.5% ($P = 0.0017$) in 2015 (Table 4).

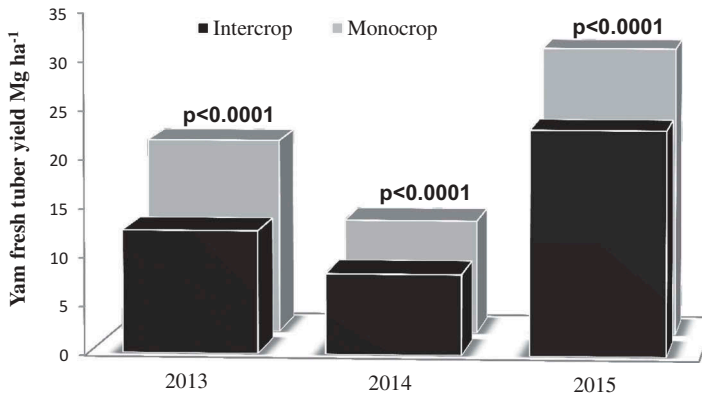


Figure 4. Effect of intercropping on yam fresh tuber yield (Mg ha⁻¹).

Table 4. Effect of tillage and fertilizer on yam tuber yield (Mg ha⁻¹). Means across the planting densities.

Treatment	Level	2013	2014	2015
Tillage	Flat	16.79	8.94	25.57
	Ridge	16.09	11.21	27.65
P diff		0.139	<.0001	0.192
Fertilizer	Fertilizer	16.58	9.52	29.16
	Nil	16.29	10.64	24.06
P diff		0.538	0.0046	0.0017

Maize yield

Effect of yam plant density on maize grain yield

In 2013 and 2015, maize grain yield was negatively affected by the intercropped yam. Sole crop maize grain yield (50,000 plants ha⁻¹) was 3.25 Mg ha⁻¹, significantly higher by 0.94 Mg ha⁻¹ in 2013 (+ 40.5%, $P < 0.01$) than grain yield when planted with yam across yam densities. In 2015 sole maize grain yield was 2.66 Mg ha⁻¹, being 0.61 Mg ha⁻¹ (+29.2%; $P < 0.001$) more than that of intercropped maize. In 2014 the situation was reversed with a numerical, yet not significantly lower yield of 1.589 Mg ha⁻¹ in sole maize with an advantage of +0.31 Mg ha⁻¹ or +16.3% in the intercropped maize. When intercropped, the increasing yam densities caused a slight decrease in maize grain yields yet the differences within the intercrops were not significant.

Effect of tillage and fertilizer on maize grain yield

Tillage had no significant effect on maize grain yield in 2013 and 2014 (Table 5). However, ridge tillage reduced grain yield significantly in 2015 (1.99 Mg ha⁻¹; $P < 0.0002$), compared with the yield in flat soil (2.29 Mg ha⁻¹).

Table 5. Effects of tillage and fertilizer application on maize grain yields (Mg ha⁻¹). Means across all yam densities and including sole maize.

Treatment	Level	2013	2014	2015
Tillage	Flat	2.39	1.77	2.29
	Ridge	2.51	1.94	1.99
P diff		0.263(ns)	0.056(ns)	0.0002
Fertilizer	Fertilizer	2.646	1.958	2.266
	Nil	2.259	1.552	2.031
P diff		0.001	0.001	0.001

Table 6. Land equivalent ratios in a yam/maize intercropping system as affected by tillage and fertilizer application.

Year	Tillage		p diff	Fertilizer		p diff
	Ridged	Flat		Fertilizer	Nil	
2013	1.21	1.461	0.001	1.274	1.397	0.042
2014	2.288	1.976	ns	2.499	1.765	0.0117
2015	1.583	1.54	ns	1.433	1.697	0.0002

Table 7. Revenue index of yam intercropped with maize and sole yam.

Year	2013	2014	2015
Yam/maize intercrop	37.04	33.21	53.70
Sole Yam	52.38	44.81	64.00
p diff	<.0001	<.0001	<.0001

In all 3 years fertilizer application increased maize grain yield significantly ($P < 0.01$), with a 0.33 Mg ha^{-1} increase in 2013 (+17.3%), a 0.42 Mg ha^{-1} increase in 2014 (+25.6%) and a 0.24 Mg ha^{-1} increase in 2015 (+11.9%) (Table 5).

Land equivalent ratio

Yam plant density did not affect the LER. The LER was not significantly affected by tillage in 2014 and 2015 (Table 6). In 2013 the LER was higher in flat soil than when ridged. Fertilizer application reduced LER in 2013 and 2015 significantly, yet in 2014 LER was higher when fertilizer was applied.

Revenue

Due to the large differences in yam yields and the increasing prices, the total market value of the crops was highly variable between the years. The revenue index was in all 3 years higher in sole yam than when intercropped (Table 7).

Discussion

Yam yield and soil chemical properties and planting date

Soil chemical properties were with few exceptions, best in 2014, when yields were the lowest. Except for pH and exchangeable Mg soil properties were worst in 2015 when yields were the highest. Concrete critical soil nutrient levels for yam have not been established for West Africa. In a compilation by Carsky et al. (2010) it was reported that various authors determined that responses to fertilizer are likely on soils containing $<0.1\% \text{ N}$, $<10 \text{ mg kg}^{-1}$ available P (Bray-1) and $<0.15 \text{ cmol } [^+]\text{ kg}^{-1}$ of exchangeable K. It could thus be inferred that these soil nutrient levels are somewhere close to critical levels. According to O'Sullivan (2010) critical values for yam response to Mg have not been established, yet for other crops, Mg levels of $0.83\text{--}1.65 \text{ cmol } [^+]\text{ kg}^{-1}$ are considered to bear a risk of Mg deficiency. Except for Mg, soil chemical parameters in our trial sites exceeded the values found in the literature. The Mg values in 2014 were the lowest amongst the sites and may have contributed to the low yields. The importance of Mg was demonstrated by Aduayi and Okpon (1990) showing that with increasing leaf Mg concentration final tuber yields increased, with correlation coefficients ranging from $r = 0.46^*$ to $r = 0.67^{**}$, all increasing with increasing plant age.

Although a low Mg supply in 2014 may explain the low yields in 2014, the difference between 2013 and 2015 cannot be explained by the soil properties. The results rather indicate that other factors have a strong influence on yam tuber yields.

The 2014 season planting was delayed due to the near complete failure to germinate of the first planting. Although reasons for this could not be identified it can be assumed that the late planting was a major contributor to low yields. Eruola et al. (2012) reported lower yields in two consecutive years from later planted yams compared with earlier planted yams at Abeokuta, a site not far from Ibadan. For water yam (*D. alata* L.) Marcos et al. (2011) found lowest yields from latest plantings.

Yam yield response to fertilizer application

The effect of fertilizer application on yam tuber yield was inconsistent between years, yet with increasing average yields the positive fertilizer response increased. Considering that the soil properties were the least favorable in the year with highest yields, it appears that other factors than soil properties and nutrient supply play a more important role in yam yield formation. Tuber yield response of yam to fertilizer application was reported to be highly variable (Carsky et al. 2010). They reported from Togo that yam did not respond to N, yet K application increased yields and P promoted larger tubers thus a higher proportion of commercial tubers. Contrary to results from Togo, Irving (1956) found consistently positive effects of N application in trials in eastern Nigeria between 1947 and 1951. The effect of K was less and P affected yields only after grass fallow. Kpeglo et al. (1981) attained tuber yields up to 42.6 Mg ha⁻¹ with 45 kg N ha⁻¹ and 30 kg K ha⁻¹ at IITA in southwestern Nigeria. On different soils in the northwest highlands of Cameroon, Lyonga (1981) obtained significant responses to application of N alone, K alone, NP and NK. Contrary to these results Kayode (1985) did not find a response to N over 4 years on soils with 4.6 and 5.6% SOM. At lower SOM contents an application of 35 kg ha⁻¹ N fertilizer increased yam yields. P and K had no effect at >8 mg kg⁻¹ P and >0.15 cmol[+] kg⁻¹ K. From northern Ghana, Koli (1973) reported yield increases by N and P application on soils with < 0.8% SOM and 13.7 mg kg⁻¹ P, respectively. No response to K was observed at 0.29 meq/100 g. Diby et al. (2009) reported from Cote d'Ivoire, that the application of inorganic fertilizer (NPK) to yam had no effect on the fresh tuber yield but it increased significantly the shoot growth. Srivastava (2010) applied 30:30:60 kg ha⁻¹ NPK in the savanna of Benin Republic and observed significant tuber yield increases. Combination with organic inputs did not increase yields over the level attained by mineral fertilizer alone.

Similar inconsistent results were reported by O'Sullivan and Ernest (2008) from the Pacific Region.

Unlike yam, maize grain yield response was positive to fertilizer in each year, a result that was expected yet no references on the grain yield response of maize intercropped with yam could be found. In cassava/maize intercrop with or without fertilizer application, cassava root yields declined, yet maize grain yield remained unaffected (Olasantan et al. 1996). Although there is not much literature to compare these results with, it appears that yam and maize are incompatible crops with the yam suffering the rapid growth and nutrient uptake of maize which cannot be compensated for by fertilizer. At the same time, the increase in maize grain yield was not sufficient to compensate for the tuber yield losses in all years. As such, fertilizer use to increase yam production remains a high risk investment that requires further research before reliable recommendations can be made.

Yam tuber yield and yam plant density

A reliable optimal plant density for yam has not yet been determined for any larger area. Results here indicate that the minimum density is around 14–15,000 plants ha⁻¹ to maximize tuber yields in sole yam. Most trials on yam density were conducted with densities above those commonly used by farmers. Ferguson et al. (1983) conducted trials at 17,940 and 35,880 plants ha⁻¹ with the higher plant density producing the higher yield. Law-Ogbomo and Osaigbovo (2014) showed increased yam yields with increasing density between 10,000 and 26,667 plants ha⁻¹. Baker (1964) reported an asymptotic increase of yam yields with increasing plant density thus similar to the situation found here in 2014 and 2015. King and Risimeri (1992) tested 2500, 4444 and 10,000 plants ha⁻¹ of *Dioscorea esculenta* on different stake heights in Papua New Guinea. Highest tuber yields were

attained at 10,000 plants ha⁻¹, yet when considering the cost of stakes highest returns were attained at 4444 plant ha⁻¹. Staking cost and seed yam costs need to be considered in formulating recommendations on planting density.

Attaining the optimal yam plant density appears to be a problem in yam production considering the variable and in 2 years low survival rates. Despite fungicide and insecticide treatment the 2013 and 2014 survival rates have to be considered unacceptably low. Yam planting material quality and soil conditions, specifically pests and diseases that may have caused the low survival in 2013 and 2014 require further research to reduce the risk of poor crop performance or failure. The mass of the planting material used in these trials was apparently sufficient as indicated by the high 2015 survival rates. Yam planting material is expensive compared to that of other crops, such as cassava and maize grown commonly in the region. Farmers tend towards planting yam at relatively low densities to produce large tubers with a regular shape, which will fetch premium prices (Banson and Danso 2013), yet require deep, stone free soils. Today the processing industry requires yam at competitive prices and size and shape do not matter. This opens opportunities to farmers on soils considered suboptimal for yam production. With yam yield being the primary target when producing for the processing industry, farmers would need agronomic intensification measures. The results of all 3 years show that an increased yam plant density would be one important first step.

Yam response to intercropping

The general reduction in yam yields when intercropped shows that maize competes in the early stages with significant effects on yam tuber yield across the yam densities. Similar yam tuber yield reductions when intercropped with maize were reported by Odurukwe (1983) from south East Nigeria. The strong competitive effect of the maize may be due to the faster growth and earlier nutrient uptake. There could have been some competition for light, yet the yam was staked and had grown above the maize height by the time the maize flowered. However, the important aspect is that the yams were not able to compensate for the phase with competition during the following 3–4 months after the maize harvest. Obviously, some stages in the yam development up to 3 months after planting (the growing phase of the maize) are critical for the later yam yield formation and should not be compromised by an intercrop. There are no references on the impact of intercrops with different length of growing period to relate our results to, but from weed competition studies, it has been shown that yam suffers yield losses if not weeded over the first 3–4 months after planting (Onochie 1974; Beale 1983; Akobundu 1987) which coincides with the phase the maize was in the field and competed with the yam. In our trials, the high maize density (Muoneke and Asiegbu 1997) and the row distance of 0.75 m have probably aggravated the situation with increasing planting density of the crops in the mixture.

Despite the generally >1 land equivalent ratios, based on the dry matter yields of yam and maize, intercropping cannot be recommended. The price difference between yam and maize requires looking at the income generation from sole versus intercropped yam. According to Willey (1979), practical significance of productivity in intercropping could only be fully assessed when related to the actual economic or monetary returns. The value of the crops was generally higher in sole yam and the normalized revenue index was significantly higher in sole yam in all 3 years. As such, the LER has no relevance in intercrops that are traded fresh versus dry and attain different prices per unit mass.

Yam yield response to tillage

Yam is commonly planted in mounds or ridges, thus requires a large amount of labor. Only in 1 year was the response to ridging significantly positive, which raises the question on how important tillage is in yield formation. Research in other crops shows that ridging reduces weed infestation and concentrates topsoil around the planting material. In our trials, the maximum yield advantage in intensively tilled plots was 2.27 Mg ha⁻¹, which would need to balance the cost of plowing, harrowing and ridging, which

was around 225 \$ ha⁻¹. The traders' offers averaged Naira 30 kg⁻¹ in 2013, equivalent to 0.1875 \$ kg⁻¹. With a numerical yield reduction in ridged soil, the farmers would have sustained a loss. In 2014, assuming the same trader farm gate price, farmers would have gained 200 \$ ha⁻¹ through ridging. We do not have a trader offer for 2015 yet would assume a slight increase in prices which would have led to a similar gain through ridging in 2015. Vine et al. (1984) found lower yam yields when ridged on a sandy Alfisol in Ibadan, Nigeria, due to delayed emergence and vine growth caused by slumping and compaction of the soil after heavy rainstorms. Agbede (2006) found a 35% increase in average individual tuber mass when the soil was mounded, yet the yield was not quoted. Opara-Nadi and Lal (1987) found higher yam yields when soil was ploughed (12.4 Mg ha⁻¹) than in no-till soil (10.9 Mg ha⁻¹). Contrary to these results, Maduakor et al. (1984) did not find yam tuber yields being affected in no-till versus ridged soil. There was no information on the soil properties in the quoted studies thus any tillage × soil fertility interaction has not been investigated. However, as the strongest tillage effect was found on the richest soil the concentration of top soil around the seed tuber may not have been an issue. Fertilizer application had a significant negative effect on tuber yield in the same year thus nutrient supply was likely not limiting. Nevertheless, due to the late planting in 2014, ridging may have improved soil conditions leading to higher yields albeit at a generally lower level than in the other years.

None of the factors interacted significantly in a positive synergistic manner. Thus yam cropping can focus on single factors that farmers can change or manipulate. Of the tested factors, intercropping yam with maize is not recommendable. Fertilizer application and tillage are highly unreliable factors in yam production. Positive responses to either appear to be depending on other factors or conditions. Because we did not find significant interactions between the factors, research can focus on identifying the conditions under which tillage and fertilizer application will increase yields and productivity. For yam farmers the most reliable way to increase yields is planting increased yam plant densities. However, as seed yams are expensive this option is limited by seed yam prices. Affordable seed yam supply systems would allow farmers to exploit this option.

Conclusion

Yam agronomy requires further research on fertilizer responses and the effectiveness of tillage before recommendations can be formulated. Farmers with a commercial production objective will need to abstain from intercropping and should focus on high plant density yam production systems. Improved seed yam supply would facilitate the transformation of information obtained in this study into farmer applicable approaches to increase their production and productivity.

Disclosure statement

No potential conflict of interest was reported by the authors.

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