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On-farm assessment of cassava root yield response to tillage, plant density, weed control and fertilizer application in southwestern Nigeria

Olabisi Omolara Onasanya [a,b,*], Stefan Hauser [c], Magdalena Necpalova [d], Felix Kolawole Salako [b], Christine Kreye [c], Meklit Tariku [e], Johan Six [a], Pieter Pypers [e]

[a] Department of Environmental Systems Science, Group of Sustainable Agroecosystems, Swiss Federal Institute of Technology, ETH Zurich, CH-8092, Zurich, Switzerland
[b] Department of Soil Science and Land Management, Federal University of Agriculture, Abeokuta, Nigeria
[c] Root and Tuber Agronomy, International Institute of Tropical Agriculture, Ibadan, Nigeria
[d] School of Agriculture and Food Science, University College Dublin, Belfield Dublin 4, Ireland
[e] International Institute of Tropical Agriculture, ICIPE Campus, P.O. Box 30772-00100, Nairobi, Kenya

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ABSTRACT

Cassava is growing in importance in Nigeria as a food and industrial crop. Current yields are low due to poor soil fertility and because farmers do not use improved germplasm, clean planting material, or improved crop management in Nigeria. To provide feasible agronomic recommendations targeting increased root yield, the effects of tillage intensity, fertilizer application, plant density and weed control were tested in 230 farmers' fields in southwestern Nigeria over two years. In 2016, tillage treatments were zero, single and double passage with a disc plough, followed by ridging (soil shaping) versus leaving the soil flat. Fertilizer application at 75:20:90 kg ha^{-1} NPK was tested against a control and two plant densities (10,000 versus 12,500 ha^{-1}) were compared. In 2017, plant density at 10,000 ha^{-1} and double plough were excluded, while pre- and post-emergence herbicide application versus farmer's choice of weed control (i.e. manual weeding using hand hoe) was introduced. Cassava was harvested at 12 months after planting, and yields were recorded as fresh root mass. In 2016, double plough (15.9 Mg ha^{-1}) had a minor advantage over single plough (14.3 Mg ha^{-1}), while zero plough produced 12.9 Mg ha^{-1} ($P < 0.001$). Ridging increased yield significantly ($P < 0.01$) by 2.3 Mg ha^{-1} after single and zero plough, but not after double plough. Across tillage treatments, planting at 12,500 plants ha^{-1} and fertilizer application increased yields by 1.5 and 4.2 Mg ha^{-1}, respectively. In 2017, ridging resulted in a yield increase of 1.7 Mg ha^{-1} after single plough and 5.6 Mg ha^{-1} after zero plough. Fertilizer application increased root yield by 2.9 Mg ha^{-1} across tillage treatments. The use of herbicides negatively affected cassava yields in zero plough fields, compared with manual weeding. After ploughing, yield in herbicide based and manual weed control were not different. Cassava root yield response to tillage intensity strongly varied across fields, with low-yielding fields commonly responding less frequently to tillage. We conclude that unresponsive fields require measures other than increased tillage intensity to increase cassava root yields and that cost-intensive tillage operations must be targeted to responsive fields together with fertilizer application and improved weed control.

1. Introduction

Cassava (*Manihot esculenta* Crantz) is an important staple food crop (Fasinmirin and Reichert, 2011; Salau et al., 2015) and accounts for 50 % of the food intake in sub-Saharan Africa (Ojeniyi et al., 2012). Apart from being a staple crop, it also serves as an industrial raw material to produce starch, confectioneries, alcohol, gum, pharmaceuticals and livestock feed. It is regarded as a hardy crop, growing on marginal land with little or no inputs, and it is usually planted as the last crop in the crop rotation cycle (Salami and Sangoyomi, 2013). Indeed, cassava can produce some yields in depleted soils where other crops would fail, but still, cassava cultivation removes substantial amounts of nutrients with the roots at harvest (Ayoola and Makinde, 2007).

Nigeria is the largest cassava producer in the world, with an annual output of 59.5 million Mg fresh cassava roots from 6.8 million hectares of land (FAO, 2019). Nevertheless, cassava yields in Nigeria are low at

* Corresponding author at: Department of Environmental Systems Science, Group of Sustainable Agroecosystems, Swiss Federal Institute of Technology, ETH Zurich, CH-8092, Zurich, Switzerland.
E-mail address: olabisi.onasanya@usys.ethz.ch (O.O. Onasanya).

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an average of 8.8 Mg ha^{-1} yr^{-1} fresh roots (FAO, 2019). The cassava yield potential is estimated at 90 Mg ha^{-1} yr^{-1}, which was obtained in experiments under near optimum conditions in Columbia (Okogbenin et al., 2013). This large yield gap in Nigeria is attributed to low soil fertility, aggravated by poor agronomic practices and nutrient deficiency and imbalances (Borin and Frankow-Lindberg, 2005). Adeniji et al. (2000) reported that the most important soil and agronomic factors affecting cassava production in Nigeria are soil temperature and moisture, soil erosion, low soil fertility and poor agronomic practices. In the past, most farmlands in Nigeria were traditionally managed, i.e. nutrient replenishment was done through leaving the land fallow for 3–10 years after cassava cultivation (Borin and Frankow-Lindberg, 2005) without the use of external inputs. Fallow phases have been shortened or completely abandoned due to a limitation of available land (Ayoola and Makinde, 2007) and increasing demand for food (Salami and Sangoyomi, 2013). Nowadays, many smallholder cassava farmers cultivate cassava on marginal land assuming that cassava does not produce adequately high yields on fertile land and neither requires nor responds to the application of mineral fertilizer (COSCA Tanzania, 1996). In Nigeria, cassava is often cultivated with intensive mechanical and/or manual tillage, traditionally on mounds or ridges (Fasinmirin and Reichert, 2011). Reports on the effects of tillage intensity on cassava yield are contradictory (Adekiya et al., 2009; Ohiri and Ezumah, 1990). Furthermore, land preparation methods for cassava are very variable. Farmers may plant in untilled soil or do minimal superficial manual tillage by a hand hoe. Traditionally, the soil was manually ridged or mounded, yet recently tractors are used to plough or double plough. Often, the soil is ridged before planting either following ploughing or directly on the untilled soil. The agronomic appropriateness of these practices under the prevailing edaphic and climatic conditions across the cassava growing area in Nigeria is yet to be verified (Agbede, 2006).

In India, fertilizer application generally increased cassava root yield (Byju et al., 2012; Ishaq et al., 2002). In western Kenya, central-eastern Uganda, Ghana, and coastal Tanzania, cassava responded positively to N, P and K fertilizers (Asadu et al., 2008; Asadu and Dixon, 2005; Senkoro et al., 2018). Since 1989, the fertilizer recommendation of NPK 15−15-15 at 400 kg ha^{-1} in Nigeria has not changed (FPDD, 1989). However, Fondufe et al. (2001) found that this blanket fertilizer application did not consistently improve cassava root yield when compared to control and plots that received fertilizer based on soil testing. In Asia, India, Latin America, and some parts of Africa, research has shown root yield response to fertilizer application (Biratu et al., 2018; Howeler and Aye, 2014; Senkoro et al., 2018), however, fertilizer use in Nigeria has not been much researched.

Planting density is another important factor influencing cassava root yield. Henrique Campos de Almeida et al. (2016); Silva et al. (2013), and Wholey and Booth (1979) reported cassava root yield increases at increased plant populations. In Africa, planting at low population densities and not replacing missing cassava plants is a common practice (Hauser and Ekeleme, 2017). In many countries, 10,000 plants ha^{-1} is the standard recommendation, but higher densities can improve yields, especially for non-branching varieties (Hauser et al., 2014). Interactions between plant density and other management practices such as fertilizer use and tillage are, however poorly understood.

Weed infestation facilitated by large inter and intra-row spacing at low plant density and/or poor land preparation is also reported to reduce cassava yield (Ekeleme et al., 2016; Hauser and Ekeleme, 2017). Cassava is a poor competitor and may suffer serious yield losses if not adequately weeded, especially at an early growth stage (Howeler, 2013). Tongglum et al. (2003), found the highest cassava yields in plots that were maintained weed-free for at least three months after planting. Nigerian farmers traditionally control weeds by a hand hoe, which is labour and cost-intensive. Today, the use of herbicides is becoming more prevalent because of their cost and time efficiency (Hauser and Ekeleme, 2017; Howeler, 2013; Tongglum et al., 2003). Tillage practices are known to have an important influence on weed infestation during the first months after planting (Shrestha et al., 2006), with double ploughing and ridging both expected to delay weed infestation and even saving on an early weeding requirement.

Multilocational trials were conducted in southwestern Nigeria in 2016 and 2017, with the aim to develop recommendations for tillage and weed control interventions that increase cassava root yields. Since increased plant density and fertilizer application have been shown to increase cassava root yields, these factors were combined with a range of tillage intensities to identify potential synergistic effects.

2. Material and methods

2.1. Study sites

On-farm trials, 150 in 2016 and 80 in 2017, were established in Oyo and Ogun states of southwestern Nigeria along a north-south gradient. Sites were selected based on the area covered by a specific environment (cluster). A total of 23 bioclimatic, 21 edaphic and 18 environmental covariates derived from remote sensing products (Alabi et al., 2019) were used to classify 14 different environmental conditions and the area in Oyo and Ogun state in which these conditions prevailed. The largest six environments covering more than 80 % of the total area were selected and the equivalent number of trials allocated to them. Trials were established as clusters of 10, within a 5 km radius around selected villages, and each trial was hosted by a different farmer. The selection of participating farmers was upon recommendation of farmer associations, and extension agents (EA) of development partners who had been working with farmers in the region. Each farmer presented a field that is representative for cassava cultivation and had been grown to cassava during the past two years.

Oyo state is largely in the derived savannah, while Ogun state is partially derived savannah with the southern part being humid forest transition zone. Both states experience bimodal rainfall patterns: rains start in March/April and fall to the end of July. In August rainfall is low with the sky dominantly cloudy and high relative humidity. The second season rains start in late August to early September and last to mid-November. The highest rainfall is in July and October. A long dry season, usually without rainfall and clear sky lasts from mid-November to March, unless when the northern dust-loaded wind called harmattan is blowing. Cumulative rainfall received during the experimental period for each trial location is presented in Fig. 1.

2.2. Experimental design and treatments

In 2016, the trials were set up following a complete four-factorial 3 × 2 × 2 × 2 split-split-plot design. The first factor (main plot: primary tillage) was plough passage at three levels: zero, single and double disc-plough passage; the second factor was soil shaping (subplot: secondary tillage) at two levels: ridging versus flat soil surface; the third factor was plant density at 10,000 versus 12,500 plants ha^{-1}; the fourth factor was fertilizer application of 75:20:90 kg ha^{-1} N, P and K versus a control. Planting density and fertilizer application treatments were randomly allocated within the sub-subplots. Depending on farmers' land availability and willingness to maintain the trials, the complete set of treatments or two-thirds were offered to be established. In sites where farmers opted for the two-thirds set up, only two of the three plough levels were implemented, and within these, all other factors were established. In 2016, the full set of treatments required 49 m by 29 m on each farmer's field, and 32 m by 29 m for a two-third set of treatments. Ten trials were overseen by one extension worker with support from technicians of the International Institute of Tropical Agriculture (IITA) and the Federal University of Agriculture Abeokuta, Nigeria (FUNAAB). Each plot measured 7 m by 7 m at the low plant density and 7 m by 7.2 m at the high plant density. In 2016, participating farmers had agreed to conduct manual weed control at 4, 8, 12 and 24 weeks after planting (WAP). Some farmers, however, did not strictly adhere to this schedule,

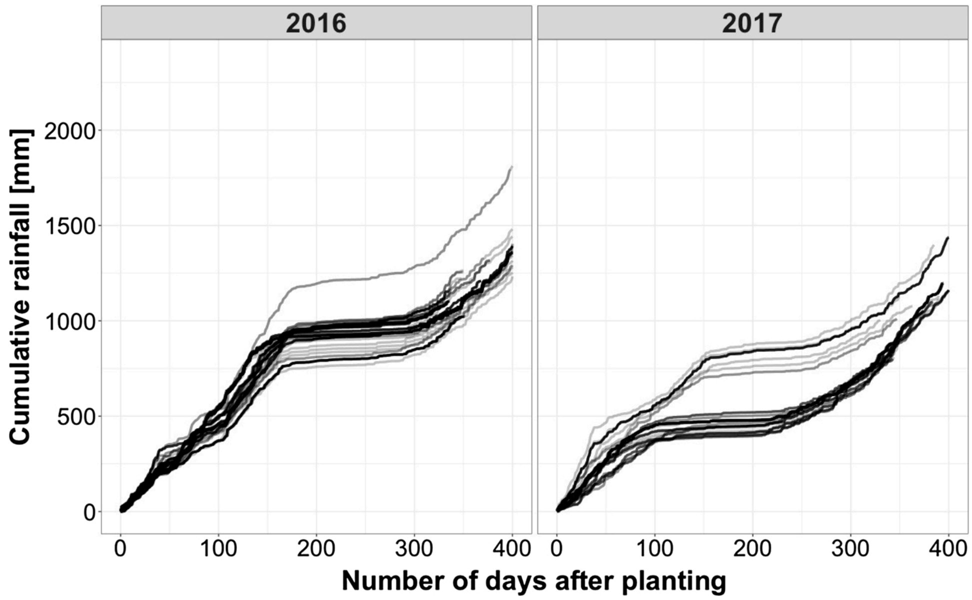

Fig. 1. Cumulative rainfall received in each trial location from planting until harvest during 2016 and 2017 growing seasons. Source:(CHIRPS, 2020).

potentially causing yield differences due to weed competition.

In 2017, trials were repeated in different fields and with a modified design. The double plough passage treatment was removed from the design due to root yields generally not being different from those in a single plough passage. The 10,000 plants ha^{-1} density was as well removed from the design because this generally produced lower yields than the 12,500 plants ha^{-1} density. In 2016, many farmers expressed the frequent weeding requirements to be an impediment, and therefore, we introduced weed control method as a factor at two levels: herbicide-based versus manual weed control.

2.3. Soil sampling and analysis

Soil samples were collected each year in each trial before establishment at 0−20 cm and 20−50 cm depth with a 20 mm diameter soil auger. In each trial, a minimum of 6 samples were taken and bulked into a single sample for analysis. Samples were air-dried, passed through a 2 mm sieve and analyzed at the IITA service laboratory. Organic C was determined by chromic acid digestion (Heanes, 1984), and total N by Kjeldahl digestion and colorimetric determination on a Technicon AAII Autoanalyzer (Bremner and Mulvaney, 1982; Technicon, 1971). Exchangeable K, Mg, Na and Ca were determined by Mehlich 3 extraction and Atomic Absorption Spectrophotometer (Model Buck 211) following procedures of Mehlich (1984). Available P was determined by the Bray-1 method (Bray and Kurtz, 1945). Soil pH was measured in water at 1:2.5 soil/water ratio.

2.4. Establishment and management of trials

Cassava variety TME 419 cuttings of about 25 cm length were inserted at roughly 45° into the soil and buried to 2/3 of their length pointing along the crest of the ridge or the planting line. At about 3 WAP, non-sprouted cuttings were replaced.

In total, the cassava received 75 kg N, 20 kg P and 90 kg K ha^{-1}. Two equal dressings of 150 kg ha^{-1} NPK 15:15:15 each were applied at 4 and 8 WAP. Urea was applied at 65 kg ha^{-1} at 12 WAP. Finally, muriate of potash was applied at 53 kg ha^{-1} in two equal dressings each at 16 and 20 WAP. Fertilizer was applied in a half-moon shaped shallow furrows at about 15 cm distance from the cassava planting stake in flat plots and on the side of the ridge in a shallow hole 15 cm away from the planting stake in ridged plots. The fertilizer was covered with soil.

The herbicide-based weed control in 2017 consisted of a pre-emergence application at 4 L ha^{-1} herbicide with active ingredient 290 g/L S-Metolachlor +370 g/L Atrazine. Post-emergence weed control was with glyphosate (360 g/L) at 4 L ha^{-1} using a spray shield to prevent herbicide touching green cassava leaves at 4, 8, 12 and 24 WAP. Herbicides were applied by technicians. Participating farmers conducted hoe-weeding simultaneously in the plots with manual weed control. Planting, soil sampling, data collection and harvest were performed by research teams from IITA and FUNAAB in all trials.

2.5. Root harvest

Cassava harvest was conducted between 48 and 52 WAP. First, all border plants were removed, then the net plot plants and stems were counted. The net plot size was 25 m^2 in the 10,000 plants ha^{-1} density and 28 m^2 in the 12,500 plants ha^{-1} density in 2016. The cassava was uprooted, and the storage roots were cut off the planting stakes and separated into roots with a diameter greater than 1.5 cm, without damages or rot, further called marketable roots versus all other roots that farmers would leave in the field, thus do not contribute to revenue. The marketable roots were cleaned of any attached soil before they were weighed on a digital scale, and their mass per plot was recorded.

2.6. Statistical analysis

The R software version 3.6.0 was used for all data analysis (R Core Team, 2019). Data were checked for normal distribution using the qqnorm function, and all outliers (0.08 %) were removed. Data were then subjected to analysis of variance (ANOVA) using a linear mixed-effects model to determine the effect of treatments across locations in each year. The two years data were modelled separately because of the different designs in 2016 and 2017. In the model for 2016, primary tillage, secondary tillage, plant density and fertilizer application and all possible interactions were included as fixed factors, while fields and trials nested in each field were included as a random factor . The same model was used for the 2017 data analysis, except that plant density was replaced by weed control. Then an analysis across years was conducted by pooling common factors in both years; this excluded the double plough and low plant density treatment from 2016 and herbicide weed control from 2017. ANOVA and mean separation was done with the lmer and lsmeans function, respectively. Relationships between cassava response to tillage and soil properties, and rainfall data were evaluated using pearsons correlation coefficients.

3. Results

3.1. Soil chemical properties

Soil chemical properties varied widely at both soil depths (Table 1). At 0–20 cm depth, soil pH ranged from 6.5–7.4 (mean 6.7). Total organic C ranged from 3.0–21.0 g kg^{-1} and total N ranged from 0.3 to 1.8 g kg^{-1} with a mean of 0.6. The average, sand, silt and clay contents were 803 g kg^{-1}, 75 g kg^{-1} and 122 g kg^{-1}, respectively. At 20–50 cm soil depth, soil pH ranged between 6.4 and 7.3. The average total organic C, total N and exchangeable K, Ca and Mg contents were lower in 20–50 cm soil depth than in the topsoil.

3.2. Cassava fresh root yields in 2016

In the 2016 planting season, the main effects of primary tillage, secondary tillage, planting density and fertilizer application on cassava fresh root yield were highly significant, and there was a significant secondary tillage × fertilizer application interaction (Table 2). The interaction of primary × secondary tillage was marginally significant at P = 0.07.

Although the interaction between primary × secondary tillage was not significant (P = 0.07), it is important to note that ridging after single plough and zero plough further increased yields by 15.2 % and 22.3 %, respectively, but failed to increase root yields in double plough fields (Fig. 2a). In addition, double plough flat and ridge had no yield advantage over single plough ridge (Fig. 2a). The secondary tillage × fertilizer application interaction was such that without fertilizer, ridged and flat fields did not produce different yields. When fertilizer was applied, root yield increased by 3.3 Mg ha^{-1} from 11.9–15.2 Mg ha^{-1} in flat fields, yet by 5.1 Mg ha^{-1} from 12.5–17.6 Mg ha^{-1} in ridged fields (Fig. 2b).

Table 1
Variation in soil physical and chemical properties across experimental sites.

Soil Depth	Soil properties	Lower range	Upper range	Mean	CV (%)
0–20	pH (1:2.5 H_2O)	6.5	7.4	6.7	2.5
	Total organic C (g kg^{-1})	3.0	20.7	6.4	45.8
	Total N (g kg^{-1})	0.3	1.8	0.6	50.5
	P (mg kg^{-1})	0.1	12.0	4.2	80.1
	Sand (g kg^{-1})	696.0	856.0	802.6	4.7
	Silt (g kg^{-1})	16.0	144.0	75.1	29.2
	Clay (g kg^{-1})	88.0	212.0	122.3	21.1
	Exch. Ca ($cmol_c$ kg^{-1})	0.9	6.3	2.1	49.5
	Exch. Mg ($cmol_c$ kg^{-1})	0.2	2.1	0.4	82.5
	Exch. K ($cmol_c$ kg^{-1})	0.1	0.4	0.2	35.0
	Exch. Na ($cmol_c$ kg^{-1})	0.0	0.1	0.1	34.5
20–50	pH (1:2.5 H_2O)	1.2	7.7	2.7	47.4
	Total organic C (g kg^{-1})	6.4	7.3	6.7	2.5
	Total N (g kg^{-1})	2.4	14.7	5.6	50.2
	P (mg kg^{-1})	0.2	1.3	0.4	49.9
	Sand (g kg^{-1})	1.1	31.1	8.0	84.3
	Silt (g kg^{-1})	708.0	856.0	804.6	4.8
	Clay (g kg^{-1})	44.0	146.0	76.7	49.9
	Exch. Ca ($cmol_c$ kg^{-1})	92.0	192.0	118.8	19.1
	Exch. Mg ($cmol_c$ kg^{-1})	0.8	5.9	1.8	59.4
	Exch. K ($cmol_c$ kg^{-1})	0.1	1.7	0.4	70.7
	Exch. Na ($cmol_c$ kg^{-1})	0.1	0.4	0.2	31.6

Table 2
Analysis of variance of treatments imposed during the experimental years.

	2016	2017	2016–2017
Source of variation	Pr(>F)	Pr(>F)	Pr(>F)
Primary tillage	0.00***	0.00***	0.00***
Secondary tillage	0.01**	0.00***	0.00***
Fertilizer application	0.00***	0.00***	0.00***
Plant density	0.00***	–	–
Weed control	–	0.62	–
Primary tillage: Secondary tillage	0.07	0.00**	0.04*
Primary tillage: Fertilizer application	0.58	0.43	–
Secondary tillage: Fertilizer application	0.03*	0.67	0.05*
Primary tillage: Plant density	0.94	–	–
Secondary tillage: Plant density	0.96	–	–
Fertilizer application: Plant density	0.24	–	–
Primary tillage: Weed control	–	0.60	–
Secondary tillage: Weed control	–	0.05	–
Weed control: Fertilizer application	–	0.19	–
Primary tillage: Secondary tillage: Fertilizer application	0.63	0.35	–
Primary tillage: Secondary tillage: Plant density	0.47	–	–
Primary tillage: Fertilizer application: Plant density	0.87	–	–
Secondary tillage: Fertilizer application: Plant density	0.88	–	–
Primary tillage: Secondary tillage: Weed control	–	0.04*	–
Primary tillage: Weed control: Fertilizer application	–	0.14	–
Secondary tillage: Weed control: Fertilizer application	–	0.25	–
Primary tillage: Secondary tillage: Fertilizer application: Plant density	0.43	–	–
Primary tillage: Secondary tillage: Weed control: Fertilizer application	–	0.25	–

- Means that the analysis of variance was not conducted because the treatment was not installed (i.e. weed control in 2016 and plant density in 2017.

3.3. Cassava fresh root yield in 2017

In 2017, primary tillage, secondary tillage and fertilizer application significantly increased cassava root yields (Table 2). Primary and secondary tillage interacted significantly. There was a significant secondary tillage × weed control interaction, and a significant three-way interaction of primary tillage × secondary tillage × weed control (Table 2). Fertilizer application increased average root yields by 18 % (2.6 Mg ha^{-1}) from 14.8 Mg ha^{-1} to 17.4 Mg ha^{-1} in flat fields, and by 3.2 Mg ha^{-1} from 18.1 Mg ha^{-1} to 21.3 Mg ha^{-1} in ridged fields (Fig. 3a). The three-way interaction of primary tillage × secondary tillage × weed control was such that the use of herbicide negatively affected root yield in zero plough flat fields: cassava root yield was 33 % higher in zero plough flat with manual (hoe weeding) than in herbicide-treated fields (Fig. 3b). In all other tillage treatments no differences were observed between herbicide-based and manual weed control.

3.4. Results across the years

Across both years, ploughing and ridging had the same effect of increasing root yields over zero plough and leaving the soil surface flat, respectively (Fig. 4). In 2017, root yield increases were larger than in 2016 and on average across the two years, ridging increased yields by 13 % after single plough and by 30 % in zero plough fields. Ploughing increased yields by 53 % and 33 % when the soil was left flat versus ridged, respectively.

3.5. Site-specific response to tillage intensity

Cassava root yield increases due to single plough versus zero plough strongly varied across fields (Fig. 5a), with most cases attaining higher

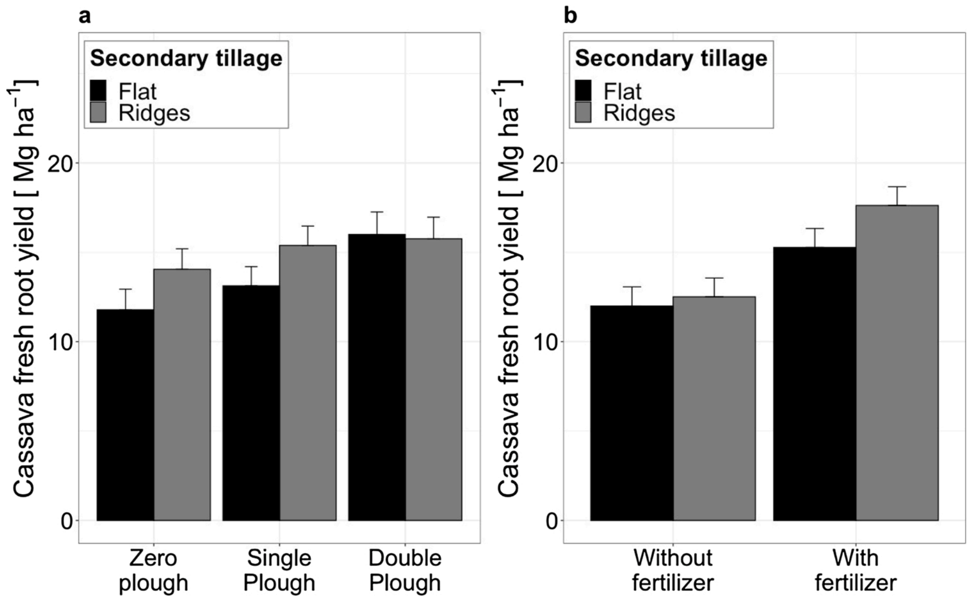

Fig. 2. (a) Interaction between primary tillage (ploughing) and secondary tillage (ridging) on cassava root yield in farmers' fields in 2016; (b) interaction between secondary tillage (ridging) and fertilizer application on cassava root yield in farmers' field in 2016.

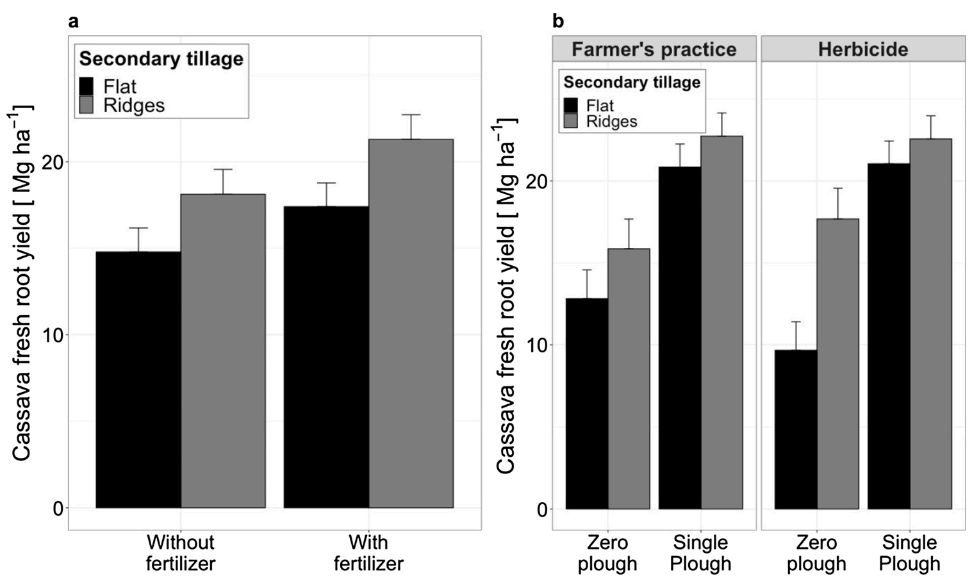

Fig. 3. (a) Interaction between secondary tillage (ridging) and fertilizer application on cassava root yield in farmers' fields in 2017; (b) Interaction between primary tillage (ploughing) and secondary tillage (ridging) as affected by weed control technique (farmer's practice = manual weed control by hand hoe; herbicide = combination of pre- and post-emergence herbicide application) on cassava root yield in farmers' fields in 2017.

yields in single plough compared with zero plough fields, independent of ridging or not. In both ridged and flat fields, the yield responses to single plough were relatively low when yields in zero plough plots were low. Whereas, the yield response to single plough increased with increasing yield in zero plough plots in both, ridged and flat fields and was largest in fields where yields in zero plough plots varied between 10 and 20 Mg ha^{-1}. In cases with negative yield effects of single plough versus zero plough, the yield losses were relatively small.

Similarly, variation in response to ridging versus leaving the soil flat was found when single ploughed (Fig. 5b). The response to ridging in single plough fields was larger when the yield after single plough flat was low. In contrast, ridging in zero plough plots increased root yields the most when the yield was lower in the flat fields (Fig. 5b). Largest responses to ridging were observed when yield on flat plots varied between 5 and 20 Mg ha^{-1}.

Response of cassava to ploughing had a weak significant relationship with the cumulative rainfall amount received at 60 DAP and 150 DAP with a correlation coefficient of 0.14 (Table 3). On the other hand, there was no significant relationship between the yield response of cassava to ridging and cumulative rainfall amount at any DAP. The response of cassava to ridging was not related to soil properties (Table 3). We could not evaluate the response of ploughing in relation to soil properties as we had too few trials with zero plough tillage treatment. This is because farmers were allowed to install a partial design by dropping one of the primary tillage treatments, and in most cases the zero plough treatment was dropped, hence preventing a comparison of plough versus no plough. In addition, in a few trials with zero plough, farmers abandoned these plots as the manual weed control method proved to be too labour intensive.

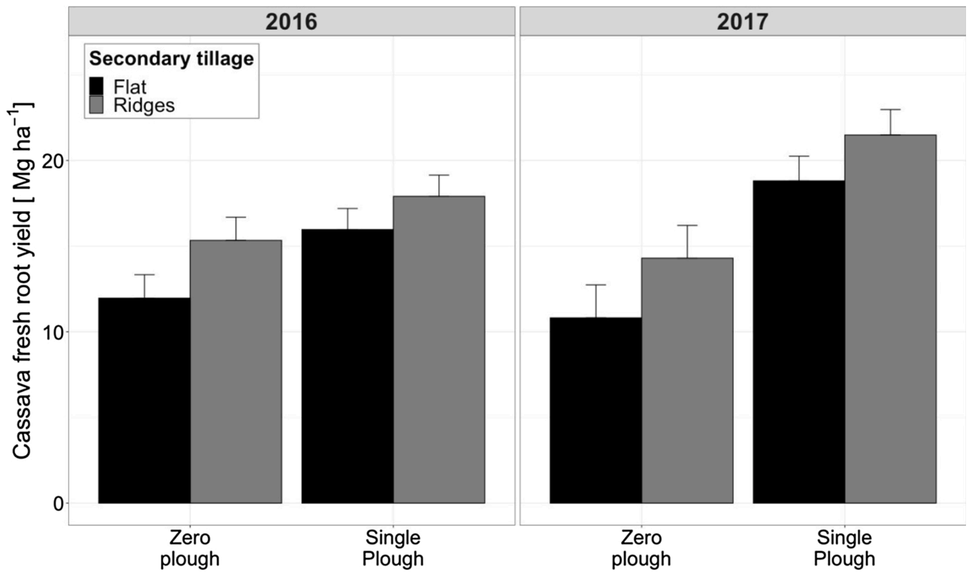

Fig. 4. Interaction between primary tillage (ploughing) and secondary tillage (ridging) on cassava root yield in farmers' fields for common treatments in 2016 and 2017.

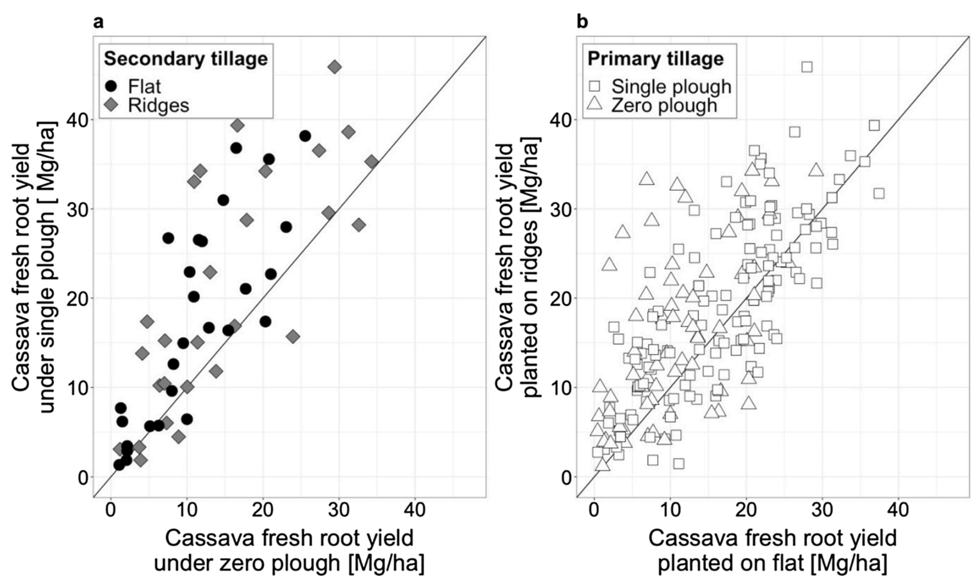

Fig. 5. (a) Cassava root yield under single plough versus zero plough and as affected by secondary tillage in farmers' field for common treatments in 2016 and 2017; (b) Cassava root yield when planted on ridges versus yield when planted on flat beds and as affected by primary tillage in farmers' field for common treatments in 2016 and 2017.

4. Discussion

The highly consistent positive effect of an increased plant density of 12,500 ha^{-1} over the current recommendation of 10,000 plant ha^{-1} (Hauser et al., 2014) warranted the change in the trial design in 2017. Similar results were reported by Hauser et al. (2015) albeit with soil fertility-dependent variations. While increased yields with increasing plant densities may be variety-dependent (branching versus non-branching), a large portion of the effect may stem from improved weed control at higher densities. Hauser and Ekeleme (2017) found significantly lower weed biomass at 12,500 than at 10,000 plants ha^{-1}. Henrique Campos de Almeida et al. (2016) and Silva et al. (2013) found that planting cassava at densities between 12,000 and 14,000 plants ha^{-1} produced twice the yield compared with yields at 5000 plants ha^{-1}. Our study revealed that these yield increases from increased plant density occurred independently from the use of fertilizer or tillage, suggesting that the yield increase associated with an increased plant density of 12,500 ha^{-1} over 10,000 plant ha^{-1} is indeed attributed to reduced competition with weeds for light, water and nutrients since the space for weed growth and the infestation was minimal.

Yield increases following fertilizer application are likely associated with the fact that cassava in Nigeria is cultivated on soils with low nutrient reserves and as the last crop in rotation schemes. Thus, when such soils receive fertilizer inputs, cassava responds positively, as long as other factors are not limiting, e.g. rainfall (Olaniyan et al., 2011; Kihara et al., 2016). This validates our findings because we observed an interaction between fertilizer use and secondary tillage in 2016 but not in 2017. In 2016, the early growth phase of cassava coincided with the time the crop received most of its rainfall and its split fertilizer dressings, which explain the observed fertilizer and secondary tillage interaction, realizing average yield increases of close to 10 Mg ha^{-1} in ridged fields versus about 5 Mg ha^{-1} in flat fields. Whereas in 2017, the crop received

Table 3
Correlation coefficient and P-values of cumulative rainfall days after planting (DAP), soil properties and cassava root yield response to ploughing and ridging.

	Response of cassava to ploughing		Response of cassava to ridging	
	Correlation coefficient	P-value	Correlation coefficient	P-value
Cumulative rainfall received at 30 DAP	0.13	0.06	−0.02	0.83
Cumulative rainfall received at 60 DAP	0.14	0.05*	0.05	0.67
Cumulative rainfall received at 90 DAP	0.08	0.28	−0.09	0.39
Cumulative rainfall received at 120 DAP	0.12	0.10	−0.06	0.58
Cumulative rainfall received at 150 DAP	0.14	0.05*	0.01	0.95
Soil pH	–	–	−0.08	0.44
Soil organic carbon	–	–	0.10	0.34
Total nitrogen	–	–	0.09	0.41
Available phosphorus	–	–	−0.34	0.00**
Calcium	–	–	0.01	0.92
Magnesium	–	–	0.02	0.88
Potassium	–	–	−0.03	0.80

- No values as there were insufficient fields with a full design that included zero-plough plots to evaluate the response of cassava to ploughing.

less rain during the early growth phase because planting was later; hence there was no interactive effect of fertilizer and secondary tillage on cassava root yield, and yield increases of about 5 Mg ha^{-1} were achieved. Despite this, we found overall higher cassava root yields in 2017 than in 2016. This observation can be attributed to the difference in rainfall pattern relative to the growing phase of the crop. Between 180 and 300 days after planting, when root bulking occurs, the crop received more rainfall in 2017 than in 2016.

In the first year of the study, we identified a weed control problem, which was evident during the field monitoring of the trials. Hauser et al. (2015) reported that weed biomass production in ridged cassava fields was generally lower than in fields left flat after single plough in Nigeria. The herbicide treatment was introduced in the second year to reduce or eliminate differences in weed competition caused by the tillage treatments. However, we observed that weed control by herbicides resulted in significantly lower cassava root yields compared with hoe weeding in zero plough flat fields. This is likely caused by the pre- and post-emergence herbicide not effectively controlling all weeds. The post-emergence herbicide was not selective and thus could not be applied over the cassava crop. Application with a shield in the interrow space failed to kill weeds close to the planting stakes, causing particularly strong competition due to proximity. It is likely that weeds close to the planting stake are more detrimental than those at a larger distance and they are likely to compete over a longer time, as it is unlikely that later herbicide applications would reach them under the cassava canopy. In addition, the usually stronger weed infestation on flat (not ridged) soil, would lead to higher weed densities and more severe competition with the cassava in the zero plough flat fields. However, it cannot be excluded that in some cases cassava plants suffered from glyphosate contamination, which would hamper growth for some time by reducing the leaf area of newly emerging leaves (Hauser and Ekeleme, 2017). Regardless, a complete herbicide-based weed control in zero-plough flat fields should be discouraged, and a first manual weeding operation recommended, ensuring weeds are effectively controlled in the early stages when cassava is young. Afterwards, once the cassava is taller and the lower parts of the main stems have lignified, glyphosate-based herbicides can be applied.

Hoe weeding is, to some extent, also a tillage operation as it disturbs the soil. Farmers tend to scoop the soil rather intensively and deep to uproot certain species if known to regrow rapidly. The scooped soil is usually moved towards the cassava and piled around the planting stake. This loosening of the soil might have resulted in an additional positive effect on root yield. The lack of a difference between cassava yields when weeds were controlled by herbicide versus hand hoe in single plough ridged versus single plough flat fields is likely due to weed control through ploughing (Jasinskaite et al., 2009), which leaves the field weed-free for the first week. The pre-emergence herbicide would be more efficient as only germinating weed seeds would be killed, while in zero plough, established weeds would need to be killed and biomass at the soil surface shields the pre-emergence herbicide from forming the active film at the soil surface. Relying on herbicides in cassava systems when using zero plough approaches should probably entail a weed control by systemic herbicides before planting to attain a weed-free situation similar to that after ploughing. However, if such pre-planting herbicide use is not an option, chemical weed control should only be used after ploughing to maximize yields and reduce labour cost. In zero plough systems, manual (hoe) weeding would remain required at the early stages.

Because cassava requires relatively loose soil for the expansion of bulking roots, the intensity of tillage is important for optimizing cassava root yield (Martin and Ejike, 2016). The required intensity of the tillage for high cassava yields was revealed by the results of the first-year trials. Across all sites, double plough passage with or without ridging did not significantly increase root yields further as compared with a single plough passage. Thus, it was concluded that a double plough passage is not necessary. With our results from both years of study, it can be conclusively said that primary tillage (ploughing) and secondary tillage (ridging) have a synergistic effect on cassava root yield. This is apparent from the additional yield obtained when ridging after single plough of 1.9 Mg ha^{-1} in 2016 and 2.7 Mg ha^{-1} 2017. The reason for this effect is probably that both ploughing and ridging alter soil conditions which affect both microbial activity, nutrient and water availability and thus plant growth as disc ploughing produces adequately smaller aggregates before planting (Ojeniyi, 1986), while ridging alters soil physical conditions by loosening the soil (Hulugalle, 1987; Vinther et al., 2005).

The observed stronger effect of ploughing (primary tillage) on cassava root yield compared with ridging (secondary tillage) (Fig. 4) is likely attributed to the high sand proportion of soils in the studied farmer's fields (Table 1). Our results confirmed reports by Ezumah and Okigbo (1980) and Maduakor (1997) and Howeler (2000), which indicated that ridging does not always increase cassava root yield on light-textured soil. On the other hand, one major reason for the pronounced effect of ploughing on root yield is most often an increased soil porosity. High soil porosity affects aeration of the soil, soil moisture content and the soil air-water balance. This also limits mechanical impedance to root penetration and expansion during bulking. Our results indicate that the effect of ridging on cassava root yield decreases with increasing intensity of the primary tillage. In our study, single plough plus ridging was sufficient. In Asia, higher cassava root yields were reported with two or more tillage operations (Howeler and Aye, 2014). Although this contradicts the results of this study, the lack of further yield increases with more intensive tillage may be due to the soils of our study sites being light-textured, which may neither require nor attain further loosening with increased tillage intensity.

Our results indicate that tillage increases cassava root yield by a larger margin on the soils that produce higher yields when not tilled (Fig. 5). Although this response was not related to soil chemical properties, it indicates that on more productive soils, tillage causes higher yield increments than on less fertile soils. Kintché et al. (2017) did not find close correlations between soil chemical properties and cassava yields in DR Congo. It remains therefore unclear under what conditions, the highest yield improvements due to tillage can be realized.

Moreover, we found that cassava fresh root yield response to tillage operations differed between fields (Fig. 5). This variation is likely related to several factors, including previous management practices employed by the farmer as well as the land-use history of individual farmland, or subsoil conditions and water storage. Another possible explanation for this varied response is the composition of weed species, the intensity of infestation and the effectiveness of the tillage operation in controlling the weeds across the fields. From our field observations, especially in the first year of this study, we realized that farmers' attitude to weed control differs. While some diligently adhered to prompt and proper weed control measures, others did not. This could account for the observed variation in root yield between fields. Tongglum et al. (2003) reported that cassava yield might be reduced by 25–50 % if weed infestation is not controlled, particularly at the early growth stages. Thus, low yielding sites probably require other measures to increase cassava root yields, such as replacing or complementing cost-intensive tillage operations by more intensive weed control.

Since we found that cassava response to ploughing is related, albeit weakly, to cumulative rainfall amount at 60 and 150 DAP, this suggests that ploughing influences soil water availability and its utilization by cassava during the first 150 DAP. Munodawafa (2012) reported maize yield variation in different tillage systems as conditioned by rainfall. Jakab et al. (2017) and Mohammadshirazi et al. (2016) confirmed that ploughing increases soil water infiltration. This may have favoured cassava yields. However, our study also revealed no significant relationship between cumulative rainfall and response of cassava to ridging. This means that ridging did not influence the yield response of cassava to rainfall received in the first 150 days; hence, ridging unlikely played a role in enhancing water utilization of cassava during the early growth phase. Our results showed an insignificant negative correlation between the response of cassava to ridging and soil properties indicating that soil properties had no effect on the yield response to ridging. Although one would expect that there should be a link, our results suggest that other factors than soil fertility affect cassava root yield response to tillage. This confirms the conclusion of Kintché et al. (2017) that an integrated approach encompassing appropriate planting time, timely weed control, improved soil fertility, and tillage is required to close the cassava yield gap.

5. Conclusion

This study shows that planting density in cassava, at least for an erect variety such as TME 419, should generally be increased to a minimum of 12,500 plants ha^{-1}. The use of herbicide as a weed control measure in cassava cannot be recommended in zero-tillage systems. The perception of cassava not responding to or not requiring fertilizer is incorrect, as fertilizer use can substantially increase yields. The extension system is called upon to develop new fertilizer recommendations. Furthermore, on the sandy soils of southwestern Nigeria, no more than two tillage operations are required to attain the highest cassava root yields. Further research is required to understand under what conditions benefits from tillage manifest and how they are related to the productivity of the field and the type and intensity of weed infestation.

CRediT authorship contribution statement

Olabisi Omolara Onasanya: Investigation, Data curation, Writing - original draft. **Stefan Hauser:** Conceptualization, Methodology, Investigation, Supervision, Writing - review & editing, Funding acquisition. **Magdalena Necpalova:** Methodology, Supervision, Writing - review & editing. **Felix Kolawole Salako:** Methodology, Investigation, Supervision, Project administration. **Christine Kreye:** Methodology, Investigation, Writing - review & editing, Project administration, Funding acquisition. **Meklit Tariku:** Data curation, Methodology, Writing - review & editing. **Johan Six:** Conceptualization, Supervision, Methodology, Writing - review & editing, Funding acquisition. **Pieter Pypers:** Conceptualization, Methodology, Data curation, Writing - review & editing, Funding acquisition.

Declaration of Competing Interest

The authors report no declarations of interest.

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