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Towards closing cassava yield gap in West Africa: Agronomic efficiency and storage root yield responses to NPK fertilizers

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ABSTRACT

Nutrient management of cassava has received little attention compared with cereal crops. We evaluated cassava yield potential and nutrient use efficiency when supplied with nitrogen, phosphorus and potassium at high rates and when supplied with increasing rates of K. On-farm experiments were conducted at six locations in Nigeria across the major cassava growing agro-ecologies of Western Africa (Tropical Rainforest – Cross River, Forest Transition Savanna – Edo, and Guinea Savanna – Benue) during two seasons (2016–2017 and 2017–2018). Nitrogen, P and K fertilizers were applied at various rates, including treatments with and without added secondary and micronutrients. Storage root dry matter (DM) yields ranged between 11 and 35 t DM ha^{-1}. The largest yields were obtained with a mean agronomic efficiency of 60, 162 and 51 kg DM of storage roots per kg of N, P and K applied, with average uptakes of 364, 44 and 242 kg N, P and K ha^{-1} respectively. Storage root yield responses to applied N, P and K fertilizers (2–18, 3–16 and 3–22 t DM ha^{-1}, respectively) varied across the locations, reflecting variability in potential yields and applied NPK ratios. Addition of a mixture of secondary and micronutrients did not affect cassava yields. We found that the caloric energy yield of cassava per kg of N applied is 2.7 times larger than the value reported for maize. Increasing the supply of K gave a high agronomic efficiency of N even when supplied at high rates, supporting the theory of "increasing returns to scale" of De Wit. We conclude that cassava has a major role in future food security of sub-Saharan Africa, with potentially larger DM yields, a better recovery of applied nutrients and larger energy yield per kg of applied N fertilizer when compared with grains.

1. Introduction

Cassava (*Manihot esculenta* Crantz) is a major staple food in sub-Saharan Africa (SSA), providing an important source of calories and options for food security for the increasing population (De Souza et al., 2017). Cassava roots can be harvested throughout the year, which ensures a continuous food supply for smallholder farmers and raw materials for related processing industries (Rahman and Awerije, 2016). Cassava is currently cultivated in 40 of the 53 countries in SSA, which account for half of the total world production of cassava (FAOSTAT, 2019). Cultivation has expanded because cassava can grow in relatively marginal soils and under erratic rainfall conditions (Howeler, 2017), important characteristics especially for future more variable climates. Although cassava plays a major role in SSA, the current average root yield in smallholder farmers' fields is estimated at only 2.5 t DM ha^{-1}, equivalent to 7.2 t ha^{-1} fresh roots (De Souza et al., 2017). This is only one third of average yields obtained in Asia (Howeler, 2017).

Results from on-station and on-farm researcher-managed trials in the region have shown that cassava yield can be improved substantially with improved crop establishment, genotype and management. Root yields up to 19 t DM ha^{-1} (equivalent to 54 t ha^{-1} of fresh roots) were recorded in on-farm trials with fertilizer application in Southern Togo within 10–11 months after planting (Ezui, 2017). Fresh root yields of 40 t ha^{-1} were attained with improved varieties in on-station trials in Nigeria (Eke-Okoro and Njoku, 2012). Fermont et al. (2007) reported fresh root yields ranging from 14 to 59 t ha^{-1} in Uganda and western

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Table 1
Characteristics of experimental sites with planting and harvest dates, and the amount of rainfall (mm) from planting to harvest.

Year	2016			2017		
Location	Ekpoma (Edo)	Ogoj (Cross River)	Otukpo (Benue)	Ekpoma (Edo)	Ikom (Cross River)	Otukpo (Benue)
Geographic coordinates	7.05 °N 6.13 °E	6.76 °N 8.69 °E	7.27 °N 8.18 °E	6.80 °N 6.23 °E	5.96 °N 8.77 °E	7.27 °N 8.19 °E
Elevation (masl)	214	47	135	215	105	139
Planting date	May 24, 2016	Jun 16, 2016	Aug 16, 2016	May 12, 2017	Jun 3, 2017	Jun 15, 2017
Harvest date	Aug 4, 2017	Aug 25, 2017	Oct 6, 2017	May 21, 2018	May 3, 2018	Jun 15, 2018
Crop duration (MAP)	14	14	13.5	12	11	12
Agro ecological zone	Transition rainforest savanna	Rainforest	Guinea savanna	Transition rainforest savanna	Rainforest	Guinea savanna
Rainfall amount (mm)	3157	3067	1747	2357	2141	1359
Previous crop(s)	Cassava, maize intercrop	Cassava	Cassava, maize intercrop	Cassava, maize intercrop	Cassava, maize intercrop	Soybean
Max. rooting depth (m)	> 3.2	NA	1.6	> 3.2	NA	1.4
Main soil type	Nitisol	Acrisol	Acrisol	Nitisol	Nitisol	Acrisol

NA: rooting depth sampling was not done at the location; MAP: months after planting.

Kenya in on-farm breeding trials. The ideal plant type simulated by Cock et al. (1979) suggested that potential cassava yields could be as large as 90 t ha^{-1} of fresh roots (32 t DM ha^{-1}) in a 12-month growing period. Indeed, with improved cultivars under optimal growing conditions cassava yields as high as 90 t ha^{-1} of fresh roots (equivalent to 27–32 t DM ha^{-1}) have been observed within 10 months in Cauca, Colombia (El-Sharkawy et al., 1990; El-Sharkawy, 2007). Fukai and Hammer (1987) obtained cassava yield of 23 t DM ha^{-1} at 12 months in northern Australia. Thus, cassava has a very high yield potential when growth conditions and management are optimal.

Nigeria is the largest cassava-producing country in the world with about 60 Mt of fresh cassava roots produced in 2017 (FAOSTAT, 2019). Increases in production over the years have been achieved largely by expansion of the area cropped with cassava and improved varieties. Average fresh root yield of cassava farmers from 1965 to 2017 ranged from 7 to 12 t ha^{-1}, much below its potential productivity. Cassava yields could be increased in a sustainable manner through improved crop management and fertilizer application, thereby reducing the need for a further expansion of cropland.

Crop yield is a key measure of the response of any cropping system to changed management practices, but this response must be considered alongside nutrient use efficiency (NUE) (Janssen, 2011; Norton, 2014). Nutrient use efficiency is an important concept for evaluating crop production systems and can be greatly impacted by fertilizer management as well as soil- and plant–water relationships (Norton, 2014; Fixen et al., 2015). Only few studies have focused on increasing cassava yield and NUE in tropical rain-fed agricultural systems (Ezui et al., 2016, 2017; Senkoro et al., 2018). Improvements in agronomic practices combined with balanced fertilizer (N, P and K) application can markedly improve NUE and, when implemented concurrently with increased nutrient rates, can result in simultaneous increase of both crop yields and NUE (De Wit, 1968; Fixen et al., 2015). This means that if uptake of a particular nutrient increases then uptake of other nutrients (if available) will increase too. At incremental rates of fertilizer in which all nutrients are present in proper proportions, in theory, each additional kg of the fertilizer will initially give a greater production increase than the preceding kg up to a certain optimum, followed by a decrease. Furthermore, if other essential production factors (including genetics) are improved, this optimum will be achieved at high nutrient availability (De Wit, 1994; Nijland and Schouls, 1997), a concept known as "Increasing returns to scale" (De Wit, 1994).

Strategic research should search for the minimum of each production resource that is required to allow maximum utilization of all other resources (De Wit, 1992). In this work, we aimed to quantify the yield potential and nutrient use efficiency of cassava in the major cassava growing agro-ecologies of Nigeria. We studied especially the effect of K application on storage root yield as K is an essential nutrient for plant physiological processes, it improves crop yield and quality and enhances stress tolerance (Guo et al., 2019). Also, K is absorbed in large amounts by cassava and removed from the field through harvest of the storage roots (Howeler and Cadavid, 1983). Our objectives were to: (1) assess cassava yield potential and response to fertilizer application; (2) evaluate yield responses to varying K supply with steady N and P rates; (3) test the need for secondary and micro-nutrients; and (4) evaluate nutrient uptake, agronomic efficiency, internal utilization efficiency, apparent recovery efficiency and nutrient harvest index of N, P and K of cassava.

2. Materials and methods

2.1. The study area

A two-year study was conducted on-farm in southern Nigeria from 2016 to 2018. Each year, experiments were established in new fields in three agroecological zones (AEZs) (Rain Forest – Cross River, Transition Rain Forest – Edo, and Guinea Savanna — Benue), covering the major cassava-producing regions in Nigeria. These agroecologies also encompass the major cassava-cropping environments of other countries of SSA. The growing season of each region begins with the onset of rains from April–May–June for Cross River – Edo – Benue, respectively. The dry season with intermittent or no rainfall runs from November to early April–May. Mean annual rainfall at the field locations in the years 2008–2017 were 2300, 2200, and 1400 mm for Cross River, Edo, and Benue, respectively (NIMET, 2012; Ukhurebor and Abiodun, 2018). Weather data were obtained from the closest station of the Nigerian Meteorological Agency (NIMET). Detailed characteristics of the experimental fields are shown in Tables 1 and 2.

2.2. Experimental treatments and management

The experimental design for all six on-farm experiments was a randomized complete block (RCBD) with three replicates (blocks). Plot size was 10 m by 8 m and treatments were randomized within the blocks at each location. The blocks were placed perpendicular to the slope. Treatments were N, P, K, and other nutrients (secondary and micronutrients) applied in different amounts and combinations

Table 2

Nutrient application rates per treatment, (f) represents full rate of the optimized nutrient and K60, K120, K180, K240, were varied rates of K at 60, 120, 180, and 240 kg ha^{-1}. S, Ca, Mg, Zn, and B were applied in combination.

	Treatment	Nitrogen (k N ha^{-1})	Phosphorus (k P ha^{-1})	Potassium (kg K ha^{-1})	Secondary and micronutrients S–Ca–Mg–Zn–B (kg ha^{-1})
1.	Control	0	0	0	0
2.	N0PfKf	0	100	300	0
3.	NfP0Kf	300	0	300	0
4.	NfPfK0	300	100	0	0
5.	NfPfK60	300	100	60	0
6.	NfPfK120	300	100	120	0
7.	NfPfK180	300	100	180	0
8.	NfPfK240	300	100	240	0
9.	NfPfKf	300	100	300	0
10.	NfPfKfMN	300	100	300	16 – 10–10 – 5–2.5
11.	N150P40K180	150	40	180	0
12.	N75P20K90	75	20	90	0

(Table 2). The rates applied ranged from 0 to 300 kg N ha^{-1}, 0 to 100 kg P ha^{-1}, and 0 to 300 kg K ha^{-1} in various combinations. One treatment received additional S, Ca, Mg, Zn, and B at the rates of 16.6, 10, 10, 5, and 2.5 kg ha^{-1}, respectively. Treatment names are as shown in Table 2, where (f) represents full rate of the optimized nutrient and K60, K120, K180, K240, were varied at rates of K at 60, 120, 180, and 240 kg ha^{-1} (Table 2). The optimized fertilizer rates and combinations for the experimental treatments were determined using the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model for cassava (Ezui, 2017), aiming at a yield of 90 t fresh roots ha^{-1} (equivalent to 32 t DM ha^{-1}). Cassava variety TME 419 was grown in all experiments: this is a popular variety in Nigeria and West Africa because it has high dry matter and is nutrient use efficient (De Souza and Long, 2018). Further, it has erect stems and minimal branching, which allows intercropping as well as higher planting densities (Eke-Okoro and Njoku, 2012; Ezui et al., 2017). Planting was done at the onset of rains each year, except in Benue in 2016, where planting was done about 3 months after the first rains. The late planting at Benue was due to the re-establishment of the experiment in a different field as the first planting was badly damaged by soil erosion. Stem cuttings of 25 cm long were planted at distances of 1.0 m by 0.8 m, following the recommended planting density of 12,500 plants per hectare. Phosphorus was applied at planting, while nitrogen and potassium were applied in three equal splits at 1, 2.5, and 3.5 months after planting (MAP) and secondary and micro-nutrients were applied at 2.5 MAP. The N, P and K fertilizers used were urea, triple super phosphate and muriate of potash. The fields were weeded regularly, especially before each fertilizer application and there was no observed pest or disease outbreaks. TME 419 is considered to be resistant to pests and diseases. It has high water use efficiency through its lower stomatal conductance, with higher photosynthetic rates than most improved cultivars (De Souza and Long, 2018).

2.3. Soil sampling and rooting depth

Composite soil samples were collected before land preparation from five points in a “W” pattern from 0 to 30 cm depth in each plot and bulked together. The samples were air-dried and sieved through a 2 mm mesh sieve. The pH was measured in a 2.5:1 soil suspension in water. The hydrometer method was used to determine the particle size. Soil organic carbon was obtained by the combustion method and N by Kjeldahl digestion. The Mehlich-3 extraction was used for Ca, Mg and K, while available P was determined using the Olsen extraction method. All soil analyses were done at the IITA laboratory, Ibadan, Nigeria. In order to measure cassava rooting depth, several soil pits were dug in plots (NfPfKf, N0PfKf, NfP0Kf and NfPfK0), in the area where intermediate harvests were carried out. Cassava roots were clearly identified and differentiated from other roots as they were creamy-yellowish and when cut secrete a cloudy-whitish latex. The depth at which the deepest cassava roots were found were recorded at each location (Table 1).

2.4. Yield assessment

At physiological maturity, a net plot of 6.4 m^2 containing eight consecutive plants, was harvested in each experimental plot. Plants were separated into leaves, stems and storage roots and weights of each harvested plant part (leaf with petiole, stem, and storage root) were recorded for each plot. Sub-samples of about 400 g fresh weight were collected in the field using a digital field scale, and oven dried at 60 °C until constant weight, then weighed and dry matter content calculated, and fresh roots yields converted to DM yield. Dried subsamples from leaves with petioles, stems and storage roots were analysed for total N, P and K concentration. Total N in the tissue was analysed by Dumas combustion using a Carlo Erba EA1108 elemental analyser. Total P and K concentrations were measured in sulphuric acid digests with an inductively coupled plasma (ICP) (iCAP 7400, Thermo Fisher Scientific, USA).

2.5. Calculations and data analysis

To estimate the nutrient use efficiency of cassava, parameters of yield response, nutrient uptake, agronomic efficiency (AE), apparent recovery efficiency (RE) and internal utilization efficiency (IE) were calculated using the following equations (Fixen et al., 2015; Chuan et al., 2016):

$$\text{Agronomic efficiency } (AE_i) = \frac{Y_f - Y_{0,i}}{\mathrm{f}_{\mathrm{app,i}}} \tag{1}$$

$$\text{Apparent recovery efficiency } (RE_i) = \frac{U_f - U_{0,i}}{\mathrm{f}_{\mathrm{app,i}}} \tag{2}$$

$$\text{Internal utilization efficiency } (IE_i) = \frac{Y_i}{U_i} \tag{3}$$

With i = N, P, or K: Y_{f} = storage root yield for NfPfKf treatment [kg DM ha^{-1}]; $Y_{0,i}$ = storage root yield with either N, P, or K omitted [kg DM ha^{-1}]; $\mathrm{f}_{\mathrm{app}}$ = rate of nutrient i applied [kg ha^{-1}]; U_0 = nutrient uptake in below- and aboveground biomass with either N, P, or K omitted [kg ha^{-1}]; U_f = nutrient uptake in below- and aboveground biomass with N, P and K applied at full rate. N, P and K uptake by the crop were calculated by multiplying each nutrient percentage with the

Table 3
Soil texture and chemical characteristics for samples taken at 0–30 cm depth before land preparation and planting at Benue, Cross River and Edo in 2016.

Location	pH	SOC %	N %	C:N	P Olsen mg kg^{-1}	K $cmol_c$ kg^{-1}	Ca $cmol_c$ kg^{-1}	Mg $cmol_c$ kg^{-1}	Sand %	Silt %	Clay %
Benue	5.9	0.8	0.09	8.9	4.7	0.10	1.7	0.8	60.2	25.5	14.3
Cross River	5.4	0.5	0.04	12.5	2.8	0.10	1.1	0.7	65.0	19.0	16.0
Edo	5.7	0.6	0.05	12	3.7	0.07	1.3	0.5	83.0	4.9	12.0

total plant biomass dry matter. Nutrient harvest indices (NHI) were calculated as the ratio between nutrient (N, P and K) uptake in storage roots and N, P and K uptake in storage root plus shoot (Fageria, 2014). Energy and protein efficiencies of cassava (the quantity of calories/energy or protein produced by a kilo of N applied), were calculated as a product of agronomic efficiency of N and energy or protein content, which were derived from literature, with energy and protein content of 16.54 MJ kg^{-1} DM and 33.73 g N kg^{-1} DM, respectively (Montagnac et al., 2009).

The treatment effects on DM storage root yield were analysed separately for each location and year, using a linear mixed model with DM root yield as response variable and fertilizer treatment as explanatory factor, while blocks were considered random effects. Interactions of yield response with locations and year were analysed with a mixed linear regression model. Effects were analysed with a type-III ANOVA using Satterthwaite's approximation method. Also, NUE (AE, RE, and IE) of applied N, P, and K fertilizers and NHI were analysed using a linear mixed model. Differences between treatment means were considered significant when probability ≤ 0.05. R software (R Core Team, 2019), version 3.5 with the lme4, lmerTest, and Predictmeans packages was used for statistical analysis.

Table 4
Average storage root yield with standard deviation in t dry matter (DM) ha^{-1} for different fertilizer combinations at Benue (Guinea Savanna), Cross River (Rainforest), and Edo (Forest Transition). The f denotes full (300 kg N and K, 100 kg P ha^{-1}).

	Benue		Cross River		Edo	
	2016	2017	2016	2017	2016	2017
Control	8.6	5.9	9.3	12.5	11.2	9.2
N0PfKf	10.0	8.9	10.7	9.9	17.0	14.5
NfP0Kf	10.0	7.6	13.1	13.8	19.4	11.9
NfPfK0	19.3	7.6	11.6	9.9	12.8	10.6
NfPfK60	17.3	6.9	14.3	14.1	19.7	13.0
NfPfK120	19.5	7.4	16.6	16.6	21.0	14.3
NfPfK180	19.3	7.8	19.2	12.2	24.1	16.0
NfPfK240	14.5	12.3	25.5	16.0	24.6	25.2
NfPfKf	25.5	11.4	29.7	22.7	35.5	22.3
NfPfKfMN	27.0	10.8	28.7	21.5	34.8	27.6
N150P40K180	16.1	7.8	19.5	12.4	22.5	12.9
N75P20K90	11.0	9.3	13.4	13.2	16.1	13.7
ANOVA						
Treatment	***(3.14)	ns	***(2.54)	**(2.70)	***(3.47)	***(2.85)
Location	***(1.29)					
Treatment*Year	*(2.4)					

Standard errors (SE) in parentheses and relates only to comparisons between significant terms.
ns = not significant.
* Significant at P < 0.05.
** Significant at P < 0.01.
*** Significant at P < 0.001.

3. Results

3.1. Soil nutrient status and rainfall distribution

Average soil organic matter (SOM) was 1.4, 0.9, and 1.0 % for Benue, Cross River and Edo, in 2016 respectively. Soil concentrations of

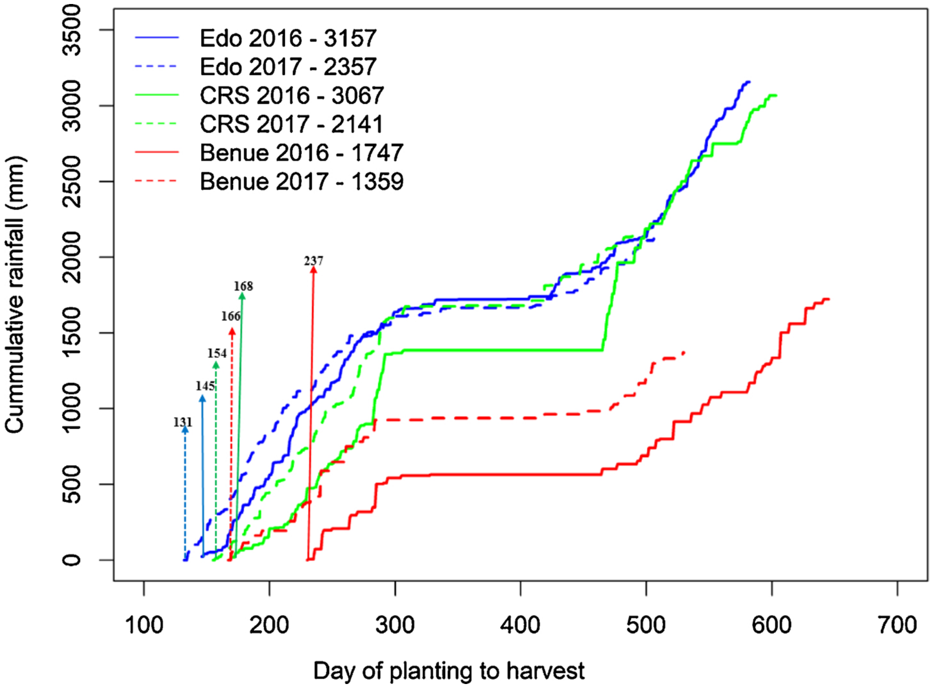

Fig. 1. Cumulative daily rainfall amount (mm) during the two growing seasons across the regions. The 2016 experiments were planted on day of the year (DOY) 145, 168, and 237 and the 2017 experiments were planted on DOY 131, 154, and 166 at Edo, Cross River (CRS), and Benue respectively. Total rainfall for the cropping period is given after each site name in the legend.

available P, K, Ca, and Mg were below standard critical nutrient concentrations for crop production, indicating that the soil nutrient status of all experimental sites was poor (Table 3). All sites used in 2017 were also deficient for P and K, with a mean of 2.66 ± 0.07 (standard error) mg kg^{-1} for P, and 0.17 ± 0.02 cmol kg^{-1} for exchangeable K. Rainfall amounts received during each cropping seasons at the experimental sites from planting to harvest were adequate for proper establishment. Benue received the least rainfall in both years (Fig. 1). During both years, rainfall began late March (Cross River), April (Edo) or mid-May (Benue) and continued until the start of the dry season from November to March.

3.2. Yield responses to nutrients

The crops were harvested at approximately 14 months in 2016, whereas in 2017 the experiments in Benue and Edo were harvested at 12 MAP, and at 11 MAP at Cross River (Table 1), when the crops were recovering from drought. Average yields in the control treatments (N0P0K0) for both years were 10.2, 10.3, and 7.3 t DM ha^{-1} in Edo, Cross River, and Benue, respectively (Table 4). Yield responses to N, P and K were most pronounced in Edo, then Cross River and least in Benue. Generally, yields increased with fertilizer application rate. Yields differed greatly between the plots which received full rates of all three nutrients (NfPfKf) and the corresponding PK, NK, and NP plots. Cassava storage root yield in the full PK treatment plots (N0PfKf) ranged from 9 to 18 t DM ha^{-1}, with yield responses to N from 2 to 18 t DM ha^{-1} across the locations (Table 4). Yield from NK and NP (NfP0Kf and NfPfK0) plots ranged from 8 to 19 t DM ha^{-1} with yield responses from 3–16 to P and 3–22 t DM ha^{-1} to K respectively. Yield response to treatments within the two years and across all locations was highly significant ($p < 0.001$). The largest yields were obtained in the NfPfKf plot, though not significantly different from NfPfKfMN plots, with Edo recording the largest yield of 35 and 22 t DM ha^{-1}, Cross River 30 and 22 t DM ha^{-1}, and 26 and 11 t DM ha^{-1} for Benue, in the 2016 and 2017 growing seasons, respectively (Table 4). The N150P40K180 treatments yielded less than with the full amount of nutrients with average yields of 23, 20, 16 DM t ha^{-} and 13, 12, and 8 t DM ha^{-1} in 2016 and 2017 for Edo, Cross River and Benue, respectively.

3.3. Nutrient uptake

Cassava that received fertilizer at full rate (NfPfKf) took up more nutrients across the seasons and locations and uptake was significantly different from other treatments. Average N uptake by cassava in both years was 416 kg ha^{-1} (Edo), 326 kg ha^{-1} (Cross River), and 215 kg ha^{-1} (Benue). Average P uptake in both years was 56 kg ha^{-1} (Edo), 38 kg ha^{-1} (Cross River), and 24 kg ha^{-1} (Benue) (Fig. 2c and

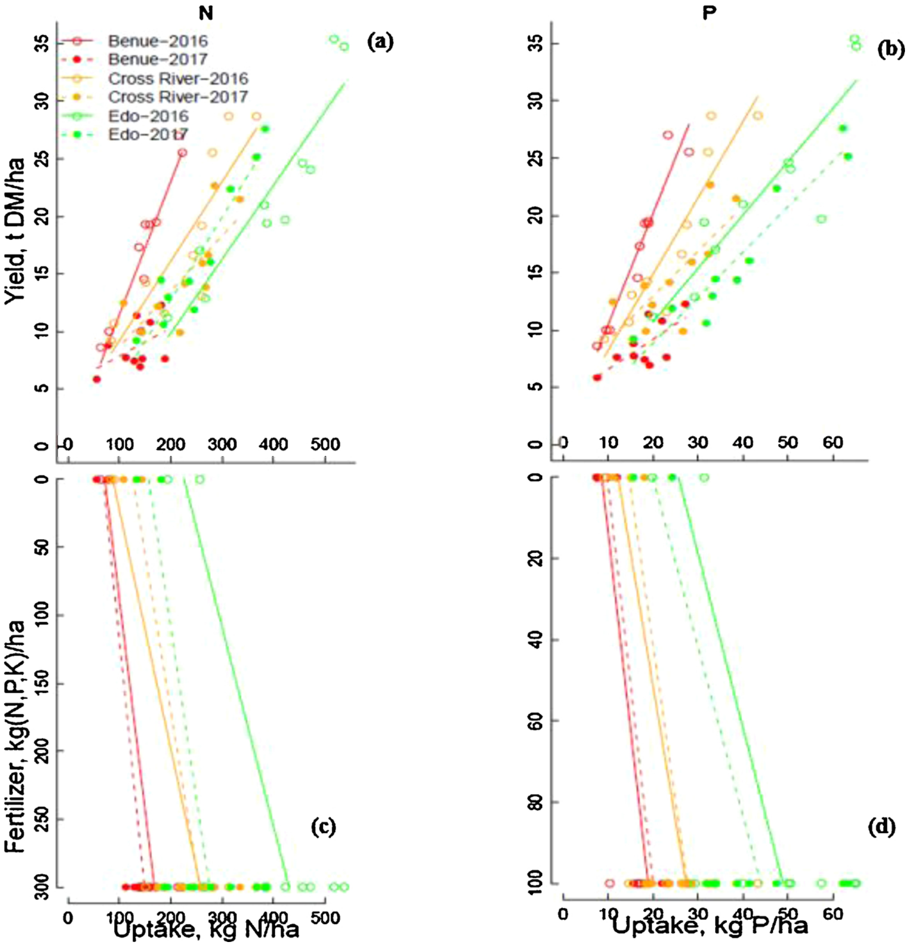

Fig. 2. Relationship between optimized fertilizer rate and uptake (c, d), uptake and yield (internal utilization efficiency (a, b) of nutrients N and P, across the three states (Edo, Cross River, and Benue) during the 2016 and 2017 growing seasons.

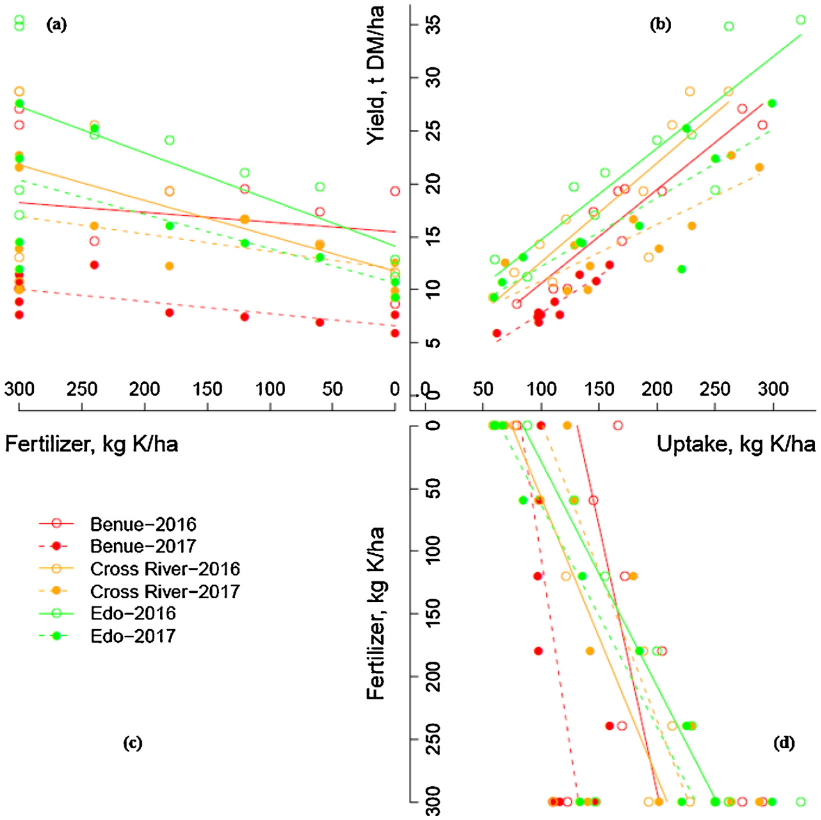

Fig. 3. Three-quadrant diagram showing the relation between K rates and uptake in quadrant (d), uptake and yield in quadrant (b) and fertilizer rate and yield in quadrant (a).

Table 5
Agronomic efficiency (AE) of N, P, and K (kg kg^{-1}) when balanced and optimized N, P, K, rates (kg ha^{-1}) were applied to cassava in 2016 and 2017, at Benue, Cross River, and Edo, Nigeria.

Location	Year	AE_N	AE_P	AEK_{60}	AEK_{120}	AEK_{180}	AEK_{240}	AE_{K300}
Benue	2016	52	155	34	1.7	−0.2	−20	21
Cross River		61	161	36	37	40	56	59
Edo		68	172	104	63	59	47	73
	Average	60	162	58	34	33	28	51
Benue	2017	16	59	12	−1.7	0.7	19	25
Cross River		43	88	75	58	25	26	43
Edo		24	94	35	32	30	66	37
	Average	27	80	40	30	18	37	33

ANOVA

	Year	Location	Location*Year
AE_N	*(7.34)	ns	ns
AE_P	**(6.92)	ns	ns
AE_K	ns	ns	ns

N = 300 kg ha^{-1}, P = 100 kg ha^{-1}.
Standard errors in parentheses.
ns = not significant.
* Significant at $P < 0.05$.
** Significant at $P < 0.01$.

d). Potassium uptake was on average 287, 263, and 212 kg ha^{-1}, in Edo, Cross River, and Benue, respectively (Fig. 3d). Treatment N150P40K180 in both years had average N uptake of 250 (Edo), 196 (Cross River), 122 (Benue) kg ha^{-1}. Phosphorus uptake was 30, 19, and 14 kg ha^{-1}, while K uptake was 140, 159, and 132 kg ha^{-1} in Edo, Cross River, and Benue, respectively. Uptake of K increased with increasing rates (Fig. 3b) and was higher in 2016 than 2017. Three-quadrant diagrams explaining further the relation between N and P fertilizer rate and uptake, uptake and yield, and fertilizer rate and yield are included in Appendix A.

3.4. Agronomic efficiency (AE)

Agronomic efficiency of N and P was similar across the locations, but differed between the two years, while the AE of K differed only across locations (Table 5). Overall, the AE of all nutrients was highest with the full treatment (NfPfKf). Average AE of N, P and K were 49, 129 and 53 kg kg^{-1} for the 2016 and 2017 cropping season in Edo and Cross River. Benue had the lowest AE values for all treatments in both years (Table 5).

3.5. Internal utilization efficiency (IE)

Internal utilization efficiency (IE) of N, P and K differed greatly between locations, with Benue recording the highest IE_N and IE_P (Fig. 2a, b). The largest IE_K was observed in Edo. IE_N was higher in the PK plots, but consistently lower in NK and NP plots, when compared with treatments that received the same rates of N fertilizers, across all locations and years. IE_N ranged between 47–80, 45–118, and 40 – 126 kg kg^{-1} N in Edo, Cross River and Benue, respectively. The NfPfKf treatment had an IE_N of 76, 89 and 115 kg kg^{-1} N in 2016 and 59, 78 and 59 kg kg^{-1} N in 2017, at Edo, Cross River and Benue, respectively. IE_P ranged between 334–619, 370–791, and 400–1000 kg kg^{-1} P, in Edo, Cross River, and Benue respectively. The NfPfKf treatment had an

Table 6
Recovery efficiency of N, P, and K when balanced and optimized N, P and K, rates (kg ha^{-1}) were applied to cassava in 2016 and 2017, at Benue, Cross River, and Edo, Nigeria.

Location	Year	RE_N	RE_P	RE_{K60}	RE_{K120}	RE_{K180}	RE_{K240}	RE_{K300}
Benue	2016	0.47	0.18	0.07	0.1	0.21	0.19	0.42
Cross River		0.92	0.28	0.37	0.37	0.62	0.57	0.62
Edo		0.79	0.32	0.57	0.79	0.7	0.71	0.88
	Average	0.73	0.26	0.34	0.42	0.51	0.49	0.64
Benue	2017	0.20	0.08	0.04	0.02	0.01	0.24	0.24
Cross River		0.47	0.15	0.1	0.47	0.44	0.45	0.48
Edo		0.50	0.24	0.3	0.58	0.58	0.58	0.61
	Average	0.37	0.16	0.15	0.36	0.34	0.41	0.44

ANOVA

	Year	Location	Location*Year
RE_N	*(0.05)	*(0.06)	ns
RE_P	*(0.01)	*(0.02)	ns
RE_K	*(0.04)	*(0.05)	ns

N = 300 kg ha^{-1}, P = 100 kg ha^{-1}.
Standard errors in parentheses.
ns = not significant.
* Significant at $P < 0.05$.

Table 7
Nutrient harvest index and storage roots nutrient concentration of N, P, and K (kg t^{-1} DM), at Benue, Cross River, and Edo in 2016 and 2017.

Treatment	HI_N	HI_P	HI_K	N (kg N t^{-1} DM roots)	P (kg P t^{-1} DM roots)	K (kg K t^{-1} DM roots)
Benue						
Control	0.39	0.59	0.7	2.20	0.44	4.61
N150P40K180	0.46	0.61	0.67	3.12	0.56	5.50
NfPfK180	0.43	0.6	0.63	3.29	0.60	4.82
NfPfKf	0.47	0.64	0.69	3.77	0.72	6.17
Cross River						
Control	0.37	0.52	0.71	2.57	0.40	3.30
N150P40K180	0.37	0.53	0.62	2.95	0.42	4.14
NfPfK180	0.33	0.46	0.57	2.90	0.46	3.87
NfPfKf	0.39	0.53	0.62	2.96	0.45	3.88
Edo						
Control	0.28	0.39	0.58	2.88	0.45	2.57
N150P40K180	0.34	0.42	0.59	2.31	0.46	2.89
NfPfK180	0.31	0.4	0.49	3.02	0.47	2.40
NfPfKf	0.42	0.43	0.54	3.33	0.56	3.08

ANOVA

	Treatment	Location		Treatment	Location
HI_N	*(0.02)	**(0.02)	N	ns	ns
HI_P	**(0.01)	***(0.01)	P	ns	*(0.04)
HI_K	*(0.02)	***(0.02)	K	ns	***(0.23)

N = 300 kg ha^{-1}, P = 100 kg ha^{-1}.
Standard errors in parentheses.
ns = not significant.
* Significant at $P < 0.05$.
** Significant at $P < 0.01$.
*** Significant at $P < 0.001$.

IE_P of 599, 767 and 911 kg kg^{-1} P in 2016 and 433, 653 and 405 kg kg^{-1} P in 2017, in Edo, Cross River and Benue, respectively. Also, IE_K was highest in the NP plots across locations and years. It ranged between 91–213 (Edo), 69–150 (Cross River), and 65–116 (Benue) kg kg^{-1} K in both years. The IE_K of NfPfKf treatment was 150 and 91, 111 and 85, and 88 and 77 kg kg^{-1} K, in 2016 and 2017, respectively at Edo, Cross River and Benue, respectively (Fig. 3b). The mean highest IE_K was obtained from Edo and was significantly different from other locations. The slopes of Figs. 2a, b and 3 b, reflect the IEs of N, P and K across treatments.

3.6. Recovery efficiency (RE)

Recoveries of N, P and K was significantly different in 2016 and 2017 and among the locations. (Table 6). Recovery efficiency of all nutrients was greater in 2016 at 14 MAP than in 2017 at 12 MAP. The NfPfKf treatment had average N, P and K recovery efficiencies of 0.73, 0.26 and 0.64 in 2016, respectively across the locations. Recovery of N was lowest in Benue in both years (Table 6). RE of P was different ($p < 0.05$) and varied from 0.05 to 0.32 across locations. Also, RE of K differed across the locations and varied from 0.42 to 0.88 in 2016 and 0.24 to 0.61 in 2017 (Table 6). RE of N, P and K was larger in Edo and Cross River than in Benue. Average RE of K across the locations in both years increased with higher rates with full rates of N and P and was least in the NfPfK60 treatment (RE_{K60}) (Table 6).

3.7. Nutrient harvest index (NHI)

Nutrient harvest index of N and P was largest in the full nutrient treatment, with averages of 0.43 for HI_N and 0.54 HI_P across locations and years, when compared with the treatments where less K fertilizer was applied. These NHI values were significantly larger than what was observed in the control. By contrast, HI_K did not differ among treatments but differed between locations with smallest values for Edo (Table 7). N, P and K concentration in the storage roots were highest in the NfPfKf treatment and differed significantly from other treatments and locations. Averages of N, P and K concentrations in both years were 3.35, 0.56, and 4.38 kg t^{-1} DM. The lowest concentrations were in the control treatment, with averages of 2.55, 0.43 and 3.49 kg N, P and K t^{-1} DM. The nutrient with largest concentration in the storage root across the treatments and locations in both years was K, except in Edo, where the K concentration was lower than that of N (Table 7).

4. Discussion

4.1. Yield potential of cassava in West Africa

Cassava yield responded strongly to applied nutrients on very infertile soils which clearly exhibited large macro-nutrient deficiencies with soil nutrients below critical concentrations of about 10 mg kg^{-1} for P, and 0.20 cmol kg^{-1} for exchangeable K, 5.0 and 1.0 cmol kg^{-1} for Ca and Mg (Howeler, 2002). The rainfall distribution was adequate for establishment and growth of cassava in the selected locations; the field in Cross River experienced a short dry period in 2016 and Benue suffered from a seasonal dry period in both years. Nevertheless, a yield of 29 t DM ha^{-1} was recorded in Cross River in 2016. The largest cassava yield of 35 t DM ha^{-1} at 14 MAP was achieved in Edo, equivalent to 97 t ha^{-1} of fresh storage roots. No effects of drought were observed in 2016 for Edo, despite a brief dry season, due to the rooting depth of cassava in this field, which was greater than 3.2 m. This observed yield is larger than the target yield of 90 t ha^{-1} of fresh roots which we used to determine the nutrient requirements with the QUEFTS model (Ezui, 2017). These yields are comparable to the simulated ideal yield of 32 t DM ha^{-1} at 12 MAP proposed by Cock et al. (1979) and to the actual recorded yields of 27–32 t DM ha^{-1} at 10 MAP reported from Cauca, Colombia (El-Sharkawy et al., 1990). Cassava storage root yield responses to applied N, P and K (2–18, 3–16 and 3–22 t DM ha^{-1}) varied across the locations reflecting variability in site conditions and water availability. A linear response to K application was observed, without reaching the expected plateau that would result from diminishing returns Although root growth was not measured, we suspect that K application strongly increased root growth and increased the capacity to access water from deeper soil layers during the dry seasons and intercept leached N from upper soil layers. The most limiting nutrient in Edo was K, while N was most limiting in Cross River, and P was most limiting in Benue.

4.2. Nutrient uptake and nutrient use efficiency

Nutrient use efficiency was addressed in terms of agronomic efficiency (AE), internal utilization efficiency (IE) and the apparent recovery efficiency (RE) of N, P and K of cassava. AE was lowest at Benue reflecting the poorest growth conditions with shallow soil inhibiting deeper root growth in both years, which was exacerbated by drought, reflecting the need for adjustment of fertilizer applications to water-limited potential production. High average AE values of N, P and K (60, 162 and 51 kg kg^{-1}) were obtained in line with the ranges of recorded AEs in other studies in the region of 53–91, 84–110 and 112 – 124 kg kg^{-1} (NYI, 2014; Senkoro et al., 2018). These AE values are much greater than those found in cereal crops (maize, rice and wheat) which range from 15 to 30, 15–40 and 8–20 kg kg^{-1} for N, P and K, under optimal management (Fixen et al., 2015; Ichami et al., 2019). The average uptakes of N, P and K from the NfPfKf treatments in Edo and Cross River were 364, 44 and 242 kg ha^{-1}, while that of the control (N0P0K0) treatments were 141, 15 and 73 kg ha^{-1}, reflecting nutrient uptakes N > K > P for cassava (Howeler, 2014). Roots acted as storage of especially K, with K concentrations and HI_K declining when K supply was limited.

The high nutrient recovery of cassava and limited N leaching may be attributed to the longer growing period and more intensive and extensive root system when compared with cereals (Howeler, 2002, 2014). The recorded average total uptake of N, P and K was 13.5–13.7, 1.5–1.7 and 7.0–9.7 kg N, P and K t^{-1} DM and 4.3–4.8, 0.52 – 0.53, 2.4–3.1 kg N, P, K t^{-1} FM root yield respectively were similar to values found in the literature (Howeler and Cadavid, 1983; Howeler, 2002, 2014; Howeler, 2017). The observed internal utilization efficiency (IE) corresponded with those reported for balanced nutrition at high yields under good management (Norton, 2014; Fixen et al., 2015) and the estimated minimum and maximum IEs of nutrients for cassava (Ezui et al., 2017). The observed IE_P in Benue was 41 % higher and IE_K was 25 % higher in Edo than the calculated maximum IE_P and IE_K for cassava by Ezui et al. (2017), reflecting P deficiency in the field at Benue and K deficiency at Edo.

The high RE_N at Edo and Cross River in 2016 could be due to the long growing season of 14 months with adequate soil water availability. Ezui et al. (2016) recorded maximum RE_N, RE_P, and RE_K values of 0.95, 0.6 and 0.95, respectively for cassava under optimum management. The relatively lower P recovery is typical (Janssen et al., 1990; Syers et al., 2008). Nevertheless, P recovery by cassava is much better than cereal crops with typical first-year recovery values around 0.1–0.25 in tropical systems (Wolf and Van Keulen, 1989; Van der Eijk et al., 2006). Cassava roots form a symbiosis with native vesicular-arbuscular mycorrhiza, strongly increasing P uptake (Howeler, 2017). The N and P harvest index increased with increased rates. The smallest HI_K was observed in Edo (Table 7), reflecting K limitations at the Edo sites in 2016 and 2017. The decline in K concentration in the storage roots may have resulted from limited supply of K when compared to N and P. The low harvest index values indicate that most of the nutrients taken up by the plant could be recycled back to the soil by re-incorporation of the residues from the shoot, and especially the leaves (Howeler, 2014).

4.3. Cassava and food security in SSA

In SSA, expected population growth (UNDESA, 2017) demands a doubling of crop production by 2050 (Van Ittersum et al., 2016), with changing dietary preferences (Cassidy et al., 2013) and increasing demands from biofuel and industrial products. Cassava is more resilient to adverse conditions and climate change than maize (Rosenthal and Ort, 2012; De Souza et al., 2017) or other cereals, and seems a better option for various reasons. High-yielding cassava can play a key role towards meeting the rising food demands, because of its high energy content and efficiency. For example, the energy contents of cassava and maize are 16.5 and 14.9 MJ kg^{-1} DM (Montagnac et al., 2009). The efficiency of energy production per unit of N is 2.7 times greater for cassava (993 MJ kg N^{-1}) than for maize (372 MJ kg N^{-1}). For proteins legumes may provide the most efficient options (Zhang et al., 2019), yet the efficiency of cassava is 2023 g protein kg^{-1} N compared to e.g. 3348 g protein kg^{-1} N for maize. Under limited N availability, applying fertilizer to cassava results in more energy per kg N applied with lower environmental risks, evidenced by higher recovery and nutrient use efficiency than for maize. Furthermore, cassava is well adapted to rainfall variability and drought. However, there is an urgent need to develop value chains that can support sustainable intensification.

5. Conclusion

This study was designed to explore the yield potential of cassava under rain-fed conditions in the three major cassava growing agro-ecological zones across SSA. Strong responses to applied N, P and K fertilizers depict the inherent ability of cassava for large yields, and the need for fertilizer application. The recovery and the yield response to K increased with increasing rates of K applied when both N and P were also applied in large amounts, indicating a positive feedback mechanism through improved uptake and growth. Irrespective of the poor soil fertility, addition of secondary and micronutrients did not increase storage root yield. Our results clearly show that agronomic and internal utilization efficiency of nutrients by cassava are larger than for cereals such as maize. This indicates that environmental risks are less, but at the same time risks of mining soil nutrient reserves are larger with cassava. Also, cassava yield gaps may be larger than previously thought, providing options to increase food production on existing farmland. Investment in fertilizer for cassava gives a 2.7 times larger dietary energy return than similar fertilizer investment in maize. To realistically end hunger, achieve food security and promote sustainable crop production systems in SSA, more research to further understand cassava growth and production is required. We see a large potential to address future energy needs of the growing population with cassava, with smaller environmental risks than cereal crops.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Figs. A1 and A2.

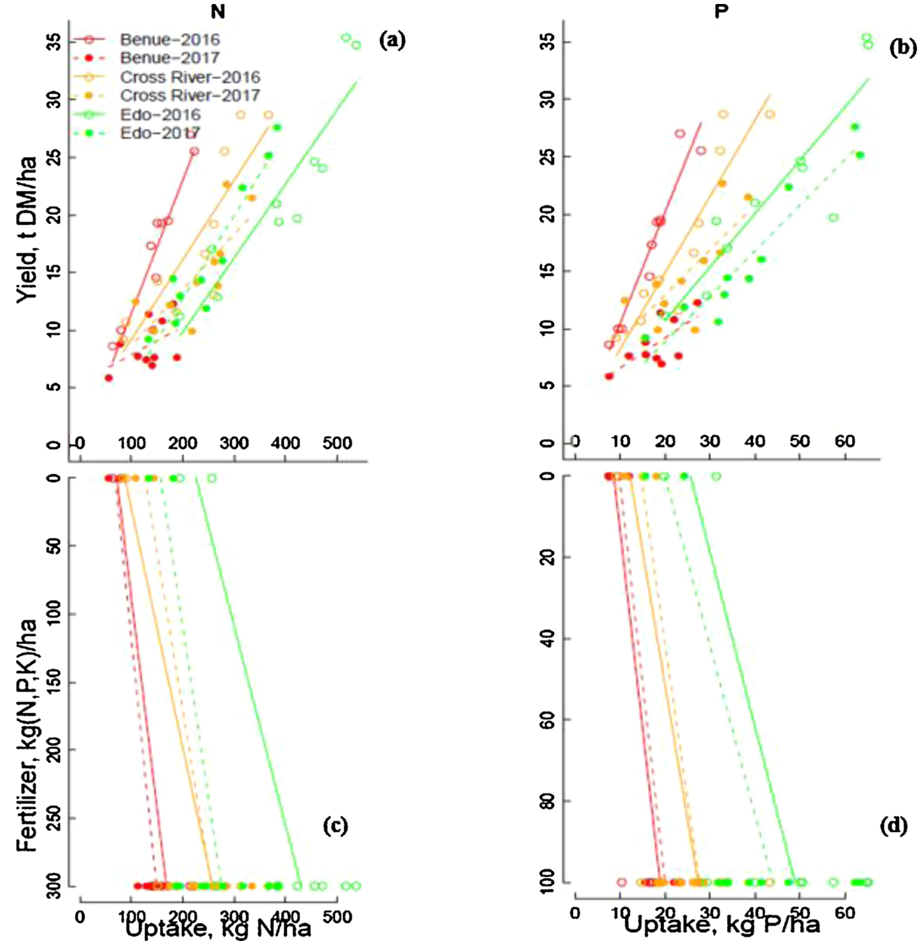

Fig. A1. Three-quadrant diagram showing the relation between N rates and uptake in quadrant (d), uptake and yield in quadrant (b) and fertilizer rate and yield in quadrant (a).

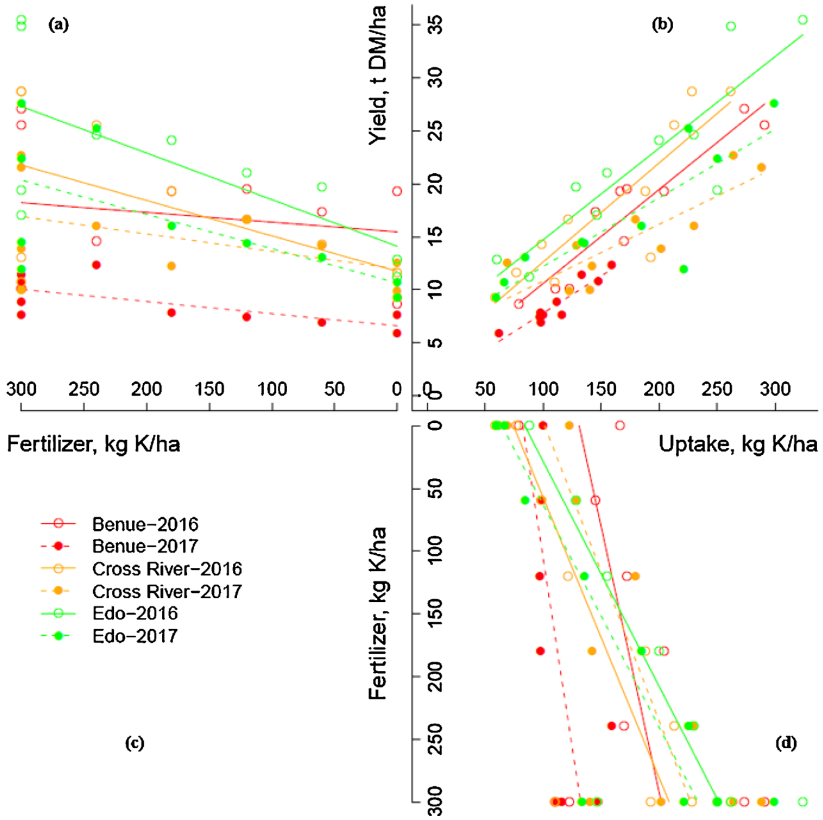

Fig. A2. Three-quadrant diagram showing the relation between P rates and uptake in quadrant (d), uptake and yield in quadrant (b) and fertilizer rate and yield in quadrant (a).

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