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ABSTRACT

Yield response of irrigated lowland rice (*Oryza sativa* L.) to nutrient application was determined to improve the information base for fertilizer use in the Sudan and Southern Guinea Savannas of Nigeria. Economically optimal rates (EOR) and agronomic efficiency (AE) were determined. Five N levels and four levels each P, K, and Zn were evaluated with two varieties at two locations. Nitrogen effects varied by variety and location but mean paddy yield with 0 kg ha^{-1} N was 3.4 Mg ha^{-1} and was increased by 1.3 Mg ha^{-1} with 40 kg ha^{-1} N. The mean EOR of N with fertilizer use cost to paddy price ratios (CP) of 2 to 6 were 56 to 38 kg ha^{-1} N, respectively. Yield increases with P, K and Zn application were infrequent. Paddy yield was increased in one of four cases with up to 1.5 kg ha^{-1} Zn. There were no paddy yield increases but some decreases with application of Mg-S-B in addition to N-P-K-Zn. The overall AE of N at EOR with a CP of 4 was 25.3 kg kg^{-1}. The profit potential of N application was greater for Faro 44 compared with Faro 52 at both locations. Financially constrained farmers who opt to apply N at 50 compared with 100% EOR when CP was 4 can expect 16% less yield increase but 67% higher AE and value to cost ratio. Application of fertilizer N, maybe with P at Kadawa, can be highly profitable for irrigated lowland rice in these agro-ecological zones.

Core Ideas

- Lowland irrigated rice is increasing in importance in West Africa.
- The irrigated lowland rice response to N was curvilinear to plateau.
- Irrigated lowland rice was inconsistently affected by applied P.
- A profitable rice response to K, Mg, S, Zn and B is not likely.

Rice (*Oryza sativa* L.) is the main staple food for almost 50% of the human population providing 21% of energy and 15% of protein for human diets globally (Maclean et al., 2002). The demand for rice may increase by 60% by 2025 (Fageria et al., 2003). Consumption of rice is growing faster than for any other commodity in Africa, especially in urban areas (Seck et al., 2012). It is a major dietary energy source in West Africa and the third most important for Africa (Macauley and Ramadjita, 2015).

Nigeria is the continent's leading consumer and a major importer of rice (FAO, 2017). About 6.7 million Mg of rice paddy, that is the grain before dehulling, was produced from 3300,000 ha in 2014 (FAOSTAT, 2016). Most of the rice production is in central and northern Nigeria. Rice production is mostly by smallholder farmers, with an average farm size of 1 to 2 ha. Rice production includes rainfed and irrigated. Some of the growing demand for rice in West Africa will be met from increased production in irrigated lowlands, now about 12% of the regional rice-growing area (Becker and Johnson, 1999).

The average paddy yield has been only 3.0 to 3.5 Mg ha^{-1} in irrigated lowlands of Nigeria (Diagne et al., 2013; Nwilene et al., 2008). Inadequate nutrient availability is a yield constraint (Ezui et al., 2010; Liverpool-Tasie et al., 2014), although fertilizer use in Nigeria may not be as low as often reported (Sheahan and Barrett, 2014; Liverpool-Tasie et al., 2017). Ezui et al. (2010) reported N to be the most yield-limiting nutrient for rice. Rice crop response to K is low for the savannas of Nigeria (Ezui et al., 2010; Apaseku and Dowbe, 2013). The fertilizer recommendation for all irrigated rice in Nigeria has been 100, 20, and 36 kg ha^{-1} N, P and K, respectively, (Chude et al., 2011) or 100 to 120, 24, and 48 kg ha^{-1} (Nwilene et al., 2008) with the assumption that the need for applied nutrients is constant over varieties, time and diverse agro-ecological zones. These recommendations do not consider the financial ability of farmers and do not account for variation in the cost of fertilizer use relative to the value of paddy (CP). Recommendations for fertilizer use with no financial constraint commonly strive to

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Abbreviations: AE, agronomic efficiency of nutrient use; CP, cost of one kg of nutrient applied relative to the value of one kg of rice paddy; EOR, economically optimal rate of nutrient application or the rate expected to maximize net return to nutrient application; VCR, value to cost ratio, calculated as the ratio of value of increased crop output to the cost of fertilizer use.

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maximize mean net return per hectare. Fertilizer use by finance-constrained smallholders, however, needs to aim at maximizing net returns on small investments with an optimized choice of crop-nutrient-rate combinations (Kaizzi et al., 2014; Ndungu-Magiroi et al., 2017; Tarfa et al., 2017). As fertilizer cost increases relative to paddy value, the fertilizer rate that would maximize profit, often referred to as the economically optimal rate (EOR), is expected to decrease (Jansen et al., 2013). Robust rice-nutrient response functions are needed for fertilizer use decisions for maximizing profitability in consideration of the farmer's agronomic and financial context (Jayne et al., 2016).

Ezui et al. (2010) reported different recommendation options tailored to meet farmer financial capacity and production goals for upland rice production on loam soils of the Nigerian Northern Guinea Savanna. Kaizzi et al. (2014) reported that EOR for upland rice ranged from 54 to 92 kg ha^{-1} N depending on the CP. Tarfa et al. (2017) developed a basis for fertilizer recommendations for rice across six agro-ecological zones that considered the farmer's context using fertilizer use optimization decision tools (Jansen et al., 2013; Kaizzi et al., 2017). The information base for the rice decision tools was not very robust due to scarcity of response data applicable for the Guinea and Sudan Savannas of Nigeria. Rice nutrient response functions need to be better determined for irrigated lowland rice production areas of Nigeria.

The general objective of the study was to improve the information base for fertilizer use decisions by rice farmers. We hypothesized that N application will increase rice paddy yields when compared with no application and that application of P, K, and/or Zn will increase yield compared with N alone. The specific objectives were to: (i) quantify the response of irrigated lowland rice to N, P, K and Zn; (ii) determine the agronomic and economic efficiency for applied N, P, K and Zn; and (iii) evaluate additive or synergistic effects of nutrients on rice yield.

MATERIALS AND METHODS

Experimental Sites

Irrigated rice research was conducted in 2015 at two locations. The Irrigation Research Station of the Institute of Agricultural Research (IAR) located at Kano River Irrigation Project near Kadawa (11°39¢ N, 8°27¢ E, 500 m elevation) in the Sudan Savanna was one site. The area is characterized by a mono-modal rainfall distribution averaging 1050 mm yr^{-1} with 91% falling during May to October (https://en.climate-data.org/Location/390897/, Accessed 6 July 2017). The monthly mean temperature ranges from 22 to 29°C and is lowest in November to February and highest in March to April. Lowland rice production is mostly produced during the rainy season with irrigation from the Kano River. The soils are alfisols that overlay older granites and younger metasediments of Precambrian to lower paleozoic (McCurry, 1976).

The second research site was the Upper Niger Basin Authority Irrigation Site near Wushishi of Niger State in the Southern Guinea Savannah (09°39.75′ N, 6°5.69≤ E; 104 m elevation). It is located within the flood plains of the Ubandawaki and Bankogi Rivers. The mean rainfall is 1220 mm yr^{-1} with about 83% falling during June to October (https://en.climate-data.org/Location/390897/, Accessed 6 July 2017). The mean temperature is 28°C. The soils are generally flat inceptisols of the USDA aquaept great group, derived from alluvial deposits and the interphase of the Nupe sandstone and basement complex (Oladipo, 1998).

The soil samples of 0 to 20 cm depth were collected and analyzed at the Soil Science Department of Ahmadu Bello University in Zaria. Particle size, soil pH in water and 0.01 mol L^{-1} $CaCl_2$ using a soil-solution ratio of 1:2.5, electrical conductivity, organic C by Walkley-Black (Nelson and Sommers 1982), ammonium acetate extracted exchangeable bases, Bray-1 P, and DTPA-Zn (IITA, 1989) were determined (Table 1). Mehlich-3 S and B were determined at the laboratory of the World Agroforestry Centre in Nairobi Kenya. The surface soil texture was sandy loam at Kadawa and clay at Wushishi. Soil organic C was 5 g kg^{-1} at Kadawa and 8.8 g kg^{-1} at Wushishi. Bray-1 P was low at Kadawa and moderately adequate at Wushishi. All the sites had moderate or high levels of soil K, Mg and Zn.

Experimental Design and Agronomic Practices

There were 20 treatments in a randomized complete block design with three replications (Table 2). The five fertilizer N nutrient rates had 40 kg ha^{-1} increments with 0 and 15 kg ha^{-1} P uniformly applied. The four levels of P, K and Zn were in increments of 7.5, 10, and 0.5 kg ha^{-1}, respectively. A diagnostic treated consisted of 10 kg ha^{-1} Mg, 0.5 kg ha^{-1} B and 15 kg ha^{-1} S, in addition to N, P and Zn applied. The P rate effects were evaluated with 120 kg ha^{-1} N uniformly applied, expecting N to be the most limiting nutrient. The effects of K, Zn and the diagnostic treatment were evaluated with 120 kg ha^{-1} N and 15 kg ha^{-1} P uniformly applied. There were two trials at each location differing for variety, Federal Agricultural Research Oryza release numbers 44 and 52, referred to as Faro 44 and Faro 52 (Imolehin and Wada, 2000; Nwilene et al., 2008). These varieties are shorter and more responsive to high doses of fertilizer than traditional cultivars. Faro 44 is a long grain variety resistant to rice blast and matures in 110 to 120 d. Faro 52 matures in 120 to 135 d.

The nutrient sources were urea for N, triple super phosphate for P, murate of potash for K, magnesium sulfate for Mg and S, zinc sulfate for Zn and S, and borax for B. The diagnostic treatment (treatment 17 in Table 2) served to determine the combined effect of other nutrients once N, P, and K were applied. All of the P, K, Zn, and the diagnostic package plus 25% of N were applied at one wk after transplanting. The remaining N was broadcast applied with 25% at tillering and 50% at panicle initiation.

Glyphosate (Roundup; 2-(phosphonomethylamino)acetic acid) was applied 10 d before land preparation at a rate of 5 L ha^{-1}. The rice fields at Kadawa were plowed and harrowed using a tractor while land preparation at Wushishi was with hand hoes. Plot sizes were 5 m by 3 m and enclosed with 1-m wide bunds.

Seed was sown in a nursery on 15 April for Kadawa and 23 May for Wushishi. Transplanting was at three wk after sowing with a spacing of 20 cm by 20 cm with two seedlings per stand. Orizoplus (2,4-D amine + Propanil; 2-(2,4- acid + N-(3,4-Dichlorophenyl)propanamide) was applied with a rate of 5 L ha^{-1} at 3 wk after transplanting to control weeds. Manual hoe weeding supplemented with regular hand pulling was subsequently used to control weeds. Plots were continuously flooded at Wushishi. Flood irrigation was provided at

Table 1. Soil properties for rice research sites at Kadawa in Kano State and Wushishi in Niger State, Nigeria.

Property	Kadawa	Wushishi
Texture	Sandy loam	Clay
pH water (1:2.5)	7.8	6.6
pH $CaCl_2$ (1:2.5)	6.8	5.9
	g kg^{-1}	
Clay	198	416
Silt	202	329
Sand	599	254
Organic C	5.0	8.8
Total N	0.6	0.7
	cmol kg^{-1}	
Ca	6.31	15.2
Mg	2.9	5.1
K	0.45	0.28
Na	1.8	0.12
ECEC†	11.6	25.9
	mg kg^{-1}	
Bray 1 P	10.2	13.6
S	7.4	8.6
Zn	3.5	1.52
B	0.25	0.13
	dS m^{-1}	
EC‡	0.13	0.07

† ECEC, effective cation exchange capacity.

‡ EC, electrical conductivity.

Table 2. Nutrient rate treatments for nutrient response research of irrigated lowland rice conducted in Nigeria.

Treatment	N	P	K	Zn
	kg ha^{-1}			
1†	0	0		
2	40	0		
3	80	0		
4	120	0		
5	160	0		
6	0	15		
7	40	15		
8	80	15		
9	120	15		
10	160	15		
11	120	7.5	0	0
12	120	15	0	2
13	120	22.5	0	0
14	120	15	10	0
15	120	15	20	0
16	120	15	30	0
17‡	120	15	20	2.5
18	120	15	0	0.5
19	120	15	0	1
20	120	15	0	1.5

† Treatments numbered 1 to 10 had no K and Zn.

‡ Diagnostic treatment which also had 10 kg ha^{-1} Mg, 0.5 kg ha^{-1} B and 15 kg ha^{-1} S applied.

Kadawa every three wk before the onset of the rains followed by less frequent irrigation. Karate (720EC) insecticide solution (lamba cyhalothrin; [cyano-(3-phenoxyphenyl) methyl] (1R,3R)-3-[(Z)-2-chloro-3,3,3-trifluoroprop-1-enyl]-2,2-dimethylcyclopropane-1-carboxylate) at a rate of 1 L ha^{-1} was applied during grain fill to control the stem borer complex.

Observations and Data Analyses

Panicles were counted for ten hills. The average plant height from the base to panicle tip was determined from measurements for 10 plants, and the average length was determined from 10 panicles.

Harvesting was done when the mature rice panicle ripened to a golden-brown color. Rice was harvested manually by cutting with sickles from a net plot of 3 m^2 and threshed. The harvest was dried for 7 d and threshed after which paddy and straw yields were calculated. Paddy and straw were subsampled and oven-dried at 70°C for 72 h to determine the water content. Paddy and straw yields were then adjusted to 140 g kg^{-1} water content.

Plot level data were analyzed with Statistix 10 (Analytical Software, Tallahassee, FL). A combined analysis of variance was not conducted across trials due to heterogeneity of variance. The $P = 0.05$ level of probability was used for determination of significant effects. When treatment effects were significant, the effects of P, K and Zn rate and of the diagnostic treatment on paddy and straw yields of rice were evaluated using orthogonal contrast tests. The contrast tests for rate effects included tests of the mean effect of the applied nutrient and for linear and quadratic rate effects. The N rate and N × P rate interaction effects were tested by repeating the ANOVA for the sub-set of the first 10 treatments which included the five N rates with 0 or 15 kg ha^{-1} P uniformly applied. The relationship between rice paddy yield and yield parameters of plant height, panicle length, and panicle number per square meter were examined using Pearson correlation and multiple linear regression analysis using experimental unit data across all trials and fertilizer treatments.

Yield responses were fitted to asymptotic curvilinear to plateau response functions $Y = a - bc^r$ where Y is yield, a is the yield at the plateau for the nutrient application, b is the maximum yield gain due to the application of the nutrient, c is a curvature coefficient, and r is the nutrient application rate. Linear regression was applied when a realistic asymptotic function failed to converge due to linear effects of nutrient rates.

The agronomic efficiency of N use was determined as the gain in paddy yield per unit of N applied (kg kg^{-1}) (Cassman et al., 2002). The rate that maximized net return per ha, or the EOR, was determined for a CP of 2, 4, or 6. The value to cost ratio (VCR) was used to determine gross returns to fertilizer N use. The VCR was calculated as a ratio of the value of increased crop yield from fitted N response functions to the cost of fertilizer use. Therefore, VCR = 1 meant that the value of the yield increase over the control equaled the cost of nutrient application. A VCR ≥ 2 is considered sufficient to attract investment by many financially constrained farmers (CIMMYT Economics Program, 1988; Kihara et al., 2016). Jama et al. (2017) proposed a VCR > 3 to be an appropriate threshold in high-risk production environments for small scale farmers.

RESULTS

Plant Height and Panicle Number and Length

There was an average of 167 panicle m^{-2} but 57% more at Wushishi compared with Kadawa and 90% more with Faro 44 compared with Faro 52. Mean panicle length was 26 cm and 5%

Table 3. Overall trial means and analysis of variance results for the response of irrigated lowland rice varieties FARO 44 (F44) and FARO 52 (F52) to applied nutrients at Kadawa and Wushishi in Nigeria.

		Kadawa		Wushishi		Kadawa		Wushishi		Kadawa		Wushishi	
		F44	F52	F44	F52	F44	52	F44	F52	F44	F52	F44	F52
	df	Plant height				Panicle number				Panicle length			
		cm				No. m^{-2}				cm			
Mean		60	99	100	103	146	114	291	117	21	22	29	31
T†	19	ns‡	***	***	***	*	***	***	*	ns	***	**	**
N	4	ns	***	***	***	ns	** *	** *	*	ns	***	**	**
N×P	4	ns	*	ns	ns	ns	*	ns	ns	ns	*	ns	ns
P	3	ns	ns	ns	**	*	ns	**	ns	ns	ns	**	**
Zn	4	ns	***	ns	ns	ns	***	ns	ns	ns	***	ns	ns
K	3	ns	ns	***	ns	ns	ns	*	ns	ns	ns	*	ns
D§	1	ns	31*	ns	–22*	ns	ns	ns	–27*	ns	7*	ns	ns
		Paddy yield				Straw yield							
		Mg ha^{-1}											
Mean		3.83	3.07	7.45	4.68	2.52	4.29	9.44	11.00				
T	19	***	***	***	*	***	***	***	***				
N	4	*	***	***	*	ns	***	**	*				
N×P	4	ns	**	ns	ns	ns	**	ns	ns				
P	3	**	ns	*	ns	ns	ns	ns	ns				
Zn	4	**	***	ns	ns	ns	***	ns	ns				
K	3	ns	ns	*	ns	ns	ns	**	ns				
D	1	-0.72*	ns	ns	–0.11*	ns	1.34*	-4.00*	ns				

* Significant at $P \leq 0.05$; ** Significant at $P \leq 0.01$; *** Significant at $P \leq 0.001$.

† T, treatment.

‡ ns, not significant.

§ D, a Mg-S-B diagnostic treatment. The change in yield (Mg ha^{-1}) is presented when the effect was significant.

Table 4. Response of yield components of irrigated lowland rice varieties FARO 44 (F44) and FARO 52 (F52) to applied N with 0 (0P) and 15 (15P) kg ha^{-1} P uniformly applied at Kadawa and Wushishi, Nigeria in 2015.

	Kadawa			Wushishi			Kadawa			Wushishi		
	F44	F52		F44	F52	Mean	F44	F52		F44	F52	Mean
	0P-15P†	0P	15P	0P-15P	0P-15P	0P-15P	0P-15P	0P	15P	0P-15P	0P-15P	0P-15P
N rate	Panicle number						Panicle length					
kg ha^{-1}	No. m^{-2}						cm					
0	122	72	81	202	99	125	17	14	15	20	21	18
40	142	120	133	282	120	168	21	19	20	24	26	23
80	137	87	141	322	120	173	21	17	25	30	28	25
120	156	117	120	279	115	167	22	23	22	26	29	25
160	141	90	163	305	119	173	21	18	31	30	29	26
$LSD_{(0.05)}$	ns‡	25.1	30.7	34.3	14.9	12.9	ns	3.9	6.9	4.9	3.9	2.1

† 0P-15P, the mean N level effect for 0 and 15 kg ha^{-1} P levels.

‡ ns, not significant.

longer with Faro 52 compared with Faro 44 and 40% longer at Wushishi compared with Kadawa. Plant height, panicle m^{-2} and panicle length were increased by nutrient application for all trials except for panicle length of Faro 44 at Kadawa (Table 3). Plant height, panicle m^{-2} and panicle length of Faro 52 at Kadawa were affected by the N × P interaction with greater and more consistent N effects with 15 compared with 0 kg ha^{-1} P applied. These variables were maximized with 160 kg N ha^{-1} when 15 kg ha^{-1} P was applied but at 40 kg ha^{-1} N with 0 kg ha^{-1} P (Table 3, 4). The N × P interaction was not significant for the other three variety-location combinations. Application of 40 compared with 0 kg ha^{-1} N on average resulted in 22% more plant height, 34% more panicle m^{-2} and 28% more panicle length (Fig. 1; Table 4). Further increments in N rate had little effect on these traits with the exception addressed above for Faro 52 at Kadawa.

Application of P, with 120 kg N ha^{-1} uniformly applied, increased plant height and panicle length of only Faro 52 at Wushishi but the P rate effect was inconsistent (Table 5). Application rate of P did not affect panicle m^{-2} for Faro 52 and had an inconsistent effect for Faro 44. There were also some K and Zn effects on yield components but with much inconsistency across trials and nutrient rates.

Only Faro 44 at Wushishi was affected by K application with 33% more plant height, 22% more plant m^{-2}, and 34% more panicle length with K applied compared with 0 kg ha^{-1} K. Application of 1.5 kg ha^{-1} Zn resulted in increased plant height and panicle length of Faro 52 at Kadawa but such increases did not occur with 0.5 and 1.0 kg ha^{-1} Zn. Panicle m^{-2} for Faro 52 was decreased with 0.5 and 1.0 kg ha^{-1} compared with 0 kg ha^{-1} Zn. Yield components of Faro 44 and at

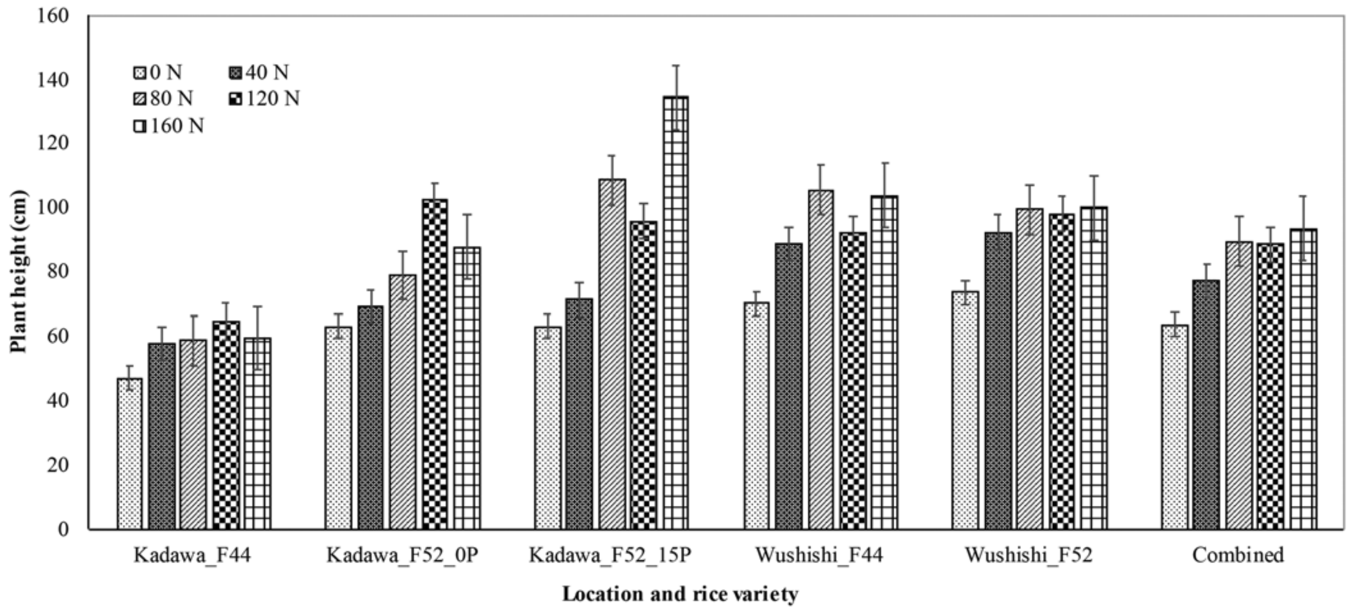

Fig. 1. Irrigated lowland rice plant height response to N (kg ha^{-1}) with 0 (0P) or 15 (15P) kg ha^{-1} P uniformly applied for varieties FARO 44 (F44) and FARO 52 (F52) at Kadawa and Wushushi in Nigeria, 2015.

Table 5. Response of yield components of irrigated lowland rice varieties Faro 44 (F44) and Faro 52 (F52) to applied P with 120 kg ha^{-1} N uniformly applied at Kadawa and Wushushi, Nigeria in 2015.

	Kadawa		Wushishi		Kadawa		Wushishi		Kadawa		Wushishi	
P	F44	F52	F44	F52	F44	F52	F44	F52	F44	F52	F44	F52
rate	Plant height				Panicle number				Panicle length			
kg ha^{-1}	cm				No. m^{-2}				mm			
0	69	102	94	97	163	117	306	116	233	230	247	287
7	59	103	105	114	134	120	356	112	220	217	270	367
15	61	96	90	99	150	120	251	113	200	220	273	297
22	71	118	96	126	183	133	282	126	230	260	270	400
LSD$_{(0.05)}$	ns†	ns	ns	14.0	29.8	ns	44.1	ns	ns	ns	ns	5.8

† ns, not significant.

Wushishi were not affected by Zn application. The diagnostic treatment resulted in 33% more plant height and 32% more panicle length for Faro 52 at Kadawa and 18% less plant height and 19% less panicle m^{-2} of Faro 52 at Wushishi (Table 3). The diagnostic treatment did not affect the yield component constraints for other variety-location combinations.

The respective Pearson correlation coefficients of paddy yield with plant height, panicle m^{-2} and panicle length were 0.37, 0.91, and 0.51. The three components combined accounted for 94% of the variation in paddy yield. Paddy yield = −0.978 + 0.0185′(panicle m^{-2}) + 0.0117′(plant height, cm) + 0.0681′(panicle length, mm).

Paddy and Straw Yield

The mean paddy yields across locations and treatments were 5.17 Mg ha^{-1} for Faro 44 and 3.54 Mg ha^{-1} for Faro 52 (Table 6; Fig. 2). The N × P interaction affected paddy yield of Faro 52 at Kadawa. Yield increases of 43 and 73% were realized due to N application with the response plateau beginning at a lower N rate, respectively, with 0 compared with 15 kg ha^{-1} P uniformly applied. The N rate x location x variety interaction effect on yield could not be tested due to heterogeneity of variance but was indicated as the effect of 40 kg ha^{-1} N on paddy yield differed by variety and location, ranging from increases of 0.87 Mg ha^{-1} with Faro 52 at Wushishi to 2.00 Mg ha^{-1} with Faro 44 at Wushishi, averaged across P levels. The paddy yield response to N fitted asymptotic functions in all cases (Fig. 2). The overall yield response function for the pooled analysis was $Y = 4.775 - 1.368'(0.930^{N})$. The mean paddy yield response to N rate was curvilinear to plateau with a 38% and 1.29 Mg ha^{-1} mean yield increase occurring with application of 40 kg ha^{-1} N while the additional yield increase for the 40 to 80 kg ha^{-1} N was 0.07 Mg ha^{-1}.

The mean straw yields were 5.58 and 4.03 Mg ha^{-1} for variety Faro 44 and Faro 52, respectively (Table 6). The N × P interaction affected straw yield of Faro 52 at Kadawa. The response to N was curvilinear and little yield response with rates greater than 40 kg ha^{-1} N with 0 kg ha^{-1} P compared with a linear and greater response to N with 15 kg ha^{-1} P. The N x P interaction effects for Faro 52 at Kadawa on yield and yield components were the only N x P synergistic effects of nutrient application in these trials with other positive effects of applying two or more nutrients being additive. Straw yield increases with 40 kg ha^{-1} N ranged from 0.30 Mg ha^{-1} with Faro 52 and 0 kg ha^{-1} P at Kadawa to 1.15 Mg ha^{-1} with Faro 44 at Wushishi. The straw yield response to N fitted asymptotic functions in all cases except for a linear response for Faro 52 at Kadawa with 15 kg ha^{-1} P uniformly applied. The overall mean straw yield response to N rate was

Table 6. Paddy and straw yield response of lowland rice varieties FARO 44 (F44) and FARO 52 (F52) to applied N with 0 (0P) and 15 (15P) kg ha^{-1} P uniformly applied at two sites in Nigeria.

	Kadawa			Wushishi		Kadawa			Wushishi	
	F44	F52		F44	F52	F44	F52		F44	F52
	0P-15P†	0P	15P	0P-15P	0P-15P	0P-15P	0P	15P	0P-15P	0P-15P
N rate	Paddy yield					Straw yield				
kg ha^{-1}	Mg ha^{-1}					Mg ha^{-1}				
0	2.60	1.95	2.18	5.05	3.92	2.00	2.70	2.72	7.00	3.92
40	3.55	3.23	3.60	7.05	4.79	2.40	3.00	3.07	8.15	4.68
80	3.42	2.34	3.81	8.05	4.79	2.44	3.39	4.67	9.91	4.77
120	3.91	3.17	3.24	6.97	4.57	2.56	4.51	4.11	8.76	4.63
160	3.51	2.42	4.41	7.63	4.76	2.44	3.77	5.78	10.1	4.77
$LSD_{(0.05)}$	0.68	0.67	0.83	0.86	0.59	0.50	1.00	1.50	1.65	1.32
	A‡	A	A	A	A	A	A	L	A	A
a§	3.63	2.79	3.85	7.53	4.73	2.49	4.14	2.64	9.96	4.72
b	1.03	0.84	1.67	2.48	0.81	0.49	1.44	0.03	3.00	0.81
c	0.95	0.90	0.96	0.95	0.90	0.96	0.99		0.98	0.93
R^2	0.86	0.46	0.75	0.87	0.94	0.95	0.71	0.84	0.79	0.97

† 0P-15P, the mean N level effect for 0 and 15 kg ha^{-1} P levels.

‡ Letters indicate successful fitting of asymptotic (A) and linear (L) functions.

§ Coefficients *a, b, c* are for the asymptotic function of $Y = a - bc^r$ or *a* and *b* of linear functions; The units for coefficients *a* and *b* are Mg ha^{-1} and *c* is unitless.

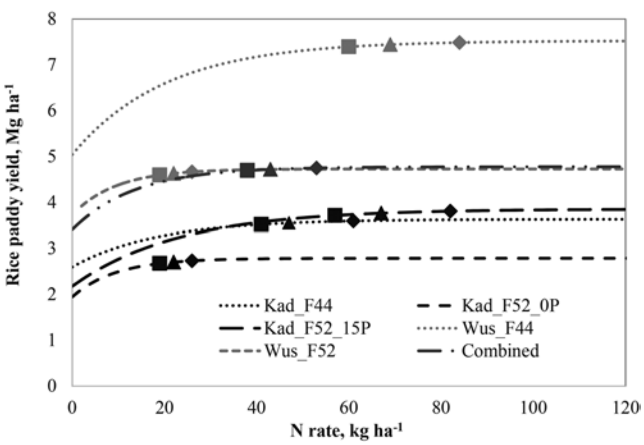

Fig. 2. Irrigated lowland rice paddy yield response to N with 0 (0P) or 15 (15P) kg ha^{-1} P uniformly applied for varieties FARO 44 (F44) and FARO 52 (F52) at Kadawa (Kad) and Wushushi (Wus) in Nigeria. The diamond, triangle and square symbols indicate the economically optimal rates when the cost of N use equals the value of 2, 4, and 6 kg of rice paddy, respectively.

curvilinear with a 20% and 0.96 Mg ha^{-1} yield increase with 40 kg ha^{-1} N, and 0.48 Mg ha^{-1} additional yield increase with the 40 to 80 kg ha^{-1} N increment.

Rice paddy yield of Faro 44 was affected by P application but the effects were not consistent with P rates (Table 7). Paddy yield of Faro 52 and straw yields of both varieties were not affected by P rate. Rice paddy and straw yields of Faro 44 increased with K application at Wushishi with responses fitting the asymptotic function but all other K rate effects on yield were not significant (Table 8).

Paddy yield was affected by Zn rate with 120 kg ha^{-1} N and 15 kg ha^{-1} P uniformly applied at Kadawa but not at Wushishi (Table 9). The response of Faro 44 was curvilinear to plateau but the effect of Zn rate on Faro 52 was too inconsistent to fit an agronomically justified function. The straw yield of Faro 52 was increased with Zn application with a linear effect at Kadawa and a curvilinear effect at Wushishi.

Paddy yield was 22% less for Faro 44 at Kadawa and 18% less for Faro 52 at Wushishi with the diagnostic treatment. The straw yield was 33% more with Faro 52 at Kadawa and 24% less with Faro 44 at Wushishi with the diagnostic treatment. The diagnostic treatment had no other significant effects on yield.

The mean EOR of N was 56 kg ha^{-1} with CP of 2 and 38 kg ha^{-1} with CP of 6, but was higher at Kadawa compared with Wushishi and slightly higher with Faro 44 compared with Faro 52 (Fig. 2). The agronomic efficiency of N use declined with increasing N rate (Fig. 3). The overall agronomic efficiency of N use was 28 kg kg^{-1} at EOR with CP of 2, and ranged from 17 kg kg^{-1} at Kadawa for Faro 52 with 0 kg ha^{-1} P to 29 kg kg^{-1} at Wushishi for Faro 44 with CP of 2. The VCR as expected was correlated to agronomic efficiency and the respective values can be determined through division by CP. The overall VCR at EOR was 14 with CP of 2 and 5.5 with CP of 6. The potential VCR was greater with Faro 44 compared with Faro 52 at both locations and for all CP.

DISCUSSION

The low soil organic C and high sand content at Kadawa indicated less potential for soil productivity and more difficulty retaining applied nutrients and maintaining adequate soil water availability compared with Wushishi (Table 1). This was confirmed by higher mean yield at Wushishi compared with Kadawa. Rice paddy yield and panicle number per square meter were more with the earlier maturing Faro 44 compared with Faro 52.

Fertilizer N application increased rice paddy yield but effects of applied P, K, Zn and a diagnostic package varied with variety and location and generally were not significant. The fertilizer treatment effects on yield were not consistent across varieties at both sites with differing shapes and magnitudes of response.

Application of N resulted in increased rice yield as well as in panicle number and length, consistent with other results (Onaga et al., 2012; Haefele et al., 2008; Jibrin et al., 2010). The mean paddy yield increased from 3.4 Mg ha^{-1} with 0 kg ha^{-1} N to 4.7 Mg ha^{-1} with 40 kg ha^{-1} N and with lesser rates of yield

Table 7. Irrigated lowland rice yield response to applied P with 120 kg ha^{-1} N uniformly applied for varieties FARO 44 (F44) and FARO 52 (F52) at Kadawa and Wushushi, Nigeria in 2015.

	Kadawa		Wushishi		Kadawa		Wushishi	
	F44	F52	F44	F52	F44	F52	F44	F52
P rate	Paddy yield				Straw yield			
kg ha^{-1}	Mg ha^{-1}							
0	4.07	3.17	7.64	4.63	2.79	4.51	8.37	10.16
7.5	3.35	3.23	8.91	4.46	2.58	4.42	9.14	12.97
15	3.74	3.24	6.29	4.52	2.33	4.11	9.14	10.52
22.5	4.39	3.60	7.40	5.02	2.73	5.10	8.94	14.12
$LSD_{(0.05)}$	ns†	ns	1.32	ns	ns	ns	ns	ns

† ns, not significant.

Table 8. Irrigated lowland rice yield response to applied K with 120 kg ha^{-1} N and 15 kg ha^{-1} P uniformly applied at Kadawa and Wushushi, Nigeria in 2015.

	Kadawa		Wushishi		Kadawa		Wushishi	
	F44	F52	F44	F52	F44	F52	F44	F52
K rate	Paddy yield				Straw yield			
kg ha^{-1}	Mg ha^{-1}							
0	3.74	3.24	6.29	4.52	2.33	4.11	9.14	10.52
10	4.19	3.10	7.96	4.98	2.03	4.06	11.74	10.95
20	4.09	2.97	8.32	5.71	2.20	4.09	12.32	12.50
30	3.98	3.41	7.73	4.15	2.47	4.26	12.85	11.08
	ns†	ns	*	ns	ns	ns	**	ns
a‡			8.02				12.88	
b			1.73				3.73	
c			0.69				0.89	
R^2			0.926				0.995	

* Significant at $P \le 0.05$; ** Significant at $P \le 0.01$.

† ns, not significant.

‡ Coefficients *a, b, c* are for the asymptotic function of $Y = a - bc^r$; The units for coefficients *a* and *b* are Mg ha^{-1} and *c* is unitless.

Table 9. Irrigated lowland rice varieties FARO 44 (F44) and FARO 52 (F52) yield response to applied Zn with 120 kg ha^{-1} N and 15 kg ha–^{1} P uniformly applied at Kadawa and Wushushi, Nigeria in 2015.

	Kadawa		Wushishi		Kadawa		Wushishi	
	F44	F52	F44	F52	F44	F52	F44	F52
Zn rate	Paddy yield				Straw yield			
kg ha^{-1}	Mg ha^{-1}							
0.0	3.74	3.24	6.29	4.52	2.33	4.11	9.14	10.52
0.5	3.94	2.15	8.06	5.23	2.84	3.84	10.74	13.15
1.0	4.32	1.65	8.39	5.48	3.02	4.56	7.75	11.88
1.5	5.73	2.94	8.45	4.08	3.64	6.32	9.79	16.20
2.0	4.05	4.17	7.33	4.11	2.93	5.96	8.40	12.72
$LSD_{(0.05)}$	0.939	0.621	ns†	ns	ns	0.76	ns	4.31
	A‡	NF				L		A
a§	4.83					3.72		13.98
b	0.19					1.24		3.41
c	0.27							0.14
R^2	0.315					0.766		0.434

† ns, not significant.

‡ Letters indicate successful fitting of asymptotic (A) and linear (L) functions; NF, no fit.

§ Coefficients *a, b, c* are for the asymptotic function of $Y = a - bc^r$ or *a* and *b* of linear functions; The units for coefficients *a* and *b* are Mg ha^{-1} and *c* is unitless.

increase with high N rates but there was much variation in yield response to 40 kg ha^{-1} N for the variety-location combinations.

The application of P increased the agronomic efficiency of N and the response of yield components and yield to N for Faro 52 at Kadawa but did not affect paddy or straw yield response to N for Faro 44 and at Wushishi (Table 6). This inconsistency in the effect of the N × P interaction was consistent with Oikeh et al. (2008) who reported a significant interaction for upland rice in one year but not in another year. The occurrence of N × P interactions in this study and in Oikeh et al. (2008) occurred due to an enhanced magnitude of response and response to higher N rates with 15 compared with 0 kg ha^{-1} P. Such an interaction suggests that P deficiencies became limiting once some N was applied and that the P limitation needed to be alleviated to achieve the full response to N. However, it appears that the P limitation was marginal as the interaction

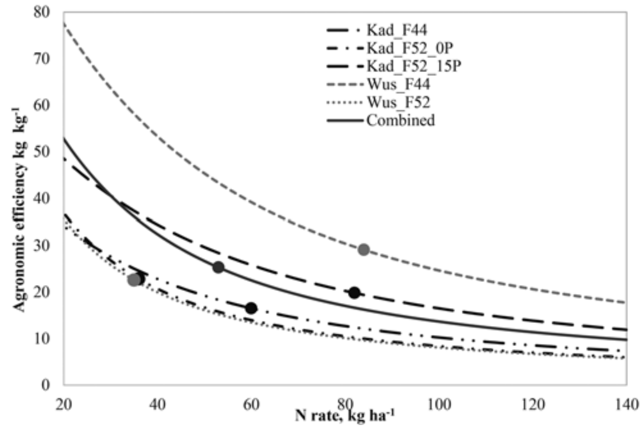

Fig. 3. Agronomic efðciency as affected by N rate for rice paddy yield for varieties FARO 44 (F44) and FARO 52 at Kadawa (Kad) and Wushishi (Wus) in Nigeria. The round symbols indicate the economically optimal rate when the cost per kg of nutrient use is equal to the value of 2 kg paddy.

was not significant for Faro 44 and the P rate effect was not significant.

Variation in the panicle number per square meter alone, or together with variations in panicle length and plant height, accounted for 83 and 94% of the variation in paddy yield. Panicle number per square meter is determined early in the season, especially at tillering through to panicle initiation and formation. Therefore, avoidance of crop stress at these growth stages appears to be especially important to paddy yield and validates the decision to apply 75% of the fertilizer N at these stages. Soil water availability during these growth stages would be important, and was not monitored, but with continuous flooding at Wushishi and periodic flood irrigation accompanied by rainfall at Kadawa soil water deficits were an unlikely constraint.

Application of 15 kg ha^{-1} P increased the response of Faro 52 to N at Kadawa, but yield components and yield were generally not affected by P rate (Tables 3, 4, and 7). The exception was of Faro 44 at Wushishi and then the P rate effect was inconsistent with yield maximized at near 7.5 kg ha^{-1} P (Table 7). Therefore, the results indicated that 15 kg ha^{-1} P, and may be less, should be applied for Faro 52 at Kadawa but did not provide justification for P application in other situations.

Yield was not affected by K rate except for increased grain and straw yield of Faro 44 at Wushishi (Table 8) where yield was maximized with 20 kg ha^{-1} K. These findings generally conflict with the conclusions of others that N needs to be applied together with P or with P plus K for sustainable short- and long-term rice production (Rajput et al., 1988) but agree with others reporting little rice response to K in Nigeria (Ezui et al., 2010; Apaseku and Dowbe, 2013). Given that the need for high returns to investments is an essential key to the sustainability of financially constrained smallholder operations, the results of the current study give little justification for investments in P and K application for lowland rice production. There may be significant delivery of nutrients to fields with the river water used to irrigate the rice fields which would contribute to the lack of more response to P even though soil test P was low at Kadawa. Such delivery of nutrients in the irrigation water has not been confirmed for the research locations but Ahiarakwem and Onyekuru (2011) reported PO_4^{-1} concentration of 2 g m^{-3} for water of the Njaba River, a tributary of the Niger River in Nigeria and they did not account for organic and inorganic sediment bound P which likely was more than dissolved P. With such a P concentration, 20 kg ha^{-1} yr^{-1} dissolved P would be delivered to a field with each 1 m yr^{-1} of irrigation water applied and likely with considerably more sediment bound P delivered.

There was a positive response of 0.19 Mg ha^{-1} of Faro 44 to Zn rate at Kadawa but the effect for Faro 52 at Kadawa was inconsistent and generally negative (Table 9). There was no Zn rate effect at Wushishi. Application of the Mg-S-B diagnostic package more often resulted in decreased rather than increased yield (Table 3) compared with application of N-P-Zn alone. The occurrence of these negative effects on grain yield could not be explained. The soil test values indicated adequate availability of Mg, Zn and B (Chude et al., 2011; Nwilene et al., 2008), but given the low soil organic C, the extractible S may be borderline for adequacy. The results indicate that farmers should not invest in Mg, S, Zn or B application for lowland rice production unless major constraints to yield are mitigated.

Response to N differed by variety and location but the results are not sufficient to justify variety- or location-specific recommendations. Therefore, the results are best applied using the mean response function of $Y = 4.77 - 1.37'(0.93^{N})$ (Table 6). Using this equation, the lower and upper confidence limits of 0.95 probability for yield increase due to N application are estimated to be, respectively, 0.65 and 1.59 Mg ha^{-1} for 40 kg ha^{-1} N and 0.70 and 2.00 Mg ha^{-1} for 80 kg ha^{-1} N. Consideration of more research results, however, may provide the basis to narrow these confidence ranges, to recommend N with agro-ecological zone specificity, and to formulate recommendations of P application (Tarfa et al., 2017; Wortmann et al., 2017).

Application of N at EOR was more profitable at Wushishi compared with Kadawa due to a greater yield response to N. Resource-poor farmers are usually unable to apply fertilizer at EOR to all of their cropland and can apply at the nutrient rates that maximizes profit for the available money invested in fertilizer (Jansen et al., 2013; Van Asten et al., 2003). However, EOR were considerably less than currently recommended rates (Chude et al., 2011; Nwilene et al., 2008). Financially constrained farmers require high returns on small investments to justify fertilizer use. Enabling farmers to maximize profit from fertilizer use is a potential means to breaking out of their cycle of poverty. The overall EOR for N with CP of 4 was 44 kg ha^{-1}. However, because of the curvilinear response to N, the VCR increases as N rate decreases. At 100 and 50% of EOR with CP of 4, the EOR were 44 and 22 kg ha^{-1}, respectively, with paddy yields of 4.72 and 4.51 Mg ha^{-1} and VCR of 7.5 and 12.5 \$ $\$^{-1}$ for applied N. This comparison would indicate that with curvilinear to plateau responses, the paddy yield increase is about 16% less but agronomic efficiency and VCR is about 66% more with 50% compared with 100% EOR. Therefore, the greatly improved VCR at 50% EOR with the affordable fertilizer applied over twice as much cropland compared with 100% EOR presents an opportunity for smallholders to optimize on their financial resources and gradually improve their financial situation. Tarfa et al. (2017) presented recommendations for seven crops for each of six agro-ecological zones in Nigeria with decision tools available at http://www.agronomy.unl.ed/OFRA. The recommendations are differentiated according to the farmer's financial ability and based on results of recent and past research conducted in conditions homologous to the AEZ (Wortmann et al., 2017). The current rice results were considered in developing these recommendations intended to maximize farmer profit from fertilizer use for all crops on the farm.

CONCLUSION

Lowland rice yield can be profitably increased with N application. Occasional yield increases due to 7.5 kg ha^{-1} P application, either through an enhanced effect of N or a direct P rate effect, may be sufficient for some profit potential, especially at Kadawa. However, the results indicate that profitable response to K, Mg, S, Zn, or B is not likely to occur for lowland rice production areas of the Sudan and Guinea Savanna areas of Nigeria. The application of N at EOR is recommended when fertilizer use is not financially constrained. These results indicate the use of much lower rates of N-P-K application than is currently recommended. The financially constrained farmer can apply at 50% EOR for about 66% higher VCR with only about 5% yield loss as compared to 100% EOR. There was inconsistency in response to N but these results alone are not sufficient to justify variety- or location-specific N rate recommendations. Combining these results with N response results from homologous production conditions from past or future research may enable more site- or zone-specific recommendations and may justify P application.

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