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Rainfed rice response to fertilizer in the Sudan Savanna of West Africa

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In West Africa, rice (*Oryza sativa* L. and *Oryza glaberrimal* Steud) production is not meeting current demand. Low yields are attributed to diverse biotic and abiotic constraints including nutrient deficiencies, inadequate agronomic practices, and socio-economic constraints. This study quantified yield and profit responses of rainfed rice produced in the Sudan Savanna of Burkina Faso and Mali to fertilizer N, P, K, and Mg-S-Zn-B treatment. The mean yields were 2.2 and 2.4 Mg ha^{-1} for upland rice in Finkolo and for lowland rice in Longorola in Mali, respectively, and 1.5 and 2.2 Mg ha^{-1} for upland rice at Boni and Karaba in Burkina Faso. Lowland rice grain yield was not affected by nutrient application at Longorola. The grain yield increases with 30 and 60 kg ha^{-1} N were, respectively, 0.30 and 0.48 Mg ha^{-1} at Karaba, 0.21 and 0.34 Mg ha^{-1} at Boni, and 0.32 and 0.41 Mg ha^{-1} at Finkolo indicating similarity in response. Grain yield response to P was observed only at Karaba. If fertilizer were applied at 50% rather than 100% of the economically optimum rate, as might be the case for financially constrained farmers, the mean yield increase was 36% less but agronomic efficiency was 23% higher and the profit cost ratio was 66% higher. There was no response to K or to Mg-S-Zn-B. The results, therefore, indicate high potential for profitable response of rainfed upland rice production for Sudan Savanna to fertilizer N but little potential for other fertilizer nutrients. These results should, however, be considered together with other field research results in making fertilizer use decisions.

Key words: Agronomic efficiency, economically optimal rate, response function, yield.

INTRODUCTION

Rice (*Oryza sativa* and *O. glaberrima*) production in West Africa has increased by > 2% year^{-1} recently but demand has a higher rate of increase (WARDA, 2005; CROPSTAT, 2013; Muthayya et al., 2014). Inadequate production practices, financial limitations, and various biotic and abiotic constraints contribute to declining or stagnant yields (Fosu et al., 2016). Mean rainfed rice grain yield has been estimated to be about 2 Mg ha^{-1}

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across several African countries (Aune and Bationo, 2008; Apaseku et al., 2013) and approximately one-third of the rainfed potential (GYGA, 2017). The Sudan Savanna covers about 350,000 km^2 in Burkina Faso and Mali and is very important for crop production in these countries.

Rainfed rice can be very responsive to fertilizer application; highly profitable curvilinear to plateau responses of upland rice grain yield to applied N occurred in Uganda and for the Northern Guinea Savanna of Nigeria (Kamara et al., 2010; Okonji et al., 2012; Kaizzi et al., 2014). Curvilinear to plateau response to applied P has also been reported (Bationo, 2008; Okonji et al., 2012; Kaizzi et al., 2014). Rainfed rice yield in Burkina Faso and Mali was often increased by more than 100% with the application of N and P (Bado, 2002).

Current blanket fertilizer recommendations in Mali and Burkina Faso do not consider local conditions and farmer's financial capacity, and are not well based on field research results. Such results were few and mostly from trials conducted on land of the research stations that may not represent the farmers' situations. Optimization of fertilizer use may improve yields and profitability from rainfed rice production in West Africa. This requires determination of robust crop-nutrient response functions specific to recommendation domains. It was hypthesized that rainfed rice produced in the Sudan Savanna will be responsive to N, P and K but that the responses will vary with nutrient, production conditions and location, and that yield is affected by deficiencies of other nutrients. The objectives of this research were to: (i) Quantify the yield response of rainfed rice to N, P and K; (ii) Determine the profit opportunities of fertilizer use for rainfed rice production; and (iii) Diagnose other nutrient deficiencies.

MATERIALS AND METHODS

Study sites

Trials were conducted in Burkina Faso and Mali during the 2014 and 2015 rainy seasons to determine the responses of rainfed upland and lowland rice to applied nutrients. All research sites were in the Sudan Savanna with unimodal rainfall falling mostly from May to October. The sites were selected to represent rainfed rice production in the respective areas and to avoid soils with atypical edaphic constraints that might prevent response to applied nutrients.

In Mali, trials were conducted for upland rice near Finkolo and for lowland rainfed rice near Longorola with 1200 to 1400 mm of seasonal rainfall (Table 1 and Figure 1). The trials in Mali were on farmers' fields with farmers managing land preparation and weed control and researchers managing treatment application, sowing and harvesting. In Burkina Faso, upland rice trials were conducted on land of a research station at Boni about 20 km northeast of Houndé and on-farm at Karaba about 7 km north of Houndé. The rainfall distribution was unimodal with seasonal precipitation of 800 and 950 mm year^{-1}. The trials sites were within 0.5° latitude band but separated by 2.3° longitude

Composite soil samples for the 0-0.2 m depth were collected for each replicate before fertilizer application, dried, sieved to 2-mm, and sent to the World Agroforestry Center Soil-Plant Spectral Diagnostic Laboratory in Nairobi, Kenya for analysis (https://www.worldagroforestry.org/sd/landhealth/soil-plant-spectral-diagnostics-laboratory/sops) (Table 1). The analysis was with mid-infrared spectral analysis. About 10% of the samples, with at least one sample per site, were analyzed by wet chemistry for calibration of the spectral analysis (Shepherd and Walsh, 2007; Terhoeven-Urselmans et al., 2010; Towett et al., 2015). Organic C and N were determined with a Thermal Scientific Flash 2000. Soil pH was measured in a 1:2.5 soil:water slurry. The nutrient extraction was by Mehlich-3 (Mehlich, 1984). A Horiba LA 950 Laser Scattering Particle Size Distribution Analyzer was used for the determination of particle size distribution.

In Mali, the soil organic C was 5 and 13 g kg^{-1} at Finkolo and Longorola, respectively, with soil pH 5.2 at both sites. The sites in Burkina Faso had 1% slope, 5.2-5.5 pH, <10 g kg^{-1} soil organic C, and low base availability.

Experimental design and agronomic practices

The treatments for all trials included five rates of N and four rates of P and K (Table 2). The N rate effect was evaluated with 0 and 15 (22.5 in Burkina Faso for 2014) kg ha^{-1} P uniformly applied. The N rate increments were 30 kg ha^{-1} with the exception of 25 kg ha^{-1} at Finkolo. The P and K rate increments were 7.5 and 10 kg ha^{-1}, respectively. A diagnostic treatment (Mg-S-Zn-B) containing NPK plus 15 kg ha^{-1} S, 2.5 kg ha^{-1} Zn, 10 kg ha^{-1} Mg, and 0.5 kg ha^{-1} B was included and compared to the treatment with the same NPK rates.

The experimental design was a randomized complete block design with three replicates. The plots were 6 × 3 m with 30 rows of 3-m length. In Burkina Faso, four adjacent trials were conducted with different varieties, and with and without 5 Mg ha^{-1} of manure applied and incorporated. The mean manure values were pH 7.8 and C:N ratio 17.0 kg kg^{-1} with contents of 206, 12, 4, and 21 g kg^{-1}, respectively, for C, N, P and K. The manure was broadcasted and incorporated before sowing. The trials in Mali were shifted to nearby sites for the 2015 trials but the 2015 trials in Burkina Faso used the same experimental units for study of the residual effect of manure.

The land was plowed to 0.2-m depth and harrowed except for Longorola where the land was plowed and plots were enclosed with bunds when the soil was well drained. The rice varieties used in Burkina Faso were FKR 45N, with 95 days to maturity, and WAB C165, with 90 days to maturity, for which nutrient responses were evaluated in adjacent trials. In Mali, 3- to 4-weeks old seedlings of SIK350-A15, with 120 days to maturity, were transplanted at Longorola. At Finkolo, NERICA4 with 105 days to maturity was directly sown. All varieties were *O. sativa* except for NERICA4 which was derived from hybridization of *O. sativa* and *O. glaberrima.* Sowing and harvest dates were reported in Table 1. Direct sowing was performed manually at 0.05-m depth. The sowing or transplanting points were spaced at 0.2 by 0.2 m for all trials. Weeds were controlled with manual hoeing at 3 and 6 week after sowing. In both countries, fertilizers were band applied 2 week after sowing of upland rice at least 5 cm from the rows and covered, but broadcast were applied and incorporated prior to transplanting of lowland rice. Nitrogen was split applied with 50% applied at panicle initiation. The nutrient sources were urea, triple super phosphate, potassium chloride, magnesium sulfate, zinc sulfate and borax.

Rice was harvested from a distance of 13 m^2 after excluding two borders rows at maturity in each plot. The harvest was dried, threshed, and milled to remove the grain hull. Grain yields were determined at 140 g kg^{-1} water content.

Data analysis

The analysis of variance to assess treatment effects and their

Table 1. Site and soil test properties for the 0 to 0.2 m depth, and sowing and harvest dates, for two sites each in Burkina Faso and Mali.

Properties[†]	Burkina Faso		Mali	
	Boni	**Karaba**	**Finkolo**	**Longorola**
Latitude, N	11.542	11.535	11.274	11.384
Longitude, W	3.346	3.543	5.304	5.662
Elevation, m	325	335	450	340
Mean monthly temperatures for August to December (°C)				
Maximum	32		32	
Minimum	19		15	
Soil properties				
Soil class	Luvisol	Luvisol	Lixosol	Fluvisol
pH, water†	5.2	5.5	5.2	5.2
OC, g kg^{-1}	3.8	6.0	5.4	13
Total N, g kg^{-1}	0.3	0.4	0.3	0.8
Mehlich3 P, mg kg^{-1}	19.7	13.8	31.0	6.9
S, mg kg^{-1}	11.7	10.8	11.7	16.7
K, cmol kg^{-1}	0.18	0.18	0.17	0.37
Ca, cmol kg^{-1}	1.45	2.78	1.9	3.9
Mg, cmol kg^{-1}	0.56	0.74	0.54	1.88
Na, cmol kg^{-1}	0.15	0.13	0.1	0.2
B, mg kg^{-1}	0.16	0.08	0.07	0.13
Mn, mg kg^{-1}	57.19	58.39	93.4	134.9
Zn, mg kg^{-1}	2.23	4.08	3.86	2.09
Clay, g kg^{-1}	310	373	292	786
Silt, g kg^{-1}	324	298	263	146
Textural class	Clay and loam	Clay and loam	Clay and loam	Clay
Sowing and harvest dates				
2014 sowing	30 July		14 July	17 July[‡]
2014 harvest	6 Nov		30 Oct	4 Dec
2015 sowing	22 July		13 July	26 July
2015 harvest	30 Oct		26 Oct	30 Nov

[†] Soil test values were means of composite soil samples taken by block. Nutrient extraction was by Mehlich-3. ‡Dates of transplanting for Longorola.

interactions was conducted by location across years for Mali, but by year and across varieties and manure rates in Burkina Faso due to differing P rate increments in 2014 and 2015. The N rate main and interaction effects were further analyzed for the sub-set of 10 N rate treatments. The effects of P and K rate and of Mg-S-Zn-B were evaluated using linear contrast tests.

When nutrient rate effects were signficant, fitting of curvilinear to plateau response functions was attempted, with yield (Mg ha^{-1}) = $a-bc^r$, where *a* was the yield at the plateau for that nutrient, *b* was the maximum gain in yield due to application of the nutrient, *c* was a curvature coefficient, and *r* was the nutrient rate. When the response was not curvilinear, a linear fitting was attempted with yield (Mg ha^{-1}) = $a + br$, where *a* was the yield at 0 kg ha^{-1}, *b* was the yield increase per kg ha^{-1} of nutrient applied, and *r* was the nutrient rate.

Data analyses were done using Statistix 10 (Analytical Software, Tallahassee, FL). Results were considered significant when $P \leq 0.05$.

The agronomic efficiency of nutrient use was calculated as the gain in crop yield per unit of nutrient applied (kg kg^{-1}). The economically optimal rate (EOR; kg ha^{-1}) of nutrient application was determined as the rate of maximum net return of fertilizer use or the rate where the value of yield gain due to a one kilogram increment in nutrient rate equals the cost per kilogram of nutrient use. The EOR were determined for nutrient use costs relative to on-farm grain value ratios equal to 3, 6, 9 and 12 (kg kg^{-1}). The profit:cost ratio (PCR) was calculated as the value of increased crop yield minus the cost of fertilizer nutrient use difference divided by the cost of fertilizer nutrient use.

RESULTS

In Mali, the mean 2014 and 2015 yields were, respectively, 2.4 and 1.9 Mg ha^{-1} for upland rice at

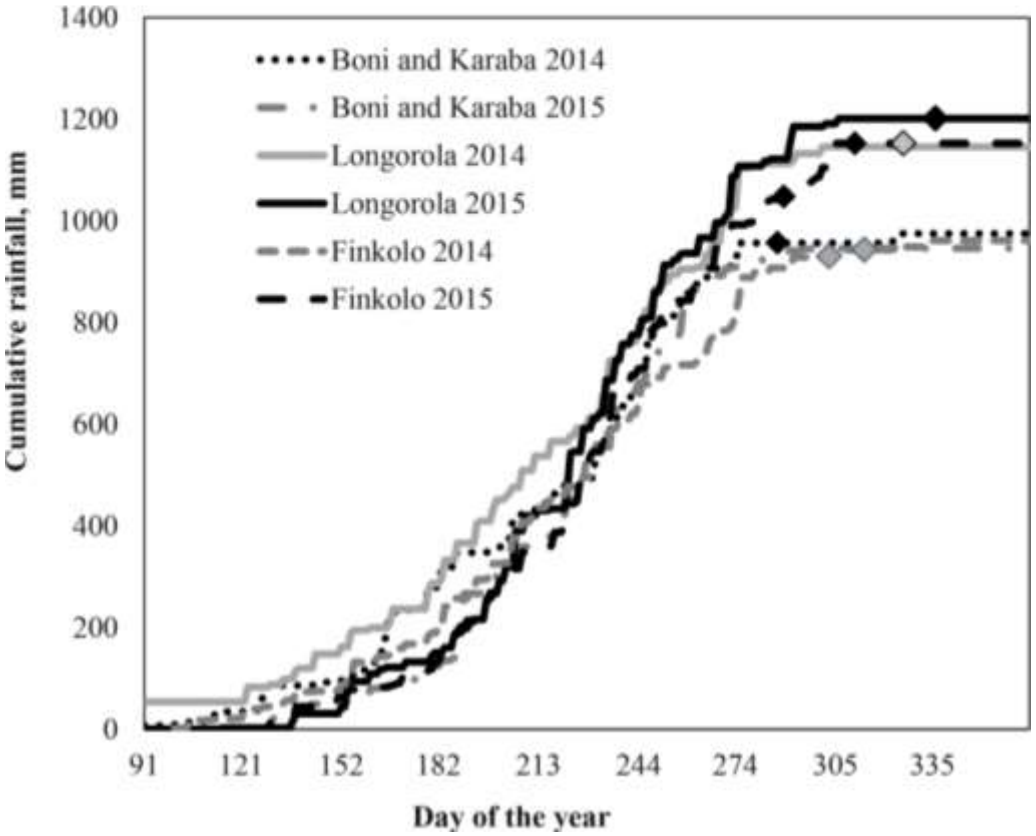

Figure 1. Cumulative rainfall for rainfed rice research site-years in Mali and Burkina Faso. The diamond symbols indicate the harvest dates.

Table 2. Treatment structure for rainfed rice nutrient response trials conducted in Burkina Faso and Mali.

Burkina Faso		Mali	
Boni	**Karaba**	**Longorola**	**Finkolo**
2014	**2015**	**2014-5**	**2014-5**
0-0-0	0-0-0	0-0-0	0-0-0
30-0-0	30-0-0	30-0-0	25-0-0
60-0-0	60-0-0	60-0-0	50-0-0
90-0-0	90-0-0	90-0-0	75-0-0
120-0-0	120-0-0	120-0-0	100-0-0
0-22.5-0	0-15-0	0-15-0	0-15-0
30-22.5-0	30-15-0	30-15-0	25-15-0
60-22.5-0	60-15-0	60-15-0	50-15-0
90-22.5-0	90-15-0	90-15-0	75-15-0
120-22.5-0	120-15-0	120-15-0	100-15-0
90-7.5-0	90-7.5-0	90-7.5-0	75-7.5-0
90-15-0	90-22.5-0	90-22.5-0	75-22.5-0
90-30-0	90-15-10	90-15-10	75-15-10
90-22.5-10	90-15-20	90-15-20	75-15-20
90-22.5-20	90-15-30	90-15-30	75-15-30
90-22.5-30	90-15-20-D	90-15-20-D	75-15-20-D
90-22.5-20-D			

The trials in Burkina Faso were with and without 5 Mg ha^{-1} of manure applied. The nutrient rate treatments refer to: N-P-K with D as the diagnostic treatment with N-P-K-S-Zn-Mg-B.

Table 3. The N rate effects on rainfed rice grain yield (Mg ha^{-1}) for two locations in Burkina Faso and in Finkolo, Mali.

N rate (kg ha^{-1})	Finkolo 2015	Finkolo Mean	N rate (kg ha^{-1})	Boni 2014	Boni 2015	Boni Mean	Karaba† 2015	Karaba† Mean
0	0.92	1.69	0	1.52	0.79	1.16	1.18	1.60
25	1.25	1.92	30	1.90	0.87	1.39	1.43	1.86
50	1.81	2.09	60	2.09	1.07	1.58	1.46	2.00
75	2.16	2.21	90	1.96	0.95	1.46	1.70	2.15
100	2.37	2.35	120	2.06	1.28	1.67	1.71	2.01
‡	***	*		*	*	*	***	*
a§	2.454	2.406	*a*	2.041	1.570	1.756	2.000	2.053
b	1.534	0.716	*b*	0.523	0.00585	0.601	0.809	0.453
c	0.982	0.982	*c*	0.951		0.986	0.991	0.961

The N x P rate interactions were not significant. In Burkina Faso, the N rate interactions with manure and variety and of NxP were not significant. †Yield was not affected by N rates at Karaba and Finkolo in 2014 and at Longorola in both years. ‡* and *** are significant at $P \leq 0.05$ and 0.001, respectively. §Grain yield responses to nutrient rate were curvilinear to plateau if coefficients *a, b, c* are present ($Y = a - bc^r$ with r = rate) or linear if only *a* and *b* are present.

Table 4. The P rate (kg ha^{-1}) effects on rainfed rice grain yield (Mg ha^{-1}) in Karaba, Burkina Faso†.

P rate (kg ha^{-1})	Karaba 2015	Karaba Mean
0	1.52	2.04
7.5	1.84	2.16
15	1.88	2.22
22.5	1.90	2.26
	*‡	ns
a	1.893	2.276
b	0.371	0.236
c	0.765	0.905

†Yield was not affected by P rates at Karaba in 2014 and at Boni, Finkolo, and Longorola in both years. ‡: ns and * are not significant and significant at $P \leq 0.05$, respectively. §: The *a, b, c* coefficients for the yield response to P functions $Y = a - bc^r$ with r = P rate.

Finkolo, and 2.8 and 1.9 Mg ha^{-1} for lowland rice at Longorola. In Burkina Faso, the mean 2014 and 2015 rice yields were, respectively, 2.0 and 1.0 Mg ha^{-1} at Boni, and 2.6 and 1.7 Mg ha^{-1} at Karaba.

The treatment x year interaction was significant at Finkolo due to no treatment effects in 2014 while there was a weakly curvilinear response to N in 2015 and across years (Table 3). Rice yield was not affected by P or K rate, or by Mg-S-Zn-B. In Longorola, fertilizer treatments did not affect lowland rice grain yield in either years.

At Boni, the N x P interactions were not significant (Table 3). There were no interactions of treatment with manure rate or variety. The P and K rate effects and the Mg-S-Zn-B effect were not significant for grain yield. The response to N was curvilinear in 2014, linear in 2015, and curvilinear for the means of 2014 and 2015 combined.

Rice yield at Karaba was not affected by treatments in 2014 but was affected by N and P rate in 2015 (Tables 3 and 4). The effects of K rate, Mg-S-Zn-B and interactions were not significant. The grain yield response to N rate was near linear in 2015 but curvilinear for the mean response across years. The P rate effect was curvilinear to plateau (Figure 2).

Depending on the cost of N use relative to grain value, the mean EOR for N ranged from 9 to 81 kg ha^{-1} for Finkolo, 10 to 45 kg ha^{-1} for Karaba, and 24 to 74 kg ha^{-1} for Boni (Figure 2). For Boni, N application was not profitable when the cost of N use per kilogram was equal to the value of 9 or more kilogram grain. Depending on the cost of P use relative to grain value, the mean EOR for P ranged from 6 to 20 kg ha^{-1} for Karaba.

The yield gains at EOR for N ranged from 0.11 to 0.55 Mg ha^{-1} with the greatest N cost effect at Finkolo (Table 5). The yield gains at EOR for P ranged from 0.11 to 0.21 Mg ha^{-1} at Karaba. The agronomic efficiency at EOR

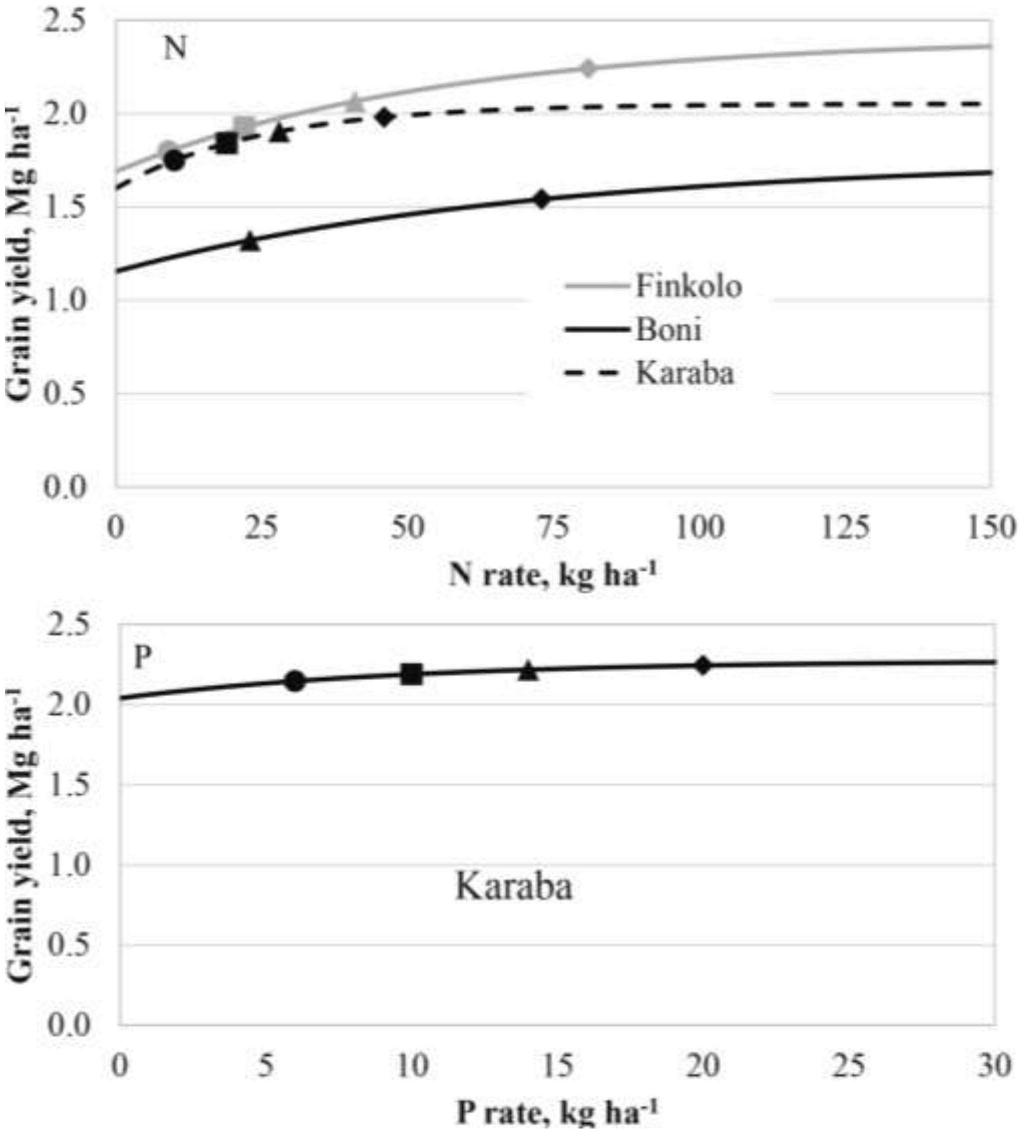

Figure 2. Rice grain yield responses to applied N at Boni and Karaba in Burkina Faso and Finkolo in Mali and to applied P at Karaba in Burkina Faso when the cost of nutrient use is equal to the value of 3 (♦), 6 (■), 9 (■), or 12 (●) kg of rice grain.

ranged from 4.6 to 14.9 kg kg^{-1} for N and from 10.4 to 16.0 kg kg^{-1} for P. The PCR at EOR in cases of significant response functions ranged from 0.00 to 1.79 \$ \$$^{-1}$ for N, and from 0.33 to 2.45 \$ \$$^{-1}$ for P at Karaba. If fertilizers were applied at 50% rather than 100% EOR, as might be the case for financially constrained farmers, the mean yield gain was reduced by 36% but for means AE it was increased by 23% and for mean PCR by 66%.

DISCUSSION

Crop-nutrient response data is required for profit optimization from fertilizer use. The on-station and on-farm research sites for the 20 trials of this study differed for soil properties and included Fluvisols, Luvisols and Lixisols with ranges of pH 5.2 to 5.5, Mehlich-3 P 6.9 to 31.0 mg kg^{-1} and Mehlich-3 K 0.18 to 0.37 cmol kg^{-1} (Table 1). The SOC was <10 g kg^{-1}, except at Longorola, and probably had little new organic material input to the soil in recent years due to crop residue harvest, grazing, or burning. Low soil pH may have constrained yield and response to nutrient application and the range of inference for the results should be limited to soil pH of <5.6. There were no yield responses to Mg-S-Zn-B indicating that deficiencies of these nutrients are not of concern for current rainfed rice production in Sudan Savanna. With irrigated lowland rice in Mali, but not in Niger, there were yield responses to Mg-S-Zn-B (Garba et al., 2018a) and there were occasional responses to Zn

Table 5. The effect of nutrient application at 100% compared with 50% of the economically optimal rate (EOR) on rice yield increase (Yield□), agronomy efficiency of nutrient use (AE), and profit to cost ratio (PCR) for rainfed rice at Finkolo in Mali and at Boni and Karaba in Burkina Faso.

CP	**Application at 100% EOR**				**Application at 50% EOR**			
	EOR	**Yield△**	**AE**	**PCR**	**EOR**	**Yield△**	**AE**	**PCR**
kg kg^{-1}	**kg ha^{-1}**	**kg ha^{-1}**	**kg kg^{-1}**	**\$ \$$^{-1}$**	**kg ha^{-1}**	**kg ha^{-1}**	**kg kg^{-1}**	**\$ \$$^{-1}$**
Nitrogen								
Finkolo								
3	81	552	6.8	1.27	40.5	373	9.2	2.07
6	43	388	9.0	0.50	21.5	231	10.7	0.79
9	20	218	10.9	0.21	10	119	11.9	0.32
12	9	108	12.0	0.00	4.5	56	12.4	0.04
Boni								
3	74	339	4.6	0.53	37	244	6.6	1.20
6	24	172	7.2	0.19	12	93	7.8	0.29
9	0				0			
12	0				0			
Karaba								
3	45	377	8.4	1.79	22.5	268	11.9	2.97
6	28	304	10.9	0.81	14	193	13.8	1.30
9	17	223	13.1	0.46	8.5	130	15.3	0.70
12	10	149	14.9	0.24	5	82	16.4	0.37
Phosphorus								
Karaba								
3	20	207	10.4	2.45	10	149	14.9	3.97
6	14	178	12.7	1.12	7	119	17.0	1.83
9	10	149	14.9	0.66	5	93	18.6	1.07
12	7	112	16.0	0.33	3.5	70	20.0	0.67

The results are in consideration of the cost of nutrient use per kg relative to the value of one kg of rice grain (CP).

and B in Nigeria (Daudu et al., 2017).

The rice grain yield was higher with lowland production at Longorola compared to the other sites but below the country mean yield for rainfed rice of 2.9 Mg ha^{-1} and far below the estimated potential yield of 6.1 Mg ha^{-1} (GYGA, 2017). The site captures runoff from the watershed that is retained within bunds. This water capture, together with high SOC and clay content compared with the upland sites, likely resulted in few or no occurrences of early and mid-season soil water deficits. However, rainfall ceased 50 to 60 days before harvest in both years and it is likely that yield was constrained by soil water deficit during grain filling (Figure 1). Rice is most sensitive to stress during the early reproductive stages but stress during grain filling is also important (O'Toole, 1982). The lack of more response to fertilizer at Longorola may also be due to the delivery of nutrients in the runoff captured from other parts of the watershed.

Nutrient response information suitable for estimation of response functions is scarce for rainfed lowland rice in Western Africa. However, irrigated lowland rice mean yield increases due to 80 kg ha^{-1} N were estimated to be: 2.34 Mg ha^{-1} and 105% for four trials in Burkina Faso (Segda et al., 2005; Segda et al., 2014); 1.37 Mg ha^{-1} and 40% for four trials in Nigeria (Daudu et al., 2017); 0.58 Mg ha^{-1} and 25% for three trials in Niger (Garba et al., 2018a); and 1.56 Mg ha^{-1} and 52% for two trials in Mali (Garba et al., 2018a). For the same irrigated lowland trials, the mean responses to 15 kg ha^{-1} P were estimated to be: 0.74 Mg ha^{-1} and 20% in Burkina Faso; 0 Mg ha^{-1} in Nigeria; 0.53 Mg ha^{-1} and 19% in Niger; and 0.92 Mg ha^{-1} and 20% in Mali. Similarly, the mean responses to 20 kg ha^{-1} K were estimated to be: 0.15 Mg ha^{-1} and 3% in Burkina Faso; 0.82 Mg ha^{-1} and 19% in Nigeria with much inconsistency; 0.00 Mg ha^{-1} in Niger; and 0.80 Mg ha^{-1} and 15% in Mali. The yields in these trials were much higher compared with Longorola. Alleviation of constraints to higher yield, other than nutrient deficiencies, is likely to increase response to applied nutrients at Longorola.

Rice responded to N at the three upland rice locations agreeing with other results indicating that N deficiency is a common constraint to upland rice yield (Okonji et al., 2012; Haefele et al., 2014; Kaizzi et al., 2014; Niang et al., 2017) (Table 3). The mean responses for each location fitted the curvilinear to plateau function. The yield responses to N were greater at Finkolo and Karaba compared with Boni where the yield with no fertilizer applied was relatively low (Table 5 and Figure 2). Therefore, the history of upland rice yield for a location may be an indicator of the potential response to N. For example, if yield without N applied is typically less than 1.5 Mg ha^{-1}, the potential for profitable response to N may be small.

A curvilinear to plateau response to P occurred at Karaba with about 60% of the potential response occurring with 10 kg ha^{-1} P applied and generally agreeing with results of Okonji et al. (2012) and Kaizzi et al. (2014) (Table 4). There was no response to P at Boni and Finkolo which had higher Mehlich-3 P compared with Karaba (Table 1). The response to 10 kg ha^{-1} P at Karaba was 0.15 kg ha^{-1} more grain yield (Table 5) compared with an average paddy yield response of 0.54 Mg ha^{-1} in Uganda where Mehlich-3 P mean was on average lower compared with Karaba.

The lack of response to K is consistent with upland rice results from Uganda (Kaizzi et al., 2014) and with results for other upland crops in Sudan and Sahel Savanna (Garba et al., 2017a; Garba et al., 2017b; Tarfa et al., 2017). With sufficient mitigation of other constraints to growth and much increased yield, response to applied K may occur as Mehlich-3 K was low for the upland rice sites.

Manure application and rice variety did not affect upland rice response to nutrients in Burkina Faso. Therefore, application of manure may increase yield with or without fertilizer application, but this would be an additive rather than a synergistic effect. Garba et al. (2018b) found additive effects of manure and fertilizer P application for Sudan Savanna but synergistic effects for Sahel Savanna. Kaizzi et al. (2014) also found that well-adapted upland rice varieties responded consistently to applied nutrients with no significant variety x treatment interaction.

The agronomic efficiency of nutrient use was low to moderate because of small yield responses to applied nutrients and, as expected, declined with increased nutrient rates (Table 5). For comparison, the agronomic efficiencies for N reported by Kaizzi et al. (2014) were determined to be 18 and 26 kg kg^{-1} for application of 60 and 30 kg ha^{-1} N, although this was for paddy yield. Fageria et al. (2014) also reported relatively higher agronomic efficiency for upland rice.

Profit considerations are very important to farmer decision making and especially for smallholders who are very constrained financially but account for most agricultural production in Sudan Savanna. Such farmers need profit to cost ratios >1 for an investment to compete with other uses of available finance (CIMMYT, 1988). Application of nutrients at 50% of EOR greatly improves the PCR but the PCR is still generally <1 if fertilizer use cost relative to grain value is relatively high. The results indicate that financially constrained farmers need to consider fertilizer use for rainfed rice production very carefully relative to alternative uses of available finance such as fertilizer use for other crops. Given the low EOR for N, application of all N at panicle initiation may reduce N losses and improve recovery and agronomic efficiency of fertilizer N. The farmer may also make the in-season N application conditional on observed crop performance until that time.

The results from this and other studies were used to develop a decision tool for Sudan Savanna that considers the farmer's land allocation to different crops and the amount of finance available for fertilizer use, the fertilizer use costs, and the grain values (http://agronomy.unl.edu/OFRA). The tool then gives the crop-nutrient-rate choices expected to maximize profit from fertilizer use.

Conclusions

The results indicate that K, Mg, S, Zn and B deficiencies are not constraining rainfed rice yield in the Sudan Savanna. Nutrient response functions for rainfed rice indicated profit potential from applied N for rainfed upland rice production in the Sudan Savanna but the results do not support N application for lowland production where stress due to soil water deficits during grain fill are likely to occur. However, the indicated profit potential is not great enough to be attractive to financially constrained farmers unless fertilizer N costs are uncommonly low relative to on-farm rice grain value and if applied at less than EOR. The profit potential for N application appears to be greater for fields if mean past yields were more compared with less than 1.5 Mg ha^{-1} unless other constraints to productivity are mitigated. Fertilizer P application resulted in increased grain yield for upland rice at only one of three locations and there were no responses to K suggesting that, unless other research results indicate otherwise, fertilizer P and K use does not have much profit potential for rainfed rice in Sudan Savanna. The results of this study do not justify fertilizer application for rainfed lowland rice production in the Sudan Savanna but are from a single location with two years of results with drought stress during grain fill. These results are from two years of research at one location and need to be considered with other nutrient response results in making fertilizer use decisions. Based on the results of this study, fertilizer N application for upland rice in the Sudan Savanna should be applied only if the yield history for the field indicates a high probability of >1.5 Mg ha^{-1} yield but should be limited to 25 kg ha^{-1} N unless fertilizer N use relative to grain value is uncommonly inexpensive. This N application should be at panicle initiation with no pre-plant application to minimize the risk of nitrate-N leaching loss. The in-season N application decision may also be in consideration of the observed yield potential of the crop. The results indicate that fertilizer P, K, Mg, S, Zn, and B should not be applied for upland rice in the Sudan Savanna if farm profits are of major concern. Even though the upland rice results are from 18 trials conducted at 3 locations, fertilizer use decisions for upland rice should consider not only these results, but also other results of other well-conducted field research, especially if soil pH is >5.5. Some investigation of the effect of lime application where soil pH is 5.2 may be justified, especially if pulses are in the crop rotation.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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ABBREVIATIONS

EOR, Economically optimal rate of nutrient application or the rate expected to maximize net return per hectare to nutrient application; **Mg-S-Zn-B,** a diagnostic treatment containing NPK plus 15 kg ha^{-1} S, 2.5 kg ha^{-1} Zn, 10 kg ha^{-1} Mg, and 0.5 kg ha^{-1} B; **PCR,** profit to cost ratio, or the net return divided by the cost of fertilizer nutrient use.

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