Received: 10 July 2019 | Accepted: 24 October 2019 | Published online: 16 February 2020

DOI: 10.1002/agj2.20006

Agronomy Journal

ARTICLE

Soil Tillage, Conservation, & Management

Lowland rice yield and profit response to fertilizer application in Rwanda

Nsharwasi Léon Nabahungu[1] | Athanase R. Cyamweshi[2] | John Kayumba[2] | Kintché Kokou[1] | Athanase Mukuralinda[3] | Jackson M. Cirhuza[1] | Charles S. Wortmann[4]

[1]International Institute of Tropical Agriculture, Bukavu, South Kivu, Democratic Republic of the Congo

[2]Rwanda Agricultural Board, P.O. Box 5016, Kigali, Rwanda

[3]World Agroforestry Centre, Kigali, Rwanda

[4]University of Nebraska-Lincoln, Agronomy and Horticulture, 279 Plant Science, Lincoln, NE 68583

Correspondence

Charles S. Wortmann, University of Nebraska-Lincoln, Agronomy and Horticulture, 279 Plant Science, Lincoln, NE 68583.
Email: cwortmann2@unl.edu

Funding information

Bill and Melinda Gates Foundation, Grant/Award Number: AGRA-SHP 1303; Alliance of a Green Revolution in Africa

Abstract

Rice (*Oryza sativa*) production in Rwanda increased by 70% while yield ha^{-1} decreased during the past decade. Yield has biotic and abiotic constraints including inadequate nutrient supply. Yield response functions for N, P, and K were determined in eight marshlands grouped into four clusters. Additional treatment allowed for the diagnosis of response to Mg–S–Zn–B (MgSZnB). Rice grain yield with no fertilizer applied was 2.27 Mg ha^{-1}. Mean yield increases were 2.35, 1.53, and 1.71 Mg ha^{-1} with N, P, and K application, respectively. The mean economically optimal rates (EOR) were 58 to >150, 11–30, and 21–35 kg ha^{-1} for N, P, and K, respectively, depending on cluster and the cost of fertilizer. Yield responses to nutrient rates were similar across marshland clusters, and a single response function for each of P and K can serve all four clusters, while the response to N differed for Cluster B compared with A, BC, and C. Net returns to applied P and K were greater than for N, but the application of N is likely needed for such responses to P and K. The MgSZnB resulted in a mean grain yield increase of 1.72 Mg ha^{-1} with increases in all marshlands, but the information was not sufficient to determine which nutrients of MgSZnB were deficient or their optimal application rates. Fertilizer use can be very profitable for rice production in Rwanda. Profit can be enhanced with the application at less than EOR when fertilizer use is financially constrained.

1 | INTRODUCTION

In Rwanda, lowland rice (*Oryza sativa*) cultivation is practiced between <1000- to 1800-m elevation with an average of 0.20–0.25 ha per farmer (Gasore, 2016). Rice production in Rwanda has increased by 70% over the last decade due to a 120% increase in production area, but with 24% less mean yield due to expansion to lands of marginal suitability for rice production (FAO CropStat, 2018). The mean yields for 2015–2017 were 3.33 Mg ha^{-1} season^{-1} with 31,700 ha of production, for a total production of 105,670 Mg yr^{-1}. Inappropriate fertilizer use and several other abiotic and biotic factors constrain yields (Diagne et al., 2013). The current blanket fertilizer recommendation of 80, 16, and 31 kg ha^{-1} N, P, and K, respectively, has been in use since the 1980s, lacks specificity for production conditions, and was developed for yield maximization rather than profit (Alivelu et al., 2006; Cyamweshi, Kayumba, & Nabahunga, 2017). Application of secondary and micronutrients is rare (Xu et al., 2017).

Abbreviations: AEZ, agro-ecological zone; CP, kg of rice grain required to equal the cost of 1 kg of nutrient use; EOR, economically optimal rate of nutrient application; MgSZnB, a diagnostic package of Mg, S, Zn, and B.

Farmers recognize the value of fertilizer use in Rwanda, but fertilizer use depends on availability, the farmer's financial ability, profit potential, dealer motivation and promotion, and tradition. Most farmers are financially constrained which affects fertilizer use decisions, thus making optimization of the profit from their investment in fertilizer use especially important (Jansen, Wortmann, Stockton, & Kaizzi, 2013). Flexibility in fertilizer use decisions is needed for a balance of economic, agronomic, and environmental concerns (Xia & Yan, 2012).

Most lowland rice production in sub-Saharan Africa is at <500 m elevation and very different from the production areas of Rwanda. Kulumuna, Masuki, Mkavidanda, & Wickama (2000) reported yield increases, averaged across four trials, of 2.34 Mg ha^{-1} with 50 kg ha^{-1} N and an additional 0.43 Mg ha^{-1} with 100 kg ha^{-1} N in the Sukuma land of Tanzania with a mean elevation of 1230 m. Similarly, in Ethiopia, the yield increases, averaged across four trials, were 0.98 Mg ha^{-1} with 50 kg ha^{-1} N and an additional 0.22 Mg ha^{-1} with 100 kg ha^{-1} N for a mean elevation of 1380 m (Anbessa & Dereje, 2018; Gebrekidan & Seyoum, 2006; Yesuf & Balcha, 2014). The mean response to P in Ethiopia averaged across two trials was 0.60 Mg ha^{-1} with 10 kg ha^{-1} P and an additional 0.15 Mg ha^{-1} with 20 kg ha^{-1} N for a mean elevation of 1380 m (Anbessa & Dereje, 2018; Gebrekidan & Seyoum, 2006).

Improved decisions for the optimization of fertilizer use for maximizing net returns on investment require good information derived from field research in the nature of crop response to applied nutrients. The objectives of the present research were to quantify the rice yield response to fertilizer N, P, and K, and a diagnostic package of Mg, S, Zn, and B (MgSZnB) for major marshland rice production areas in Rwanda, and to determine the economically optimal rates (EOR) and profit potential for N, P, and K application.

2 | MATERIALS AND METHODS

2.1 | Site characteristics

Fertilizer response trials were conducted in eight marshlands across four agro-ecological zones (AEZs), representing the main rice production areas of Rwanda, during 2014 and 2015 (Table 1; Figure 1). The AEZs were: the Imbo in Rusizi district of Western Province, the Central Plateau in Huye and Kamonyi districts of Southern Province, the Eastern Savanna in Gatsibo and Nyagatare districts of Eastern Province, and in the Nyanza district of Southern Province. The eight marshlands were: Bugarama in Rusizi district, Rusuli and Rwasave in Huye district, Rwagitima and Kanyonyomba in Gatsibo district, Cyabayaga in Nyagatare district, Mukunguri in Kamonyi district, and Nyarubogo in Nyanza district.

The marshlands were grouped according to past rice yield records into four clusters. Cluster A had the highest yield with sites at Nyarubogo and Bugarama. Kanyonyomba represented Cluster B with intermediate yield. Rwagitima, Cyabayaga, Mukunguri, and Rwasave were in Cluster BC. Rusuli represented Cluster C with the lowest yield.

All marshlands had bimodal rainfall with rice production seasons of approximately February–July and August–January (Table 1). The rainfall of the growing seasons, including the month prior to sowing, ranged from less than 450 mm at Cyabayaga in 2014 and 2015 to 620 mm at Rwasave in 2014 and 2015 (Figure 2). The mean temperature of the month prior to sowing ranged from <20°C at Mukunguri in 2014 to 21.3°C at Cyabayaga in 2014 and 2015. The elevation ranged from 998 to 1706 m, and the major soil groups were Cambisol and Ferralsol at three sites each and Acrisol and Nitosol at one site each.

Composite soil samples were collected from the 0- to 20-cm depth for each replication prior to application of fertilizer and analyzed for texture and chemical properties (Table 2). The analyses were done at the World Agroforestry Center Soil–Plant Spectral Diagnostic Laboratory in Nairobi, Kenya (https://www.worldagroforestry.org/sd/landhealth/soil-plant-spectral-diagnostics-laboratory/sops). The analysis was performed with mid-infrared spectral analysis, complemented by wet chemistry analysis of about 10% of the samples for calibration of the spectral analysis (Shepherd & Walsh, 2007; Terhoeven-Urselmans, Vagen, Spaargaren, & Shepherd, 2010; Towett, Shepherd, Sila, Aynekulu, & Cadisch, 2015). Organic C and N were determined with a Thermal Scientific Flash 2000 (Thermo Fisher Scientific, Walton, MA). Soil pH was measured in a 1:2.5 soil/water slurry. Available P, exchangeable bases, and available micronutrients were extracted by Mehlich 3 (Mehlich, 1984). An LA 950 Laser Scattering Particle Size Distribution Analyzer (Horiba, Kyoto, Japan) was used for determination of particle size distribution. The soils were mostly sandy clays. Soil property ranges included: pH of 5.1–6.5; 20.0–38.1 g kg^{-1} soil organic C; 13.2–19.7 C/N; 0.07–0.44 cmol$_c$ kg^{-1} K; 2.0–18.1 mg kg^{-1} P; 1.7–3.4 mg kg^{-1} Zn; and 0.04–0.34 mg kg^{-1} B (Table 2).

2.2 | Experimental design, crop management

The experiments had an incomplete factorial design with 15 treatments for the determination of response functions for N, P, and K (Table 3). One treatment was added to determine the response to MgSZnB. Trials had five N levels, with 30 kg ha^{-1} increments, evaluated with 0 or 15 kg ha^{-1} of uniformly applied P. There were four levels of P with 7.5 kg ha^{-1} increments with a uniform application of 90 kg ha^{-1} N, and four level of K with 10 kg ha^{-1} increments with a uniform

TABLE 1 Marshland characteristics with planting and harvest dates for trials conducted to evaluate rice response to applied nutrients in Rwanda. Clusters were pre-determined according to rice yield potential, based on past yields, in four clusters with A representing the highest and C the lowest yield potential

				Elev		Trials of 2014 and 2015			
Marshland	**Cluster**	**Lat**[a]	**Long**	**m**	**Soil**	**Plant**	**Harvest**	**Plant**	**Harvest**
Nyarubogo	A	−2.434	29.919	1365	CM	25 Feb. 2014	7 July 2014	8 Aug. 2014	14 Jan. 2015
Bugarama	A	−2.678	29.024	998	NTh	24 Feb. 2014	7 July 2014	15 Aug. 2014	1 Jan. 2015
Kanyonyomba	B	−1.794	30.376	1455	FR	18 Feb. 2014	13 July 2014	18 Aug. 2014	20 Jan. 2015
Rwagitima	BC	−1.668	30.478	1473	FR	25 Feb 2014	7 July 2014	18 Aug. 2014	20 Jan. 2015
Cyabayaga	BC	−1.404	30.279	1352	FR	28 Feb. 2014	25 July 2014	20 Aug. 2014	14 Jan. 2015
Mukunguri	BC	−2.142	29.928	1384	CM	25 Feb. 2014	7 July 2014	7 Apr. 2014	11 July 2014
Rwasave	BC	−2.585	29.755	1653	CM	14 Feb. 2014	29 July 2014	26 Aug. 2014	20 Feb. 2015
Rusuli	C	−2.480	29.754	1706	AC	15 Aug. 2014	13 Feb 2015	26 Aug. 2014	20 Feb. 2015

[a]Lat, latitude (from WGS 84); Long, longitude (from WGS 84); Elev, elevation; Soil, soil type by FAO (Jones, 2013); Plant, planting date; Harvest, harvest date; CM, undifferentiated Cambisol; NTh, humic Nitosol; FR, undifferentiated Ferralsol; AC, undifferentiated Acrisol.

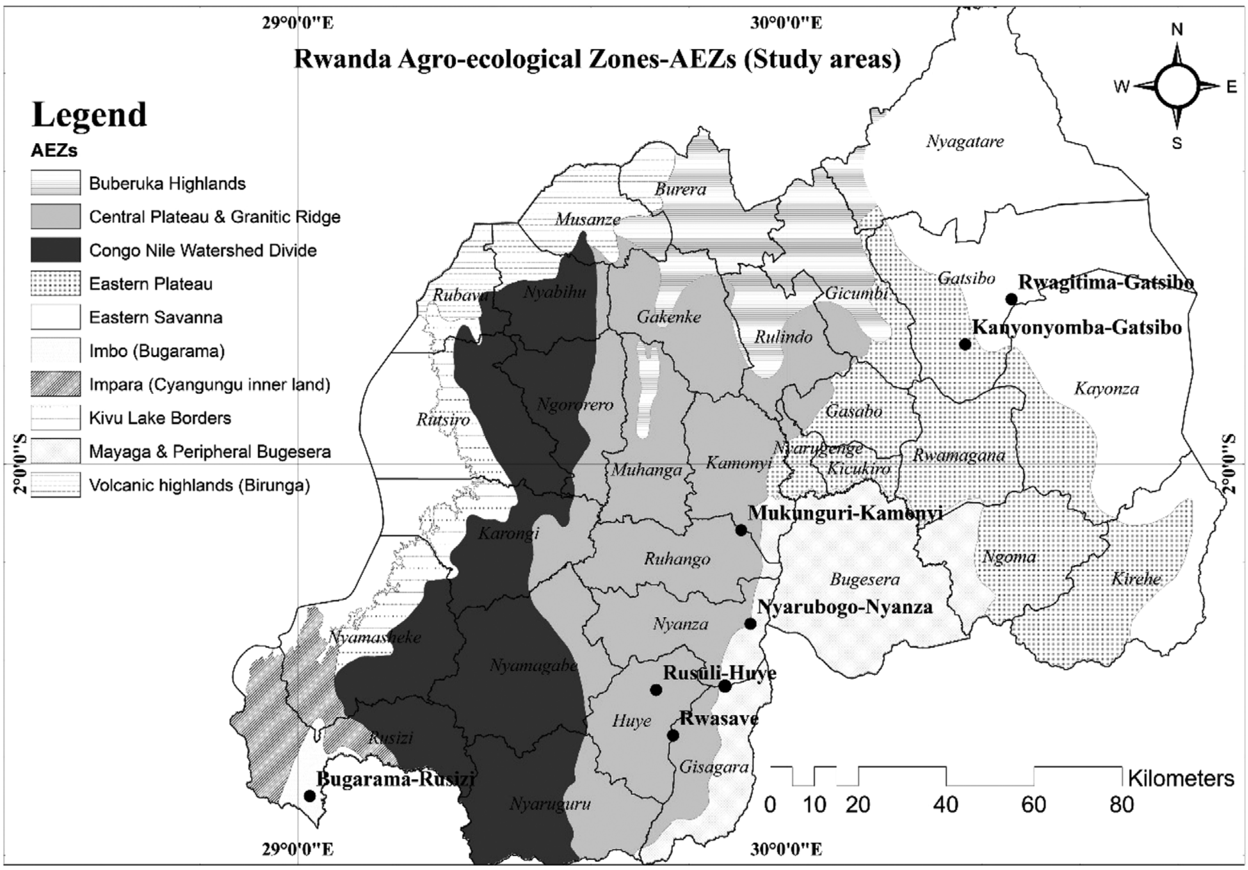

FIGURE 1 Rwandan agro-ecological zones (AEZs) with research site indicated by •

application of 90 kg ha^{-1} N and 15 kg ha^{-1} P. The MgSZnB treatment contained 90, 15, 20, 10, 15, 2.5, and 0.5 kg ha^{-1} of N, P, K, Mg, S, Zn, and B, respectively, and was compared to the treatment of the same N–P–K rates. On-station trials had three replications per marshland, with 2, 1, 3, and 1 on-station trials for Clusters A, B, BC, and C, respectively. On-farm trials had four or more replications with each replication in a different field with total replications of 11, 6, 14, and 13 for Clusters A, B, BC, and C, respectively. Plots were 4-m wide and 6-m long with access alleys. Some on-farm trials had smaller plots due to small fields. The area harvested for yield determination was 4 m^2. Trials were planted on different land each year to avoid residual effects of fertilizer treatments.

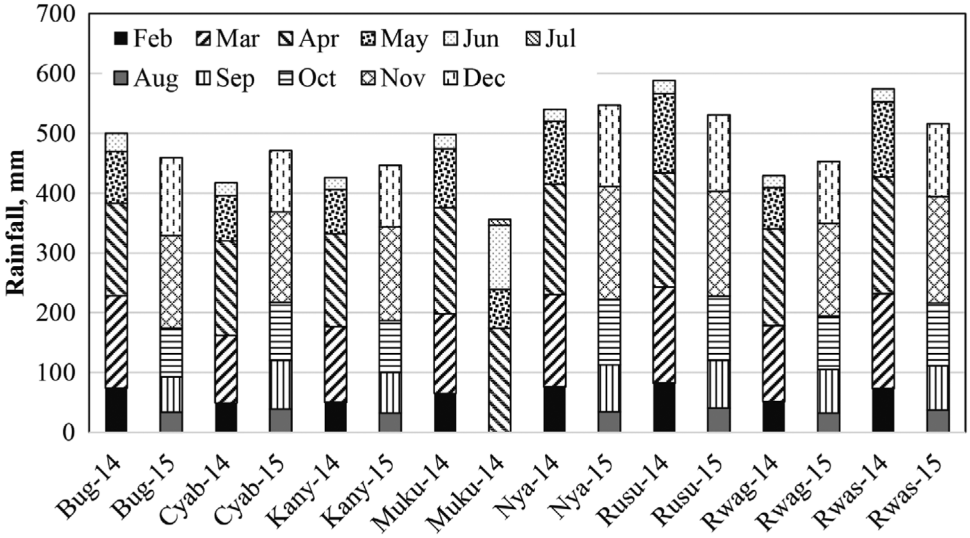

FIGURE 2 Rainfall for eight marshlands of Rwanda for determination of rice response to applied nutrients. Bug, Bugarama; Cyab, Cyabayaga; Kany, Kanyonyomba; Muku, Mukunguri; Nya, Nyaburogo; Rusu, Rusuli; Rwag, Rwagitima; Rwas, Rwasave

TABLE 2 Soil properties determined from composite soil samples and averaged across three or more replications, for the 0–20-cm depth of eight marshlands grouped into four clusters in Rwanda to determine nutrient responses for rice. All soils were sandy clay

		C	N	K	Ca	Mg	P	S	Zn	B
Marshland	pH	g kg^{-1}		cmol$_c$ kg^{-1}			mg kg^{-1}			
Nyarubogo	6.2	25.7	1.4	0.34	11.01	3.87	8.2	31.1	1.7	0.3
Bugarama	6.5	35.4	2.0	0.38	19.34	8.14	7.6	34.8	3.4	0.3
Kanyonyomba	5.3	20.2	1.3	0.18	6.72	2.71	10.4	50.3	2.8	0.2
Rwagitima	5.8	38.1	2.4	0.38	17.88	5.29	15.1	228.5	3.2	0.7
Cyabayaga	5.4	30.0	2.4	0.44	8.61	2.41	18.1	79.8	3.4	0.3
Mukunguri	5.5	29.2	2.4	0.41	8.55	2.21	12.3	87.9	2.7	0.3
Rwasave	5.1	34.2	2.3	0.07	4.95	1.48	3.7	39.4	2.5	0.1
Rusuli	5.1	26.8	1.8	0.11	3.83	1.19	2.0	36.5	2.5	<0.1

TABLE 3 Treatments for determination of nutrient response functions for lowland rice in Rwanda

Treatment	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15[a]
N, kg ha^{-1}	0	30	60	90	120	0	30	60	90	120	90	90	90	90	90
P, kg ha^{-1}	0	0	0	0	0	15	15	15	15	15	7.5	22.5	15	15	15
K, kg ha^{-1}	0	0	0	0	0	0	0	0	0	0	0	0	10	20	30

[a]Treatment 16 was a diagnostic treatment (Mg–S–Zn–B) that contained 90–15–20–10–15–2.5–0.5 kg ha^{-1} of N–P–K–Mg–S–Zn–B and was compared to Treatment 14 for determination of the Mg–S–Zn–B effect.

All trial fields had bunds enclosing plots to prevent runoff and were irrigated according to water need or availability by flooding from delivery canals. Cooperating farmers did bund maintenance, land preparation, sowing, and weed control for on-farm trials. Research teams conducted or supervised trial layout, treatment application, harvest, and other data collection. The rice cultivar was Yun Yin. Transplanting of 21-day old seedlings was at 20- by 20-cm spacing. Hand hoe-weeding was done twice. No pesticides were applied.

Nutrient sources were urea for N (460 g kg^{-1} N), triple superphosphate for P (200 g kg^{-1} P), muriate of potash for K (500 g kg^{-1} K), magnesium sulfate for Mg and S (150 g kg^{-1} Mg; 220 g kg^{-1} S), zinc sulfate for Zn and S (340 g kg^{-1} Zn; 180 g kg^{-1} S), and borax for B (145 g kg^{-1} B). All fertilizer was broadcast applied and incorporated before planting except for urea which was split-applied with 50% at preplant and 50% at tillering for the 30 and 60 kg ha^{-1} rates, and with a three-way split at preplant, tillering, and panicle initiation for

the 90 and 120 kg ha^{-1} rates. The MgSZnB was applied as a mixture of these fertilizers. The land was tilled before sowing.

2.3 | Data collection and analysis

At maturity, harvest began with manually cutting the heads from the stems using knives. The heads were air-dried, threshed, and winnowed. The paddy grain was weighed, tested for grain water content and paddy grain yield (hereafter referred to as grain yield), and water content was determined at 14 g kg^{-1}.

The analysis of variance (ANOVA) was combined across marshland clusters using Statistix 10 software (Analytical Software, Tallahassee, FL) after confirming trial variance homogeneity. Replications within trials and sites within clusters and their interactions were treated as random effects which were included in the residual of the ANOVA. The N rate main and interaction effects were further analyzed by ANOVA for the first 10 treatments (Table 4). Orthogonal contrasts were used to test for quadratic effects of P and K rates, and for the effect of MgSZnB on yield. These tests were done across marshland clusters as the P, K, and diagnostic treatments did not have significant interaction with marshland cluster. Treatment effects were considered statistically significant at $P < .05$. The percent of sum of squares due to the sources of variance of nutrient treatments and their interactions was determined.

Response functions for N, P, and K were determined for significant nutrient rate effects by fitting a curvilinear to plateau asymptotic function expressed as: Yield (Mg ha^{-1}) = $a - bc^x$. The coefficient a was yield at the plateau for the nutrient application, b was the maximum increase in yield due to the nutrient application, c determined the shape of the response curve, and x was the nutrient application rate.

The EOR was determined as the nearest full kg ha^{-1} of nutrient applied beyond which the value of the yield increase was less than the cost of added nutrient, understanding that the cost of nutrient use was inclusive of the purchase cost, other procurement costs, application costs, and financial credit or opportunity costs. Therefore, EOR was the point where marginal cost equaled marginal revenue. The nutrient use cost was expressed in terms of kg of rice grain required to equal the cost of 1 kg of nutrient use (CP; kg kg^{-1}) with CP of 5, 9, 13, and 17 kg kg^{-1} used to determine the sensitivity of EOR to fertilizer costs relative to grain value. For example, CP = 5 kg kg^{-1} when the cost per kg of nutrient use was equal to the value of five kg of rice paddy grain.

Further economic analyses were conducted to determine the net returns per investment in a nutrient application at 100 and 50% of EOR using N, P, and K response functions combined across clusters. These analyses were performed with a CP of 9 kg kg^{-1} for N (US \$2.70 kg^{-1} N) and a CP of 13 kg kg^{-1} for P and K (\$3.90 kg^{-1} P or K) while rice paddy grain was valued at \$0.30 kg^{-1}. Using fertilizer N as an example, the investment or cost at 100% of EOR was EOR ha^{-1} times \$2.70 kg^{-1} N. The net return or profit due to N application at 100% EOR was equal to the value of the yield gain due to N application (kg ha^{-1} yield gain times \$0.30 kg^{-1}) minus the investment in N application. The profit divided by the cost gave the profit/cost ratio at 100% EOR. Similarly, the profit/cost ratio was determined for N applied at 50% EOR.

TABLE 4 Analysis of variance for rice grain yield in Rwanda including percent of treatment-related variation due to each treatment source

Source of variation	*df*	% of variance	*P > f*
Season (SN)	1		ns[a]
Cluster (CL)	3		***
N rate (N)	4	89.4	***
P rate (P)	3	5.8	***
K rate (K)	3	2.3	***
SN × CL	3		***
SN × N	4	0.9	***
CL × N	12	0.5	***
SN × P	3	0.1	ns
CL × P	9	0.2	ns
N × P	12	0.1	ns
SN × K	3	0.1	*
CL × K	9	0.1	ns
SN × CL × N	12	0.1	ns
SN × CL × P	9	0.0	ns
SN × N × P	12	0.0	ns
CL × N × P	36	0.4	***
SN × CL × K	9	0.0	ns
SN × CL × N × P	36	0.1	ns
Residual	784		
Total	964		

*Significant at the .05 probability level.
***Significant at the .001 probability level.
[a]ns, nonsignificant.

3 | RESULTS

3.1 | Agronomic results

The mean rice grain yields in Rwanda were 5.06, 4.70, 4.60, and 4.28 Mg ha^{-1} at marshland Clusters A, B, BC, and C, respectively. The yield was affected by N, P, and K rate; cluster; MgSZnB; and by the interactions of season × cluster, season × N, cluster × N, season × K, and cluster × N × P (Table 4).

TABLE 5 Rice grain yields in Rwanda as affected by N rate, averaged across 0 and 15 kg ha^{-1} P uniformly applied, and the yield response to the application of a nutrient package of Mg, S, Zn, and B (MgSZnB), and the coefficients of asymptotic response functions of yield (y) response to N with $y = a - bc^N$, where a is the yield at the asymptote or yield plateau, b is the maximum gain in yield due to N application, and c^N determines the shape of the response curve where c is a curvature coefficient and N is the N rate (kg ha^{-1})

	N rate, kg ha^{-1}									
	0	30	60	90	120	MgSZnB	*a*	*b*	*c*	r^2
Clusters	Mg ha^{-1}									
A	2.73	3.86	4.73	5.26	5.27	1.61	5.73	3.03	0.982	.99
B[a]	2.54	2.89	4.07	4.85	5.06	2.13	10.13	7.73	0.996	.96
BC	2.52	3.41	4.26	4.87	4.63	1.68	5.14	2.67	0.982	.96
C	2.27	3.15	3.63	4.45	4.47	1.46	5.44	3.18	0.989	.98
Combined	2.51	3.33	4.17	4.76	4.86	1.72	5.74	3.27	0.988	.99

[a]The near linear response for cluster B could also be represented by $y = 2.482 + 0.0233N$, $r^2 = .95$.

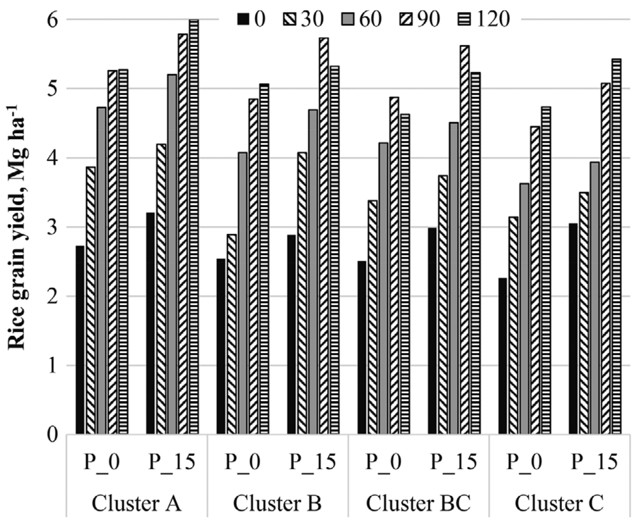

FIGURE 3 The N × P × marshland cluster interaction affected rice yield response to N rates with 0, 30, 60, 90, and 120 kg ha^{-1}, with 0 or 15 kg ha^{-1} P applied, in Rwanda. The LSD$_{.05}$ for the three-way interaction was 0.66 Mg ha^{-1}

The mean yield increase with 120 kg ha^{-1} N was 2.35 Mg ha^{-1} (Table 5). The N × P interaction was not significant (Table 4), but the cluster × N × P interaction occurred because yield increases with N increments >60 kg ha^{-1} were relatively small for Clusters A and BC with 0 kg ha^{-1} P, but relatively greater for Cluster C with 15 kg ha^{-1} of uniformly applied P. While statistically significant, this three-way interaction was not of agronomic significance as it accounted for just 0.4% of the treatment-related variation in grain yield while N and P rates accounted for 96% of the variation.

The marshland cluster × N interaction was significant with a relatively large response to N for Cluster A and relatively low response for Cluster BC (Table 4; Figure 3). Differing shapes of responses, such as a nearly linear increase with N rate for Cluster B compared to the other clusters with very similar curvilinear responses, contributed to the cluster × N interaction (Table 5; Figure 4). While there may be justification for a

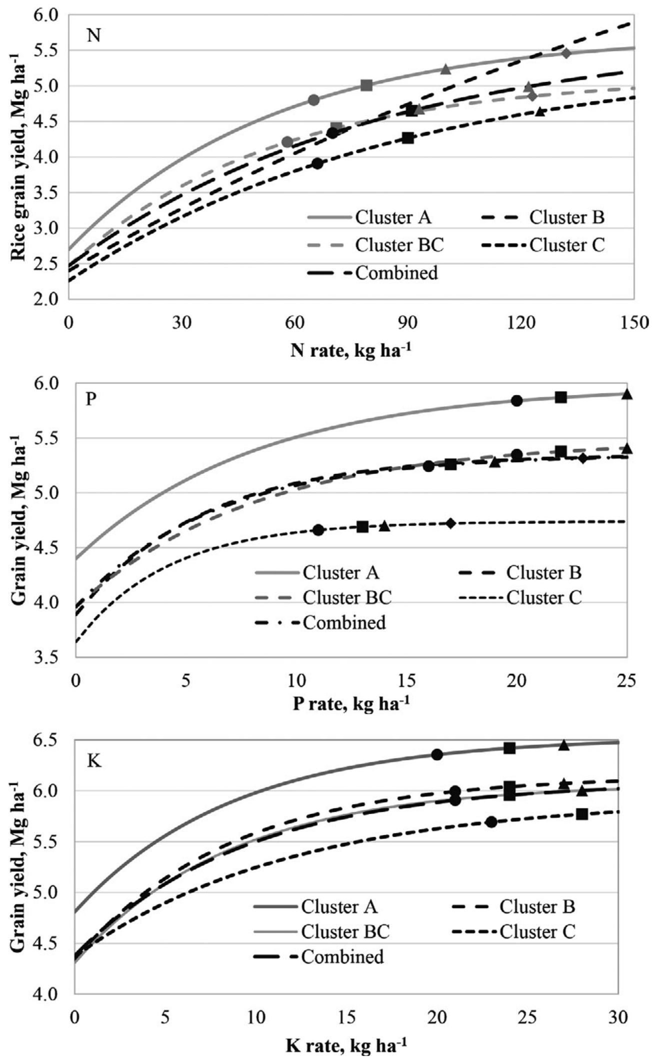

FIGURE 4 Rice grain yield response to N, P, and K application in Rwanda by marshland cluster of sites as determined from functions presented in Tables 5 and 6. The nutrient rates for maximizing profit per hectare are indicated for the cost per kg of nutrient use equal to 5 (diamond), 9 (filled triangle), 13 (square), and 17 (circle) kg of rice grain. Response to P and K for Cluster BC is overlain by the combined response

TABLE 6 Rice grain yields in Rwanda as affected by P and K rate and the coefficients of asymptotic response functions of yield (y, Mg ha^{-1}) response to P or K with $y = a - bc^N$, where a is the yield at the asymptote or yield plateau (Mg ha^{-1}), b is the gain in yield (Mg ha^{-1}) due to P or K application, and c^N represents the shape of the response curve where c is a curvature coefficient and N is the P or K rate (kg ha^{-1})

Cluster	P rate, kg ha^{-1}				Coefficients			
Phosphorus	**0**	**7.5**	**15**	**22.5**	***a***	***b***	***c***	***r*²**
	Mg ha^{-1}							
A	4.37	5.52	5.40	6.06	5.98	1.58	0.886	.89
B	3.88	5.05	4.99	5.48	5.35	1.46	0.842	.93
BC	3.92	5.06	4.87	5.58	5.48	1.52	0.885	.85
C	3.64	4.59	4.58	4.83	4.74	1.10	0.788	.98
Combined	3.95	5.05	4.96	5.48	5.35	1.39	0.852	.91
	K rate, kg ha^{-1}							
Potassium	**0**	**10**	**20**	**30**	***a***	***b***	***c***	***r*²**
	Mg ha^{-1}							
A	4.82	5.94	6.45	6.42	6.53	1.72	0.892	.99
B	4.35	5.54	6.09	6.03	6.15	1.81	0.890	.99
BC	4.31	5.50	5.94	5.99	6.07	1.76	0.890	1.00
C	4.05	4.87	5.38	5.42	5.92	1.55	0.920	.99
Combined	4.38	5.46	5.96	5.97	6.09	1.71	0.899	.99

response function specific for Cluster B, the cluster × N interaction accounted for just 0.5% of the variation in grain yield while N rate overall accounted for 89.4% of the variation. The overall response to N rate in Rwanda was Yield = 5.74 − (3.27)(0.988^{N}) which was similar to the responses for Clusters A, BC, and C.

The P and K interactions with marshland cluster were not significant, but the main effects of P and K rate and the season × K interaction were significant for grain yield (Table 4). The responses to P and K fit asymptotic response functions. Grain yield increased in response to 22.5 kg P ha^{-1} but there was not a significant response to 30 compared with 20 kg ha^{-1} K (Table 6). The lack of P and K rate interactions was due to near parallel response curves even though yield levels differed (Figure 4). The season × K interaction was of little agronomic significance as it accounted for only 0.1% of the treatment effects on yield. The response to P combined across clusters was represented by Yield = 5.35 − (1.39)(0.852^{P}) and response to K was represented by Yield = 6.09 − (1.71)(0.899^{K}). Soil test P indicated low availability for most sites, and soil test K indicated low availability at Kanyonyomba, Rwasave, and Rusuli.

The MgSZnB resulted in a significant rice grain yield increase for all four marshland clusters with an overall yield increase of 1.72 Mg ha^{-1} compared to 90–15–20 N–P–K kg ha^{-1} (Table 5). Response to MgSZnB was not well-related to soil test values, and the available data were not sufficient to determine which of the four diagnostic nutrients was most limiting of yield. Critical values for soil test nutrient availability with Mehlich 3 extraction have not been verified for tropical soils of Africa (Garba, Serme, & Wortmann, 2018a). Considering critical values determined elsewhere, however, the soil test results indicate generally adequate Mg and S availability, but low availability of Zn for all sites, and low B at Kanyonyomba, Rwasave, and Rusuli (Wortmann et al., 2019).

3.2 | Economic results

The EOR of N ranged from 58 to >150 kg ha^{-1} N depending on the cluster and CP for N use (Figure 4). The highest experimental N rate was 120 kg ha^{-1}, and caution prevented extending the range of inference for the response functions beyond 150 kg ha^{-1} N. The EOR of N for Clusters B and C, and combined across clusters, were high compared with Clusters A and BC. The range of EOR for P was from 11 to 30 kg ha^{-1} and relatively low for Cluster C compared with other clusters. The EOR for K was from 21 to 35 kg ha^{-1} with variation due to CP, but was consistent across clusters.

Using the response functions combined across clusters, the grain value of \$0.30 kg^{-1}, and fertilizer use costs of \$2.70 kg^{-1} N and \$3.90 kg^{-1} P or K, the EOR were 122 kg ha^{-1} N, 17 kg ha^{-1} P, and 23 kg ha^{-1} K. The corresponding profit/cost ratios were 1.30 for N, 4.01 for P, and 3.53 for K. Application of N, P, and K at EOR is expected on average to increase grain yield by 5.37 Mg ha^{-1} with an investment of \$485 ha^{-1} for an overall profit/cost ratio of 3.3.

A financially constrained farmer may apply the same amount of N, P, and K at 50% EOR to twice the amount of land. At 50% EOR, the profit/cost ratios were 2.1 for N,

7.1 for P, and 6.0 for K. The average yield increase at 50% EOR was expected to be 3.94 Mg ha^{-1} with an investment of \$242.5 ha^{-1}. Therefore with the \$485 of fertilizer applied at 50% EOR to 2 rather than 1 ha, the total grain yield increase was calculated to be 7.89 Mg ha^{-1} with a profit/cost ratio of 4.9, a gain of 48% compared with the application at 100% EOR.

4 | DISCUSSION

The overall mean yield increase with N application across the four marshland clusters was 2.35 Mg ha^{-1} (Table 5). These results confirm the prevalence of low soil N availability as a constraint to rice yield (Garba, Dicko, Kamissoko, Maman, & Wortmann, 2018b). The response to 120 kg ha^{-1} N was relatively great compared with irrigated rice yield increases of 1.36 Mg ha^{-1} in Nigeria (Daudu et al., 2018), 1.27 Mg ha^{-1} in Niger, 1.64 Mg ha^{-1} in Mali (Garba et al., 2018b), and 1.66 Mg ha^{-1} in Tanzania (unpublished data).

The observed differences in yield and response to applied N between sites and marshland clusters could not be explained by variations in soil properties, although low soil pH and nutrient availability for Cluster C was associated with relatively low yield and low response compared with the means for other clusters (Table 2). However, Cluster C was also at a high elevation where the rice variety may be less adapted compared with lower elevations. Response to N tended to be greater where soil organic C was higher, implying little mineralization of soil organic N but other potential benefits such as improved water infiltration and slightly improved available water holding capacity may have affected response (Minasny & McBratney, 2017). The variation in the N response combined across P rates and across marshland clusters (Tables 4 and 5; Figure 4) indicates that Cluster B needs to have its own N recommendation and that a single N response function can be applied across Clusters BC, C, and A.

Yield increase and profit potential with fertilizer K and P were similar, which contrasts with results from Mali, Niger, Nigeria, and Tanzania. Garba et al. (2018b) reported mean yield increases in Niger and Mali of 0.55 and 1.40 Mg ha^{-1}, respectively, due to 22.5 kg ha^{-1} P and 0 and 0.045 Mg ha^{-1} with 30 kg ha^{-1} K. There was not a consistent rice grain yield response to P and K in Nigeria (Daudu et al., 2018). In Tanzania, the mean grain yield response to 22.5 kg ha^{-1} P was 0.44 Mg ha^{-1} but no results were reported for response to K (unpublished data). The lack of interaction of P and K rates with marshland clusters indicated that response functions determined from the combined data can serve all clusters.

Response to MgSZnB was relatively great in Cluster B and low in Cluster C but great enough for all clusters to have profit potential. The relatively low response in Cluster C was likely not due to the relatively low soil test availability of these nutrients (Tables 2 and 5) and such a lack of relationship of soil test information with response agrees with findings for upland crops and lowland rice (Kihara et al., 2016; Garba et al., 2018a; Steusloff, Nelson, Motavalli, & Singh, 2019). Daudu et al. (2018) reported lowland irrigated rice response to Zn in one of four trials but no response to MgSB. Cyamweshi et al. (2018) found that 50% of the MgSZnB rates used in this study were sufficient to achieve 90% of the potential wheat (*Triticum aestivum*) response to these nutrients in Rwanda.

The EORs were affected by fertilizer use cost relative to grain value. As the cost per kg of nutrient use increased from the equivalent of 5 to 17 kg grain value, the mean EOR decreased from 122 to 78 kg ha^{-1} of N, 24 to 16 kg ha^{-1} P and >30 to 22 kg ha^{-1} K (Figure 4). The cost of fertilizers in sub-Saharan Africa is commonly high (Sanchez, 2002), and exacerbated by the very high opportunity cost of money for resource-poor farmers (Wortmann & Ssali, 2001). The returns to fertilizer use by smallholder farmers are variable with significant risk. Financial constraints often cause farmers to sell at harvest when commodity prices are low compared with several months later, and this further reduces the profitability of fertilizer use (Nkonya, Kaizzi, & Pender, 2005). Therefore, Jansen et al. (2013) and Cyamweshi et al. (2017) suggested that decisions for financially constrained fertilizer use need to consider crop-nutrient-rate choices not only for rice but all crops important to the farmer for profit optimization. For example, the profit to cost ratio for high and low cost fertilizer applied at EOR to wheat ranged from 0.2 to 1.8 for N, 1.0 to 3.3 for P, and 0.5 to 2.0 for K (Cyamweshi et al., 2018). Similar ranges for bush and climbing bean (*Phaseolus vulgaris*) in Rwanda were, respectively, 1.0–3.3 and 1.1–3.6 for N, 1.4–4.1 and 1.7–5.0 for P, and 2.4–6.2 and 1.3–4.0 for K (Kaizzi et al., 2018).

While the rice yield increase is greater with N than with P and K, higher rates of N are required and profit potential appears to be greater with P and K than with N (Figure 4). For example, \$40 ha^{-1} invested in P and K application was estimated to give a profit/cost ratio of 6, while \$40 ha^{-1} invested in N use gives a profit/cost ratio of 1.2. However, while the monetary returns to P and K application were better than for N, it is important to recall that the response to P and K occurred with 90 kg ha^{-1} N uniformly applied, and failure to apply N would likely greatly reduce response to P and K.

Fertilizer use decisions need to be based on field research results, but profit potential can be increased by subsidized fertilizer use, improved input supply and markets, and enabling farmers to get credit on stored produce to enable delayed marketing at more favorable grain prices (Nkonya et al., 2005). Fertilizer use decision tools that consider the farmer's economic and agronomic context were developed based on these and other research findings for eastern, northern, and southern Rwanda in order to optimize

farmer profit from the use of fertilizer for rice and other crops (http://agronomy.unl.edu/OFRA).

5 | CONCLUSIONS

Lowland rice grain yield increased by a mean of 2.3, 1.5, 1.7, and 1.7 Mg ha^{-1} with the application of N, P, K, and MgSZnB, respectively, in Rwanda with great implications for food security and farm profitability. Compared with the previously recommended nutrient application rates, these results indicate that rates for optimization of net returns to fertilizer use should be 34% higher for N, 20% higher for P, and 64% higher for K with intermediate fertilizer use costs. A single N response function can be applied for Clusters A, BC, and C, but the results indicate a need for a different N response function for Cluster B. The variation in response to P and K across clusters was small, and a single response function each for P and K could be applied for all clusters. The P and K results are only valid if fertilizer N is applied; otherwise, N deficiency is likely to severely limit response to P and K. The response to MgSZnB needs further research. Until most profitable rates for each of the MgSZnB nutrients are determined, the results indicate a recommendation of routine application of a package of these nutrients at rates used in this study, but only in addition to N, P, and K application. Rwandan farmers are often resource-poor and the results show greatly increased returns on investment by applying nutrients at less than EOR. Using available fertilizer over more land, and maybe more crops, at less than the EOR may also be a means to reduce risk of profit loss.

ACKNOWLEDGEMENT

We are grateful to the Alliance for a Green Revolution in Africa (AGRA) and the Bill and Melinda Gates Foundation for funding, to CAB International for project management, to the University of Nebraska-Lincoln for scientific and advisory support, and to other colleagues who participated in the network for Optimization of Fertilizer Use in Africa. The high level of participation by cooperating farmers, field assistants, and extension staff in the efficient implementation of trials is appreciated.

ORCID

Charles S. Wortmann
https://orcid.org/0000-0001-9715-8469

REFERENCES

Alivelu, K., Subba-Rao, A., Sanjay, S., Sing, K. N., Raju, N. S., & Madhuri, P. (2006). Prediction optimal N application rate of rice based on soil test values. *European Journal of Agronomy*, *25*, 71–73. https://doi.org/10.1016/j.eja.2005.10.011

Anbessa, B., & Dereje, G. (2018). Influence of nitrogen and phosphorus rate on grain yield of rice at Kamashi Zone of Benshangul Gumuz Region, Ethiopia. In G. Agegnehu, G. Gurmu, T. Abera, & D. Muleta (Eds.), *Soil fertility and plant nutrient management*. Addis Ababa Ethiopia: Ethiopia Institute of Agricultural Research.

Cyamweshi, A. R., Kayumba, J., & Nabahunga, N. L. (2017). Optimizing fertilizer use within the context of integrated soil fertility management in Rwanda. In C. S. Wortmann & K. Sones (Eds.), *Fertilizer use optimization in sub-Saharan Africa* (pp. 165–175). London, UK: CABI. https://doi.org/10.1079/9781786392046.0164

Cyamweshi, A. R., Nabahungu, L. N., Senkoro, C. J., Kibunja, C., Mukuralinda, A., Kaizzi, K. C., … Wortmann, C. S. (2018). Wheat nutrient response functions for the East Africa highlands. *Nutrient Cycling in Agroecosystems*, *111*, 21–32. https://doi.org/10.1007/s10705-018-9912-z

Daudu, C. K., Ugbaje, E. M., Oyinlola, E. Y., Tarfa, B. D., Alhaji, Y. A., Amapu, I. A., & Wortmann, C. (2018). Lowland rice nutrient response functions for Nigeria. *Agronomy Journal*, *110*, 1079–1088. https://doi.org/10.2134/agronj2017.08.0469

Diagne, A., Alia, D. Y., Amovin-Assagba, E., Wopereis, M. C. S., Saito, K., & Nekelsev, T. (2013). Farmer perception of the biophysical constraints to rice production in sub-Saharan Africa, and potential impact of research. In M. C. S. Wopereis, D. E. Johnson, N. Ahmadi, E. Tollens, & A. Jalloh (Eds.), *Realizing Africa's rice promise* (pp. 46–68). Croydon, UK: CABI. https://doi.org/10.1079/9781845938123.0046

CropStat, F. A. O. (2018). Retrieved from http://www.fao.org/faostat/en/#data/QC.

Garba, M., Dicko, M., Kamissoko, N., Maman, N., & Wortmann, C. S. (2018b). Fertilizer use efficiency and profitability of irrigated rice in Mali and Niger. *Agronomy Journal*, *110*, 1951–1959. https://doi.org/10.2134/agronj2017.09.0512

Garba, M., Serme, I., & Wortmann, C. S. (2018a). Relating crop yield response to fertilizer and soil test information for Sub-Saharan Africa. *Soil Science Society of America Journal*, *82*, 862–870. https://doi.org/10.2136/sssaj2018.02.0066

Gasore, E. R. (2016). *Growth and productivity of irrigated rice (Oryza sativa L.) for a tropical high altitude environment in Rwanda*. PhD thesis. University of Arkansas, Fayetteville AR.

Gebrekidan, H., & Seyoum, M. (2006). Effects of mineral N and P fertilizers on yield and yield components of flooded lowland rice, lowland on vertisols of Fogera Plain, Ethiopia. *Journal of Agriculture and Rural Development in the Tropics and Subtropics*, *107*, 161–176.

Jansen, J., Wortmann, C. S., Stockton, M. C., & Kaizzi, K. C. (2013). Maximizing net returns to financially constrained fertilizer use. *Agronomy Journal*, *105*, 573–578. https://doi.org/10.2134/agronj2012.0413

Jones, A. (2013). *Soil Atlas of Africa*. Luxembourg: European Commission, Publications Office of the European Union.

Kaizzi, C. K., Cyamweshi, R. A., Kibunja, C. N., Senkoro, C., Nkonde, D., Maria, R., & Wortmann, C. S. (2018). Bean response to fertilizer in eastern and southern Africa. *Nutrient Cycling in Agroecosystems*, *111*, 47–60. https://doi.org/10.1007/s10705-018-9915-9

Kalumuna, M. C., Masuki, K. F. G., Mkavidanda, A. T., & Wickama, J. M. (2000). *Responses of cotton, maize and rice, lowland to fertilizers in Sukumaland*. Mlingano, Tanzania: National Soil Service.

Kihara, J., Nziguheba, G., Zingore, S., Coulibaly, A., Esilaba, A., Kabambe, V., … Huising, J. (2016). Understanding variability in crop response to fertilizer and amendments in sub-Saharan

Africa. *Agriculture Ecosystems and Environment*, *229*, 1–12. https://doi.org/10.1016/j.agee.2016.05.012

Mehlich, A. (1984). Mehlich-3 soil test extractant: A modification of Mehlich-2 extractant. *Communications in Soil Science and Plant Analysis*, *15*, 1409–1416. https://doi.org/10.1080/00103628409367568

Minasny, B., & McBratney, A. B. (2017). Limited effect of organic matter on soil available water capacity. *European Journal of Soil Science*, *2000*, 1–9. https://doi.org/10.1111/ejss.12475

Nkonya, E., Kaizzi, C. K., & Pender, J. (2005). Determinants of nutrient balances in maize farming system in eastern Uganda. *Agricultural Systems*, *85*, 155–182. https://doi.org/10.1016/j.agsy.2004.04.004

Sanchez, P. A. (2002). Soil fertility and hunger in Africa. *Science*, *295*, 2019–2020. https://doi.org/10.1126/science.1065256

Shepherd, K. D., & Walsh, M. G. (2007). Infrared spectroscopy–enabling an evidence-based diagnostic surveillance approach to agricultural and environmental management in developing countries. *Journal of Near Infrared Spectroscopy*, *15*, 1–19. https://doi.org/10.1255/%2Fjnirs.716

Steusloff, T. W., Nelson, K. A., Motavalli, P. P., & Singh, G. (2019). Validation of soil-test-based phosphorus and potassium fertilizer recommendations for flood-irrigated rice. *Agronomy Journal*, *111*, 2512–2522. https://doi.org/10.2134/agronj2019.02.0108

Terhoeven-Urselmans, T., Vagen, T. G., Spaargaren, O., & Shepherd, K. D. (2010). Prediction of soil fertility properties from a globally distributed soil mid-infrared spectral library. *Soil Science Society of America Journal*, *74*, 1792–1799. https://doi.org/10.2136/sssaj2009.0218

Towett, E. K., Shepherd, K. D., Sila, A., Aynekulu, E., & Cadisch, G. (2015). Mid-infrared and total x-ray fluorescence spectroscopy complementarity for assessment of soil properties. *Soil Science Society of America Journal*, *79*, 1375–1385. https://doi.org/10.2136/sssaj2014.11.0458

Wortmann, C. S., Kaizzi, K. C., Maman, N., Cyamweshi, R. A., Dicko, M., Garba, M., … Serme, I. (2019). Diagnosis of crop nutrient deficiencies in sub-Saharan Africa. *Nutrient Cycling in Agroecosystems*, *113*, 127–140. https://doi.org/10.1007/s10705-018-09968-7

Wortmann, C. S., & Ssali, H. (2001). Integrated nutrient management for resource poor farming systems: A case study of adaptive research and technology dissemination in Uganda. *American Journal of Alternative Agriculture*, *16*, 161–167. https://doi.org/10.1017/S0889189300009140

Xia, Y., & Yan, X. (2012). Ecologically optimal N application rates for rice cropping in the Taihu Lake region of China, *Sustainability Science*, *7*, 33–44. https://doi.org/10.1007/s11625-011-0144-2

Xu, X., He, Y. F., Ma, J., Pampolino, M. F., Johnston, A. M., & Zhou, W. (2017). Methodology of fertilizer recommendation based on yield response and agronomic efficiency for rice in China. *Field Crops Research*, *206*, 33–42. https://doi.org/10.1016/j.fcr.2017.02.011

Yesuf, E., & Balcha, A. (2014). Effect of nitrogen application on grain yield and nitrogen efficiency of rice (*Oryza sativa* L.). Asian J. *Crop Science*, *6*, 273–280. https://doi.org/10.3923/ajcs.2014.273.280

How to cite this article: Nabahungu NL, Cyamweshi AR, Kayumba J, et al. Lowland rice yield and profit response to fertilizer application in Rwanda. *Agronomy Journal*. 2020;112:1423–1432. https://doi.org/10.1002/agj2.20006