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Finger millet response to nitrogen, phosphorus and potassium in Kenya and Uganda

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Abstract Finger millet (*Eleusine coracana* (L.) Gaertn) is an important food crop of semi-arid to sub-humid Africa where little is known of its response to applied nutrients. Yield responses to nitrogen (N), phosphorus (P) and potassium (K) together with a diagnostic treatment (S, Mg, Zn, B) were determined from field research conducted in western Kenya and eastern and central Uganda. Grain yield was not affected by applied nutrients in some sites in Kenya, likely due to other prevailing stresses. Grain yield increased with N application for all sites and years in Uganda by a mean of 127% from the no N treatment (0 N) yield of 1.00 Mg ha⁻¹. Grain yield increases ranged from 0.76 to 1.40 Mg ha⁻¹ with 30 kg N ha⁻¹ applied, with little added increase with >60 kg N ha⁻¹. The mean economically optimal rate for N in Uganda was 72 and

43 kg N ha⁻¹ with expected net returns to N of 166 and 279 \$ ha⁻¹ when the N cost to grain value was 3 and 9 kg kg⁻¹, respectively. Yield was increased with P and K application at two of four production areas of Uganda. Yield was increased by >20% with application of Mg–S–Zn–B in addition to N–P–K for all sites in Uganda with foliar concentrations indicating possible S and B deficiency. There is great profit potential in Uganda, and less for Kenya for N, but not for P and K, application to finger millet. Response to S and B needs further exploration.

Keywords Economically optimal rate · Net return to fertilizer · Optimization · Response functions · Curvilinear to plateau · Asymptotic

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Abbreviations

CP	Nutrient cost to grain price ratios [CP; \$ kg ⁻¹ (\$ kg ⁻¹) ⁻¹]
EOR	Economically optimal rate and the rate to maximize net return per hectare due to nutrient application
LR	Long rain season
SR	Short rain season

Introduction

Finger millet (*Eleusine coracana* (L.) Gaertn) is a food crop of importance for the semi-arid and sub-humid tropics of Africa and has been ranked fourth in importance globally among the millets (Gupta et al. 2012; Kerr 2014). It was domesticated in Africa, probably in Ethiopia, has been grown in Uganda and Ethiopia for thousands of years and produced in 10 or more countries of eastern and southern Africa, and was introduced to Asia about 3000 years ago (Doggett 1989). Finger millet is an important component of many small scale farming systems for its contribution to food security and high market demand. It stores well with low post harvest losses and has high nutritional quality (Dida et al. 2007; Rurinda et al. 2014). Finger millet is adapted to semi-arid and humid conditions and is commonly produced in maize production areas but preferred varieties often mature early compared with the prevalent maize varieties with potential to enhance cropping system resilience to climate variability (FAO 2008).

Finger millet has been neglected politically and scientifically and mean yields are less than 1 Mg ha⁻¹ in Africa (Salasya et al. 2009) although yield potential is much higher (Onyango 2016). In Kenya, the yield potential of cv P224 released in 1989 was 2.5 Mg ha⁻¹ but was only grown by about 10,000 farmers (CGIAR 2011; Export Processing Zones 2005). In Uganda, yield potential of 4.5 Mg ha⁻¹ has been reported (Tenywa et al. 1999). Inadequate nutrient availability contributes to low yield since little fertilizer is applied for finger millet production (NRC 1996; NAAIAP and KARI 2014).

Scanty information on finger millet response to applied nutrients exists for Africa (Thilakarathna and Raizada 2015). In Uganda, Tenywa et al. (1999) found significant finger millet grain yield responses to

fertilizer P applied alone or in combination with N or manure, but no response to N alone. However in other studies, good yield responses to N occurred (NRC 1996). Finger millet establishment and grain yield was improved more with a combined NPK application compared to either nutrient alone (Tenywa et al. 1999; Rurinda et al. 2014) but agronomic N use efficiency declined with increased rates of NPK due to a curvilinear response. Hegde and Gowda (1986) and Rao et al. (1989) reported finger millet yield increases in India with up to 20 kg N ha⁻¹ but no increments at higher rates and concluded that both N and P should be applied. For Alfisols and Vertisols with low organic C in Karnataka India, grain yield was increased by 1.1 Mg ha⁻¹ due to Zn, B and S along with NPK (Srinivasarao et al. 2008).

Grain price of finger millet is commonly almost twice that of maize and sorghum (NRC 1996) and the grain has diverse markets (Shibairo et al. 2016). Profit oriented fertilizer use decisions for finger millet production require better information of the nature of responses to applied nutrients for determination of EOR (Kaizzi et al. 2007). The objectives of the study were to determine (1) nutrient response functions and EOR of finger millet for N, P and K in Kenya and Uganda, and (2) to assess deficiencies of some secondary and micro nutrients in finger millet production.

Materials and methods

Sites and soil sampling

Fertilizer N, P and K response trials were conducted for 28 site year combinations (SY) including both farmer and researcher managed trials between 2012 and 2015 at finger millet production areas of Apac, Kawanda, Pallisa, and Tororo in Uganda (Table 1). As weather data was not well recorded for the on-farm trials in Uganda, the mean rainfall amounts for the 3 months of most finger millet growth were reported for the long rains (LR) and short rains (SR) of the locations. On-station trials were conducted during 2014–2015 at KALRO Kitale (370 mm), KALRO Alupe (440 mm) and Migori-Oyani Livestock Station of the Ministry of Agriculture (400 mm) in Kenya as these offered conditions common for finger millet production in western Kenya. Sites with serious

Table 1 Site mean characteristics for finger millet trials conducted in Uganda and Kenya with the mean trial grain yields (GY, Mg ha⁻¹)

Yr ^a	S	GY	Yr	S	GY	Yr	S	GY
Apac, Uganda ^b : 1060 m asl, 1.95°N, 32.67°E, 410 mm LR, 430 mm SR								
2012	SR	1.21	2013	LR	1.35	2014	LR	2.17
Kawanda, Uganda: 1175 m asl, 0.41°N, 32.54°E, 400 mm LR, 370 mm SR								
2012	LR	1.50	2013	LR	1.12	2014	LR	2.14
2012	SR	1.36	2013	SR	1.60	2014	SR	1.28
Palissa, Uganda: 1055 m asl, 1.26°N, 33.87°E, 510 mm LR, 350 mm SR								
2012	LR	1.41	2013	LR	1.83	2014	LR	2.33
2012	LR	2.29	2013	LR	1.88	2014	SR	2.98
2012	SR	1.91	2013	SR	1.43			
2013	LR	1.23	2013	SR	1.47			
Tororo, Uganda: 1170 m asl, 0.70°N, 34.13°E, 550 mm LR, 370 mm SR								
2012	LR	2.57	2013	LR	1.44	2014	LR	2.85
2012	LR	1.77	2013	LR	2.15	2014	SR	2.35
2012	SR	2.47	2013	SR	2.13	2015	LR	2.81
Alupe, Kenya: 1150 m asl, 0.50°N, 34.13°W, 600 mm LR, 440 mm SR								
2015	LR	0.52						
Kitale, Kenya: 1864 m asl, 1.00°N, 34.99°E, 390 mm LR, 370 mm SR								
2015	LR	1.74						
Oyani, Kenya: 1420 m asl, 0.98°S, 34.52°E, 520 mm LR, 400 mm SR								
2014	LR	2.43	2014	SR	0.58			

^a Yr, year; S, season with LR and SR being long and short rain season; GY, grain yield; m asl, m above sea level; latitude and longitude are in WGS84 decimal degrees; with mean precipitation for the 3 months of the season most important for finger millet production

^b The Apac and Palissa and some of the Tororo trials were conducted on farmers' fields and the others were conducted on land of research centers

known edaphic constraints were avoided such as shallow depth to plinth or another restrictive layer, sand soil texture, and a history of unusually severe erosion as such sites are not of high importance for finger millet production in these areas.

The soil was sampled before fertilizer application and planting, using soil augers for the 0–20 cm depth. A composite sample of 10 sampling points was collected for each block. The analyses were done by the World Agroforestry Centre Soil–Plant Spectral Diagnostic Laboratory in Nairobi, Kenya using mid-infrared spectral analysis, with fine-tuning of the calibration using data from wet chemistry analysis for about 10% of the samples (Shepherd and Walsh 2007; Terhoeven-Urselmans et al. 2010; and Towett et al. 2015; <https://www.worldagroforestry.org/sd/landhealth/soil-plant-spectral-diagnostics-laboratory/sops>). The analysis for organic C was done with a Thermal Scientific Flash 2000; for pH with a 1:2.5 soil: water slurry; for available P and exchangeable K with the Mehlich-3 extraction (Mehlich 1984); and for particle size distribution using the Horiba LA 950 Laser Scattering Particle Size Distribution Analyzer. The soils included sandy clay loam, sandy clay, clay loam, loam and clay texture (Table 2). Soil property ranges included 5.7–6.3 for pH,

8.8–17.1 g kg⁻¹ for soil organic C, and 5.3–20.2 mg kg⁻¹ Mehlich-3 P except for very high P at Oyani. Exchangeable K was >100 mg kg⁻¹ except for the Kawanda 2014 long rain season (LR).

Experimental design and treatments

An incomplete factorial treatment allocation with 14 and 17 treatments for Kenya and Uganda, respectively, was adopted (Table 3). The treatments were assigned in a randomized complete block design in plots of 4.5 by 6 m. Trials typically had three replications but some on-farm trials in Uganda had more than three replications with one replication per farmer's field. Trials were planted on different land each SY to avoid residual effects of treatments and across several seasons variation in weather conditions to affect crop response to treatments. The varieties in Kenya were P224 in Kitale, Gulu E in Alupe and KARI FM1 in Oyani. Plots were split in Uganda to accommodate a comparison of cv Pesse II and Seremi II for all SY. These varieties mature in about 110 days at 1200 m above sea level.

The nutrient sources were urea, triple super phosphate (TSP) and muriate of potash (KCl) in Uganda,

Table 2 Soil physical and chemical properties and crop management for finger millet research sites in Kenya and Uganda

Country	Site	Year	S ^a	T	Sand %	Clay	pH	SOC mg kg ⁻¹	P	K ^b	Previous crop	Planting date	Harvesting date
<i>Soil properties</i>													
Kenya ^c	Oyani	2014	LR	C	11	62	6.07	24.1	95.6	421	Maize	5/4/2014	6/8/2014
Uganda	Apac	2012	SR	SCL	57	28	5.80	30.0	4.6	1236	Maize	13/9/2012	27/12/2012
Uganda	Apac	2013	SR	C	23	59	6.16	16.4	9.5	168	Cowpea	12/9/2013	18/12/2013
Uganda	Apac	2014	LR	C	26	56	6.06	15.6	7.8	129	Maize	25/3/2014	22/7/2014
Uganda	Apac	2014	SR	C	22	60	6.08	17.1	11.2	176	Simsim	8/9/2014	17/12/2014
Uganda	Kawanda	2012	SR	C	43	49	5.60	24.0	5.3	1502	Maize	17/9/2012	14/1/2013
Uganda	Kawanda	2012	LR	C	41	48	5.40	26.0	6.7	1115	Soybean	10/3/2012	9/7/2012
Uganda	Kawanda	2013	SR	SCL	49	31	5.93	15.7	18.6	293	Maize	14/9/2013	13/12/2013
Uganda	Kawanda	2014	LR	C	25	58	6.05	14.2	16.1	82	Soybean	13/9/2014	15/1/2015
Uganda	Kawanda	2014	SR	C	16	70	5.70	14.2	5.9	101	Maize	29/3/2014	14/7/2014
Uganda	Pallisa	2012	LR	SL	75	18	6.60	29.0	1.9	788	Potato ^d	15/3/2012	1/07/2012
Uganda	Pallisa	2013	SR	L	46	19	6.18	12.7	20.2	222	Cowpea	10/9/2013	17/12/2013
Uganda	Pallisa	2014	LR	L	34	17	6.27	12.6	15.4	183	Simsim	27/3/2014	9/7/2014
Uganda	Pallisa	2014	SR	SCL	47	33	6.28	13.5	17.1	211	Maize	10/3/2014	15/7/2014
Uganda	Tororo	2012	LR	SL	77	13	6.20	25.0	2.50	554	Soybean	2/3/2012	15/7/2012
Uganda	Tororo	2012	SR	SL	70	17	5.40	21.0	8.50	507	Cowpea	15/3/2012	15/6/2012
Uganda	Tororo	2013	SR	C	39	41	5.82	8.4	19.2	156	Rice ^d	8/9/2013	19/12/2013
Uganda	Tororo	2014	LR	SC	46	37	5.78	8.5	15.3	113	Soybean	25/3/2014	7/7/2014
Uganda	Tororo	2014	SR	CL	43	39	5.77	8.8	14.4	113	Rice	12/9/2014	30/12/2014

^a S, season; T, soil texture class including C for clay, SL for sandy loam, L for loam, SCL for sandy clay loam; SOC, soil organic carbon; LR, Long rainy season; SR, Short rainy season

^b The median Mehlich-3 values for: Mg were 257, 185, 224 and 77 cmol kg⁻¹; S were 12.3, 12.5, 9.1 and 11.6 mg kg⁻¹; Zn 6.1, 7.0, 5.2 and 6.0 mg kg⁻¹; Cu were 3.3, 3.0, 2.6 and 1.3 mg kg⁻¹; Mn were 208, 172, 174 and 74 mg kg⁻¹; and B were 0.43, 0.28, 0.32 and 0.09 mg kg⁻¹ at Apac, Kawanda, Palissa and Tororo, respectively

^c Soil test results are not available for the Kitale and Alupe sites in Kenya

^d Potato was sweet potato; rice was upland rice

while calcium ammonium nitrate (CAN) substituted for urea in Kenya. The secondary and micro nutrients of the diagnostic treatment were applied as magnesium sulfate, zinc sulfate and borax. Pre-planting application was by banding 5 cm from the seed to avoid salt effects (IPNI 2015). A top-dress application of 50% of the N was done at about 6 weeks after planting except for the 90 and 120 kg N ha⁻¹ rates in Kenya with application of one-third each before planting, and at 6 and 8 weeks after planting.

Trial management and observations

Continuous cropping was practiced at all trial sites and the previous crop may have been a legume or a non-legume (Table 2). Land was tilled before planting. Seed was sown with 30 cm row spacing and later

thinned to 6 cm between plants. Weeding was done twice after planting with hand hoes. Chemical pest control to control insect and termite damage was done using various insecticides including cypermethrin (Cypermethoate TM) and chloropyrifos 5% (DursbanTM). Most management of on-farm trials was by the cooperating farmers except for researcher participation in treatment application, planting, insecticide application, harvest, and other sample and data collection. Seed and chemical inputs were provided by research.

Ten flag leaves were sampled at panicle emergence from treatments 14 and 12 for Kenya and Uganda, respectively, for diagnosis of nutrient disorders expressed with N–P–K applied. The foliar samples were placed in labeled brown paper bags, oven dried at 60 °C for 2 days and milled before sending 30 g of

Table 3 Treatment structure for determination of finger millet response to applied nutrients

No. ^a	Kenya			Uganda		
	N	P	K	N	P	K
1	0	0	0	0	0	0
2	30	0	0	30	0	0
3	60	0	0	60	0	0
4	90	0	0	90	0	0
5	0	15	0	120	0	0
6	30	15	0	0	10	20
7	60	15	0	30	10	20
8	90	15	0	60	10	20
9	90	7.5	0	90	10	20
10	90	22.5	0	120	10	20
11	90	15	10	60	10	20
12	90	15	20	60	20	20
13	90	15	30	60	30	20
14 ^a	90	15	20	60	10	20
15				60	10	40
16				60	10	60
17 ^a				60	10	20

^a No. is for treatment number. Treatment 14 for Kenya and 17 for Uganda were diagnostic treatments which included application of 10, 15, 2.5 and 0.5 kg ha⁻¹ of Mg, S, Zn, and B, respectively, for comparison with treatment 12 and 14

sample to the World Agroforestry Centre Soil–Plant Spectral Diagnostic Laboratory in Nairobi, Kenya. Sample analysis used mid-infrared spectral analysis with fine-tuning of the calibration using data from wet chemistry analysis of about 10% of the samples. Analyses were done for N, P, K, Ca, Mg, S, Na, Fe, Zn, Cu, B, Mn, and Mo. The crop was harvested after physiological maturity from a net harvest area of 12.6 m². The grain harvest was done by manually cutting the panicles from the stems with knives, air-drying, threshing and winnowing. The grain was weighed and tested for grain water content for grain yield determination at 14% water content.

Statistical and economic analysis

The plot data were first analyzed for each country in a combined analysis of variance (ANOVA) across sites and years within sites using the general ANOVA (AOV/AOCV) statement in Statistics 10 (Analytical

Software, Tallahassee, FL). Treatment effects were considered fixed and significant when $P < 0.05$. The SY effects were considered random. When the nutrient treatment \times variety interaction was found not to be significant for all sites in Uganda, the ANOVA was done across all years within sites with the variety means as the plot values. Response functions by SY were determined for significant nutrient effects by fitting a curvilinear to plateau asymptotic function expressed as:

$$\text{Yield}(\text{kg ha}^{-1}) = a - bc^r$$

where a is yield at the plateau for the nutrient application, b is the maximum gain in yield due to the nutrient application, c determines the shape of the curve, and r is the nutrient application rate. The coefficient of determination (R^2) was recorded. When the c value was low due to no response to rates above the lowest applied P or K rate, the minimum c value was 0.75 to avoid functions estimating very abrupt yield increases to very low nutrient rates. Since no fully comparable control treatment for the P and K responses were included in the Uganda treatment structure, treatment 60–0–0 was used as the control in determining the P and K response functions; this choice was expected to over-estimate responses to P and K but since responses to P and K were very small, the choice was justified. The mean agronomic efficiency for N with 50 kg ha⁻¹ applied, expressed as grain yield gain per unit N applied (kg kg⁻¹), was calculated using the overall N response functions determined for the four production areas of Uganda.

The EOR for five different nutrient cost to grain price ratios [CP; \$ kg⁻¹ (\$ kg⁻¹)⁻¹] were determined as the rate of maximum profit due to the nutrient application. Finger millet grain was valued at US\$ 0.33 kg⁻¹ on farm in consideration of the value for that kept for home consumption and the estimated market value. Fertilizer nutrient costs were varied at 3, 4.5, 6, 7.5, and 9 times the grain value for N and K but at 6, 9, 12, 15, and 18 times the grain value for elemental P. The EOR was determined as the nearest full kg of nutrient beyond which the value of the yield increase was less than the cost of added nutrient. Linear regression was applied to determine the equations for estimating EOR with CP as the independent variable. Net returns to nutrient application were calculated as the cumulative value of yield

gained due to nutrient application at a given nutrient rate minus the total fertilizer costs for that rate where fertilizer cost relative to grain value is quantified as CP.

The diagnostic effect was assessed through orthogonal contrasts conducted for each SY comparing yield with the diagnostic treatment to yield with the comparable NPK treatment. Significant diagnostic treatment effects were evaluated in consideration of foliar nutrient concentrations results relative to estimated critical levels of 2.8, 0.22, 1.2, 0.20, 0.10, and 0.11%, respectively, for N, P, K, Ca, Mg, and S. Critical values of 20, 15, 3, 3, 15, and 0.1 mg kg⁻¹ were applied in interpretation of foliar concentration results for Fe, Zn, Cu, B, Mn and Mo, respectively.

Results

Kenya

Mean grain yields over all treatments were 0.58, 0.52, 1.74 and 2.43 Mg ha⁻¹ for Oyani 2014 short rains (SR), Alupe 2014 long rains (LR), Kitale 2015LR, and Oyani 2014LR, respectively. Severe soil water deficits constrained yield and nutrient responses for Oyani 2014 SR and Alupe 2014LR. Grain yield was not

affected by fertilizer application at the Alupe and Oyani sites. In Kitale, application of 30 kg N ha⁻¹ increased grain yields by 82% above the 0 N treatment (Table 4), but increasing N rates beyond 30 kg ha⁻¹ did not affect yield. Grain yield at Kitale was not significantly affected by application of N with 10 kg P ha⁻¹ applied, or by P and K application.

Uganda

Variety effects on grain yield occurred inconsistently across years. Yield was more with Seremi II compared with Pesse II for 2012LR of Pallisa and Kawanda, but the opposite occurred for 2014 in Apac. However, there was no variety × fertilizer treatment interaction effect. Grain yield was affected by the year × site × treatment interaction.

The season × N rate interaction was significant for all sites because of differences in magnitude of response and shape of the response curve (Table 5). The curvilinear to plateau functions fitted the N response well for all SY.

For Tororo, the season × N interaction was because the magnitude of the response to N was much greater for 2012LR compared with 2013LR, and the response was only slightly curvilinear up to 120 kg N ha⁻¹ for 2012LR compared with 2013LR and 2013SR when the plateau was approached at 90 kg N ha⁻¹ (Table 5). The N rate × PK interaction was significant only for Tororo with lower 0 N grain yield without compared to with PK applied. There was a greater yield increase with 30 kg N ha⁻¹ without compared to with PK applied. Minimal yield increments occurred when PK was applied with N rates above 30 N, indicating that PK application in this site is only beneficial at lower N rates.

The season × N rate interaction was also significant for the other sites (Table 5). For Pallisa, this was due to relatively large yield increases with 30 kg N ha⁻¹ applied for the 2014 seasons, especially compared with the 2013 seasons. At Kawanda, the response with 30 kg N ha⁻¹ was greater for 2014LR compared with other seasons. For Apac, the response to 30 kg N ha⁻¹ was relatively small for 2012SR compared with other seasons and the response to the 60–90 kg N ha⁻¹ increment was relatively great for 2014LR. While mean yield levels differed across sites, the response to applied N as indicated by the b and c coefficients was very similar for Tororo, Pallisa, and

Table 4 Nitrogen effects on finger millet grain yield and the asymptotic response coefficients at Kitale Kenya

N rate (kg N ha ⁻¹)	Grain response (kg/ha)	
	N	NwP ^a
0	1.14	1.76
30	2.09	1.68
60	1.18	2.00
90	1.48	1.84
120	1.98	1.92
P > F	**	ns
a	1.681	2.005
b	0.536	0.280
c	0.850 ^b	0.990
R ²	0.29	0.38

** Significance at $P < 0.01$

^a NwP: response to N with 15 kg P ha⁻¹ applied

^b The calculated c value was 0.436. The C value is raised to 0.850 to avoid estimation of very abrupt yield increases to very low nutrient rates

Table 5 Finger millet yield response to N rate and the asymptotic response coefficients determined for four production areas in Uganda

	N rate (kg ha ⁻¹)					P > F	Coefficients			R ²
	0	30	60	90	120		a	b	c	
Tororo (N***; S ^a ***; S × N***; N × PK***)										
2012LR ^a	1.23	1.78	2.20	2.36	2.43	***	2.858	1.366	0.981	1.00
2012SR	1.26	2.05	2.54	2.72	2.68	***	2.805	1.558	0.974	0.99
2013LR	1.26	1.61	1.79	1.88	1.79	***	1.847	0.597	0.967	0.97
2013SR	1.16	2.06	2.19	2.21	2.06	***	2.153	0.994	0.921	0.98
2014LR	1.41	2.34	2.81	2.79	2.85	***	2.879	1.476	0.964	0.99
2015LR	1.79	2.73	2.94	2.98	2.90	***	2.952	1.163	0.945	1.00
Mean _{OPK} ^b	0.92	1.92	2.33	2.39	2.41	***	2.448	1.532	0.963	1.00
Mean _{WPK}	1.75	2.15	2.39	2.49	2.43	***	2.500	0.757	0.972	0.98
Mean	1.33	2.03	2.36	2.44	2.42	***	2.471	1.147	0.966	1.00
Pallisa (N***; S***; S × N***; N × PK, ns)										
2012LR	0.59	1.33	1.5	1.35	1.54	***	1.468	0.879	0.938	0.96
2012SR	1.03	1.87	2.22	2.27	2.41	***	2.409	1.384	0.969	1.00
2013LR	0.86	1.38	1.72	1.60	1.78	***	1.752	0.894	0.968	0.96
2013SR	0.97	1.38	1.52	1.45	1.31	***	1.421	0.457	0.915	0.87
2014LR	1.31	2.25	2.51	2.55	2.58	***	2.583	1.273	0.956	1.00
2015LR	1.51	2.91	3.27	3.17	3.50	***	3.370	1.857	0.955	0.98
Mean	1.00	1.71	1.99	1.93	2.04	***	2.155	1.110	0.956	0.99
Kawanda (N***; S***; S × N***; N × PK, ns)										
2012LR	0.70	1.22	1.25	1.37	1.59	***	1.587	0.860	0.980	0.93
2012SR	0.83	1.29	1.39	1.36	1.53	***	1.500	0.629	0.961	0.95
2013LR	0.60	1.05	1.08	1.09	1.27	***	1.182	0.576	0.961	0.92
2013SR	0.93	1.57	1.49	1.55	1.65	***	1.565	0.635	0.850	0.96
2014LR	1.14	2.16	2.01	2.24	2.57	***	2.362	1.202	0.960	0.88
2014SR	0.64	1.26	1.41	1.48	1.42	***	1.455	0.815	0.953	0.99
Mean	0.81	1.43	1.44	1.51	1.67	***	1.583	0.763	0.956	0.95
Apac (N***; S***; S × N***; N × PK, ns)										
2012 SR	0.54	1.03	1.31	1.34	1.32	***	1.368	0.834	0.967	0.99
2013LR	0.45	1.42	1.50	1.48	1.34	***	1.439	0.989	0.874	0.98
2014LR	1.07	2.06	2.22	2.80	2.68	***	2.842	1.756	0.977	0.96
Mean	0.69	1.51	1.67	1.88	1.78	***	1.826	1.140	0.960	0.99

ns, *, **, *** are not significant at $P \leq 0.05$, and significant at $P \leq 0.05$, 0.01, and 0.001, respectively

^a S, site; LR, long rain season; SR, short rain season

^b Mean_{OPK} and Mean_{WPK}: means without and with P and K applied

Apac while the magnitude of the response to N was less for Kawanda. The mean agronomic efficiency for N with 50 kg ha⁻¹ applied varied widely. It was 26.0 and 11.5 kg kg⁻¹, respectively, for Tororo with 0 and 15 kg P ha⁻¹ applied, and 19.9, 13.7 and 19.8 kg kg⁻¹ for the mean responses at Palissa, Kawanda and Apac.

Nitrogen application was profitable for all CP and all SY, with EOR by site ranging from 20 to 78 kg N ha⁻¹ (Table 6). The EOR decreased with increasing cost of fertilizer N when grain prices were kept constant. The EOR for Kawanda were relatively low as indicated by

the relatively small yield increase with N application (Table 5). A graphic representation of N rate effects on net returns to fertilizer N is given for Apac where net return to N application was about 60% with the lowest compared with the highest CP (Fig. 1). The EOR were linearly related to CP (Table 6).

The grain yield response to applied P was much less than for N (Table 6). The P rate effect averaged across seasons was significant for Kawanda and Tororo only but for just one and two seasons, respectively, while there was no response to P in other seasons. The mean yield increases with 10 kg P ha⁻¹ were just 90 and

Table 6 Economically optimal rates of N for finger millet with N fertilizer use with cost/grain price (CP) of 3 to 9 across production areas of Uganda

Site	CP = 3	CP = 4.5	CP = 6	CP = 7.5	CP = 9	a ^a	b	R ²
Tororo _{OPK}	78	68	60	54	49	90.6	-4.8	0.98
Tororo _{WPK}	69	55	45	37	31	85.0	-6.3	0.97
Palissa	62	53	47	42	38	72.0	-3.9	0.97
Kawanda	54	45	39	34	30	64.0	-3.9	0.97
Apac	67	59	50	45	40	79.4	-4.5	0.98

^a a and b are the coefficients of the linear models relating EOR to CP

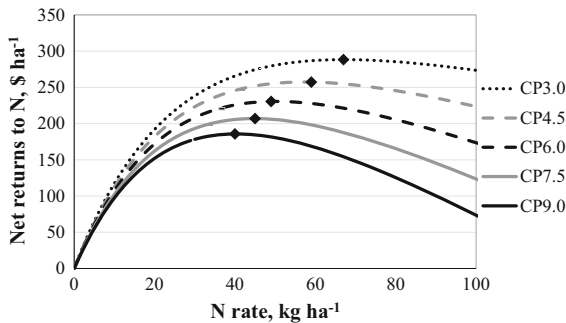


Fig. 1 The average net returns to fertilizer N application to finger millet in Apac, Uganda at varying N rates and with five N cost to grain price ratios (CP) with the economically N optimal rates indicated by the symbols at the peak of the curves

220 kg ha⁻¹ at Tororo and Kawanda, respectively. The mean EOR for P at Kawanda and Tororo ranged from 6 to 12 and 1 to 5 kg ha⁻¹ for the range of CP 18 to 6 kg of grain, respectively.

The K rate effect was small and averaged across seasons was significant for Kawanda and Tororo only. The season × K rate effect was significant for Kawanda as there were K effects in 2012LR and 2013LR but not in other seasons. The mean yield increases with 10 kg K ha⁻¹ were just 80 and 260 kg ha⁻¹ at Tororo and Kawanda, respectively, with no further yield increase with higher K levels. The mean EOR for K at Kawanda ranged from 7 to 11 kg ha⁻¹ for CP 9 and 3.

Yield response to secondary and micronutrients

The effect of a package of secondary and micronutrients in the diagnostic treatment as compared with a similar NPK treatment was not significant for the Kenya SY but there were increased yields by between 24 and 100% at the Uganda sites (Fig. 2). Grain yield

increases were greater for the farmer compared with researcher managed trials. Foliar concentrations of B and S were low for farmer managed trials at Pallisa and Tororo compared with other trials. The B and S were still above the critical levels but this may indicate that the critical levels are inappropriate for finger millet. Foliar concentrations of N and P were below the critical levels used for interpretation even though N and P had been applied to these plots and there was no response to applied P for Pallisa and only a small response to P for Tororo. Interpretation of the foliar nutrient concentration results for finger millet using critical values calls for caution.

Discussion

There was much variation in previous crop, soil texture and soil chemical properties for the trials such as low soil organic C at Tororo and some sites with very low P or K. Crop residue removal results in most soil organic C being recalcitrant with low nutrient mineralization rates (Sanchez et al. 1997; Kaizzi et al. 2012a, b, c). The soil's inherent ability to provide nutrients bond in organic matter such as N, P, B, and S is therefore small. However, yield with 0 N, yield increase with 30 kg N ha⁻¹ applied, and the maximum yield increase with N, P or K applied were not related to previous crop, soil texture and soil chemical properties.

Low yield and the lack of response of finger millet to applied nutrients in Alupe and Oyani was attributed to abiotic constraints. Flooding and subsequent water deficits occurred in the two sites. Prolonged soil water deficits following planting at Alupe were so severe that the in-season N application was not made. Plant stands at Oyani were uneven after a period of excess water. Given the contrast with the effects of N

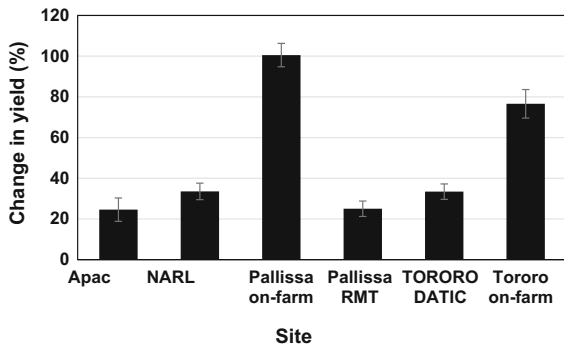


Fig. 2 The percent increase in finger millet grain yield from farmer managed trials (FMT) and researcher managed trials (RMT) in Uganda with N, P, K, Mg, S, Zn and B applied compared with N, P, and K applied alone. Error bars are for the standard error of the mean

application in Uganda (Table 5; Fig. 1), additional research is needed for before concluding that fertilizer N applied to finger millet in these sites is not likely to be profitable.

There was no significant varietal by fertilizer effect in all sites in Uganda with varieties responding similarly to applied nutrients. The varieties tested were recommended for the research sites with similar growth habit and time to maturity. This varietal consistency in response agrees with other results for maize, sorghum, upland rice and pulse crops in Uganda (Kaizzi et al. 2012a, b, c, 2014).

Finger millet responded well to applied N in all sites in Uganda, showing that N is the most limiting nutrient. Grain yield without N or PK applied was low (1.00 Mg ha^{-1}). Soil organic C levels overall were high enough to expect a higher grain yield with 0 N but it is likely that little of the existing soil organic matter is easily decomposed due to low levels of annual return of organic materials (Table 2). About 70% of the potential response to applied N occurred with 30 kg N ha^{-1} and yield gain with more than 60 kg N ha^{-1} was small. The curvilinear to plateau function represented crop response well (Table 5). This type of response concurred with results for other cereals (Fig. 3; Kaizzi et al. 2012a, b, 2014; Jansen et al. 2013) although finger millet mean yields and magnitudes of response to N were relatively low, especially compared with maize and upland rice. Finger millet response to applied N has been reported by others (Hegde and Gowda 1986; Opole et al. 2013). The trials were not designed to determine the effect of

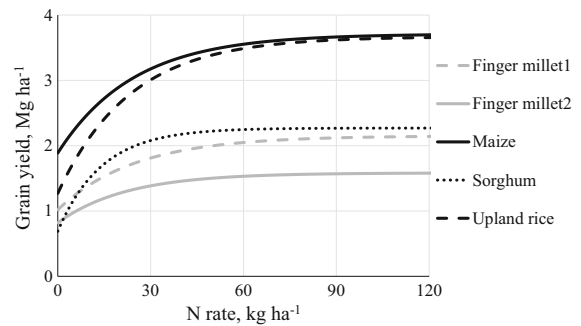


Fig. 3 A comparison of cereal responses to applied N in Uganda. Finger millet1 and finger millet2 represents results from Tororo, Apac and Palissa and from Kawanda, respectively

crop rotation on yield or response to applied nutrients, but there was no evidence of previous crop effect.

Responses to P and K were minimal and occurred in a few seasons at Tororo and Kawanda (Table 7). Responses were not related to soil test results or previous crop. Similar observations were made by Kaizzi et al. (2012a, b, 2014) and Wortmann and Ssali (2001). Soil test K was always above 125 mg kg^{-1} , except for Kawanda 2014LR and SR and Tororo 2014LR and SR, and not much response was expected, keeping in mind that Mehlich-3 compared with ammonium acetate extracts about 10% more K. Mehlich-3 P varied from very low to very high and foliar P concentration with P applied was low at all sites except for Kawanda suggesting that a grain yield increase with P application should have occurred. The lack of more frequent yield response to P application suggests that other abiotic or biotic constraints were more limiting than P deficiency. Soybean and groundnut responded well to applied P in Uganda (Kaizzi et al. 2012c) suggesting that P application should be to these crops with finger millet benefiting from any residual effects (Table 8).

Finger millet yield for the four sites in Uganda had positive responses to the application of the N–P–K–Mg–S–Zn–B diagnostic package compared to N–P–K (Fig. 2). Low foliar concentrations of S and B where response to the diagnostic package was greatest indicated S and B deficiencies. Soil Mehlich-3 S and B were relatively low at Pallisa and Tororo compared with Apac and Kawanda (Table 2). Sulfur is required for plants to synthesize amino acids, an essential component of protein and chlorophyll. Boron deficiency may restrict flowering and grain development

Table 7 Finger millet response to P rate with 60 and 20 kg ha⁻¹ of N and K applied, and to K rate with 60 and 10 kg ha⁻¹ of N and P applied, for four production areas in Uganda. Season data is presented only in cases of significant P or K effects

Season ^a	P rate (kg ha ⁻¹)				P > F	Season ^a	K rate (kg ha ⁻¹)				P > F
	0	10	20	30			0	10	20	30	
	Yield (Mg ha ⁻¹)						Yield (Mg ha ⁻¹)				
Tororo (P*; S**; S × P*)						Tororo (K***; S, ns; S × K, ns)					
2012LR ^a	2.41	2.79	2.64	3.04	*	Mean	2.33	2.41	2.28	2.32	**
Mean ^b	2.33	2.42	2.40	2.44	*	Kawanda (K***; S**; S × K***)					
Kawanda (P***; S**; S × P***)						2012LR	1.02	1.96	1.78	1.71	***
2012LR	1.02	1.74	1.83	1.90	***	2013LR	1.01	1.34	1.20	1.40	*
2014LR	1.95	2.29	2.25	2.23	*	Mean	1.39	1.65	1.57	1.67	***
Mean ^b	1.39	1.61	1.65	1.67	***	Pallisa (K, ns; S, ns; S × K, ns)					
Pallisa (P, ns; S***; S × P ns)						Mean	1.91	2.02	2.02	2.00	ns
Mean	1.91	2.04	1.83	1.98	ns	Apac (K, ns; S, ns; S × K, ns)					
Apac (P, ns; S**; S × P, ns)						Mean	1.65	1.59	1.60	1.69	ns
Mean	1.65	1.58	1.63	1.64	ns						

ns, *, **, *** are not significant at $P \leq 0.05$, and significant at $P \leq 0.05$, 0.01, and 0.001, respectively

^a Season; LR, long rain season; SR, short rain season

^b The P response functions for Tororo and Kawanda were $Y = 2.420 - 0.090 \times 0.750^P$ and $Y = 1.669 - 0.279 \times 0.816^P$. The K response function for Kawanda was $Y = 1.630 - 0.240 \times 0.750^K$

Table 8 Mean foliar nutrient concentrations for finger millet sampled from plots where N, P and K had been applied in Uganda

Site	N	P	K	Ca g kg ⁻¹	Mg	S	B	Cu	Fe mg kg ⁻¹	Zn	Mo
Apac	1.58	0.19	2.13	0.86	0.28	0.17	4.34	5.57	218	28	0.74
Kawanda	1.64	0.33	2.78	0.91	0.23	0.22	5.00	6.17	835	51	1.20
Pallisa	1.30	0.21	2.17	0.80	0.23	0.13	3.75	4.85	311	29	2.05
Tororo	1.44	0.20	2.10	0.83	0.24	0.14	3.86	5.15	180	29	1.12
Critical	2.8	0.22	1.2	0.2	0.1	0.11	3	3	20	15	0.1

The critical values for interpretation of foliar results was determined from other warm season cereals as no values specific to finger millet were found

(Marschner 1995). Availability of B and S is associated with soil organic matter and mineralization of these nutrients may be slow due to little active compared with stable, recalcitrant soil organic matter. In India, Srinivasarao et al. (2008) found a 56% finger millet yield increase with application of Zn, B and S in addition to N–P and that B uptake was increased by 22%.

High fertilizer costs reduced EOR and profit potential. Financially constrained farmers require high returns on small investments to justify fertilizer use in finger millet. However, for all CP considered, there is potential for high net return on investment in fertilizer N use with up to 30 kg N ha⁻¹ applied for all Uganda

sites (Fig. 1). Opportunity for profitable returns to fertilizer P or K applied to finger millet is very limited.

Conclusions

Fertilizer N application for finger millet has potential to be highly profitable in Uganda with well adapted varieties, especially for rates of up to 30 kg N ha⁻¹. Application of P and K to finger millet should be of low priority to financially constrained farmers. In other research, soybean and groundnut responded well to P application and, to ensure early return on investment, P should be applied to these crops with

finger millet subsequently gaining some benefit from the residual effect of the applied P. The contrast in N response with the Kenya and Uganda trials is not well explained given that the soil conditions, distance from the equator and elevation are similar and some verification of results in each country may be justified. Research is needed in Uganda to determine finger millet responses to S and B. The results of this research demonstrate the importance of availability and use of single nutrient fertilizers such as urea rather than blends if farmer profit is a major concern.

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References

- CGIAR (2011) Kenya: new varieties boost finger millet harvest. <http://www.cgiar.org/consortium-news/kenya-new-varieties-boost-finger-millet-harvest/>. Accessed 14 Nov 2016
- Dida MM, Srinivasachary M, Ramakrishnan S, Bennetzen JL, Gale MD, Devos KM (2007) The genetic map of finger millet, *Eleusine coracana*. *Theor Appl Genet* 114:321–332
- Doggett H (1989) Small millet—a selective overview. In: Seetharam A, Riley KW, Harinarayana G (eds) Small millets in global agriculture. Oxford and IBH Publishing Co Pvt LTD, Delhi, pp 3–17
- Export Processing Zones (2005) Grain production in Kenya. An annual report of the Export Processing Zones. Athi River, Nairobi, Kenya
- FAO (2008) Climate change, energy and food. Food and Agriculture Organization, Rome. <ftp://ftp.fao.org/docrep/fao/010/i0085e/i0085e00.pdf>. Accessed 14 Nov 2016
- Gupta N, Gupta AK, Gaur VS, Kumar A (2012) Relationship of nitrogen use efficiency with the activities of enzymes involved in nitrogen uptake and assimilation of finger millet genotypes grown under different nitrogen inputs. *Sci World J* 2012:1–10
- Hegde BR, Gowda L (1986) Cropping systems and production technology for small millets in India. In: Proceedings of first international small millets workshop. Bangalore, India., pp 209–236
- IPNI (2015) 4R plant nutrition manual: a manual for improving the management of plant nutrition. International Plant Nutrition Institute, Peachtree Corners
- Jansen JA, Wortmann CS, Stockton MA, Kaizzi KC (2013) Maximizing net returns to financially constrained fertilizer use. *Agron J* 105:573–578. doi:10.2134/agronj2012.0413
- Kaizzi KC, Byalebeka J, Wortmann CS, Mamo M (2007) Low input approaches for soil fertility management in semiarid eastern Uganda. *Agron J* 99:847–853
- Kaizzi CK, Byalebeka J, Semalulu O, Alou I, Zimwanguyizza W, Nansamba A, Musinguzi P, Ebanyat P, Hyuha T, Wortmann CS (2012a) Maize response to fertilizer and nitrogen use efficiency in Uganda. *Agron J* 104:73–82
- Kaizzi CK, Byalebeka J, Semalulu O, Alou I, Zimwanguyizza W, Nansamba A, Musinguzi P, Ebanyat P, Hyuha T, Wortmann CS (2012b) Sorghum response to fertilizer and nitrogen use efficiency in Uganda. *Agron J* 104:83–90
- Kaizzi CK, Wortmann CS, Byalebeka J, Semalulu O, Alou I, Zimwanguyizza W, Nansamba A, Musinguzi P, Ebanyat P, Hyuha T (2012c) Optimizing smallholder returns to fertilizer use: bean, soybean and groundnut. *Field Crops Res* 127:109–119
- Kaizzi CK, Wortmann CS, Byalebeka J, Semalulu O, Alou I, Zimwanguyizza W, Nansamba A, Odama E, Wortmann CS (2014) Upland rice response to fertilizer in Uganda. *Afr J Plant Sci* 8:416–425
- Kerr RB (2014) Lost and found crops: agrobiodiversity, indigenous knowledge, and a feminist political ecology of sorghum and finger millet in Northern Malawi. *Ann Assoc Am Geogr* 104:577–593
- Marschner H (1995) Mineral nutrition of higher plants, 2nd edn. Academic Press, London
- Mehlich A (1984) Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant. *Commun Soil Sci Plan* 15(12):1409–1416
- NAAIAP, KARI (2014) Soil suitability evaluation for maize production in Kenya. Nairobi, Kenya http://kenya.soilhealthconsortia.org/?wpfb_dl=3. Accessed 14 Nov 2016
- NRC (1996) Lost crops of Africa. National Academy Press, Washington
- Onyango AO (2016) Finger millet: food security crop in the arid and semi-arid lands (ASALs) of Kenya. *World Environ* 6:62–70
- Opole RA, Prasad PVV, Staggenborg SA (2013) Effect of seeding and nitrogen fertiliser application rates on field performance of finger millet. *Afr Crop Sci Soc, Kampala*
- Rao KL, Rao CP, Rao KV (1989) Response of finger miller (*Eleusine-coracana* L. Gaertn) cultivars to nitrogen under rain-fed conditions. *Indian J Agron* 34:302–306
- Rurinda J, Mapfumo P, van Wijk MT, Mtambanengwe F, Rufino MC, Chikowo R, Giller KE (2014) Comparative assessment of maize, finger millet and sorghum for household food security in the face of increasing climatic risk. *Eur J Agron* 55:29–41
- Salasya B, Oduori C, Ambitsi N, Onyango PE, Oucho P, Lumuli J (2009) The status of finger millet production in western Kenya. In: African crop science conference proceedings. Afr Crop Sci Soc, Kampala, Uganda, pp 719–723
- Sanchez PA, Shepherd KD, Soule MJ, Place FM, Buresh RJ, Izac AN (1997) Soil fertility replenishment in Africa: An investment in natural resource capital. In: Buresh RJ, Sanchez PA, Calhoun F (eds) Replenishing soil fertility in Africa. American Society of Agronomy, Madison, pp 1–46. doi:10.2136/sssaspecpub51.c1
- Shepherd KD, Walsh MG (2007) Infrared spectroscopy—enabling an evidence-based diagnostic surveillance approach

- to agricultural and environmental management in developing countries. *JNIRS* 15:1–19
- Shibairo SI, Madegwa YM, Onwonga RN (2016) Finger millet (*Eleusine corocona*) production in lower Eastern Kenya: status, constraints and opportunities. *Brit J Appl Sci Techno* 14:1–10
- Srinivasarao C, Wani SP, Sahrawat KL, Rego TJ, Pardhasaradhi G (2008) Zinc, boron and sulphur deficiencies are holding back the potential of rainfed crops in semi-arid India: experiences from participatory watershed management. *Int J Plant Prod* 2:89–99
- Tenywa JS, Nyende P, Kidoido M, Kasenge V, Oryokot J, Mbowa S (1999) Prospects and constraints of finger millet production in Eastern Uganda. *Afr Crop Sci J* 7:569–583
- Terhoeven-Urselmans T, Vagen TG, Spaargaren O, Shepherd KD (2010) Prediction of soil fertility properties from a globally distributed soil mid-infrared spectral library. *Soil Sci Soc Am J* 74:1792–1799. doi:[10.2136/sssaj2002.9880](https://doi.org/10.2136/sssaj2002.9880)
- Thilakarathna MS, Raizada MN (2015) A review of nutrient management studies involving finger millet in the semi-arid tropics of Asia and Africa. *Agron* 5:262–290
- Towett EK, Shepherd KD, Sila A, Aynekulu E, Cadisch G (2015) Mid-infrared and total x-ray fluorescence spectroscopy complementarity for assessment of soil properties. *Soil Sci Soc Am J* 79:1375–1385. doi:[10.2136/sssaj2014.11.0458](https://doi.org/10.2136/sssaj2014.11.0458)
- Wortmann CS, Ssali H (2001) Integrated nutrient management for resource-poor farming systems: a case study of adaptive research and technology dissemination in Uganda. *Am J Altern Agr* 16:167