# Sorghum Response to Fertilizer and Nitrogen Use Efficiency in Uganda

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## ABSTRACT

**Sorghum [*Sorghum bicolor* (L.) Moench] is important for smallholder production in semiarid parts of Uganda. Grain yields are low because of low soil fertility. Little fertilizer is used. Yield response to N, P, and K application, economically optimal rates for N, P, and K (EONR, EOPR, and EOKR, respectively), and N use efficiency (NUE) were evaluated at 11 site-seasons. Mean sorghum yield with no N applied ($N_0$) was 0.69 Mg ha$^{-1}$ and was consistently increased by a mean of 230% with N application. Mean EONRs were 34 to 18 kg ha$^{-1}$ N with fertilizer use cost to grain price ratios (CPs) of 10 to 30, respectively. Mean EOPRs were 11 to 2 kg ha$^{-1}$ P with CPs of 10 to 50, respectively. Sorghum did not respond to K application. Net economic returns were greater for N than P application. Mean aboveground biomass N with 0 and 90 kg ha$^{-1}$ N applied was 31.3 and 75.9 kg ha$^{-1}$, respectively. Grain N concentration, N harvest index, and internal NUE at the EONR were 1.67%, 53.2%, and 31.8 kg kg$^{-1}$, respectively, and higher than for $N_0$. Mean recovery efficiency, partial factor productivity, and agronomic efficiency declined with increased N rate and were 135%, 79 kg kg$^{-1}$, and 52 kg kg$^{-1}$, respectively, at the EONR. The profit potential of fertilizer N use is high for smallholder sorghum production in Uganda. Policy interventions to reduce fertilizer cost and improve grain marketing efficiency will enable smallholders to increase fertilizer use for substantial increases in sorghum production.**

Grain sorghum is an important food crop in semiarid areas of sub-Saharan Africa (Wortmann et al., 2009). Sorghum yield, like that of other crops, has not significantly increased in sub-Saharan Africa since the 1980s (Greenland et al., 1994; Sanchez et al., 1996; Muchena et al., 2005). Sorghum yield is limited by numerous constraints in Uganda, with soil water deficits, the stem borer complex, *Striga* species, and N deficiency being the most important constraints (Wortmann et al., 2009). Little if any fertilizer is applied for sorghum production in Uganda, and soil nutrient depletion is a cause of land degradation, with estimated mean depletion rates for N, P, and K of 21, 8, and 43 kg ha$^{-1}$ yr$^{-1}$, respectively (Wortmann and Kaizzi, 1998).

In Uganda, there is a high probability of increasing sorghum grain yield by >100% with the application of fertilizer N and P, with or without manure application (Kaizzi et al., 2007). Fertilizer costs are high, however, because of transportation and importation costs and marketing inefficiencies (Vlek, 1990; Sanchez, 2002). Grain prices are often low, especially in years with above-average harvests. Smallholder farmers require high returns on investments because they typically lack access to inexpensive credit and have little available money for investment (Heisey and Mwangi, 1996). A common guideline in determining the economical acceptance of an investment is that it give at least 100% net return, or a benefit/cost ratio (BC) of 1, to be competitive with alternative uses of scarce money (CIMMYT, 1988; Wortmann and Ssali, 2001). Therefore, sorghum yield increases with fertilizer N and P application may not be great enough for fertilizer use to be economically attractive to most resource-poor farmers (Kaizzi et al., 2007).

Several objectives were addressed in this research. The yield response of sorghum to N, P, and K in Uganda was quantified. The EONR, EOPR, and EOKR were determined at different CP. Soil test results and other site-season characteristics were related to N uptake. Components of NUE by sorghum in Uganda were determined. Equations were developed for the BC of N, P, and K applied to sorghum considering CP and application rate.

## MATERIALS AND METHODS

### Site Characteristics and Experimental Design

Fertilizer response trials were conducted during 11 site-seasons in 2009 and 2010 representing the main sorghum production areas of Uganda (Table 1). The agroecological zones of Kapchorwa, Kumi, and Abi and Ngetta are the Mt. Elgon Farmlands, Southern and Eastern Lake Kyoga Basin,

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**Abbreviations:** AE, agronomic efficiency of nitrogen use; BC, benefit/cost ratio; CP, fertilizer use cost to grain price ratio; EONR, economically optimal nitrogen rate; EOPR, economically optimal phosphorus rate; EOKR, economically optimal potassium rate; EOR, economically optimal rate; HI, harvest index; IE, internal efficiency; NHI, nitrogen harvest index; NUE, nitrogen use efficiency; $N_0$, no nitrogen applied; PE, physiological efficiency; PFP, partial factor productivity; SOM, soil organic matter; UN, total nitrogen in the aboveground biomass at harvest.

**Table 1. Characteristics for research sites at four research stations for determination of sorghum response to applied N, P, and K in Uganda.**

| Site-year† | Texture‡ | Sand | Clay | Organic matter | pH | P | K | Previous crop§ | Sowing date | Harvest date |
|---|---|---|---|---|---|---|---|---|---|---|
| | Soil properties | | | | | | | | | |
| | | g kg$^{-1}$ | | | | mg kg$^{-1}$ | | | | |
| | | | | | Season 2009b¶ | | | | | |
| Kapchorwa | C | 304 | 435 | 64 | 5.9 | 8.4 | 663 | CR | 15 Sept. | 20 Feb. |
| Kumi | SCL | 679 | 249 | 21 | 5.7 | 2.1 | 164 | FL | 13 Sept. | 5 Feb. |
| Ngetta | SL | 657 | 224 | 33 | 6.1 | 3.1 | 229 | SM | 20 Sept. | 29 Jan. |
| | | | | | Season 2010a | | | | | |
| Abi | SCL | 613 | 295 | 25 | 5.8 | 2.4 | 234 | FL | 9 Apr. | 13 Aug. |
| Kapchorwa | C | 284 | 460 | 53 | 6.0 | 9.9 | 391 | CR | 5 Mar. | 10 Sept. |
| Kumi | SCL | 645 | 257 | 20 | 5.8 | 3.3 | 143 | SP | 12 Mar. | 23 July |
| Ngetta | SL | 678 | 187 | 27 | 5.9 | 2.7 | 252 | SF | 24 Mar. | 15 Aug. |
| | | | | | Season 2010b | | | | | |
| Abi | SCL | 609 | 291 | 22 | 5.8 | 2.8 | 189 | CR | 22 Sept. | 5 Jan. |
| Kapchorwa | C | 247 | 473 | 52 | 5.8 | 7.1 | 467 | CR | 20 Sept. | 25 Feb. |
| Kumi | SCL | 672 | 234 | 25 | 6.0 | 5.8 | 143 | CR | 17 Sept. | 13 Feb. |
| Ngetta | SCL | 657 | 244 | 28 | 6.1 | 2.8 | 281 | FL | 10 Sept. | 13 Feb. |

† The latitude, longitude, elevation, and soil classification of the research locations were: Abi, 3°0′ N, 30°55′ E, 1261 m, Arenosols; Kapchorwa, 1°24′ N, 34°37′ E, 1877 m, Nitisol; Kumi, 1°29′ N, 33°56′ E, 1029 m, Acric Ferralsols; Ngetta, 2°17′ N, 32°56′ E, 1079 m, Petric Plinthsol.

‡ C, clay; SCL, sandy clay loam; SL, sandy loam.

§ CR, cereal; FL, fallow; SF, sunflower (*Helianthus annuus* L.); SM, simsim (*Sesamum indicum* L.); SP, sweet potato [*Ipomoea batatas* (L.) Lam.].

¶ The rainfall is bimodal, with planting for Season a occurring in March and April and planting for Season b in late August and September.

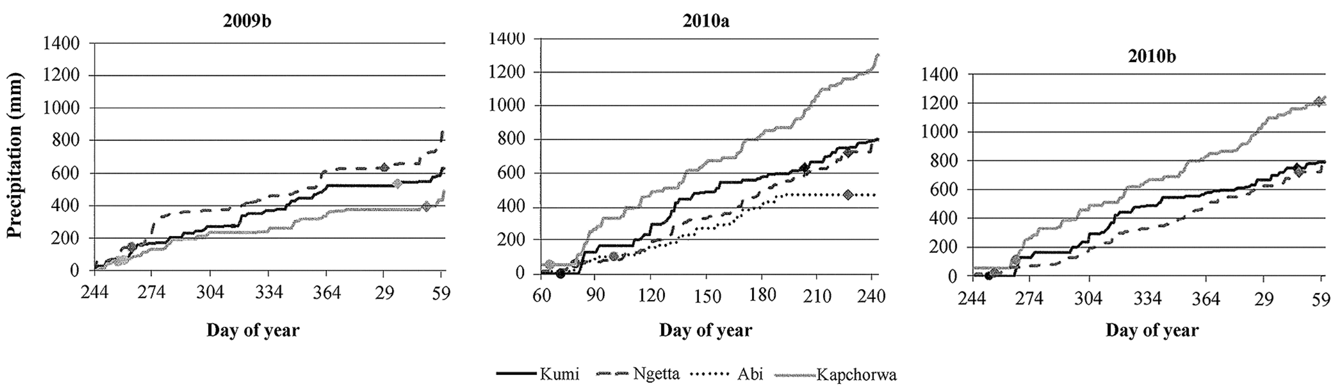


**Fig. 1. Cumulative rainfall for four sites across three cropping seasons in Uganda. Enlarged points indicate planting and harvest dates.**

and Northern Moist Farmlands, respectively (Wortmann and Eledu, 1999). Rainfall distribution is bimodal in Uganda, with a and b cropping seasons (Fig. 1). Rainfall data for the 2009b and 2010b seasons were not available for the Abi site. Rainfall ceased early relative to harvest in the 2009b season at Kapchorwa, Kumi, and Ngetta, and at Abi in the 2010a season. In other seasons, rainfall was well distributed and generally exceeded 600 mm for the cropping season.

The soils varied with site but were developed from ancient land surfaces, with the exception of Kapchorwa, and included Arenosols, Nitosols, Petric Plinthsols, and Acric Ferralsols (Table 1). The soils at all site-years had rooting depths >1.0 m. Composite soil samples of 10 cores for the 0- to 20-cm depth were collected for each site-season before planting and fertilizer application. Soil pH, soil organic matter (SOM) (Walkley and Black, 1934), available P and exchangeable K measured in a single Mehlich-3 extract and buffered at pH 2.5 (Mehlich, 1984), and soil texture (Bouyoucos, 1936) were determined. The soil texture classes were either sandy loam, sandy clay loam, or clay. Soil property ranges included 247 to 679 g kg$^{-1}$ sand content and 21 to 64 g kg$^{-1}$ SOM in the 0- to 20-cm depth (Table 1). The levels of SOM were relatively low at the Abi, Kumi, and Ngetta sites compared with other sites. Available P was below the critical level of 5 mg kg$^{-1}$ for Uganda (Foster, 1971) at Ngetta and Abi during all seasons and at Kumi during the 2010b season. The soil properties indicate less soil productivity at Abi, Kumi, and Ngetta compared with the Nitosols at Kapchorwa (Ssali, 2000).

The nutrient rates evaluated were: 0, 30, 60, and 90 kg N ha$^{-1}$; 0, 10, 20, and 40 kg P ha$^{-1}$; and 0, 30, 60, and 90 kg K ha$^{-1}$. The treatment arrangement was an incomplete factorial to limit the number of treatments. The experimental design was a randomized complete block design of three replications per site-season. Liebig's law of the minimum, proposed by J. von Liebig in 1840, was considered in treatment selection, expecting N deficiency, followed by P deficiency, to be more limiting to sorghum grain yield than other nutrient deficiencies. The N–P–K rates were: 0–0–0, 30–0–0, 60–0–0, 90–0–0, 30–10–0, 30–20–0, 30–40–0, 60–10–0, 60–20–0, 60–40–0, 90–10–0, 90–20–0, 90–40–0, 30–10–30, 30–20–60, 30–40–90, 60–10–30, 60–20–60, 60–40–90, 90–10–30, 90–20–60, and 90–40–90 kg ha$^{-1}$. The $N_0$ treatment occurred only with no P and K applied, and P and K effects were tested only with N applied. Similarly, no K was applied for the zero-P treatment. There was confounding of P and K treatments; the K effect was determined in the statistical analysis by subtracting at the plot level the K-minus treatments from the corresponding K-plus treatments after verifying that the P × K interaction was not significant. The plot size was 4.5 by 6 m.

Residue of the previous crop was removed and fallowed land was grazed before disk plowing at the onset of rains followed by secondary tillage with a disk harrow approximately 2 wk later. Tillage depth varied across site-seasons but was approximately 15 to 20 cm for plowing and 8 to 10 cm for the disk harrowing. The previous crop varied by site-season (Table 1). The sorghum cultivar was Sekedo, a popular red grain cultivar requiring approximately 100 d for maturity. The nutrient sources were urea, triple super phosphate, and KCl, which were broadcast applied before secondary tillage and incorporated. At 45 to 50 d after planting, 50% of the N and K fertilizer was sidedress applied in a band 8 to 10 cm from the crop rows and covered. Seeding was by hand hoes at approximately the 5-cm depth with 60- and 20-cm inter- and intrarow spacings, respectively, to have final plant populations of 8 plants m$^{-2}$. The trials were weeded with hand hoes twice or thrice depending on the weed intensity. Shoot fly (*Atherigona soccata* Rondani) and stem borer complex including *Chilo partellus* (Swinhoe) were controlled with earlier and later applications of cypermethrin [cyano(3-phenoxyphenyl)methyl 3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropanecarboxylate] (Cypermethoate, Bukoola Chemical Industries Ltd., Kampala, Uganda) or chlorpyrifos 5% [*O*,*O*-diethyl *O*-(3,5,6-trichloro-2-pyridinyl) phosphorothioate] (Dursban, Dow Chemical Co.), nonsystemic synthetic pyrethroid-based insecticides.

At harvest, plants from four inner rows were cut at ground level from a 2.4- by 3.0-m area. The panicles and stover were separated and air dried for at least 7 d. The panicles were threshed and the harvested grain weight was determined. After adding the panicle remnants, the stover was weighed to determine the stover yield. Grain and stover subsamples were oven dried at 70°C to determine the water content following air drying. The grain yield was calculated for 140 g kg$^{-1}$ water content. Oven-dried samples were ground to pass a 0.5-mm sieve and analyzed for total N in a single digest by a simple wet-ashing technique with colorimetric determination (Anderson and Ingram, 1993). The harvest index (HI) was calculated. Stover and grain N concentrations were used in the calculation of N uptake in grain and total biomass, the N harvest index (NHI), and other NUE values.

## Data Analysis

Statistical analyses were done by site-season and combined across site-seasons using Statistix 9 (Analytical Software, Tallahassee, FL), with site-seasons and replicates as random variables and cultivars and nutrient rates as fixed variables. When significant nutrient rate effects occurred, the asymptotic quadratic–plateau grain yield response function was fitted to nutrient rates. This function gave an exponential rise to maximum yield or to a yield plateau. The asymptotic function was yield (Mg ha$^{-1}$) = $a - bc^N$, where $a$ is yield at the plateau or maximum yield, $b$ is the gain in yield due to nutrient application, and $c^N$ determined the shape of the quadratic response, where $c$ is a curvature coefficient and $N$ is the nutrient rate. The ANOVAs and regression analyses for N rate effects included treatments with and without P and K applied, but a separate yield response analysis

**Table 2. Nitrogen application effect at rates of 0, 30, 60, and 90 kg ha$^{-1}$ on sorghum grain and stover yield for all P and K levels in 11 trials conducted in Uganda. There was no P × N rate interaction by site-season or in the combined analysis.**

| Location | Grain yield | | | | | Stover yield | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 kg ha$^{-1}$ | 30 kg ha$^{-1}$ | 60 kg ha$^{-1}$ | 90 kg ha$^{-1}$ | $P > F$ | 0 kg ha$^{-1}$ | 30 kg ha$^{-1}$ | 60 kg ha$^{-1}$ | 90 kg ha$^{-1}$ | $P > F$ |
| | Mg ha$^{-1}$ | | | | | Mg ha$^{-1}$ | | | | |
| | | | | | Season 2009b† | | | | | |
| Kapchorwa | 0.89 | 2.47 | 2.52 | 2.62 | *** | 2.52 | 4.83 | 4.81 | 4.64 | ** |
| Kumi | 0.72 | 2.30 | 2.42 | 2.74 | *** | 6.02 | 6.28 | 6.58 | 7.10 | NS |
| Ngetta | 0.33 | 1.19 | 1.25 | 1.28 | *** | 7.27 | 8.71 | 9.14 | 9.82 | NS |
| | | | | | Season 2010a | | | | | |
| Abi | 0.41 | 2.13 | 2.16 | 2.27 | *** | 1.80 | 4.70 | 4.58 | 4.54 | *** |
| Kapchorwa | 0.52 | 1.57 | 1.62 | 1.63 | *** | 1.32 | 2.96 | 3.25 | 3.26 | *** |
| Kumi | 1.07 | 2.75 | 2.82 | 2.55 | *** | 3.03 | 7.61 | 7.78 | 7.04 | *** |
| Ngetta | 1.00 | 2.95 | 2.98 | 2.75 | *** | 2.43 | 4.26 | 4.16 | 3.98 | *** |
| | | | | | Season 2010b | | | | | |
| Abi | 0.78 | 2.42 | 2.67 | 0.67 | *** | 1.99 | 6.23 | 6.82 | 6.56 | *** |
| Kapchorwa | 0.47 | 0.98 | 1.04 | 0.97 | *** | 2.67 | 2.31 | 2.37 | 2.64 | NS |
| Kumi | 0.69 | 2.19 | 2.55 | 2.39 | *** | 2.80 | 4.87 | 5.09 | 5.00 | *** |
| Ngetta | 0.91 | 2.26 | 2.39 | 2.35 | *** | 3.22 | 5.44 | 5.86 | 5.67 | *** |
| | | | | | All site-seasons | | | | | |
| Combined | 0.69 | 2.11 | 2.22 | 2.31 | *** | 3.31 | 5.48 | 5.69 | 5.73 | *** |
| SE | 0.122 | 0.046 | 0.046 | 0.046 | | 0.294 | 0.111 | 0.111 | 0.111 | |

** Significant effect at $P \leq 0.01$; NS, no significant effect at $P \leq 0.05$.

*** Significant effect at $P \leq 0.001$.

† The rainfall is bimodal, with planting for Season a occurring in March and April and planting for Season b in late August and September.

**Table 3. Asymptotic nonlinear regression coefficients (*a*, *b*, and *c*) for grain yield across all P and K levels and economically optimal N rates (EONR) for sorghum with fertilizer N use cost/grain price ratios (CP) of 10 to 30.**

| Location | Coefficients | | | EONR | | | | |
|---|---|---|---|---|---|---|---|---|
| | *a* | *b* | *c* | CP = 10 | CP = 15 | CP = 20 | CP = 25 | CP = 30 |
| | $Mg\ ha^{-1}$ | | | $kg\ ha^{-1}$ | | | | |
| Season 2009b† | | | | | | | | |
| Kapchorwa | 2.59 | 1.70 | 0.927 | 34 | 28 | 25 | 22 | 18 |
| Kumi | 2.63 | 1.43 | 0.957 | 42 | 33 | 26 | 21 | 17 |
| Ngetta | 1.30 | 0.97 | 0.937 | 28 | 22 | 18 | 14 | 11 |
| Season 2010a | | | | | | | | |
| Abi | 1.61 | 0.80 | 0.897 | 19 | 16 | 14 | 11 | 10 |
| Kapchorwa | 1.64 | 1.14 | 0.926 | 28 | 23 | 19 | 16 | 14 |
| Kumi | 2.80 | 1.72 | 0.896 | 27 | 23 | 20 | 18 | 17 |
| Ngetta | 3.04 | 2.09 | 0.934 | 39 | 36 | 31 | 27 | 24 |
| Season 2010b | | | | | | | | |
| Abi | 2.78 | 2.00 | 0.947 | 44 | 36 | 31 | 27 | 24 |
| Kapchorwa | 1.66 | 1.14 | 0.928 | 29 | 23 | 19 | 16 | 14 |
| Ngetta | 2.46 | 1.55 | 0.938 | 36 | 30 | 25 | 22 | 19 |
| Kumi | 2.54 | 1.85 | 0.947 | 42 | 35 | 30 | 26 | 22 |
| All site-seasons | | | | | | | | |
| Combined | 2.27 | 1.58 | 0.932 | 34 | 28 | 24 | 21 | 18 |

† The rainfall is bimodal, with planting for Season a occurring in March and April and planting for Season b in late August and September.

combined across site-seasons was done for N response with no P and K applied. Similarly, the ANOVAs for P rate effects included treatments with and without K applied but always with N applied.Grain yield responses to applied P were few and the response curve was determined for a combined analysis across site-seasons only. There were no grain yield increases due to applied K. Differences and relationships were considered significant at $P \leq 0.05$.

The economically optimal rate (EOR) was calculated for a range of CPs including 10, 15, 20, 25, and 30 for N and 10, 20, 30, 40, and 50 for P. A grain price of US\$0.083 $kg^{-1}$ (Uganda Sh. 2400 per US\$) was used for the economic analysis and fertilizer costs were a function of grain price and CP. Regression analyses were conducted to determine whether variation in yield with no N or P applied, maximum yield, yield response, and the EOR could be accounted for by soil properties, planting date, previous crop, and CP; these analyses included linear and polynomial analyses for individual soil and crop management factors and polynomial multiple regression analyses for sets of factors that accounted for relatively more variation in the EOR compared with others. Asymptotic functions were developed to relate the EOR to CP. Polynomial equations were developed to predict BC from CP and N or P rates.

Nonlinear functions that related aboveground plant N uptake (UN) to the N rate and grain yield were determined. Asymptotic regression analysis, using individual plot data, related NUE parameters to N rate, except for stover UN, for which a quadratic function was used after the asymptotic regression failed to converge. The NUE parameters included grain N concentration and content, HI, NHI, internal efficiency (IE) of total plant N taken up from soil and fertilizer, partial factor productivity (PFP), and physiological (PE), recovery (RE), and agronomic (AE) efficiencies of use for fertilizer N (Cassman et al., 2002). The NUE components were calculated as: IE = $Y$/UN ($kg\ kg^{-1}$) where $Y$ is grain yield ($kg\ ha^{-1}$); PFP = $Y$/N rate; NHI = grain N/UN; RE = $(UN_{+N} - UN_{N0})$/N rate; PE = $(Y_{+N} - Y_{N0})/(UN_{+N} - UN_{N0})$; and AE = $(Y_{+N} - Y_{N0})$/N rate. The units for IE, NHI, PE, AE, and PFP were kilograms per kilogram.

## RESULTS

### Yield Response to Nitrogen, Phosphorus, and Potassium

The mean sorghum grain yield was only 0.69 $Mg\ ha^{-1}$ with $N_0$ (Table 2). The predicted mean maximum grain yield was 2.27 $Mg\ ha^{-1}$ (Table 3), with no significant yield increase for >30 $kg\ ha^{-1}$ N applied. The mean HI was 172 $g\ kg^{-1}$ with no fertilizer applied and increased to 282 $g\ kg^{-1}$ with N applied, averaged across P and K rates, calculated as

$$\mathrm{HI}\left(\mathrm{kg\ kg^{-1}}\right) = 0.305 - 0.0838\left(0.912^{N}\right) \qquad [1]$$

The N × P rate and N rate × site-season interactions were not significant for grain and stover yield. Sorghum grain yield increased in response to N application for all site-seasons (Table 2). The overall mean grain yield increase was 1.42 $Mg\ ha^{-1}$ with the application of 30 kg N $ha^{-1}$ and 1.58 $Mg\ ha^{-1}$ for the combined analysis. The application of more N resulted in further yield increases for two site-seasons only. Combined across all site-seasons, the grain yield response to applied N was

$$\begin{aligned}\mathrm{Yield} &= 2.27 - 1.58\left(0.932^{N}\right) \\ &= 2.07 - 1.30\left(0.953^{N}\right) \text{ with no P or K applied}\end{aligned} \qquad [2]$$

There was not a significant difference in the yield at the N rate response plateau or in the total response with no P and

**Table 4. Phosphorus application effect at rates of 0, 10, 20, and 40 kg ha$^{-1}$ on sorghum grain yield with at least 30 kg N ha$^{-1}$ applied and the economically optimal P rate (EOPR) at five ratios of cost of P use to grain price (CP) in Uganda. The P rate × site-season interaction was not significant.**

| | Grain yield | | | | | Stover yield | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Location | 0 kg ha$^{-1}$ | 10 kg ha$^{-1}$ | 20 kg ha$^{-1}$ | 40 kg ha$^{-1}$ | *P* > *F* | 0 kg ha$^{-1}$ | 10 kg ha$^{-1}$ | 20 kg ha$^{-1}$ | 40 kg ha$^{-1}$ | *P* > *F* |
| | Mg ha$^{-1}$ | | | | | Mg ha$^{-1}$ | | | | |
| | | | | | Season 2009b† | | | | | |
| Kapchorwa | 2.31 | 2.63 | 2.57 | 2.52 | NS | 5.04 | 4.82 | 4.68 | 4.64 | NS |
| Ngetta | 1.23 | 1.18 | 1.29 | 1.27 | NS | 8.60 | 8.07 | 9.72 | 10.19 | ** |
| Kumi | 1.26 | 2.52 | 2.78 | 2.66 | *** | 6.42 | 6.43 | 6.95 | 6.69 | NS |
| | | | | | Season 2010a | | | | | |
| Abi | 1.62 | 2.26 | 2.28 | 2.30 | *** | 4.07 | 444 | 4.44 | 5.22 | * |
| Kapchorwa | 1.38 | 1.63 | 1.65 | 1.63 | NS | 2.82 | 3.10 | 3.23 | 3.29 | NS |
| Ngetta | 2.62 | 2.99 | 2.89 | 2.93 | NS | 3.79 | 4.26 | 4.01 | 4.19 | NS |
| Kumi | 2.61 | 2.69 | 2.64 | 2.84 | NS | 7.23 | 7.42 | 7.29 | 7.84 | NS |
| | | | | | Season 2010b | | | | | |
| Abi | 2.24 | 2.44 | 2.87 | 2.63 | * | 5.74 | 6.27 | 7.36 | 6.72 | * |
| Kapchorwa | 1.00 | 0.96 | 1.01 | 1.02 | NS | 2.44 | 2.64 | 2.37 | 2.32 | NS |
| Ngetta | 2.17 | 2.29 | 2.37 | 2.41 | NS | 4.73 | 5.59 | 5.61 | 5.76 | * |
| Kumi | 1.79 | 2.27 | 2.69 | 2.47 | *** | 4.65 | 4.70 | 5.23 | 5.22 | NS |
| | | | | | All site-seasons | | | | | |
| Combined‡ | 1.94 | 2.23 | 2.33 | 2.28 | *** | 5.10 | 5.22 | 5.57 | 5.61 | NS |

* Significant effect at $P \leq 0.05$; NS, no significant effect at $P \leq 0.05$.

** Significant effect at $P \leq 0.01$.

*** Significant effect at $P \leq 0.001$.

† The rainfall is bimodal, with planting for Season a occurring in March and April and planting for Season b in late August and September.

‡ The function representing sorghum grain yield response across all site-seasons is: yield = 2.346 – 0.410(0.844$^{P}$), where *P* is the P application rate. Sorghum EOPR was 11, 6, 5, 3, and 2 kg ha$^{-1}$ for CPs of 10, 20, 30, 40, and 50, respectively.

K applied (–0.20 and –0.28 Mg ha$^{-1}$, respectively) compared with the means for all N rate treatments.

Stover yield was increased by N application for eight of the 11 site-seasons, with an additional increase by applying 60 compared with 30 kg ha$^{-1}$ N at one site-season only. Nitrogen application was profitable for all site-seasons and all CPs, and the EONR ranged from 10 to 44 kg ha$^{-1}$ (Table 3). The mean EONRs determined from the analysis combined across all site-seasons were 34 and 18 kg ha$^{-1}$ with CPs of 10 and 30, respectively (Fig. 2). The mean EONR was less for sorghum than for maize (*Zea mays* L.) produced under similar conditions (Kaizzi et al., 2012). Returns to applied N were more sensitive to the N rate as the CP increased. The mean EONR can be estimated from the CP according to

$$\mathrm{EONR} = 13.2 + 43.5\left(0.932^{\mathrm{CP}}\right) \qquad [3]$$

Soil properties, rainfall amount, planting date, and previous crop were not related to the maximum trial grain yield, the yield with $N_0$, yield responses to applied N, or the EONR. The results do not indicate that site properties can be used to estimate the EONR on a site or site-season basis.

The P × K rate interaction was not significant but the P rate × site-season interaction was significant. The application of P, in the presence of applied N, resulted in increased sorghum grain yield at Abi and Kumi only (Table 4). In the combined analysis, grain yield was increased by 0.29 Mg ha$^{-1}$ with 10 kg ha$^{-1}$ P applied. The yield response function from the combined analysis was

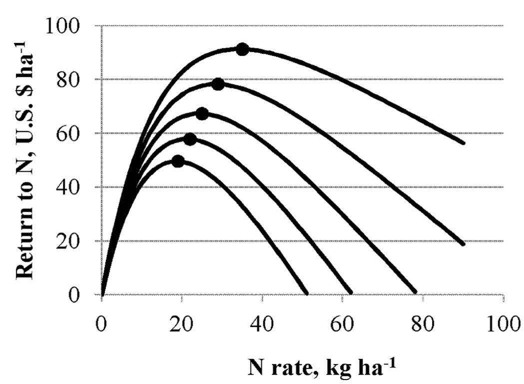


**Fig. 2. Economically optimal N rates for sorghum production in Uganda for five ratios of fertilizer use cost to farm-gate grain price (CP) determined from 11 site-seasons and averaged across all P and K levels.**

$$\mathrm{Yield} = 2.305 - 0.362\left(0.839^{P}\right) \qquad [4]$$

where *P* is the P application rate. Stover yield was increased with P application at Abi and Ngetta, and stover yield, across all site-seasons, was increased by 0.20 Mg ha$^{-1}$ with 10 kg ha$^{-1}$ P applied. The EOPR determined from the combined analysis ranged from 2 to 11 kg ha$^{-1}$, calculated as

$$\mathrm{EOPR} = 1.32 - 17.1\left(0.934^{\mathrm{CP}}\right) \qquad [5]$$

**Table 5. Mean effect of N rate on components of N use efficiency across all P and K rates by sorghum for 11 site-seasons in Uganda.**

| Component | N rate effect | | | | $P > F$ | EONR† |
|---|---|---|---|---|---|---|
| | 0 kg ha$^{-1}$ | 50 kg ha$^{-1}$ | 100 kg ha$^{-1}$ | 150 kg ha$^{-1}$ | | |
| Grain N conc., g kg$^{-1}$ | 16.3 | 16.9 | 17.4 | 17.2 | *** | 16.7 |
| Stover N conc., g kg$^{-1}$ | 5.6 | 6.2 | 6.4 | 6.8 | *** | 6.1 |
| Grain N content, kg ha$^{-1}$ | 12.7 | 35.6 | 39.3 | 38.6 | *** | 34.0 |
| Stover N content, kg ha$^{-1}$ | 18.6 | 32.3 | 35.4 | 37.3 | *** | 29.3 |
| Plant N content, kg ha$^{-1}$ | 31.3 | 67.9 | 74.7 | 75.9 | *** | 64.7 |
| Harvest index, kg kg$^{-1}$ | 0.222 | 0.300 | 0.306 | 0.305 | *** | 0.300 |
| N harvest index, kg kg$^{-1}$ | 0.448 | 0.537 | 0.538 | 0.521 | *** | 0.532 |
| Recovery efficiency, kg kg$^{-1}$ | | 1.221 | 0.723 | 0.496 | *** | 1.352 |
| Agronomic efficiency, kg kg$^{-1}$ | | 46.5 | 25.7 | 16.9 | *** | 52.0 |
| Internal efficiency, kg kg$^{-1}$ | 27.4 | 32.1 | 31.4 | 30.4 | *** | 31.8 |
| Partial factor productivity, kg kg$^{-1}$ | | 70.1 | 37.5 | 24.8 | *** | 78.9 |
| Physiological efficiency, kg kg$^{-1}$ | | 50.8 | 50.0 | 35.5 | NS | |

*** Significant effect at $P \leq 0.001$; NS, no significant effect at $P \leq 0.05$.

† The EONR (economically optimal N rate) was 24 kg ha$^{-1}$ for a fertilizer N use cost to farm-gate grain price ratio of 20.

A grain yield response to P occurred at Abi and Kumi but not at Ngetta, where Mehlich-3 P was low compared with Kapchorwa. Stover yield was increased with P application for two site-seasons each at Ngetta and Abi. The results indicate that either grain or stover yield increase is likely with P application when Mehlich-3 P is <4 mg kg$^{-1}$. Grain yield was not affected by K application for any site-season. In the analysis combined across site-seasons, stover yield was increased by 0.19 Mg ha$^{-1}$ with 30 kg ha$^{-1}$ K applied.

## Nitrogen Uptake

The mean UN with $N_0$ was 31.3 kg ha$^{-1}$ compared with 46.3 kg ha$^{-1}$ for maize under similar conditions (Kaizzi et al., 2012) (Table 5). Sorghum UN with $N_0$ is an estimate of the indigenous soil N supply and ranged from 13.4 to 54.1 kg ha$^{-1}$. Compared with $N_0$, the mean UN increased by 36.6 kg ha$^{-1}$ with 30 kg ha$^{-1}$ N applied, resulting in 121% RE, calculated as

$$\mathrm{RE}\left(\mathrm{g\,kg^{-1}}\right)=1988-30.1N+0.150N^2 \quad [6]$$

The mean RE was estimated to be 135% at the EONR of 24 kg ha$^{-1}$ when CP = 20 compared with 50% for the 90 kg ha$^{-1}$ N rate. The grain yield with $N_0$ increased curvilinearly with increased UN, calculated as

$$\text{Grain yield}_{N_0}=0.943-1.756\left(0.910^{\mathrm{UN}}\right) \quad [7]$$

## Nitrogen Use Efficiency

Internal efficiency is affected by the NHI and grain N concentration. The grain N concentration, NHI, and IE at the EONR for a CP of 20 were 0.0167, 0.532, and 31.8 kg kg$^{-1}$, respectively, which were higher than for the $N_0$ rate (Table 5). The mean IE at the EONR was similar to the IE at higher N rates. The mean NHI was high in comparison to the HI but 17% less than the NHI reported for maize at the EONR under similar conditions (Kaizzi et al., 2012). The mean grain N concentration was 27% higher than for maize in the United States (Wortmann et al., 2011). The mean PFP and AE declined with increased N rate and were 79 and 52 kg kg$^{-1}$, respectively, at the EONR. Agronomic efficiency was 26% higher than reported for maize (Kaizzi et al., 2012) and 280% higher for sorghum in the United States (Wortmann et al., 2007). The mean PE of fertilizer N was not affected by the N rate although some response was expected because the grain yield was nonlinearly related to UN. The effect of N rate on various components of NUE are represented by the following equations determined from individual plot data across 11 site-seasons:

$$\mathrm{UN}\left(\mathrm{kg\,ha^{-1}}\right)=76.23-44.90\left(0.945^{N}\right) \quad [8]$$

$$\text{Grain N concentration}\left(\mathrm{g\,kg^{-1}}\right)=17.40-0.111\left(0.970^{N}\right) \quad [9]$$

$$\text{Grain N}\left(\mathrm{kg\,ha^{-1}}\right)=39.12-26.41\left(0.934^{N}\right) \quad [10]$$

$$\text{Stover N}\left(\mathrm{g\,kg^{-1}}\right)=7.48-1.811\left(0.990^{N}\right) \quad [11]$$

$$\text{Stover N}\left(\mathrm{kg\,ha^{-1}}\right)=22.22+0.452N-2.96N^2 \quad [12]$$

$$\mathrm{HI}\left(\mathrm{kg\,kg^{-1}}\right)=0.305-0.0838\left(0.912^{N}\right) \quad [13]$$

$$\mathrm{NHI}\left(\mathrm{kg\,kg^{-1}}\right)=0.532+0.0841\left(0.455^{N}\right) \quad [14]$$

$$\mathrm{IE}\left(\mathrm{kg\,kg^{-1}}\right)=28.31+0.148N-0.00141N^2 \quad [15]$$

$$\mathrm{AE}\left(\mathrm{kg\,kg^{-1}}\right)=79.4-1.29N+0.00671N^2 \quad [16]$$

$$\mathrm{PFP}\left(\mathrm{kg\,kg^{-1}}\right)=122.6-2.085N+0.0111N^2 \quad [17]$$

## DISCUSSION

In tropical soils, SOM is a major determinate of soil productivity (Greenland et al., 1994). Considering a critical value of 30 g $kg^{-1}$ SOM for a probable response to applied N (Foster, 1971), the soils at the Kapchorwa sites were more fertile than those at the Abi, Ngetta, and Kumi sites (Table 1). Mehlich-3 P at Ngetta, Abi, and Kumi was below the critical level of 6 mg $kg^{-1}$, but available K was consistently above the critical level of 150 mg $kg^{-1}$ (Foster, 1971). The finding that N and P deficiencies are more limiting for cereal production in Uganda compared with K deficiency agrees with the findings of Kaizzi et al. (2004, 2006) and Foster (1980a,b).

The indigenous soil N supply was apparently very low and sufficient to support a mean grain sorghum yield of approximately 0.69 Mg $ha^{-1}$ with no fertilizer N applied even though the median SOM level was 27 g $kg^{-1}$ of soil. In contrast, the mean yield of rainfed grain sorghum with $N_0$ was >6 Mg $ha^{-1}$ in the U.S. Great Plains with a median SOM level of 29 g $kg^{-1}$ (Wortmann et al., 2007). The composition of the SOM is probably different, with relatively more recalcitrant SOM, less particulate organic matter, and less decomposing crop residues in the Uganda soils compared with the Great Plains soils. At the Uganda sites, residues of the previous crops had been removed and the vegetative fallow was grazed, probably with a net loss of nutrients from the field, with little replenishment of the active and labile SOM pools that are important to N cycling (Tisdall and Oades, 1982). As a result, variation in SOM levels did not account for variations in grain yield with and without N applied and in response to applied nutrients. Ssali (2000) also did not find a relationship between crop yield and SOM in Uganda. The SOM in the Uganda soils, while slow to release N, is probably very valuable for wet soil aggregate stability, water holding capacity, and cation exchange capacity (Greenland et al., 1994).

Economical optimal N rates were modest, ranging from 10 to 46 kg $ha^{-1}$ when the cost of using fertilizer N was high and low, respectively, relative to the grain price (Table 3). The EONRs were related to the maximum trial yield ($r = 0.59$) but not to the yield with $N_0$. A grain yield increase due to applied P occurred at four of 11 site-seasons, but the P rate was significant in the combined analysis across all site-seasons with an EOPR ranging from 2 to 11 kg $ha^{-1}$.

Resource-poor farmers with inadequate access to money to apply fertilizer at the EOR to all cropland need to consider the BC for different rates and nutrients. Application at less than the EONR or EOPR to more land will then give higher returns compared with applying at the EOR to less land. This is also a consideration in deciding which nutrients to apply to which crops. The BC is a function of the CP and nutrient application rate and is captured for fertilizer N and P by

$$\begin{aligned}\mathrm{BC_N} = {} & 15.44 - 0.293N - 0.751\mathrm{CP} \\ & + 0.00203N^2 + 0.0109\mathrm{CP}^2 \\ & + 0.00551N\,\mathrm{CP}\end{aligned} \quad [18]$$

$$\begin{aligned}\mathrm{BC_P} = {} & 7.537 - 0.369P - 0.285\mathrm{CP} \\ & - 0.000606P^2 - 0.00284\mathrm{CP}^2 \\ & + 0.00497P\ \mathrm{CP}\end{aligned} \quad [19]$$

These equations show the BC for P to be higher than for N at the EOR, but the $BC_P$ was determined from P response results with N already applied and with a much lower EOR for P compared with N. For the same application rate and CP, both $BC_N$ and $BC_P$ were higher for sorghum than for maize (Kaizzi et al., 2012).

In comparing the NUE components of sorghum with maize produced under similar conditions, grain and stover N concentration, RE, IE, PE, and AE were higher and NHI and PFP were lower for sorghum (Kaizzi et al., 2012). The very high sorghum RE contributed to high values for other components of fertilizer NUE. Apparently, N application stimulated plant root growth sufficiently to recover substantially more indigenous N compared with $N_0$. This additional indigenous N was at risk of loss from the system because of leaching or denitrification with $N_0$. There was an increase in HI and NHI with N application due to a proportionately greater increase in grain compared with stover yield. This illustrates that indigenous soil N accumulated since the last season was soon depleted by vegetative crop growth, with little available to support the reproductive stages. Much of the applied N at the EONR was therefore used by the crop to produce grain.

Fertilizer management practices can be important to nutrient use efficiency and net returns to fertilizer use. In-season application of at least some of the N, as practiced in these trials, can be important to RE. This raises the question of whether a larger proportion or all of the fertilizer N should be applied in-season near the time of rapid uptake. The RE was >100% at lower N rates. Some N application preplant may be necessary for this increased ability to take up indigenous soil N, which presumably occurs because of increased root growth.

Fertilizer P was broadcast applied but P recovery might have been improved by placement near the seed. Christianson et al. (1990) found it better to broadcast P rather than to place it close to pearl millet [*Pennisetum glaucum* (L.) R. Br.] seed on a sandy soil because root growth depleted the soil water near the plant, which inhibited P uptake. Muehlig-Versen et al. (2003), however, reported 72 to 88% higher yield with 3 to 7 kg $ha^{-1}$ P placed near pearl millet seed compared with a broadcast application of 13 kg $ha^{-1}$ P.

## CONCLUSIONS

The mean sorghum grain yield was increased 1.58 Mg $ha^{-1}$ with 30 kg N $ha^{-1}$, confirming the effectiveness of fertilizer use for increasing sorghum grain production and farm profitability in Uganda. The economic analysis found that the BC can be high with current fertilizer N prices but much less so for fertilizer P. Recovery of fertilizer N at the EONR was very high, minimizing losses but probably leaving little residual N for the next crop and resulting in a negative soil N balance. Policy interventions to improve returns on fertilizer use will raise the EOR by changing the CP. Fertilizer use subsidies will enable farmers to use more fertilizer with their little investment capital. Good information access to current fertilizer prices and grain market prices will enable farmers to better determine the EONR for the season.

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