Low Input Approaches for Soil Fertility Management in Semiarid Eastern Uganda

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ABSTRACT

Grain sorghum [*Sorghum bicolor* (L.) Moench] is an important food crop of semiarid sub-Saharan Africa. Crop yields are generally low, partly due to low soil fertility. Research was conducted with farmers to evaluate, soil fertility management practices in sorghum-based cropping systems including: mucuna [*Mucuna pruriens* (L.) DC.] fallow; cowpea [*Vigna unguiculata* (L.) Walp.] rotation with sorghum; animal manure application; N and P fertilizer application; and reduced tillage. Four studies, comprised of 142 on-farm trials, were conducted at three locations over 3 yr in drought-prone parts of eastern Uganda. Mucuna on average produced 7 Mg ha^{-1} of aboveground dry matter containing 160 kg N ha^{-1} across the three locations. Application of 2.5 Mg ha^{-1} of manure and of 30 kg N plus 10 kg P ha^{-1} increased grain yield by 1.05 and 1.30 Mg ha^{-1}, respectively. A combination of 2.5 Mg ha^{-1} manure with 30 kg N ha^{-1} increased grain yield by 1.50 Mg ha^{-1} above the control (1.1 Mg ha^{-1}). The increase in sorghum grain yield in response to 30 kg N ha^{-1} alone, to a mucuna fallow, and to a rotation with cowpea was 1.15, 1.55, and 0.82 Mg ha^{-1}, respectively. These soil fertility management practices, as well as reduced tillage, were found to be cost effective in increasing sorghum yield in the predominantly smallholder agriculture where inorganic fertilizer was not used much. On-farm profitability and food security for sorghum production systems can be improved by use of inorganic fertilizers, manure, mucuna fallow, sorghum–cowpea rotation, and reduced tillage.

GRAIN SORGHUM is an important crop for smallholder farmers in sub-Saharan Africa, but crop yields are low and declining in some places (Sanchez et al., 1996). Low inherent soil N and P availability are major constraints (Bekunda et al., 1997) that are exacerbated by soil fertility depletion through nutrient removal with harvest and losses in runoff and soil erosion (Vlek, 1993; Sanchez et al., 1997). Many farmers are unable to compensate for these losses, resulting in negative nutrient balances at the national level for sub-Saharan Africa countries (Stoorvogel and Smaling, 1990) and at the farm level in eastern and central Uganda (Wortmann and Kaizzi, 1998).

Nutrient availability can be improved through application of inorganic or organic nutrient sources. The profitability of fertilizer use depends on agro-climatic and economic conditions at local and regional levels (Vlek, 1990). Infrastructural and other marketing constraints, lack of agricultural subsidies, and high opportunity costs on available money make the use of inorganic fertilizers very costly in Uganda. Real costs of fertilizer use to farmers may be two to six times as much as in Europe (Sanchez, 2002). Resource-poor farmers often require a 75% return within a 6- to 12-mo period to make an investment competitive (CIMMYT, 1988; Wortmann and Ssali, 2001).

Use of organic nutrient sources is constrained by labor availability for collecting and applying the materials, limited quantities, variation in quality, and the demand for crop residues as fuel and fodder (Palm, 1995; Palm et al., 1997). Green manure production requires land that could often be used for food or cash crops (Giller et al., 1997). Farmyard manure is available to many smallholder farmers, but generally in small quantities. Transfer of plant materials from field boundary areas, or nearby fallow or grazing areas, often has potential in sub-humid areas but less potential in semiarid areas (Kaizzi and Wortmann, 2001; Wortmann and Ssali, 2001).

Biological nitrogen fixation (BNF) may contribute much N through better integration of legumes in farming systems. Giller and Cadisch (1995) reported that BNF contributes to productivity both directly, when the fixed N is harvested in protein of grain or other food for human or animal consumption, or indirectly by adding N to the soil for the maintenance or enhancement of soil fertility. Under favorable environmental conditions, BNF can meet the N requirements of tropical agriculture (Peoples et al., 1995; Giller et al., 1994, 1997). Economic constraints make BNF an attractive N source for resource-poor farmers in sub-Saharan Africa (Giller and Wilson, 1991). Mucuna has been found to be well adapted and easy to manage with high biomass and fixed N yields in other cropping systems of Uganda (Wortmann et al., 2000; Kaizzi and Wortmann, 2001; Kaizzi et al., 2004, 2006).

Several low-input soil fertility management practices for sorghum production in drought-prone areas of eastern Uganda were evaluated in four related studies to verify and fine-tune these practices for the production systems. The objectives of these studies were to determine sorghum grain yield response to mucuna fallow and cowpea rotation, application of inorganic and organic N and P, and reduced tillage.

MATERIALS AND METHODS

Location Characteristics

Four studies were conducted, each consisting of farmer-managed trials at three locations: Kadesok and Opwatetta parishes (approximately 33°45′ E and 1°12′ N) in the Southern

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Abbreviations: BNF, biological nitrogen fixation; UgSh, Uganda shillings with an exchange rate of UgSh 1800 US\$$^{-1}$.

and Eastern Lake Kyoga Basin of eastern Uganda and Kapolin parish in the Usuk Sandy Farm-Grasslands (34°0′ E and 1°40′ N) (Wortmann and Eledu, 1999). The altitude ranged from 1050 to 1150 m asl. The trials were part of a larger process of participatory research with these communities that began with farming system characterization and diagnosis, identification of potential solutions to soil fertility problems, and development of research plans. This process was to lead to farmer participation in the dissemination of research results to other farmers.

The rainfall at the research locations allows for two annual crop growing seasons per year with an annual mean of approximately 1150 mm for Kadesok and Opwatetta and 1000 mm for Kapolin (Fig. 1). The long rain season is approximately March to July and the short rain season is from August to November. The rainfall that falls outside of the annual crop growing seasons, about 25 to 30% of the total, is used by naturally growing annual or perennial vegetation that is grazed or incorporated during tillage and this rainfall is unavailable to the planted crops. The rainfall is less at Kapolin, due to a rain shadow effect of Mt. Elgon, than at Kadesok and Opwatetta.

The dominant soil type in the area is Petroferric Haplustox. Soil samples from the 0- to 20-cm depth were obtained from each trial field, dried in the open air, ground to pass through a 2-mm sieve, and analyzed according to Foster (1971). Extractable P, K, and Ca were measured in a single ammonium lactate/acetic acid extract buffered at pH 3.8. Soil pH was measured using a soil to water ratio of 1:2.5. Soil organic matter was determined according to the Walkley–Black method, modified according to Foster (1971).

Soil texture class for the research locations ranged from sandy clay loam to sand with sand contents of 580 to 920 g kg^{-1} (Table 1). The pre-dominant texture classes were sandy loam and loamy sand, and of low water-holding capacity. The soil test results were typical for the area (Ssali, 2000) and the soil of most trial fields was deficient in one or more nutrients (Foster, 1971). Soil organic matter varied widely but was often too low for adequate N supply. Available P was below the critical level in most fields (<5 mg kg^{-1}). Extractable K and Ca levels were below the critical level in 24 to 33% and 10 to 16% of the fields, respectively. Depletion of soil K probably occurred partly due to a long history of cassava (*Manihot esculenta* Crantz) and sweet potato (*Ipomoea fastigiata* Choisy) harvests, which are important crops in the area's diverse cropping systems, which may include periods of grazed fallow of 1 to 5 yr.

Experimental Design

For each of the four studies, several on-farm trials, each of one block or replication of a particular set of treatments, were conducted at each of the three locations in 2004 and 2005. Each on-farm trial was a replication for a location/year in a study as a means to minimize the probability of Type I error in extrapolating results throughout eastern Uganda, although higher coefficients of variability were expected than with researcher managed on-station trials. The number of replications, or on-farm trials in a location-year, varied. The plot size was 100 m^2 for all studies. The major crop for experimentation was sorghum produced during the long rain period of March to July (Season A; Table 2).

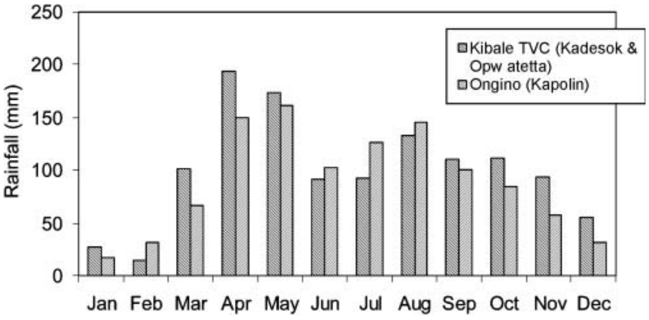

Fig. 1. Mean long-term monthly rainfall at Kibale, representing the Kadesok and Opwatetta locations, and Ongino, representing the Kapolin location.

Table 1. The median values and ranges of soil properties for the on-farm trial fields in three communities in a semiarid area of eastern Uganda.

Soil property	Kadesok	Opwatetta	Kapolin	Critical values†
$PH_{1:2.5}$	6.1 (5.4–6.6)	6.0 (5.2–7.2)	6.1 (5.3–7.5)	5.2
SOM, g kg^{-1}	28 (19–42)	28 (26–41)	22 (17–35)	30
Extractable P, mg kg^{-1}	1.3 (1–6)	1.3 (1–5)	2.80 (1–9)	5.0
Extractable K, cmol$_c$ kg^{-1}	5.1 (2–10)	6.2 (3–10)	5.4 (2–10)	0.4
Extractable Ca, cmol$_c$ kg^{-1}	41 (8–45)	36 (5–54)	31 (5–68)	0.9
Sand, g kg^{-1}	710 (660–880)	760 (580–820)	840 (620–920)	NA
Silt, g kg^{-1}	70 (26–130)	50 (13–150)	50. (30–110)	NA
Clay, g kg^{-1}	20 (65–270)	190 (140–290)	110 (50–290)	NA

† Levels below the critical values are considered to be yield limiting (Foster, 1971); NA = not applicable.

Treatments

Study 1

The rotation effects of mucuna, a herbaceous annual legume, as an improved fallow crop and cowpea, a grain legume, in rotation on the grain yield of the subsequent sorghum crop were evaluated on 36 farms (Table 3). The preceding crop was produced during the short rain period. The treatments were: (i) sorghum following sorghum; (ii) sorghum following cowpea; (iii) sorghum following sorghum with 30 kg N ha^{-1} applied to the second sorghum crop; and (iv) sorghum following a mucuna fallow crop. No nutrients were applied except for the +N treatment.

Study 2

Sorghum yield response to applied inorganic fertilizers and manure was evaluated on 61 farms (Table 5). The treatments were: (i) no nutrients applied; (ii) 30 kg N ha^{-1}; (iii) 30 kg N plus 10 kg P ha^{-1}; (iv) 2.5 Mg manure ha^{-1}; and (v) 30 kg N plus 2.5 Mg manure ha^{-1}. The nutrient content of the manure on a dry matter basis was in the range 0.7 to 1.8%, 0.1 to 0.2%, and 0.8 to 2.4% for N, P and K, respectively. The manure was from open pens where farmers kept their cattle and goats at night. A large proportion of the manure N was probably in organic rather than ammonium form, and the organic N would probably be gradually mineralized over several seasons. The crop of the previous season varied.

Table 2. The crop sequences for four studies conducted in semiarid areas of eastern Uganda in 2004 and 2005.

Months, August to July											
A	S	O	N	D	J	F	M	A	M	J	J
Short rains, season B							long rains, season A				
Study 1											
Sorghum, cowpea, mucuna							main sorghum crop				
Study 2, 3, and 4											
Cowpea							main sorghum crop				

Table 3. Sorghum grain yield (Mg ha^{-1}), following either sorghum, cowpea, or mucuna in rotation, and during the long rain seasons of 2004 and 2005 at three locations in a semiarid area of eastern Uganda.

Previous crop and N rate	Kadesok		Opwatetta		Kapolin		
	2004	2005	2004	2005	2004	2005	Overall
	5†	8	5	7	6	5	36
Sorghum	1.03	1.76	1.17	1.39	0.67	0.96	1.21
Cowpea	1.84	3.19	1.61	2.17	1.43	1.18	2.01
Sorghum, 30 kg N ha^{-1}	2.30	3.49	1.65	2.43	2.05	1.36	2.33
Mucuna	2.64	3.98	1.76	3.00	2.81	1.47	2.75
LSD$_{0.05}$	0.27	0.27	0.29	0.39	0.53	0.15	0.24

† Number of on-farm trials conducted.

Study 3

The N response curve for sorghum was determined using results from trials on 33 farms. Nitrogen levels of 0, 20, 40, and 60 kg ha^{-1} were evaluated to determine the response curve. The experimental area received a blanket application of 40 kg P ha^{-1} and 60 kg K ha^{-1}. The crop of the previous season varied.

Study 4

Reduced tillage as an alternative to conventional tillage with hand hoes and ox-ploughs was evaluated on 12 farms. The treatments were: (i) the farmer's practice of conventional tillage; (ii) reduced tillage with use of glyphosate herbicide [*N*-(phosphonomethyl)glycine] for early weed control applied at 3 L ha^{-1}; and (iii) reduced tillage with glyphosate and 30 kg N plus 10 kg P ha^{-1} applied. Sorghum was planted at the same time for all treatments and immediately after application of the herbicide. The crop of the previous season varied.

The N, P, and K fertilizers used were urea, triple super phosphate, and potassium chloride, respectively. Manure and P fertilizers were broadcast-applied before tillage and incorporated. Nitrogen was applied with 5 kg N ha^{-1} at planting and the remaining 25 kg N ha^{-1} was applied 6 wk later. For the N response curve trial, N and K were split-applied with half applied at planting and the remaining applied 6 wk later. The pre-plant N and K were applied in a furrow to the side of the planting row and covered. The second application of N and K was broadcast-applied and incorporated the same day while weeding.

Crop Management Practices

Sorghum (cv. 'Sekedo' and 'Epurpur') was planted at 60 by 20 cm during the long rains of 2004 (season 2004A) and 2005 (2005A). Mucuna was planted at a row–plant spacing of 75 by 60 cm and cowpea at 45 by 20 cm. All planting was by hand and in-season weed control was with hand hoes. The participating farmers determined other management practices, including the timing of planting and weeding operations.

Sorghum and cowpea stover were left in the field for all trials. The mucuna plants that remained after biomass measurements continued to grow until the soil water was depleted. Some of the mucuna, as well as some of the sorghum and cowpea stover, was grazed by livestock during the dry season as livestock generally graze freely after harvest of the crops. Mature mucuna seeds were not harvested but left in the fields. Mucuna seed germinated during the subsequent season and volunteer plants were controlled until the second weeding, after which emerging mucuna was allowed to grow in competition with the sorghum crop.

Data Collection and Analysis

Sorghum grain yield was determined by hand-harvest of panicles in the whole plot after physiological maturity. The panicles were dried in the open air and threshed. The grain was weighed and subsamples were collected for determination of grain water content. The grain yield was adjusted to 140 g kg^{-1} water content.

Mucuna biomass production was determined at about 22 wk after planting by harvesting an area equivalent to 3 m^2 using a 1-m^2 quadrant placed randomly at three different places within a plot. All the mucuna biomass, including dropped leaves, in the quadrant were collected and weighed. A subsample was dried in an oven at 70°C, ground to pass a 0.5-mm sieve and analyzed for total N by Kjeldahl digestion with concentrated sulfuric acid. Phosphorus and K were determined colorimetrically and by flame photometry, respectively.

Cowpea grain yield was determined after physiological maturity by picking pods for the whole plot area. The pods were dried in the open air and threshed. The grain was weighed and sampled for moisture determination. Grain yield was adjusted to 140 g kg^{-1} water content.

An analysis of variance was conducted for each study by location and year using Statistix V. 8.0 (Analytical Software, Tallahassee, FL). A combined ANOVA was not conducted as the number of participating farmers, and therefore the number of replications, varied by location–year. Differences were considered significant at $P \leq 0.05$. Exponential functions were determined for yield response to varying N rates using the forward stepwise regression function of Statistix 8 (Analytical Software, Tallahassee, FL):

$$\text{Yield} = a + b\text{N}^c$$

where a was the Y intercept or the approximate yield with no N applied and b was the slope for the change in yield for per unit change in N modified by an exponent c to account for a nonlinear effect. Agronomic N use efficiency (AE$_\text{N}$) was determined for N rates of 20, 40, and 60 kg N ha^{-1} according to the general equation $\text{AE}_\text{N} = (Y_{+\text{N}} - Y_{0\text{N}})/\text{N}$, with yields and N rates expressed in kg ha^{-1}.

The Economic Analysis

The gross returns, after deducting fertilizer use costs, were determined for Study 1. The net returns/ input use and the benefit/cost ratios (UgSh UgSh^{-1}) were determined for Studies 2 and 3. The change in gross returns after accounting for plowing, weeding, and herbicide use costs were determined for Study 4. The economic analyses were based on the following assumptions (CIMMYT, 1988; Wortmann and Ssali, 2001):

1. The minimum acceptable rate of return, which accounts for risk and opportunity cost or the value of any resource in its best alternative use, was assumed to add 25, 50, and 75% to the cost of using fertilizer and herbicide for the undefined wealth categories of less poor, poor, and very poor farmers, respectively;
2. Field grain value was estimated by reducing the farmgate prices by 10% to cover the cost of harvesting, processing, and marketing;
3. Estimation of the grazing value of the crop residuals of sorghum, cowpea, and mucuna was not attempted as it was considered to be a minor factor, especially to the individual farmer as the land is communally grazed during the dry season;
4. Field input costs were determined by increasing the purchase cost by 10% to cover transport and application costs;

5. Plot yields were assumed to be high relative to yields that small-scale farmers can achieve at a farm-level and were reduced by 10% in the economic analysis; and
6. Prices in Uganda shillings (UgSh 1800/- = US $1) were assumed to be: 200/- and 300/- kg^{-1} for sorghum and cowpea, respectively, at the farmgate; 40 000/- for 50-kg bags of urea and triple super phosphate; 11 000 L^{-1} of glyphosate herbicide; 74 000 ha^{-1} for plowing; 10 000 ha^{-1} for glyphosate application; and 60 000 ha^{-1} for one weeding operation.

RESULTS

Study 1. Sorghum Response to Improved Fallow and Rotation with Cowpea

The mean aboveground dry matter production by mucuna across the three locations was 7 Mg ha^{-1}, with a standard deviation of 1.7 mg ha^{-1}, which contained 160 kg N ha^{-1}, 14 kg P ha^{-1}, and 94 kg K ha^{-1}. The mean cowpea grain yield in this study was 0.82 Mg ha^{-1}, and the mean sorghum grain yield for the few farmers who harvested a short-season crop at Opwatetta and Kadesok was 1.05 Mg ha^{-1}; these yields for season B were used in the economic analysis.

Sorghum grain yield level and the magnitude of treatment effects varied across location–years, but the direction of treatment effects on yield was generally consistent. All treatments resulted in increased sorghum grain yield at all locations in both years relative to sorghum following sorghum with no fertilizer applied (Table 3). The overall mean increase in sorghum grain yield due to the effect of rotation with cowpea as compared to continuous sorghum was 0.82 Mg ha^{-1} with a range of 0.2 to 1.4 Mg ha^{-1} for the location–year's means. The effect of applying 30 kg N ha^{-1} to sorghum following sorghum was an overall mean increase in sorghum yield of 1.15 Mg ha^{-1} with a range 0.4 to 1.7 Mg ha^{-1}. The effect of mucuna grown during the previous season was an overall mean increase in sorghum yield of 1.56 Mg ha^{-1} with a range 0.5 to 2.2 Mg ha^{-1}. The higher mean sorghum yield with mucuna rather than cowpea as the preceding crop was expected because much N was removed in the harvest of cowpea grain while most mucuna biomass remained in the field.

The most economical cropping system was the cowpea–sorghum rotation followed by continuous sorghum with 30 kg N ha^{-1} fertilizer and the mucuna rotation (Table 4). Least profitable was continuous sorghum with no N applied. The mucuna fallow resulted in the greatest yield increase and would be relatively more profitable as sorghum grain prices increase. Production costs were assumed to be similar for the previous crops while the cost of producing mucuna was undoubtedly less than for sorghum and cowpea due to easier planting and weed control, and no harvest. The value of grazing mucuna during the dry season was not estimated but was probably greater than the value of grazing sorghum and cowpea stover. A more complete estimation of the true costs and benefits would improve the estimated profitability for the mucuna treatment to the extent that it may be the most profitable practice.

Table 4. Returns above fertilizer costs, at three minimum acceptable rate of returns, for sorghum produced in the long rain season following either sorghum, cowpea, or mucuna in rotation in eastern Uganda.

Previous crop and N rate	Gross returns†
	thousand UgSh ha^{-1}
Sorghum	373.9
Cowpea	535.9
Sorghum, 30 kg N ha^{-1}	488.5, 472.1, 457.8‡
Mucuna§	454.8

† Conversion rate of 1800 Uganda shillings (UgSh) per US dollar.

‡ Gross returns above fertilizer costs for the respective minimum acceptable rate of returns of 25, 50, and 75% for the money invested in fertilizer.

§ Production costs were assumed to be similar for the previous crops but the cost of producing mucuna was considerably less than for sorghum and cowpea. The value of grazing the mucuna during the dry season was not considered.

Study 2. Sorghum Response to Applied Manure and Inorganic Fertilizer

As in Study 1, sorghum grain yield level and the magnitude of treatment effects varied across location–years, but the direction of treatment effects on yield was generally consistent. All manure and fertilizer treatments resulted in increased sorghum grain yield at all location–years relative to the control treatment with no nutrients applied (Table 5). The mean increases in sorghum grain yield across location–years due to application of 30 kg N ha^{-1} and 2.5 Mg ha^{-1} manure were 0.78 and 1.07 Mg ha^{-1}, respectively. Application of 10 kg P ha^{-1} in addition to the 30 kg N ha^{-1} resulted in a mean additional yield increase of 0.42 Mg ha^{-1} with location–year mean increases ranging from 0.08 to 1.07 Mg ha^{-1}. Application of 2.5 Mg ha^{-1} of manure in combination with 30 kg N ha^{-1} resulted in a mean yield increase of 0.70 Mg ha^{-1} compared to N and manure used alone with location–year mean increases ranging from 0.14 to 1.04 Mg ha^{-1}. The higher yield with manure plus N compared with fertilizer P plus N may be due to a better supply of P and other nutrients or to soil amendment effects with manure.

The net returns to application of low levels of N plus P and of manure were sufficient for these practices to be profitable (Table 6). The use of animal manure, assuming that it could be obtained and applied for UgSh 20 000 Mg^{-1}, was the most profitable soil fertility management practice. The least profitable nutrient application practice was the application of N fertilizer in combination with manure.

Study 3. Nitrogen Response Curve for Sorghum

There was a significant increase in sorghum grain yield in response to increasing N levels at all locations (Fig. 2). The shapes of the response curves were very similar for all locations. The response function determined using the mean yield by N rate averaged across all locations and years accounted for 99% of the variation in mean yields for the four N rates:

$$\text{Yield} = 1.050 + 0.044\text{N}^{0.9}$$

The mean increase was 0.74, 1.24, and 1.88 Mg ha^{-1} of grain in response to 20, 40, and 60 kg N ha^{-1}, respec-

Table 5. Effects of fertilizer and manure application on sorghum grain yield (Mg ha^{-1}) at three locations in a semiarid area of eastern Uganda.

Treatment	Kadesok		Opwatetta		Kapolin			Overall
	2004	2005	2004	2005	2003	2004	2005	
	5†	9	5	17	6	7	12	61
Control	0.98	1.66	0.61	1.39	1.15	0.79	0.98	1.15
30 kg N + 10 kg P ha^{-1}	2.62	3.78	1.74	2.69	2.15	2.50	1.48	2.45
30 kg N + 2.5 Mg manure ha^{-1}	3.02	3.93	1.60	2.85	2.26	2.47	1.88	2.63
30 kg N ha^{-1}	2.54	3.23	1.46	2.46	NA	1.43	1.40	1.93
2.5 Mg manure ha^{-1}	2.06	3.51	1.44	2.41	1.74	2.04	1.74	2.22
$LSD_{0.05}$	0.50	0.25	0.34	0.31	0.57	0.44	0.15	0.13

† Number of on-farm trials conducted.

tively. The function indicates that a significant N response will occur at N application rates of more than 60 kg N ha^{-1}. The amount of additional grain produced per additional unit of N applied, that is the agronomic efficiency, decreased as N rate increased but remained high to the 60 kg N ha^{-1} rate demonstrating the importance of N deficiency as a constraint to increased sorghum yield when other nutrients are nonlimiting (Table 7).

Increasing the N rate to 60 kg N ha^{-1} was profitable at all three levels of minimum acceptable rate of return (Table 7). The benefit/cost ratios for opportunity costs of the invested money of 25, 50, and 75% were 2.0, 1.7, and 1.4, respectively, when N was applied at the rate of 60 kg ha^{-1}. However, the benefit/cost ratio was greatest with the N rate of 20 kg ha^{-1}. The results indicate that the economically optimum N rate is more than 60 kg ha^{-1} when soil P, K, and other nutrient deficiencies are less limiting than N.

Study 4. Sorghum Yield under Reduced Tillage

There was a significant increase in sorghum grain yield with the reduced tillage treatment where early weed growth was controlled with glyphosate application rather than by plowing (Table 8), with similar patterns of treatment effects at all location–years. Yield with reduced tillage was further increased with N and P application.

The monetary returns were greatest with reduced tillage when no fertilizer was applied, and least for plow tillage. The yield increase with fertilizer applied in combination with reduced tillage did not result in sufficient yield increase to justify the expense of the N + P fertilizer application, or even the cost of applied N at 30 kg ha^{-1}.

DISCUSSION

Sorghum productivity is constrained by soil N availability (Tables 3 and 5; Fig. 2). However, soil tests results show that the availability of P and other nutrients is often low as well, which may be the most limiting factor when N is applied. These nutrients are likely to be more rapidly depleted if yields are consistently higher due to N application. The application of a wide range of nutrients and organic matter with manure application may contribute to the sustainability of the higher yield levels. Much of the organic N in manure was probably not mineralized during the season of application and may benefit subsequent crops.

The use of manure, however, is a process of nutrient transfer from one part of the farming system to another rather than a replacement of nutrients exported in marketed harvest. Manure use may not, therefore, improve the farm-level nutrient balance. Eventually, there will be a need to bring nutrients to the farm to sustain higher levels of productivity and marketing of grain. Also, there is insufficient manure to apply the low rate of 2.5 Mg ha^{-1} yr^{-1} to most of the cropland, although manure is currently an under-utilized resource.

Including legumes in the rotation apparently improved N availability. The cowpea–sorghum rotation resulted in a significant increase in sorghum yield while providing a cowpea grain harvest the previous season. Cowpea production or short-term fallow, rather than sorghum production, during the short rain season (Season B) is already common practice due to the uncertainty of the rains and feeding by birds. Using the short rain season to produce a mucuna fallow resulted in the greatest increase in sorghum yield, which agrees with results reported for maize (*Zea mays* L.) in eastern and central Uganda (Fischler and Wortmann, 1999; Wortmann et al., 2000; Kaizzi, 2002;

Table 6. Increase in sorghum grain yield (Mg ha^{-1}) and net returns and benefit:cost ratios for minimum acceptable rate of returns of money of 25, 50, and 75% due to application of fertilizer or manure, averaged across all locations and seasons for a semiarid area of eastern Uganda.

Treatment	Increase in grain yield	Net returns to input use†			Benefit/cost ratio		
	Mg ha^{-1}	thousand UgSh ha^{-1}			UgSh UgSh^{-1}		
		25%	50%	75%	25%	50%	75%
30 kg N + 10 kg P ha^{-1}	1.30	88.2	63.7	39.2	1.72	1.43	1.23
30 kg N + 2.5 Mg manure ha^{-1}‡	1.47	65.7	41.2	16.7	1.38	1.21	1.08
30 kg N ha^{-1}	0.77	53.0	38.6	24.3	1.73	1.45	1.24
2.5 Mg manure ha^{-1}	1.06	121.7	121.7	121.7	3.43	3.43	3.43

† Conversion rate of 1800 Uganda shillings (UgSh) per US dollar.

‡ The cost of obtaining and applying the manure was estimated to be UgSh 20 000 Mg^{-1}.

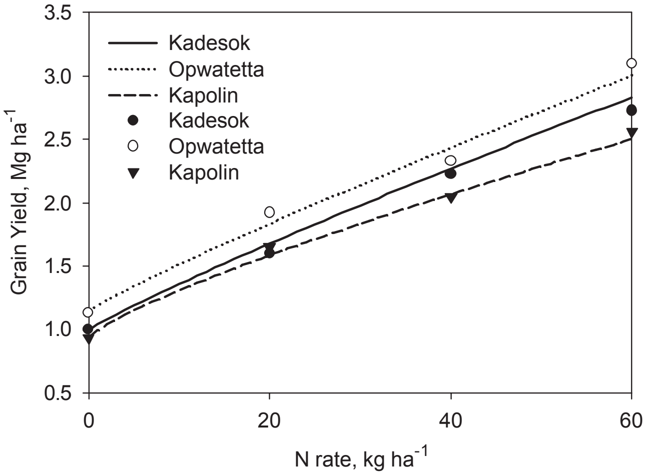

Fig. 2. Sorghum grain yield response to applied nitrogen in three communities in a semiarid area of eastern Uganda.

Kaizzi et al., 2004). Furthermore, rotation with mucuna resulted in higher maize yields than with fertilizer alone (Versteeg et al., 1998; Fischler and Wortmann, 1999; Tian et al., 2000, Kaizzi et al., 2006). The biomass yields of mucuna in the first study is consistent with other findings in eastern Uganda where mean dry matter production was 7.3 Mg ha^{-1}, containing 180 kg N ha^{-1} with 103 kg N ha^{-1} derived from BNF (Kaizzi, 2002; Kaizzi et al., 2004). Furthermore, mucuna itself had some economic value as livestock grazed it during the dry season when fodder was scarce and for addition of organic material to the soil.

The application of N fertilizer resulted in a mean sorghum grain yield that was intermediate relative to the yields following the legumes. The use of N fertilizer means a cash expense to the farmer but allows more choice in land use during the short rain season. The results of the economic analysis show that fertilizer use can be profitable for all farmers, but less so for the poorest farmers with the greatest minimum acceptable rate of return. The results of the N rate response research show that higher rates than used in the other trials is profitable but with a diminishing rate of return as the N rate increases. Rates of 60 kg N ha^{-1} will be more profitable to farmers with sufficient investment capacity but the more resource scarce farmers are likely to find lower N rates to be more appropriate.

The delayed cost of soil nutrient depletion associated with higher yields resulting from N fertilizer use is a concern that needs to be addressed in longer-term research. Soil nutrient depletion is less of a concern if manure application complements N application, as even the low rates of manure application as used in Study 2 replaces most essential nutrients, other than N, that are removed in harvest. Longer-term study is needed as well to address the residual effects of repeated manure application on available soil water holding capacity, which may be very important to crop performance on these soils of high sand content.

Table 7. Agronomic efficiency of applied N expressed as grain yield increase due to applied N, and net returns and benefit to cost ratios for minimum acceptable rate of returns of money of 25, 50, and 75%, averaged across all locations and seasons in a semiarid area of eastern Uganda.

N rate, kg ha^{-1}	Agronomic efficiency of applied N	Net returns to input use†			Benefit/cost ratios		
		25%	50%	75%	25%	50%	75%
	kg kg^{-1}	— thousand UgSh ha^{-1} —			— UgSh UgSh^{-1} —		
20	32.6	60.0	50.4	40.8	2.21	1.84	1.58
40	30.4	105.5	84.7	66.1	2.07	1.73	1.49
60	29.2	146.3	117.6	88.9	2.00	1.67	1.43

† Conversion rate of 1800 Uganda shillings (UgSh) per US dollar.

Table 8. Tillage effects on sorghum grain yield (Mg ha^{-1}) and returns above tillage, fertilizer and weed control costs during the short rains of 2004 (B) and long rains of 2005 (A) in two locations in a semiarid area of eastern Uganda.

Treatment	Opwatetta		Kadesok		Returns above tillage, fertilizer, and weed control costs
	2004B	2005A	2004B	2005A	
	3†	3	3	3	thousand UgSh‡
Plowed	0.87	1.83	1.17	1.39	23
Glyphosate	1.53	3.00	1.65	2.17	234, 226, 217§
Glyphosate + (30 kg N + 10 kg P) ha^{-1}	1.80	4.00	1.61	2.43	173, 140, 107§
LSD$_{0.05}$	0.47	0.58	0.29	0.39	

† Number of on-farm trials conducted.

‡ Conversion rate of 1800 Uganda shillings (UgSh) per US dollar.

§ Returns estimated for minimum acceptable rate of returns of 25, 50, and 75% for purchased herbicide and fertilizer. This assumes one weeding with herbicide applied compared with two weedings with no herbicide applied.

Reduced tillage is a potentially profitable option for sorghum production in eastern Uganda. The yield increase with reduced tillage was likely due to better weed control and water conservations. Farmers weeded only once with reduced tillage, as compared to twice with tillage, and achieved better weed control. Labor is scarce and costly during major weeding times and farmers give priority to weeding cash crops, resulting in late and inadequate weed control in sorghum. Water conservation was probably improved with reduced tillage, especially as significant soil water was probably lost with plow tillage and the extra weeding. Any delay in field preparation results in delayed planting, which may result in reduced yield, although this was not evaluated in this study as all treatments were planted on the same day.

CONCLUSIONS

Several practices were verified as promising and a strategy is needed to achieve widespread adoption. Use of inorganic fertilizers, animal manure, N fertilizer combined with manure, mucuna fallow, and cowpea rotation resulted in profitable increases in sorghum yield on the sandy loam and loamy sand soils of eastern Uganda. Application of a small amount of P in inorganic fertilizer or manure, in addition to N, was also profitable at all minimum acceptable rates of return. The replacement of plowing with a single glyphosate application was found to be a profitable means of increasing sorghum yield.

Farmer involvement in the full research process ensured that the practices are compatible with their farming systems. Some of these practices had sufficient effect on crop performance such that field demonstrations should be very effective if conducted throughout the semiarid sorghum production areas of eastern and northern Uganda. These practices are easily testable by farmers, incur little added risk, and are innovations that can be adopted without much modification of the current production practices. These factors should facilitate adoption (CIMMYT, 1988).

The enabling of extension staff working in the target areas to conduct and effectively use demonstrations to inform farmers of the benefits of these practices is needed. The participating farmers, who were involved from the characterization and diagnosis exercises through the implementation of trials and assessment of the results, are a potential resource for an organized farmer-to-farmer dissemination of the information. Longer-term on-station research is needed to determine the sustainability of these low-input approaches to soil fertility management.

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