academicJournals

Vol. 10(52), pp. 4795-4805, 24 December, 2015
DOI: 10.5897/AJAR2015.9638
Article Number: 8EE60D956488
ISSN 1991-637X

http://www.academicjournals.org/AJAR

African Journal of Agricultural Research

Full Length Research Paper

Using improved varieties and fertility enhancements for increasing yield of common beans (*Phaseolus vulgaris* L.) grown by small-landholder farmers in Uganda

Gerald Sebuwufu[1], Robert Mazur[1], Michael Ugen[2] and Mark Westgate[1]*

[1]Department of Agronomy, Iowa State University, 2104 Agronomy Hall, Ames, IA 50011-1050, United States.
[2]National Crops Resources Research Institute, Namulonge, P. O. Box 7084, Kampala, Uganda.

Received 19 February, 2015; Accepted 15 October, 2015

Productivity of common bean (*Phaseolus vulgaris* L.) in Uganda is less than 30% of the yield of improved varieties grown on research stations. This yield gap has been attributed mainly to low soil fertility and susceptibility of local varieties saved by farmers to pest and disease infestations. This study evaluated the impact of four improved varieties and soil fertility improvement on bean yields on small-landholder farms in three agro-ecological zones in Uganda. Yields of common bean on-farm without fertilization were on average 523 kg/ha. Enhancing soil fertility on-farm with cattle manure (10 t/ha), P (60 kg/ha), or manure (5 t/ha) + P (30 kg/ha) led to average yields of 631, 615, and 659 kg/ha, respectively. On average, improved varieties produced more yield than the local farmer-saved variety, with or without soil fertility improvement. Improved variety K131 yielded 807 kg/ha, on average, in response to manure application, which was 54% greater than the yield of the local variety. P intensification up to 180 kg/ha per season, however, did not increase bean yields significantly at any of three research stations. These results confirm the yield advantage of growing improved varieties on small-landholder farms. The combination of improved genetics and fertility intensification alone, however, did not eliminate the yield gap between on-farm and potential bean yields.

Key words: Food security, improved varieties, farmer-saved seed, soil fertility, seed quality.

INTRODUCTION

Common bean (*Phaseolus vulgaris* L.) is an important food crop in eastern Africa, where it provides an economical source of protein, minerals, and vitamins (Broughton et al., 2003). In Uganda, beans are the fifth most important food crop, with estimates of per capita consumption varying from 19 to 58 kg per year (Kilimo, 2012; Sibiko et al., 2013). In 2010, the value of domestic bean production in Uganda was estimated at $274M

*Corresponding author. E-mail: westgate@iastate.edu. Tel: 515 294-9654. Fax: 515-294-5506.

(FAOSTAT, 2013) with beans accounting for 7% of the national agricultural gross domestic product (CIAT, 2008). Despite the importance of beans as a dietary staple for rural households and agricultural product, average bean yields were estimated at 406 kg/ha in 2011 - less than 30% of the potential yield of improved varieties grown under optimum conditions (FAOSTAT, 2013).

The low productivity of the bean crop is attributed partly to widespread reliance on local varieties, which farmers save and sow year after year. According to the Uganda Census for Agriculture 2008/9, approximately 92% of rural households use saved seed; only 31% used improved or hybrid seed (UBOS, 2010). The widespread dependence on saved seed is attributed to limited access to improved seed due to poor distribution of formal seed outlets across the country, reliance on a few commercial varieties, poor marketing and marketing information systems, very narrow product range or low value addition, storage constraints, and high cost of certified seed. As part of its mandate, National Crops Resources Research Institute (NaCRRI) has released several improved varieties tolerant to several biotic and abiotic constraints in recent years. But these varieties are not widely available to farmers. These improved varieties have a greater yield potential and thus their adoption could result in significant increases in bean productivity. Field trials of the improved varieties in Uganda showed a yield advantage averaging 37% over local farmers' varieties (CIAT, 2008). A survey of farmers in areas of Uganda where improved varieties had been formally introduced showed high potential for adoption (David et al., 2000). Yet, limited accessibility to improved varieties by small-scale farmers and dietary preferences for local varieties continue to limit their use (Buruchara et al., 2011).

The most important abiotic factor limiting bean productivity in Uganda is poor soil fertility (Wortmann and Kaizzi, 1998; Wortmann et al., 1998; Bekunda et al., 2004; Lubanga et al., 2012). Phosphorus and nitrogen are the most limiting soil nutrients in bean producing areas of eastern Africa (Wortmann et al., 1998). Uganda has one of the lowest fertilizer usage in the region, estimated at only 1.8 kg/ha annually (Benson et al., 2012) compared to an average 7.1 kg/ha across sub-Saharan Africa (Druilhe and Barreiro-Hurl´e, 2012). In 2008/2009, the Uganda Bureau of Statistics estimated only 1% of the farming households in Uganda use chemical fertilizers, and only 6.8% apply manure, due to lack of availability and high cost of purchasing and maintaining animals (UBOS, 2010).

Integrating varieties that have superior yield potential with a soil fertility management program using locally available fertilizers might provide an affordable and sustainable option for small-landholder farmers to overcome these primary yield constraints (Okalebo et al., 2006; Lubanga et al., 2012). To this end, we conducted a series of on-farm and experiment station trials in three agro-ecological zones in Uganda where soils are severely depleted of nutrients. The overall goal was to identify methods for increasing bean yield on small-scale farms in these zones. The study had three specific objectives: (1) To evaluate the performance of improved varieties on nutrient depleted soils under typical on-farm conditions; (2) To determine the impact of increased nitrogen from manure and phosphorus application on bean yields on these nutrient-depleted soils under farmer conditions, and (3) To determine whether intensive phosphorus fertilization could improve bean yields.

MATERIALS AND METHODS

On-farm experiments

Three on-farm experiments were conducted in Butansi and Bugulumbya sub-counties located in Kamuli District (00°55'N, 33°06'E) in southeastern Uganda. The district is located 1100 m above sea level and typically experiences two rainy seasons with peaks in March to June (season A) and August to November (season B). The average annual rainfall is 1350 mm and the average monthly temperature varies from 19 to 25°C.

The trials involved three farmer groups from Butansi sub-county and three farmer groups from Bugulumbya sub-county that were actively involved in the establishment and evaluation of the trials. Activities performed by farmer-cooperators included site selection, brush clearing, hand hoeing, planting, weeding, harvesting, drying, threshing, and measuring seed yield. Throughout the trials, farmers were trained on standard agronomic management of beans and guided as needed by technical staff from NaCRRI and Volunteer Efforts for Development Concerns (VEDCO), an indigenous non-governmental development organization. Individual trials in each season were hosted by a farmer and managed by the farmer group to which they belonged.

The on-farm study consisted of three experiments. In the first experiment conducted in seasons A and B of 2009 and season A of 2010, farmers tested the performance of four improved varieties released by NaCRRI (K131, K132, NABE4 and NABE6) and a local variety, Kanyebwa, without soil amendments (Table 1). This involved a total of 54 on-farm trials, 18 in each season.

The second set of trials tested the response of the same varieties to 10 t/ha application of cattle manure just prior to planting. The manure was measured on a dry weight basis. The manure was evenly spread on top of the soil and incorporated by hand hoeing. The bean varieties were evaluated in two groups to reduce the size of the trial at each site and the workload for the farmer cooperators. Group 1 included K131, NABE4 and Kanyebwa; Group 2 included K132, NABE6 and Kanyebwa. A total of 36 on-farm trials, 12 in each of the three seasons, were conducted in season A and B in 2009. Plot area was 5 m × 5 m arranged in a randomized complete block design with two replicates.

A third trial evaluated the response of three varieties selected by the farmer cooperators (K131, NABE4, Kanyebwa) to cattle manure, phosphorus, and a combination of manure and phosphatic fertilizer. The fertilizer treatments were 60 kg/ha P, 10 t/ha manure, and 30 kg/ha P + 5 t/ha manure. The phosphorus source was triple super phosphate (46% P_2O_5, Lebanon Chemical Company S.A.L, Beirut, Lebanon). All fertilizer treatments were applied just prior to planting. Phosphatic fertilizer was applied manually and mixed into the soil with a hoe along the sowing line. Plot area was 3 m × 3 m arranged in randomized complete block design with two replicates. The experiment was conducted during seasons A and B in 2010

Table 1. Characteristics of six common beans varieties grown in Uganda. Information compiled from the NASECO Seed Company, Kampala, and the National Crops Resources Research Institute, Namulonge, Uganda.

Variety (Local name)	General agronomic characteristics	
K131 (Kazibwe)	Altitude: 1000-1800 m Maturity: 90 days Seed rate: 50-60 kg/ha Expected yield: 2 - 2.5 ton/ha Growth habit: Trailing (Type II) Released in 1994	Small light brown mottled seed Good taste, good yield Resistant to bean common mosaic virus (BCMV), bean rust (BR), Angular leaf spot (ALS), common bacterial blight (CBB), and anthracnose. Susceptible to root rot Performs relatively well under extreme environments Less marketable
K132 (Nambale Omuwanvu)	Altitude: 1000-1800 m Maturity: 80 days Seed rate: 90-100 kg/ha Expected yield: 1.5 - 1.8 ton/ha Growth habit: Erect (Type I) Released in 1994	Large red mottled seed Resistant to BR Susceptible to anthracnose, ALS, CBB and root rot Popularly grown in most parts of Uganda Highly marketable
NABE 4 (Nambale Omumpi / VEDCO)	Altitude: 1000-1800 m Maturity: 80-85 days Seed rate: 90-100 kg/ha Expected yield: 1.5-2.0 ton/ha Growth habit: Erect (Type Released in 1999	Large red mottled seed Resistant to major bean diseases Popularly grown in most parts of Uganda Susceptible to root rot, ALS, CBB and anthracnose Highly marketable
NABE 6 (Obweru)	Altitude: 1000-1800 m Maturity: 90 days Seed rate: 50-60 kg/ha Expected yield: 1.5-2.5 ton/ha Growth habit: Trailing (Type II) Released in 1999	Small white seed Resistant to BR Susceptible to root rot, ALS, CBB and anthracnose Marketable, cooks fast but does not keep long after cooking
Farmers seed (Kanyebwa/ Kabonge)	Growth habit: Erect (Type I)	Brick red medium size seed, susceptible to many diseases, early maturing

and season A in 2011.

On-station trials

Phosphorous intensification experiments were carried out at three research station sites managed by the National Crops Resources the Research Institute (NaCRRI): Site 1: Nakabango Variety Testing Center in East-Central Uganda (1178 m above sea level (masl), average rainfall 1000 to 1350 mm/annum); Site 2: National Crops Resources the Research Institute (NaCRRI) main research station at Namulonge in Central Uganda (1155 masl, average rainfall 1200 to 1450 mm/annum); Site 3: Mbarara Zonal Agricultural Research Institute in Southwestern Uganda (1430 masl, average rainfall 915 to 1020 mm/annum). Hereafter, these locations are referred to as Nakabango, Namulonge and Mbarara representing three agro-ecological zones where beans are commonly grown. Field trials were conducted in the first (A) and second (B) season of 2011 and the first (A) season of 2012. Typically, season A rains occur from March to June; season B rains occur from September to December.

At all three locations, the soils were acidic ferralsols with an average pH below the optimum of 6.5 to 7.0 for dry bean yields (Table 2). The average organic matter content (3.1%) was in a range considered to be moderate (Okalebo et al., 2002). Analyses also confirmed the soils were low in nitrogen, phosphorus and potassium. Thung (1991) reported the critical level for soil P ranged between 8 to 15 mg/kg (Bray 2) for beans.

The bean varieties were Kanyebwa, a landrace commonly grown in Uganda, and NABE4, an improved variety released by NaCRRI. Both varieties were sown at a spacing of 50 cm × 10 cm. giving a target plant population of 20 plants/m^2. Plot size was 5 × 5 m. The source of phosphorous and nitrogen was triple super phosphate (46% P_20_5) and urea (46% N), respectively. P was applied at 0, 60, 120 and 180 kg P/ha. The dose of N was 25 kg N/ ha to all plots according to NaCRRI recommendations. In addition, all seeds were inoculated with Rhizobia TALL 899 strain (Makerere University, Kampala, Uganda; [4 × 10^6 rhizobia/g] with one 250-g packet sufficient to inoculate 15 kg seed). Bean plots were rotated with maize variety 'Longe 5' grown with similar levels of P and N fertility. The same plot locations were used repeatedly over three seasons for each phosphorous level. Thus, bean plots treated with 0, 60,

Table 2. Characteristics of soils sampled from trials sites in Bugulumbya, Butansi, Nakabango, Namulonge, and Mbarara, Uganda. The values are averages of samples taken at each location.

Location	pH	OM	N	P	Ca	Mg	K	Sand	Clay	Silt
		%			mg/kg				%	
On-farm trials										
Bugulumbya	6.5	3.5	0.2	1.8	2425	585	435	51.3	33.2	15.0
Butansi	6.4	2.8	0.2	1.9	2172	524	384	52.2	36.5	10.8
On-Station trials										
Nakabango	4.4	3.6	0.2	5.4	1882	406	344	63.3	21.6	15.2
Namulonge	4.8	2.8	0.2	8.3	1374	331	211	62.1	23.0	14.8
Mbarara	5.8	2.8	0.2	6.6	1134	222	399	64.3	16.3	19.3
Critical values*	5.2	3.0	0.2	5.0	350	100	150	-	-	-

*Critical valued according to Soil and Plant Analysis Laboratory – NARL Kawanda.

120 and 180 kg P/ha received the same fertilizer treatment for each of three successive seasons. At each site, the eight factorial treatment combinations were arrayed in a randomized complete block design (RCBD) with three replicates.

Soil analysis

Composite soil samples obtained from the surface 20 cm were collected from each site before land preparation. Soil and manure analyses for the on-farm trials were conducted at the National Agricultural Research Laboratories at Kawanda (NARL Kawanda), while those from on-station trials were analyzed at the Makerere University soil analysis laboratory following procedures by Okalebo et al. (2002) and Analytical procedures were similar at both laboratories, except extractable P was determined using the Melich 3 method at NARL Kawanda, while the Bray 1 method was used at Makerere University.

Yield and yield components

Harvested plant population (plants/m^2), pods/plant, seeds/pod, 100-seed weight (g) and seed yield (kg/ha) were estimated at physiological maturity. Harvested plant population was estimated from the number of harvested plants divided by the harvest area. The number of pods/plant was calculated from 20 randomly chosen plants. A pod was counted if it contained at least one mature seed. Number of seeds/pod was determined from 20 randomly chosen pods from these 20 plants. Beans were threshed in the customary way with sticks after air-drying the pods. Seed moisture content was determined using a moisture meter (Steinlite SL95, Atchison, Kansas, USA). The seed yield and 100-seed weight are calculated at 13% moisture content.

Statistical analyses

The data were subjected to analysis of variance using Proc Mixed in SAS 9.3 (2007). Variety and fertility treatments were considered fixed factors. Location and replication were considered random effects. Significant differences between means were determined by least significant differences (LSD) at p = 0.10.

RESULTS AND DISCUSSION

On-farm trials

Soil chemical and physical analyses

The majority of the soils in Kamuli district are classified as orthic ferralsols (FAO and UNESCO, 1977). These soils have good drainage, but are severely weathered and tend to have a low cation exchange capacity. Most soils at the trial sites were acidic ranging in pH from 4.4 to 6.5 (Table 2). While beans generally tolerate slightly acidic soils, alkaline conditions above pH 7 decrease availability of micronutrients such as iron and zinc (Schwartz et al., 2004). Results from 116 soil samples indicated 92% of the on-farm plots had less than critical phosphorus (P), 62% were deficient in nitrogen (N), and 44% were low in organic matter (OM) (data not shown). Similar nutrient deficiencies for Kamuli soils have been reported by Wortmann and Kaizzi (1998) and Tenywa et al. (1999). The average values for soil OM, N and P were 3.15%, 0.2% and 1.85 mg/kg respectively (Table 2). As macronutrients required for proper plant growth and development, P and N deficiencies will negatively impacts seed yield. Soil deficiencies in P and N observed in these Kamuli trials certainly confirm earlier reports of low soil fertility as a primary constraint to increased yields in sub-Saharan Africa (Okalebo et al., 2006). Organic matter plays an important role in improving nutrient availability by increasing cation and anion exchange capacity, increasing water retention and improving soil structure (Johnston et al., 2009). The poor soil fertility observed was attributed to negative nutrient balances from the common small-landholder practice of continuous cultivation without replenishment of nutrients extracted by the crops (Shepherd et al., 1996; Bekunda et al., 1997; Sanchez, 2002). According to the 2008/9 Uganda Census

Table 3. Average yield, yield components, and harvested plant populations for five common bean varieties evaluated in on-farm trials. Data are pooled for three growing seasons and 60 locations in 2009 and 2010.

Variety	Yield (kg/ha)	100-seed wt (g)	Pods/plant	Seeds/pod	Plants/m^2
K131	577.2^{A}*	17.6^{D}	7.4^{A}	5.09^{A}	15.3^{A}
K132	507.4^{B}	42.9^{A}	5.2^{B}	3.24^{C}	14.0^{A}
NABE4	513.2^{B}	38.5^{B}	4.9^{B}	3.43^{B}	13.6^{A}
NABE6	478.9^{B}	17.9^{D}	7.7^{A}	5.05^{A}	13.6^{A}
KANYEBWA	463.7^{B}	33.4^{C}	5.3^{B}	3.38^{BC}	13.6^{A}
			P Value		
Variety	0.0433	<.0001	<.0001	<.0001	0.2202
Location	<.0001	<.0001	<.0001	<.0001	<.0001
REP (Location)	0.5027	0.6589	0.3513	0.6861	0.3870
Location x variety	0.0143	0.0307	0.0008	<.0001	0.0775

*Means in columns followed by the same later are not significantly different at p = 0.10.

on Agriculture, the majority of small-scale farmers do not use any form of inorganic or organic fertilizer (Okoboi and Barungi, 2012).

Yield of improved varieties on nutrient depleted soils

Adoption of improved varieties has great potential as a sustainable way to improve yields among resource poor farmers (David et al., 2000; Maredia et al., 2000). The objective of our on-farm trials was to engage farmers in direct comparisons of improved varieties - K131, K132, NABE4 and NABE6 against a popular local variety Kanyebwa under typical farming conditions. On average, the improved varieties yielded 3 to 25% more than the local bean variety (Table 3). K131, in particular, consistently produced significantly greater yield than the other four varieties. The local variety grown from farmer-saved seed generally yielded the least, averaging approximately 464 kg/ha. The superior performance of K131 was attributed to a combination of greater number of pods/plant and a greater number of harvested plants/m^2. K131 and K132 also yielded 65 and 35% more than Kanyebwa in on-farm field trials on fairly mineral-rich nitosol soils in the Mbale district of Eastern Uganda (David et al., 2000). The small seeded varieties, K131 and NABE6, produced significantly more pods/plant and seeds/pod than the large-seeded varieties Kanyebwa, K132, and NABE4.

Harvest plant population was an important determinant of crop performance across seasons and locations. It was generally far less than the recommended optimum plant population of 20 plants/m^2, which was the target planting population for all varieties (Table 3). K131 retained the most plants throughout harvest and generally produced the best yield. Kanyebwa typically had far fewer plants survive until harvest and often was the poorest yielding variety. De Brum Piana et al. (2007) also associated yield loss with a failure to maintain plant population. Failure of common bean varieties to maintain an optimum number of plants throughout the season could reflect poor seed germination, poor vigor, or mortality under stressful field conditions. Studies relating temporal loss of plants with occurrence of biotic and abiotic stresses during the growing season are needed to target management strategies that stabilize plant population density.

There were significant effects of variety, location, and location × variety interactions on yield, 100-seed weight, pods/plant, and seeds/pod (Table 3). In addition, location and location × variety interaction effects were significant for the number of plants harvested per unit area. Evidently, the improved varieties and farmer-saved variety responded differently to local soil, weather, and/or farm-management conditions. This outcome underscores the importance of active variety testing and selection for local conditions. It clearly indicates the need for farmer access to a greater number of improved bean varieties with genetic potential for yield under their local growing conditions.

Indeed, even the yields of the improved varieties were well below the potential yields observed under controlled conditions at the national research stations. Based on data provided by NaCRRI (Table 1), average productivity for the improved varieties tested was only 19 to 28% of the potential yields for NABE6, K131, NABE4, and K132. Thus, simply introducing improved varieties on small-landholder farms alone was not sufficient to bridge the yield gap. These results led us to address another major constraint to productivity, low soil fertility, in an attempt to achieve the significant yield improvements expected of these improved varieties.

Table 4. Yield and yield component responses of common bean varieties K131, K132, NABE4, NABE6, Kanyebwa to 10T/ha manure applied at planting. Data are the mean of 12 locations pooled for two growing seasons in 2009.

Variety	Treatment	Yield (kg/ha)	100 seed wt (g)	Pods/plant	Seeds/Pod	Plants/m^2
K131	Control	529.3^{B}*	17.9^{A}	8.8^{A}	5.2^{A}	14.6^{A}
K131	Manure	790.0^{A}	17.6^{A}	9.6^{A}	5.3^{A}	18.5^{A}
K132	Control	443.8^{A}	40.8^{B}	4.7^{A}	3.1^{B}	12.3^{A}
K132	Manure	565.9^{A}	42.8^{A}	5.4^{A}	3.3^{A}	12.2^{A}
NABE4	Control	485.9^{A}	38.0^{B}	5.1^{A}	3.5^{A}	10.8^{A}
NABE4	Manure	576.0^{A}	40.7^{A}	5.8^{A}	3.6^{A}	12.6^{A}
NABE6	Control	571.8^{A}	17.8^{A}	7.6^{B}	5.2^{A}	14.9^{A}
NABE6	Manure	533.6^{A}	18.9^{A}	8.7^{A}	5.1^{A}	15.6^{A}
Kanyebwa	Control	380.2^{B}	33.7^{A}	4.9^{A}	3.3^{B}	14.5^{A}
Kanyebwa	Manure	571.4^{A}	32.8^{A}	5.5^{A}	3.5^{A}	14.7^{A}
				P value		
Variety		0.1018	<.0001	<.0001	<.0001	0.3258
Treatment		0.0102	0.0200	0.0007	0.0430	0.4865
Variety × Treatment		0.0293	0.0401	0.9504	0.6056	0.2709
Location		0.0047	0.0006	0.0053	0.0504	0.2740
Replication(Location)		0.9715	0.9186	0.9412	0.0158	0.8527
Location × Variety		0.0012	0.0008	0.0702	0.0807	0.0052
Location × Treatment		0.0018	0.8444	0.7977	0.9699	0.0018
Location × Variety × Treatment		0.8919	0.9631	0.0259	0.0003	0.9732

*Means in columns followed by the same letter within each variety are not significantly different at p= 0.10.

Response to manure

As a soil improvement strategy, we tested the response of common bean varieties K131, K132, NABE4, NABE6 and Kanyebwa to 10 t/ha of locally sourced cattle manure applied at planting time. Local manure was chosen because it is a renewable resource and an economical means of soil improvement, especially for resource poor farmers. The manure used averaged 14 g N/kg, 1.6 g P/kg, and 7.2 g K/kg on a dry weight basis. Based on this analysis, 10 tons of manure per hectare would provide 140 kg N/ha, 16 kg P/ha, and 72 kg K/ha. The amount of phosphorus provided by manure was far short of the 60 kg P/ha recommended for common beans by the National Agricultural Research Laboratories at Kawanda. Manure from communally grazed cattle has been reported to contain low amounts of nitrogen, phosphorus and potassium (Palm et al., 1997; Tenywa et al., 1999; Materechera, 2010). Nonetheless, these fertility treatments were expected to improve on-farm yields, as soils in all trial sites were very low in nutrients particularly N, P and OM (Table 2).

Averaged across all varieties and locations, manure application significantly increased yields by 26% (Table 4). Comparison between varieties, however, revealed significant yield increases only for K131 and Kanyebwa, which were 49 and 50%, respectively. The observed increase was associated with greater seed weight, and increased number of pods/plant and seeds/pod. Application of manure significantly increased the seed size of the large seeded K132 and NABE4. The smaller seeded NABE6 showed a significant increase in number of pods/plant in response to manure. Although these results generally indicated that improved soil fertility management would have a positive impact on bean yields, there were significant variety x treatment and location x treatment interactions for the yield response to manure application. This interaction might have been due to variation in rates of manure decomposition, which depends on local soil and environmental conditions (Eghball, 2000; Eghball et al., 2002). Because trial sites were different each season, the long-term benefit of manure decomposition would not have been realized.

Response to manure, phosphorus, and a phosphorus-manure combination

While there were some positive results from the initial on-farm variety and fertility trials, it was evident that improved varieties and manure alone were not sufficient to bridge the yield gap between on-farm and potential yield. Soil chemical analyses indicated that phosphorus was consistently the most limiting macronutrient among

Table 5. Response of yield and yield components of three common bean varieties to phosphorus (60 kg/ha), manure (10 t/ha) and phosphorus (30 kg/ha) + manure (5 t/ha) fertilizer treatments. Data are the mean of 22 locations pooled for three seasons in 2010 and 2011.

Variety	Treatment	Yield (kg/ha)	100-seed wt (g)	Pods/plant	Seeds/pod	Plants/m^2
K131	Control	686.0^{B}*	18.5^{B}	6.1^{B}	4.6^{A}	20.1^{B}
	Manure	806.7^{A}	19.3^{A}	7.1^{A}	5.0^{A}	23.7^{A}
	Manure + Phosphorus	675.9^{B}	20.7^{A}	6.9^{A}	5.1^{A}	22.9^{A}
	Phosphorus	706.4^{AB}	19.1^{A}	6.8^{A}	4.9^{A}	22.5^{A}
NABE4	Control	512.9^{B}	41.2^{A}	4.3^{A}	3.1^{AB}	16.0^{B}
	Manure	634.8^{A}	41.7^{A}	4.1^{A}	3.1^{B}	20.2^{A}
	Manure + Phosphorus	636.7^{A}	42.9^{A}	4.7^{A}	3.3^{A}	17.2^{B}
	Phosphorus	618.5^{A}	41.7^{A}	4.2^{A}	3.2^{AB}	16.^{B}
KANYEBWA	Control	492.8^{B}	35.7^{AB}	4.1^{B}	3.1^{A}	15.0^{B}
	Manure	524.3^{B}	34.7^{B}	4.3^{AB}	3.1^{A}	14.6^{B}
	Manure + Phosphorus	664.5^{A}	37.1^{A}	4.6^{A}	3.3^{A}	18.1^{A}
	Phosphorus	518.9^{B}	35.2^{AB}	4.7^{A}	3.2^{A}	15.3^{AB}
				P value		
Variety		0.0088	<.0001	<.0001	<.0001	0.0015
Treatment		0.1221	0.0492	0.2733	0.0525	0.0416
Variety × Treatment		0.0370	0.9749	0.2675	0.0290	0.1874
Location		<.0001	0.0148	0.1222	0.0019	0.1738
Replication (Location)		0.2536	0.9659	0.1667	0.0083	0.0215
Location × Variety		<.0001	<.0001	<.0001	<.0001	<.0001
Location × Treatment		0.0017	0.5889	0.0181	0.0109	0.5245
Location × Variety × Treatment		0.9357	0.1049	0.9223	0.1734	0.0252

*Within each variety, fertility treatment means followed by the same later are not significantly different at p= 0.10.

the field sites. Phosphorus is particularly important for promoting nitrogen fixation, which is often limiting in common beans (Vance et al., 2003). Therefore, we tested whether a combination of inorganic phosphorus and manure could improve yield of common beans on smallholder farms.

The yield response to manure, phosphorus fertilizer, and the combination of phosphorus and manure varied by variety and treatment (Table 5). The yield of K131 was not improved by application of phosphorus or the combination of manure and phosphorus. Combined application of manure and phosphorus, however, increased the yield of the farmer variety, Kanyebwa. The yield advantage resulted from an increase in pods/plant and greater plant population at harvest (Table 5). NABE4 yields also responded significantly to manure, phosphorus fertilizer, and manure + phosphorus fertilization. The increase in yield from manure also was associated with greater plant population at harvest, while phosphorus + manure increased seeds/pod. Yields from application of phosphorus alone (60 kg/ha) often matched those from application of manure (10 t/ha) confirming the importance of phosphorus as a yield-limiting nutrient in farmers' fields. Further, combined application of phosphorus and manure led to significant increase in yield for both Kanyebwa and NABE4.

Although smallholder farmers generally recognize the potential benefits of manure application, it is not a common practice because of its bulkiness. Likewise, P application is limited because of its expense. The results of this study suggest such deterrents to widespread use of these yield enhancers could be overcome by combining them at modest levels without sacrificing yield response. Complementary use of inorganic and organic fertilizers has been suggested as an effective practice of soil fertility management to ensure plant nutrition while regenerating the soil (Palm et al., 1997; Lubanga et al., 2012). A combined application approach could be quite effective as a long-term strategy to increase nutrient availability in the depleted soils of Kamuli.

Effect of P intensification on bean yield

Lack of available phosphorus is often reported as the most limiting nutrient for greater bean production (Sanchez and Logan, 1992; Wortmann et al., 1998; Lunze et al., 2007). Several authors have proposed

Table 6. Effect of phosphorus intensification on the Yield (kg/ha) of two common bean varieties grown in three agro-ecological zones (Nakabango, Namulonge, Mbarara) in Uganda.

Variety	Yield (kg/ha)				
	P (kg/ha)	2011A	2011B	2012A	Mean
NAKABANGO Kanyebwa	0	1020^{A}*	804^{A}	799^{A}	874^{A}
	60	827^{A}	642^{A}	1081^{A}	850^{A}
	120	967^{A}	739^{A}	1164^{A}	957^{A}
	180	1133^{A}	724^{A}	1172^{A}	1010^{A}
NABE4	0	1047^{A}	1049^{A}	626^{A}	907^{BC}
	60	947^{A}	1054^{A}	649^{A}	883^{C}
	120	1133^{A}	1391^{A}	1133^{A}	1219^{A}
	180	1207^{A}	1244^{A}	1139^{A}	1197^{AB}
NAMULONGE Kanyebwa	0	667^{A}	180^{A}	671^{A}	506^{A}
	60	633^{A}	176^{A}	723^{A}	511^{A}
	120	542^{A}	168^{A}	553^{A}	421^{A}
	180	575^{A}	184^{A}	665^{A}	475^{A}
NABE4	0	688^{A}	161^{A}	567^{A}	472^{A}
	60	817^{A}	162^{A}	575^{A}	518^{A}
	120	510^{A}	145^{A}	437^{A}	364^{A}
	180	700^{A}	188^{A}	696^{A}	528^{A}
MBARARA Kanyebwa	0	650^{A}	749^{A}	-	700^{A}
	60	617^{A}	819^{AB}	-	718^{A}
	120	475^{A}	1017^{A}	-	746^{A}
	180	725^{A}	751^{A}	-	738^{A}
NABE4	0	592^{A}	1113^{A}	-	853^{A}
	60	642^{A}	1097^{A}	-	870^{A}
	120	717^{A}	952^{A}	-	835^{A}
	180	537^{A}	877^{A}	-	707^{A}

*Means with the same letter down the column within each variety are not significantly different at p≤0.10.

intensive application of P was required to build soil levels sufficiently to overcome the high P fixing capacity of many African soils (Sanchez et al., 1997; Sanchez, 2004; Syers et al., 2008). Sanchez et al. (1997), for example, indicated as much as 500 kg P/ha of triple super phosphate (TSP) was required to replenish soil P on deficient soils in Africa. Similarly, Yost and Eswaran (1990) reported the oxisols in Uganda required 10 kg P/ha per % clay every year following an initial application of 250 kg/ha P to become highly productive.

It was not possible to assess the potential benefits of intensive and repeated P application in the on-farm experiments because trail locations changed each season. Therefore, we established trial sites on three NaCCRI research stations that could be repeatedly fertilized with up to 180 kg P/ha over several seasons. These trials also were established using a common crop rotation with maize. Table 6 shows the effect of P application on the yield of two common bean varieties grown in three of Uganda's agro-ecological zones. Average common bean yields were 987 kg/ha at Nakabango, 771 kg/ha at Mbarara, and 474 kg/ha at Namulonge. Nakabango generally produced greater yields due to receiving greater rainfall during bean formation and filling. Yields at Namulonge were decreased dramatically during the second season - 2011B; this was attributed to the long dry periods during flowering and seed formation.

There were no significant effects of variety and P on the yield of common beans during the three seasons for

Table 7. Yield components, harvest index (HI), and harvest population as affected by intensive phosphorus applications. Values are means for NABE4 and Kanyebwa varieties grown for three3 seasons at Nakabango and Namulonge, and for two seasons for Mbarara, Uganda.

P (kg/ha)	Pods/plant	Seeds/pod	100 seed wt (mg)	HI(%)	Plants/m^2
Nakabango					
0	8.5^{A}*	2.9^{A}	45.7^{AB}	56.6^{A}	15.6^{A}
60	8.5^{A}	2.9^{A}	44.7^{B}	60.8^{A}	14.0^{A}
120	9.4^{A}	3.1^{A}	47.8^{A}	60.5^{A}	14.7^{A}
180	9.9^{A}	2.9^{A}	46.9^{AB}	57.3^{A}	14.8^{A}
Namulonge					
0	4.0^{A}	2.5^{A}	44.6^{A}	48.6^{A}	12.5^{A}
60	4.4^{A}	2.5^{A}	44.8^{A}	50.7^{A}	12.4^{A}
120	4.3^{A}	2.1^{B}	43.2^{A}	52.8^{A}	11.6^{A}
180	4.6^{A}	2.4^{AB}	45.1^{A}	43.6^{B}	12.3^{A}
Mbarara					
0	9.5^{AB}	2.8^{A}	43.2^{A}	46.1^{B}	10.2^{A}
60	9.6^{AB}	2.7^{A}	43.5^{A}	42.5^{B}	8.3^{A}
120	10.5^{A}	2.8^{A}	42.4^{A}	47.0^{AB}	9.1^{A}
180	8.1^{B}	3.0^{A}	42.9^{A}	61.5^{A}	9.8^{A}

*Means with the same letter are not significantly different at p≤0.10.

all three agro-ecological zones tested (Table 6). Analysis of combined season yield also showed there were no significant effects of P application on yields of the common bean varieties tested at all three sites. Analysis of yield components showed similar trends (Table 7). Further, there was no evidence of a positive cumulative effect of repeated P application on bean yields across thethree seasons. By the end of the third season, each trial plot had received three applications of P at their respective level of 0, 60, 120 and 180 kg P/ha. Thus, the total P applied across three seasons was 0, 180, 360 and 540 kg P/ha (not considering the additional P applied to the intervening maize crop). The highest values certainly are within the range recommended for overcoming P deficiencies in African soils (Sanchez et al., 1997; Yost and Eswaran, 1990). And they do not confirm earlier reports showing a proportionate increase in pods/plant and bean yield with P fertilizer application (Thung, 1991). The observed lack of response to repeated P application implicated a high P fixing capacity of test site soils (Yost and Eswaran, 1990). Indeed, calculation of the P fixing capacity based on available P and clay content (Morel et al., 1989) revealed very high capacity for fixing fertilizer P at all three experimental sites (Table 8). Presumably, most of the fertilizer P added at planting was quickly bound to iron oxides in the soil and rendered unavailable for subsequent plant growth. This extensive fixation of P by acidic ferralsols likely explains the lack of response to added P in our study. Complementary use of manure or other organic materials, however, might be a viable solution, coupled with proximal placement of P fertilizer and phased application to ensure synchrony with plant needs. Further investigations are needed to evaluate the dynamics of P fixation under field conditions, and plant interactions with soil biological agents that might promote P mineralization and acquisition.

Implications for improving bean yields on resource-limited small-landholder farms

Results from our study showed that variety K131 significantly and consistently yielded more than the local variety Kanyebwa under typical small-holder farming conditions even without soil fertilization. Soil fertility improvement, however, did not consistently lead to significant increases in yields across varieties. While use of improved varieties (David et al., 2000; Maredia et al., 2000; O'Gorman and Pandey, 2010) and soil fertility replenishment (Giller et al., 1997; Okalebo et al., 2006; Bekunda et al., 2010; Materechera, 2010) have been recommended as viable means of improving productivity among small scale farmers in Africa, these two strategies must be strategically targeted to local conditions if their potential for yield improvement is to be harnessed by small-scale farmers. Building soil fertility should be addressed as a component of improving soil health (chemical, physical, and biological) in the long term.

Table 8. Estimate of phosphorus fixing capacity by soils at the Nakabango, Namulonge, and Mbarara trial sites.

Location	Soil P-fixing capacity (r1/R)		
	Mean	Min	Max
Nakabango	-0.095	-0.219	0.322
Namulonge	-0.006	-0.226	0.376
Mbarara	-0.058	-0.093	-0.058

Calculations were based on available P (Bray 1) and clay % of soils sampled at the beginning of the experiment. The parameter (r1/R) estimates phosphorus fixation in the soil based on a model developed by Morel et al. (1998). At r1/R values less than 0.2, most applied phosphorus is fixed. At r1/R greater than 0.4, some of the applied P increases soil available P.

Because of the high cost of commercial fertilizers (Okoboi and Barungi, 2012), there are few options to improve soil fertility for resource limited farmers. Incorporating animal manure, crop residues as green manure, agroforestry trees and legumes into the land management system have proven beneficial. These options, however, often are required in large quantities, are labor intensive, and generally are low in nutrient quality and concentration (Okalebo et al., 2006). Widespread use of these approaches requires significant changes in local farming systems such as adopting mixed agriculture to generate adequate supplies of animal manure. An integrated approach that naturally couples these options withinorganic sources of nutrients has proven beneficial (Sauer and Tchale, 2009). To restore the depleted soils encountered in our study, nutrient additions will have to be applied for several years. Soil replenishment and logistical support for distribution of manure should be part of the development policy (Smale et al., 2013), so that there is deliberate government investment aimed at building soil nutrients as agricultural capital.

Even when grown under well-managed conditions, the yields of improved varieties were typically less than 50% of the potential yields NaCRRI has reported (Table 1). In nearly all cases, harvest populations were well below the recommended optimum of 20 plants/m^2 (in some cases 50% less than the planted population). The reasons for the extensive plant loss are not known, but much of the loss is likely attributable to poor seed quality resulting in low percent germination, poor vigor, and mortality under stressful field conditions (Ochilo et al., 2013). Documenting the temporal loss of plants during the growing season might reveal management strategies to help farmers stabilize plant population density. But changes in crop management will not overcome the widespread lack of high quality seed, which remains a major yield limitation for small landholder farmers. One promising approach to increase farmer access to quality seed is community-based seed production of Quality Declared Seed (QDS) (Takoutsing et al., 2012). The Ministry of Agriculture and Animal Industry (MAAIF) oversees this component of the Informal Seed Sector in Uganda and recognizes QDS as commercially acceptable for crop production.

MAAIF programs that link community-based seed producers with public breeders and the agricultural extension system could accelerate the production of high quality bean seed, and help small landholder farmers in Uganda overcome the gap between potential and realized bean yield.

Conflict of Interests

The authors have not declared any conflict of interests.

ACKNOWLEDGEMENTS

The authors wish to thank USAID/Dry Grain Pulse Collaborative Research Support Program and Iowa State University, Department of Agronomy for funding this project. They are also grateful to the farmers who participated in the study, the National Crops Resources Research Institute (NaCRRI), and the Volunteer Efforts for Development Concerns (VEDCO) staff for their help with the field work.

REFERENCES

Bekunda M, Sanginga N, Woomer PL (2010). Restoring soil fertility in sub-Saharan Africa. Adv. Agron. 108:183-236.

Bekunda MA, Bationo A, Ssali H (1997). Soil fertility management in Africa: A review of selected research trialsIn: Buresh RJ, Sanchez PA, Calhoun F (eds). Replenishing soil fertility in Africa. Proceedings of an International Symposium, Indianapolis, USA, 6 November 1996. Soil Science Society of America Inc., Madison pp. 63-79.

Bekunda MA, Ebanyat P, Nkonya E, Mugendi D, Msaky JJ (2004). Soil fertility status, management, and research in East Africa. East. Afr. J. Rural Dev. 20:94-112.

Benson T, Lubega P, Bayite-Kasule S, Mogues T, Nyachwo J (2012). The supply of inorganic fertilizers to smallholder farmers in Uganda: Evidence for fertilizer policy development. IFPRI - Discussion Papers VI. 41 p.

Broughton WJ, Hernandez G, Blair M, Beebe S, Gepts P, Vanderleyden J (2003). Beans (*Phaseolus* spp.) - model food legumes. Plant Soil 252:55-128.

Buruchara R, Chirwa R, Sperling L, Mukankusi C, Rubyogo JC, Muthoni R, Abang MM (2011). Development and delivery of bean varieties in Africa: The Pan-African Bean Research Alliance (PABRA) model. Afr.

Crop Sci. J. 19:227-245.
CIAT (2008). The impact of improved bush bean varieties in Uganda. Highlights CIAT in Africa. 2008, no. 43. Kampala, Uganda.
David S, Kirkby R, Kasozi S (2000). Assessing the impact of bush bean varieties on poverty reduction in sub-Saharan Africa: Evidence from Uganda. CIAT African Occasional Publications Series 21 p.
De Brum Piana CF, Correa da Silva JG, Antunes IF (2007). Adjustment of the yield for the stand variation in common bean genetic breeding experiments. Pesq. Agropec. Bras. 42:1687-1696.
Druilhe Z, Barreiro-Hurl´e J (2012). Fertilizer subsidies in sub-Saharan Africa. SA Working Paper No. 12-04. Food and Agriculture Organization of the United Nations, Rome.
Eghball B (2000). Nitrogen mineralization from field-applied beef cattle feedlot manure or compost. Soil Sci. Soc. Am. J. 64:2024-2030.
Eghball B, Wienhold BJ, Gilley JE, Eigenberg RA (2002). Mineralization of manure nutrients. J. Soil Water Conserv. 57:470-473.
FAO and UNESCO (1977). Soil map of the world 1:5 000 000. Vol. VI. Africa 299 p.
FAOSTAT (2013). FAO statistics division. Available at: http://faostat.fao.org.
Giller KE, Cadisch G, Ehaliotis C, Adams E, Sakala WD, Mafongoya PL (1997). Building soil nitrogen capital in Africa. In: Buresh RJ, Sanchez PA, Calhoun F (Eds.), Replenishing Soil Fertility in Africa. Proceedings of an International Symposium, Indianapolis, USA, 6 November 1996. Soil Society of America Inc., Madison. pp. 151-192.
Johnston AE, Poulton PR, Coleman K (2009). Soil organic matter: its importance in sustainable agriculture and carbondioxide fluxes. Adv. Agron. 101:1-57.
Kilimo T (2012). A Value Chain Analysis of the Dry Bean Sub-sector in Uganda Development of Inclusive Markets in Agriculture and Trade (DIMAT): The Nature and Markets of Bean Value Chains in Uganda.
Lubanga L, Abang MM, Buruchara R, Ugen MA, Nabahungu NL, Rachier GO, Ngongo M, Rao I (2012). Integrated soil fertility management in bean-based cropping systems of eastern, central and southern Africa. In: Whalen JK (Ed.), soil fertility improvement and integrated nutrient management - A global perspective. InTech: Rijeka, Croatia. pp. 239-272.
Lunze L, Kimani PM, Ngatoluwa R, Rabary B, Rachier GO, Ugen MM, Ruganza V, Awad elkarim EE (2007). Bean improvement for low soil fertility adaptation in Eastern and Central Africa In: Bationo A, Waswa B, Kihara J, Kimetu J (Eds.), Advances in Integrated Soil Fertility Management in Sub-Saharan Africa: Challenges and Opportunities. Springer, Dordrecht, The Netherlands. pp. 325-332.
Maredia M, Byerlee D, Pee P (2000). Impacts of food crop improvement research: Evidence from sub-Saharan Africa. Food Policy 25:531-559.
Materechera SA (2010). Utilization and management practices of animal manure for replenishing soil fertility among smallscale crop farmers in semi-arid farming districts of the northwest Province, South Africa. Nutr. Cycl. Agroecosyst. 87:415-428.
Morel JL, Fardeau JC, Beruff MA, Guckert A (1989). Phosphate fixing capacity of soils - a survey, using the isotopic exchange technique, or soils from northeastern France. Fertilizer Res. 19:103-111.
Ochilo WN, Nyamasyo GH, Nderitu JH (2013). Impact of soil fertility management practices on major insect pest infestations and yield of beans (*Phaseolus vulgaris* L.) in Taita District, Kenya. Afr. J. Food Agric. Nutr. Dev. 13:8340-8350
O'Gorman M, Pandey M (2010). Cross-country disparity in agricultural productivity: Quantifying the role of modern seed adoption. J. Dev. Stud. 46:1767-1785.
Okalebo J, Gathua K, Woomer P (2002). Laboratory methods for soil and plant analysis: A working manual. Second Edition TSBF-CIAT and SACRED Africa, Nairobi, Kenya.
Okalebo JR, Othieno CO, Woomer PL, Karanja NK, Semoko JRM, Bekunda MA, Mugendi DN, Muasya RM, Bationo A, Mukhwana EJ (2006). Available technologies to replenish soil fertility in East Africa. Nutr. Cycl. Agroecosyst. 76:153-170.
Okoboi G, Barungi M (2012). Constraints to fertilizer use in Uganda: insights from Uganda census of agriculture 2008/9. J. Sustain. Dev. 5:99-113.
Palm CA, Myers RJK, Nandwa SM (1997). Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. In: Buresh RJ, Sanchez PA, Calhoun F (Eds.), replenishing soil fertility in Africa. Proceedings of an International Symposium, Indianapolis, USA, 6 November 1996. Soil Science Society of America Inc., Madison. pp. 193-217.
Sanchez PA (2002). Ecology - Soil fertility and hunger in Africa. Science 295:2019-2020.
Sanchez PA (2004). Reducing hunger by improving soil fertility: an African success story. In: Scanes CG, Miranowski JA (Eds.), perspectives in world food and agriculture 2004. John Wiley & Sons. 5:75-81.
Sanchez PA, Logan TJ (1992). Myths and science about the chemistry and fertility of soils in the tropics. Myths and science of soils of the Tropics. SSSA special publication 29. Soil Science Society of America and American Society of Agronomy, Madison, WI. 3:35-46.
Sanchez PA, Shepherd KD, Soule MJ, Place FM, Buresh RJ, Ann-Marie N, Izac A, Mokwunye U, Kwesiga FR, Ndiritu CG, Woomer PL (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. Proceedings of an International Symposium, Indianapolis, USA, 6 November 1996. Soil Science Society of America Inc., Madison. pp. 1-46.
Sauer J, Tchale H (2009). The economics of soil fertility management in Malawi. Appl. Econ. Perspect. Pol. 31:535-560.
Schwartz HF, Brick MA, Harveson RM, Franc GD (2004). Dry bean production and integrated pest management. Reg. Bull. No. 562A. Colorado State University, Fort Collins, CO.
Shepherd KD, Ohlsson E, Okalebo JR, Ndufa JK (1996). Potential impact of agroforestry on soil nutrient balances at the farm scale in the east African highlands. Fertilizer Res. 44:87-99.
Sibiko KW, Ayuya OI, Gido EO, Mwangi JK (2013). An Analysis of Economic Efficiency in Bean Production: Evidence from Eastern Uganda. J. Econ. Sustain. Dev. Vol. 4. ISSN 2222-2855 (Online)
Smale M, Byerlee D, Jayne T (2013). Maize Revolutions in Sub-Saharan Africa. Ch 8. In: Keijiro Otsuka and Donald F. Larson (Eds.), an African green revolution 2013. Finding ways to boost productivity on small farms. Spinger Science+Business Media, Dordrecht. The Netherlands.
Syers JK, Johnston AE, Curtin D (2008). Efficiency of soil and fertilizer phosphorus use: reconciling changing concepts of soil phosphorus behavior with agronomic information. FAO Fertilizer and Plant Nutrition Bulletin.
Takoutsing B, Degrande A, Tchoundjeu Z, Asaah E, Tsobeng A (2012). Enhancing farmers access to quality planting materials through community-based seed and seedling systems: Experiences from the western highlands of Cameroon. Middle East J. Sci. Res. 12:455-463.
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.
Thung M (1991). Bean agronomy in monoculture. pp 737-834 In: Van Schoonhoven A, Voysest O (Eds.), common beans: Research for crop improvement. CAB International, Wallingford, England, UK, Centro Internacional de Agricultura Tropical, Cali, Colombia.
Uganda Bureau of Statistics (UBOS) (2010). Uganda Census of Agriculture 2008/9: Agricultural household and holding characteristics report. Kampala, Uganda 571 p.
Vance CP, Uhde-Stone C, Allan DL (2003). Phosphorus acquisition and use: critical adaptations by plants for securing a nonrenewable resource. New Phytol. 157:423-447.
Wortmann CS, Kaizzi CK (1998). Nutrient balances and expected effects of alternative practices in farming systems of Uganda. Agric. Ecosyst. Environ. 71:115-129.
Wortmann CS, Kirkby RA, Eledu CA, Allen DJ (1998). Atlas of common bean (*Phaseolus vulgaris* L.) production in Africa. CIAT, Cali, Columbia 133p.
Yost D, Eswaran H (1990). Major land resource areas of Uganda. World Soil Resources. USAID, Kampala, Uganda 227 p.