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Improved production systems for common bean on Phaeozem soil in South-Central Uganda

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Common bean (*Phaseolus vulgaris* L.) is the most important grain legume in Uganda. Beans managed under conventional systems range in yield from 500 to 800 kg ha^{-1}, with a yield gap of about 75%. The objective of this study was to compare the productivity and net profitability of four bean cultivars grown under three management systems on Phaeozem soil (Mollisol) in Masaka District, Uganda. The experimental design was a randomized incomplete block in a split-plot arrangement. Management system was the whole-plot factor and included the Conventional Farmer (CFS), Improved Farmer (IFS), and High Input systems (HIS). Management systems differed for seed fungicide treatment (no vs. yes), seeding density (10 vs. 20 seed m^{-2}), plant configuration (scatter vs. rows), fertilizer applications (P, K, Ca, and Mg), rhizobium inoculation (no vs. yes), pesticide applications (no vs. yes), and frequency and timing of weeding. Subplots were four common bean cultivars selected for varying resistance to foliar pathogens. Increasing management intensity and planting cultivars tolerant to common bean diseases improved bean grain yield. Mean grain yield was greater in HIS than IFS and CFS. For all management systems, disease resistant NABE 14 produced more grain yield than NABE 15, K132, and NABE 4. The HIS with NABE 14 produced the most grain (1772 kg ha^{-1}), most likely due to its greater resistance to angular leaf spot, bean common mosaic virus, and root rot. The economic return to labor and management was greatest for HIS with NABE 14 ($559 ha^{-1}). Many management system × cultivar combinations resulted in a net loss in the 2015A season, except for NABE 14. Increased yields and profitability are obtainable when utilizing NABE 14 or other disease resistant varieties under improved management practices with increased inputs.

Key words: *Phaseolus vulgaris*, soil fertility, crop management systems, improved cultivars, profitability.

INTRODUCTION

Common bean (*Phaseolus vulgaris* L.) is the most important grain legume in Uganda (Beebe et al., 2014) and is produced primarily by smallholder farmers (Ugen et al., 2002). About two decades ago, per capita bean consumption in Uganda exceeded 50 kg year^{-1} in some regions (Wortmann et al., 1998a), but more recent countrywide consumption averages about 11 to 16 kg person^{-1} year^{-1} (Broughton et al., 2003). Although, the per capita consumption has decreased, the total demand is still increasing due to population growth (Kilimo Trust, 2012).

Bean yields and soil quality have declined in Uganda over the past two decades (Bekunda et al., 2002), partly due to increased cropping intensity and lack of longer-term bush fallow (Chianu et al., 2011). Beans managed under conventional systems are only producing 500 to 800 kg ha^{-1}, on average, despite having a potential yield of up to 2500 kg ha^{-1} (Bekunda et al., 2002; Broughton et al., 2003). Bean production in Uganda is low due to numerous constraints including poor agronomic practices, soil infertility, lack of seed from improved cultivars, moisture stress, weed competition, and damage caused by pests and diseases (Sinclair and Vadez, 2012). Many farmers are currently looking for improved management systems to increase bean yields; however, there has been little research conducted on management systems that alleviate the aforementioned constraints. Agronomic practices that maximize bean production are not commonly used in Uganda even though some agronomic practices such as planting in rows and more frequent weeding can be implemented with minimal or no additional capital investment.

Fertilizer additions can overcome specific nutrient deficiencies, but fertilizers are expensive investments in sub-Saharan Africa, including rural Uganda, and most farmers use low levels or no fertilizer at all (Bekunda et al., 2002; Chianu et al., 2011; Lunze et al., 2012), contributing to further nutrient depletion of soil. Fertilizing bean can increase root growth providing improved access to soil water (Beebe et al., 2014) and nutrients. Soil testing of available nutrients is rarely done by smallholder farmers in sub-Saharan Africa but it is important to be aware of crop nutrient needs, especially nitrogen, phosphorus, and potassium, which are commonly deficient in these soils (Margaret et al., 2014; Sinclair and Vadez, 2012; Wortmann et al., 1998a).

Bean is generally considered to be a poor N fixer (Graham and Ranalli, 1997), but inoculation with appropriate *Rhizobium* species can increase grain yields in East Africa (Maingi et al., 2001). High levels of N fixation have been documented when the crop is not limited by other constraints (Giller et al., 1998; Amijee and Giller, 1998; Hardarson et al., 1993), and for that reason it is very important to address low soil P to prevent severely reducing symbiotic nitrogen fixation (SNF) or limiting root expansion (Graham and Ranalli, 1997; Beebe et al., 2014). Adequate K is required for improved tolerance to drought stress, protection against biotic stresses, optimal growth and productivity (Oosterhuis et al., 2014), and as cropping intensifies and higher amounts of K are exported from the field (Mengel and Kirkby, 1980). Potassium is frequently removed in large amounts from fields in sub-Saharan Africa, because crop residues are typically removed from the field at harvest rather than incorporated or left on the soil surface (Giller et al., 2009), further worsening soil K availability (Oosterhuis et al., 2014). The addition of K can increase the competitiveness of bean and therefore may also be important for weed management (Ugen et al., 2002).

Additional constraints to bean production by smallholder farmers include strong negative effects of foliar disease on bean yield in South-Central Uganda. The application of foliar or seed-applied fungicides can decrease the impacts of diseases; however, the development and deployment of bean cultivars with improved host plant resistance to commonly occurring diseases has been one of the most important strategies to improving bean yield (Sinclair and Vadez, 2012). Cultivars that are disease resistant offer a form of protection to farmers who are less likely to be able to afford pesticides and pathogen-free seed (Graham and Ranalli, 1997).

Bekunda (2002) and Esilaba et al. (2005) expressed the need for farmers to reverse soil nutrient depletion through better management of their soils and cropping systems. The development of improved management systems that alleviate the aforementioned constraints is necessary to improve grain yield and profitability. The aim of this study was to compare bean productivity and profitability as influenced by management system and cultivar on Phaeozem soil in south central Uganda.

MATERIALS AND METHODS

Experimental site

The experimental site was located approximately 13 km northeast of Masaka, Central Region, Uganda (latitude 0° 15’ 45.6228” S; longitude 31° 48’ 49.8708” E; altitude 1253 m). The climate is tropical with a bimodal rainfall pattern (Jones et al., 2013). The March-June period, Rainy Season A, averages 465 mm, while the second rainy period, Rainy Season B, averages about 540 mm

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Table 1. Monthly precipitation during the course of the study, long-term precipitation, and long-term temperature. LT is long term (1990-2012) mean for Uganda (World Bank Group, 2015).

Month	Precipitation* (mm)		Precipitation* (number of rainy days)		Mean Precipitation (LT) (mm)	Mean Temperature (LT) (°C)
	2014	2015	2014	2015	1990-2012 avg.	1990-2012 avg.
January	-	3	-	2	42	23.9
February	-	34	-	4	44	24.9
March	-	108	-	8	96	24.5
April	-	364	-	17	152	24.0
May	394	298	18	15	129	23.2
June	103	50	7	4	88	22.7
July	77	-	7	-	83	22.3
August	106	-	6	-	114	22.7
September	97	-	8	-	118	22.9
October	112	-	8	-	142	23.1
November	69	-	9	-	111	23.5
December	63	-	11	-	56	23.5
March-June	-	820	-	44	465	23.6
August-December	447	-	42	-	541	23.1
January - December	-	-	-	-	1175	23.4

*Precipitation values recorded within 1 km of the experimental site, located 13 km NE of Masaka, Central Region, Uganda.

from August-December (Table 1). The soil at the location is called Liddugavu (black) in the local language, but is defined as a Phaeozem using the FAO-UNESCO soil legend and as a Hapludoll using USDA Soil Taxonomy (FAO, 1988; USDA NRCS, 1999). The soil at the experimental site was a sandy clay loam texture and formed from alluvial deposits. Prior to adding soil amendments, soil at the 0 to 15 cm depth had a pH range of 6.6 to 6.8, Mehlich3-P ranged from 20 to 30 mg kg^{-1}, and organic matter ranged from 36 to 37 g kg^{-1}. Long term mean annual precipitation in Uganda is 1175 mm, with about 86% occurring during the two crop growing seasons (World Bank Group, 2015). Precipitation data for the specific research site were not available before this project. According to the landowner, prior to the initiation of this study, the site had been in a maize (*Zea mays* L.), bean, groundnut (*Arachis hypogaea* L.), banana (*Musa* × *paradisiaca* L.), and cassava (*Manihot esculenta* Crantz) intercrop.

Experimental design

The study was initiated in July 2014 and continued over two seasons, the second rainy season of 2014 (2014B), from the end of August through the beginning of December, and the first rainy season of 2015 (2015A), from the end of March through the middle of June. The experimental design was a randomized incomplete block in a split-plot arrangement. Management system was the whole-plot factor and included the Conventional Farmer System (CFS), Improved Farmer System (IFS), and High Input System (HIS) (Table 2). The subplots were four bush type common bean cultivars. Two cultivars, NABE 14 and NABE 15, were new and improved, and the other two, K132 and NABE 4, were conventional cultivars. The new cultivars were released 7 to 16 years later (2006 and 2010) than the older cultivars (1994 and 1999) and have greater resistance to several bean diseases prevalent in the south-central region of Uganda. Individual subplot size measured 6 × 4 m. There were four replications of each management system × cultivar subplot combination, except for three subplots, which were excluded due to limited land availability. Replications were blocked perpendicular to the slope.

Crop management practices

Perennial crops and residual weeds from the previous rainy season were removed using a hand hoe more than one month prior to planting in the 2014B season. Ground agricultural limestone with 68.85% effective calcium carbonate equivalent (ECCE) containing 38% Ca, 0.29% Mg, 0.10% S, and 1.24% P was applied at 295 kg ha^{-1} to supply Ca at 112 kg ha^{-1}. Potassium was not applied in the 2014B season, because results from preliminary soil tests in January 2014 showed adequate levels (Liebenberg, 2002). Post-harvest soil results showed available K was as low as 74 mg kg^{-1} in some plots, therefore muriate of potash was broadcast by hand prior to tillage in the 2015A season at 112 kg K_2O ha^{-1} in the IFS and HIS. One to two weeks prior to planting, tillage was conducted with a hand hoe to a depth of 15 to 20 cm. Beans planted in CFS were scatter planted at a density of 10 seeds m^{-2}, while beans in IFS and HIS were planted in rows 50 cm wide with seeds planted every 10 cm, which resulted in the recommended planting density of 20 seeds m^{-2} for both the IFS and HIS (Uganda Export Promotion Board, 2005). The 10 seeds m^{-2} rate for the CFS was determined by extensive sampling of farmer bean fields in Masaka district, the previous rainy season (unpublished results).

Bean seeds were obtained from Community Enterprises Development Organization (CEDO, Rakai, Uganda). Seed for HIS were treated with VITAVAX® (Bayer CropScience, Research

Table 2. Agricultural inputs and management methods for each management system in the 2014B season and the 2015A season. 2014B is 2014 second rainy season, 2015A is 2015 first rainy season, CFS is Conventional Farmer System, IFS is Improved Farmer System, HIS is High Input System.

Property	Units	2014B			2015A		
		CFS	IFS	HIS	CFS	IFS	HIS
Lime	kg ha^{-1}	0	295	295	0	0	0
P_20_5	kg ha^{-1}	0	34	34	0	45	45
K_2O	kg ha^{-1}	0	0	0	0	112	112
Vitavax	applied	No	No	Yes	No	No	Yes
Rhizobia	applied	No	No	Yes	No	No	Yes
Planting	seeds m^{-2}	10	20	20	10	20	20
Planting	method	Scattered	Rows	Rows	Scattered	Rows	Rows
Fungicide	g ha^{-1}	0	0	458	0	0	458
Insecticide	L ha^{-1}	0	0	2.5	0	0	2.5
Weeding*	frequency	Twice	Twice	Weekly	Twice	Twice	Weekly

*Weeding was done by hand between plants and with a hand hoe between rows.

Triangle Park, NC) fungicide (carboxin). Seeds planted in HIS were inoculated with Mak-Bio-Fixer rhizobia obtained from Makerere University prior to planting. Before planting, triple superphosphate (0-46-0) was banded at 33.6 kg P_2O_5 ha^{-1} in IFS and HIS in the 2014B season and at 44.8 kg P_2O_5 ha^{-1} in these systems in the 2015A season. Bands were placed in hand dug furrows at a depth of 8 to 10 cm and covered with 2 to 4 cm of soil, similar to the technique described by Lunze et al. (2012). Beans were then placed at the recommended depth of 3 to 5 cm (Liebenberg, 2002; Amongi et al., 2014) before being covered with soil using a hand hoe. Beans were planted on 19 and 20 August during the 2014B season and 24 and 25 March during the 2015A season.

Formulated azoxystrobin was applied as a foliar fungicide at 458 g ha^{-1} to HIS during both seasons. The fungicide was applied using a hand-pumped backpack sprayer in approximately 625 L H_2O ha^{-1} at the early stages of R8 pod filling in the 2014B season and at the late stages of R7 pod formation in the 2015A season. Four days after applying the fungicide in the 2014B season, the insecticide cypermethrin was foliar-applied to HIS beans at 2.5 L ha^{-1} with the same hand-pumped backpack sprayer in approximately 625 L H_2O ha^{-1}. Control of aphids was not needed in the 2015A season, therefore cypermethrin was not applied.

Weeding was done by hand between plants and with a hand hoe between rows twice per season for CFS and IFS. The first weeding was done at V3 in the 2014B season and between V3 and V4 in the 2015A season. The second weeding occurred between R7 and R8 both seasons. Weeding was done weekly for HIS, using the same method, so that weeds were never competitive with beans.

Crop and soil data collection

Pre-amendment and post-harvest soil samples were collected at a depth of 0 to 15 cm from 12 subsamples collected from each replication of each whole-plot. Soil samples were analyzed for pH and electrical conductivity (EC) using the potentiometric method. Extractable Al (1-N KCl), organic matter (Walkley-Black C/0.58), and N (Kjeldahl) concentrations were determined by colorimetry. The cation exchange capacity (CEC) was calculated according to Brady and Weil (2007). After extraction with Mehlich-3, inductively coupled plasma optical emission spectrometry (ICP-OES) was used for soil sample analysis of P, K, Mg, Ca, Na, Al, Mn, S, Cu, B, Zn, and Fe following extraction with Mehlich-3.

Phenological development stages were recorded weekly in each plot using the standard system developed for common bean (Van Schoonhoven and Pastor-Corrales, 1987). Briefly, V1 is emergence, V3 is first trifoliate leaf, V4 is third trifoliate leaf, R5 is preflowering, R6 is flowering, R7 is pod formation, R8 is pod filling, and R9 is physiological maturity. Between R8 and R9, aboveground crop biomass was determined by hand clipping five bean plants per plot. Biomass samples were oven-dried at 60°C for 7 days and then weighed. Yield, yield components, and extended plant height data were collected from all bean plants within the area harvested from each plot. The area harvested in CFS was selected by randomly placing two 1.0 m^2 quadrats in each plot (2.0 m^2 total). The IFS and HIS yield samples were determined from 2.0 m^2 in each plot. Stand density of bean at R9 stage was determined at harvest by counting the number of plants within each harvested area. Extended plant height was measured on every plant harvested, up to a maximum of ten plants per subplot. At harvest, all pods were hand-picked, counted, placed in a paper bag, and weighed. Pods were placed in an oven at 60°C until dry. Grain was shelled from pods by hand, counted, and weighed. The pod harvest index (PHI; dry weight of seed at harvest/dry weight of pod at harvest × 100), pod number per area (pods m^{-2}), and seed number per pod (seeds pod^{-1}) were computed as described by Beebe et al. (2013). Grain yields are reported at 100% dry matter.

Soil volumetric water content (VWC) was determined using a calibrated FIELDSCOUT® TDR 300 Soil Moisture Meter (Spectrum Technologies, Inc., Plainfield, IL). Sampling occurred weekly in each subplot at two points for each of the two depths, 7.5 and 20 cm.

The costs of production and market prices of beans were determined using local market prices for all agricultural inputs, except rhizobia, which was unavailable in the local market. Rhizobia inoculant was available at Makerere University; it was assumed that inoculation will occur every four seasons. The economic return to labor and management (ERLM) was based on land rental costs collected from farmers in the Masaka district. The market price of bean used in the analysis assumed beans were sold immediately after harvest when farm gate prices ranged from 1500 to 1700 UGX kg^{-1}, depending on the cultivar. The UGX to USD conversion rate used for this study was 3400 UGX = 1 USD.

Statistical analysis

Data were analyzed as a randomized incomplete block in a split-plot arrangement with management system as the whole-plot factor and bean cultivar as the subplot factor. Statistical analyses for yield, yield components, height, biomass, PHI, VWC, phenological, and economic data were performed with the GLIMMIX Procedure of SAS V9.4 (SAS Institute, 2013). Least squares means were generated for all variables when significant F values ($P < 0.05$) were observed and then separated using the LINES option at $P = 0.05$. Soil data were analyzed using PROC GLM, which enabled us to separate means using the multiple mean comparison of the protected least significant difference. Differences among treatments were reported as significant at $P = 0.05$ except for the phenological differences between treatments, which were reported as significant at $P = 0.01$. Management system, cultivar, rainy season, and weeks after planting (WAP) were treated as fixed effects. Replication, replication × management system, and cultivar × replication × management system were considered random effects.

RESULTS

Climate

Long-term mean annual precipitation for this region is 1175 mm, 86% of which occurs during the crop growing season (Table 1) (World Bank Group, 2015). Total precipitation during our study, July 2014 through June 2015, was 1381 mm, 18% greater than the long-term mean. Precipitation during the dry season months, July and again January through February, amounted to only 67% of the 22-year average for these months. However, the precipitation in April 2015 was 139% greater than that of the long-term average and the precipitation in May 2015 was 131% greater than that of the long-term average.

Soil

The pre-amendment soil results did not show differences among management systems; however, there were greater levels of extractable Al, Cu, Fe, N, and Mn in the post-harvest soil compared to the pre-amendment soil (Table 3). Additionally, management systems differed for post-harvest soil copper concentration. The IFS had 7 and 10% more copper than HIS and CFS, respectively. The available P, K, and Ca were similar between management systems across both sampling dates despite receiving different amounts of each as soil amendments.

Volumetric water content

The VWC differed for rainy season and the interaction of rainy season × depth. All other main effects and interactions were not significant. There was an interaction of rainy season × depth for VWC over two seasons. VWC differed for depth in both seasons. Mean VWC in the 2014B season was 0.20 and 0.23 $cm^3\ cm^{-3}$ for 7.5 and 20 cm depth, respectively, while mean VWC in the 2015A season was 0.30 and 0.27 $cm^3\ cm^{-3}$ for 7.5 and 20 cm depth, respectively. The 2014B season was wetter at 20 cm depth compared to 7.5 cm depth, while the reverse was true for the 2015A season.

Bean development

Phenological development of beans varied for cultivar, rainy season, weeks after planting (WAP), and the interaction of cultivar × rainy season, cultivar × WAP, rainy season × WAP, and cultivar × rainy season × WAP (Figure 1). In the 2014B season, there was a trend for faster development of NABE 15, while the other cultivars developed more slowly, but at a similar rate to each other, and reaching maturity in 13 weeks. In the 2015A season, development rates were similar for the four cultivars, although maturity was reached in only 11 weeks (Figure 1).

Yield, yield components, height, biomass, and pod harvest index (PHI)

At maturity (R9 stage), stand density of beans differed for management system, cultivar, and the interaction of cultivar × rainy season (Table 4). NABE 14 was among the greatest for stand density both seasons while NABE 15 had the lowest density in both rainy seasons (Table 5).

Height of beans at harvest varied for cultivar, rainy season, and the interactions of management system × rainy season and cultivar × rainy season (Table 4). In the 2014B season, beans had similar height under all management systems (Table 6). Conversely, beans in the 2015A season under HIS were taller than beans under CFS; height of beans in IFS was intermediate and not different from either the CFS or HIS. The NABE 14 and K132 were the tallest cultivars in the 2014B season and the 2015A season; NABE 15 was the shortest entry for both rainy seasons (Table 5).

Pod density of beans differed for management system, cultivar, rainy season, and the interactions of management system × rainy season, cultivar × rainy season, and management system × cultivar × rainy

Table 3. Pre-amendment and post-harvest soil (0 to 15-cm depth) nutrient concentrations, CEC, EC, organic matter, and base saturation results from the three common bean management systems. Soil collected from Masaka District, Uganda with collection period for Pre-amendment in July 2014 and post-harvest in December 2014. CFS is Conventional Farmer System, IFS is Improved Farmer System, HIS is High Input System.

Property	**Units**	**Pre-amendment**			**Post-harvest**		
		CFS	**IFS**	**HIS**	**CFS**	**IFS**	**HIS**
pH		6.7	6.6	6.8	6.6	6.5	6.5
CEC	meq 100g^{-1}	13	14	14	15	16	15
EC(S)	µS cm^{-1}	77	86	84	99	100	111
Extr. Al	meq 100g^{-1}	0.014^{b}	0.013^{b}	0.015^{b}	0.125^{a}	0.125^{a}	0.125^{a}
P	mg kg^{-1}	20	29	30	27	32	27
K	mg kg^{-1}	74	126	101	89	124	101
Mg	mg kg^{-1}	333^{ab}	311^{b}	360^{ab}	392^{a}	348^{ab}	350^{ab}
Ca	mg kg^{-1}	1710	1828	1850	1898	2058	1910
Na	mg kg^{-1}	40^{a}	55^{a}	51^{a}	11^{b}	45^{a}	27^{ab}
Al	mg kg^{-1}	830	846	854	-	-	-
Mn	mg kg^{-1}	340^{b}	335^{b}	354^{b}	467^{a}	460^{a}	473^{a}
S	mg kg^{-1}	3	3	2	2	3	5
Cu	mg kg^{-1}	2.9c	3.0 c	3.0c	4.0^{b}	4.4^{a}	4.1^{b}
B	mg kg^{-1}	0.5	0.5	0.5	0.7	0.9	0.7
Zn	mg kg^{-1}	5.1	5.7	5.2	6.4	6.6	6.2
Fe	mg kg^{-1}	97^{b}	97^{b}	97 ^{b}	132^{a}	135^{a}	134^{a}
N	%	0.11^{b}	0.12^{b}	0.12^{b}	0.16^{a}	0.16^{a}	0.16^{a}
OM	g kg^{-1}	36	37	36	38	34	36
C:N	ratio	18	18	18	14	12	13
Base Saturation	%	90	90	92	89	88	88

Means within property followed by the same letter, or no letter, are not different at *P*=0.05. OM as Walkley-Black C/0.58; other elements determined with ICP-OES following extraction with Mehlich-3. Extraction of exchangeable Al done with 1N KCl.

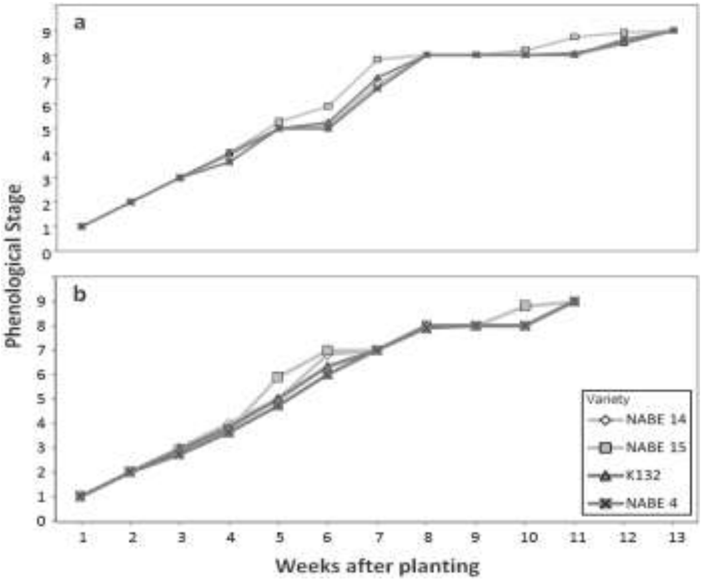

Figure 1. Weekly mean phenological stage of bean for four cultivars in (a) the 2014 Rainy Season B and (b) the 2015 Rainy Season A across three management systems, Masaka, Uganda.

Table 4. Yield, yield components, height, biomass, pod harvest index (PHI), and net profit/loss for four bean cultivars in three management systems for two rainy seasons, Masaka, Uganda.

Treatment	Plant stand (#m^{-2}) R9	Extended plant height (cm)	Pods (#m^{-2})	Seed (#pod^{-1})	Seed size (100 seed weight, g)	Biomass (g plant^{-1}) R8-R9	Grain (kg ha^{-1})	Pod harvest index (PHI)	Economic return to labor and management (USD)
Management system									
CFS	6^{b}	29	40^{b}	2.9	42.5	21	593^{b}	76	212
IFS	14^{a}	31	67^{ab}	2.8	38.7	16	818^{b}	77	124
HIS	16^{a}	34	92^{a}	2.9	43.7	18	1275^{a}	75	297
Cultivar									
NABE 14	14^{a}	36^{a}	90^{a}	3.2	41.7^{ab}	22^{a}	1212^{a}	73^{b}	378^{a}
NABE 15	10c	23c	52^{b}	2.6	37.8^{b}	18^{ab}	668c	81^{a}	79c
K132	11^{b}	34^{ab}	62^{b}	2.8	43.1^{a}	17^{b}	803^{b}c	74^{ab}	165^{b}c
NABE 4	13^{a}	32^{b}	63^{b}	2.9	43.9^{a}	16^{b}	899^{b}	76^{a}	220^{b}
Rainy season									
2014B	12	38^{a}	91^{a}	3.3	44.5^{a}	27^{a}	1318^{a}	76	466^{a}
2015A	12	25^{b}	42^{b}	2.5	38.8^{b}	9^{b}	473^{b}	76	-44^{b}
Significance	-	-	-	*P* > F	-	-	-	-	-
System (S)	***	NS	*	NS	NS	NS	*	NS	NS
Cultivar (C)	***	***	***	***	*	*	***	*	***
S × C	NS	NS	NS	NS	NS	NS	NS	NS	NS
Rainy season (R)	NS	***	***	***	***	***	***	NS	***
S × R	NS	**	*	NS	NS	**	**	NS	***
C × R	**	**	***	***	NS	***	***	NS	***
S × C × R	NS	NS	*	NS	NS	NS	*	NS	*

Means within treatment and column followed by the same letter, or no letter, are not different at *P*=0.05.*, **, ***, and NS indicate statistical significance at *P* ≤ 0.05, 0.01, 0.001, and not significant, respectively. CFS is Conventional Farmer System, IFS is Improved Farmer System, HIS is High Input System. 2014B is 2014 second rainy season, 2015A is 2015 first rainy season.

season (Table 4). In the 2014B season, pod density increased with increasing input level (Figure 2). In the 2015A season, this same trend occurred with NABE 14 and K132. Conversely, in the 2015A season, pod density of NABE 15 and NABE 4 did not increase with increasing input levels. The interaction of management system × cultivar was not significant in the 2014B season though this interaction was significant in the 2015A season. Cultivars did not differ for pod density within management systems in the 2014B season. Conversely, in the 2015A season, cultivars differed among management systems for pod density. NABE 14 produced more pods m^{-2} than all other cultivars within each management

Table 5. Interaction of cultivar × rainy season for plant stand density, height, seed number, and aboveground biomass of bean at maturity (R9) for two seasons. 2014B is 2014 second rainy season, 2015A is 2015 first rainy season.

Parameter	2014B	2015A
Plant stand (#m^{-2}) R9		
NABE 14	13^{a}	14^{a}
NABE 15	10^{b}	10^{c}
K132	12^{a}	10^{c}
NABE 4	13^{a}	13^{b}
Height (cm)		
NABE 14	39^{a}	34^{a}
NABE 15	32^{b}	15^{c}
K132	38^{a}	29^{a}
NABE 4	41^{a}	23^{b}
Seed (#pod^{-1})		
NABE 14	3.3^{ab}	3.1^{a}
NABE 15	3.3^{ab}	1.9^{c}
K132	3.0^{b}	2.6
NABE 4	3.5^{a}	2.3^{b}
Biomass (g plant^{-1}) R8-R9		
NABE 14	26	18^{a}
NABE 15	30	5^{b}
K132	26	8^{b}
NABE 4	27	6^{b}

Means within measured variable and rainy season followed by the same letter, or no letter, are not different at *P*=0.05.

Table 6. Interaction of management system × rainy season for height and biomass of bean for two seasons. CFS is Conventional Farmer System, IFS is Improved Farmer System, HIS is High Input System. 2014B is 2014 Rainy Season B, 2015A is 2015 is Rainy Season B.

Parameter	2014B	2015A
Height (cm)		
CFS	37	22^{b}
IFS	39	23^{ab}
HIS	37	30^{a}
Biomass (g plant^{-1}) R8-R9		
CFS	32^{a}	9
IFS	25^{b}	7
HIS	24^{b}	11

Means within parameter and rainy season followed by the same letter, or no letter, are not different at *P*=0.05.

system in the 2015A season while NABE 15 had the least or was among the least for pod density within each management system.

Seed number pod^{-1} varied for cultivar, rainy season,

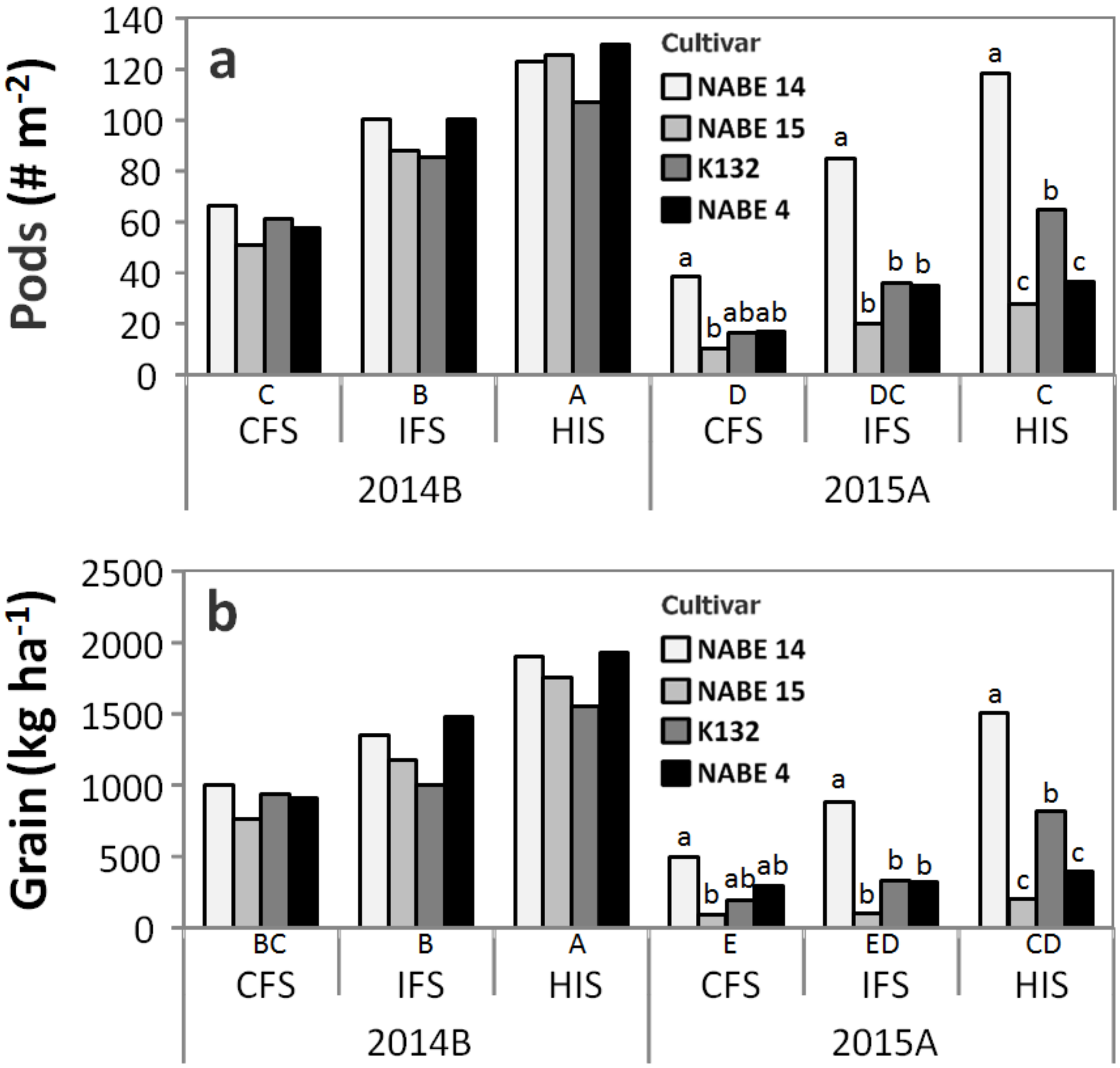

Figure 2. Interaction of management system × cultivar × rainy season for (a) pod density and (b) grain yield of beans. Management systems include the Conventional Farmer System (CFS), Improved Farmer System (IFS), and High Input System (HIS). 2014B is 2014 Rainy Season B, 2015A is 2015 Rainy Season A. Cultivar means within system and rainy season followed by the same lowercase letter, or no letter, are not different at *P*=0.05. System × rainy season combinations followed by the same uppercase letter are not different at *P*=0.05.

and the interaction of cultivar × rainy season (Table 4). Seed number pod^{-1} varied for cultivar both rainy seasons (Table 5). NABE 14 produced more seeds pod^{-1} than the other cultivars while NABE 15 generally produced fewer seeds pod^{-1} than the other cultivars. The 100-seed weight varied for cultivar and rainy season, however, all interactions were non-significant (Table 4). Management system did not influence 100-seed weight. However, seed weight across management systems in the 2014B season was 15% greater than for the 2015A season. K132 and NABE 4 produced the heaviest seeds, weighing 14 and 16% greater than NABE 15, respectively.

Aboveground biomass (g plant^{-1}) varied for cultivar, rainy season, and the interactions of management system × rainy season and cultivar × rainy season (Table 4). In the 2014B season, beans in CFS accumulated 28 and 33% greater biomass than beans under IFS and HIS, respectively; differences were not significant among management systems for biomass in the 2015A season (Table 6). The interaction of cultivar × rainy season was not significant in the 2014B season; however, this

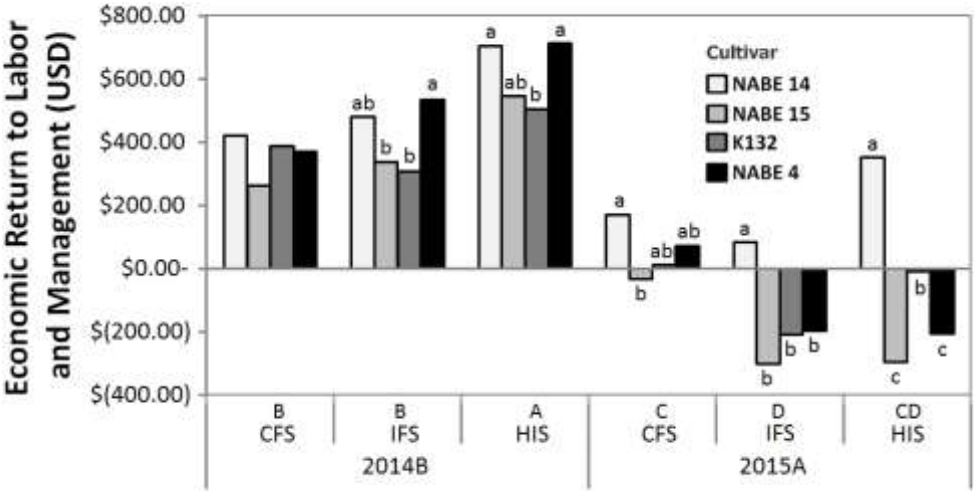

Figure 3. Interaction of management system × cultivar × rainy season for return to labor and management of beans. Management systems include the Conventional Farmer System (CFS), Improved Farmer System (IFS), and High Input System (HIS). 2014B is 2014 Rainy Season B, 2015A is 2015 Rainy Season B. Cultivar means within system and rainy season followed by the same lowercase letter, or no letter, are not different at *P*=0.05. System × rainy season combinations followed by the same uppercase letter are not different at *P*=0.05.

interaction was significant in the 2015A season (Table 5). In the 2015A season, NABE 14 accumulated 260, 125, and 200% greater biomass than NABE 15, K132, and NABE 4, respectively.

Grain yield differed for management system, cultivar, rainy season, and the interactions of management system × rainy season, cultivar × rainy season, and management system × cultivar × rainy season (Table 4). In the 2014B season, grain yield increased with increasing input level (Figure 2). In the 2015A season, this same trend occurred with NABE 14 and K132. However, for this rainy season, grain yield of NABE 15 and NABE 4 did not increase with increasing input levels. In the 2014B season, yields were similar among cultivars within each of the three management systems. In the 2015A season, NABE 14 produced greater yields than the other three cultivars within IFS and HIS, while NABE 4 and NABE 15 produced among the lowest grain yields in these management systems. NABE 14 produced 444% greater yield than NABE 15 under CFS in the 2015A season. The PHI varied for cultivar but no other treatment factor or interaction was significant (Table 4). The PHI for NABE 15 was 11% greater than for NABE 14, but was not different from the other two cultivars.

Economic analysis

Cultivar, rainy season, and the interactions of management system × rainy season, cultivar × rainy season, and management system × cultivar × rainy season influenced economic return to labor and management (ERLM) (Table 4). However, management system and the interaction of management system × cultivar did not influence the ERLM. In the 2014B season, net profit was the greatest for HIS (Figure 3). In the 2015A season, CFS realized greater profits than IFS, while HIS was intermediate and did not differ from CFS or IFS. In the 2014B season, net profits were similar among cultivars within CFS, but differed for IFS and HIS. Of the four cultivars tested in the HIS in the 2014B season, NABE 14, NABE 15, and NABE 4 realized greater profits than K132. Over both seasons, NABE 14 remained profitable in all six management system × cultivar × rainy season combinations and showed greater positive returns than other cultivars. In the 2015A season, NABE 15 realized the highest net loss in each management system; NABE 14 produced $200, $406, and $678 ha^{-1} greater profits than NABE 15 within CFS, IFS, and HIS, respectively. About 58, 88, and 90% of the total cost of production were from agricultural inputs in CFS, IFS, and HIS, respectively (results not presented).

DISCUSSION

Climate, volumetric water content, and bean development

Precipitation during the 2014B season was normal and all other environmental conditions were suitable for good growth of beans; however, precipitation during the 2015A season was abnormally intense and frequent, resulting in unusually long periods of high VWC in the early part of the growing season. The increase in soil VWC may have led to the greater frequency of diseases (results not presented) and damping-off (Athanase et al., 2013) in the 2015A season, which appeared to be related to the reduction in R9 plant stands and overall lower grain yield compared to the 2014B season (Figure 2). It was also believed that the VWC would increase with increased management level, because IFS and HIS had greater planting density, which enabled them to canopy quicker and therefore prevent soil water loss through evaporation; however, significant differences were not observed. The differences in phenological development between cultivars at each date were likely due to the differences in maturity groups between the four cultivars. NABE 15 was a short maturity cultivar, while K132 was an intermediate, and NABE 14 and NABE 4 were long maturity cultivars.

Management and cultivar selection

Farmers prefer to plant common bean on Phaeozem soil (Liddugavu in the local language) if it is available because they recognize that this soil is generally more fertile than other soils, providing a better growing environment for beans. Because the Liddugavu soil type is considered fertile, these soils typically receive little or no fertilizer applications for bean production under current management systems used by farmers. As a result, bean yield on this soil is still much lower than its potential.

Beans were planted at an increased density to promote faster canopy closure which decreases soil water evaporative losses, shades out weeds, and captures more light. We replanted beans on the same plots in the second season to develop a better understanding of nutrient carry-over effects. Doing this also allowed us to determine yield response of improved management systems in a bean-bean rotation which many smallholder farmers are now practicing due to limited land resources (Ampofo et al., 2001).

Bush-type bean cultivars were employed in this study because these cultivars are the most prevalent type in the region. Three of the four cultivars (K132, NABE 4, and NABE 15) in this study were the most popular cultivars grown in Uganda. NABE 14 was included in this study because it was a newer cultivar with tolerance to low soil fertility and resistance to angular leaf spot (*Phaeoisariopsis griseola*) (ALS), bean common mosaic virus (*Potyvirus* spp.) (BCMV), and root rots (*Fusarium solani* f. sp. *phaseoli*). Therefore, this cultivar should have better yield potential under greater disease pressure. The beneficial effects of host plant resistance to foliar and root diseases in NABE 14 were apparent in the abnormally wet 2015A season. To our surprise, NABE 15 grain yields were very poor for a newly released cultivar, especially during the 2015A season. Not all new and improved cultivars perform well under every environment and we suggest that multiple cultivars be included in subsequent cropping systems studies. NABE 15 and the older cultivars, K132 and NABE 4, likely produced lower yields than NABE 14 because they are susceptible to root rot, which was observed in the wet 2015 Rainy season A.

Agricultural inputs and soil nutrient status

Potassium fertilizer was not applied in the 2014B season, because preliminary soil data showed extractable K was adequate for bean production. However, mid-season, pre-amendment soil nutrient results became available that documented soil was deficient in both P and K. Determining fertilizer application was challenging, because very little work has been done on fertilizer recommendations for common bean in Uganda, especially for individual soil types within different regions of the country (Benson et al., 2013). Additional studies should develop recommendations for fertilizer application rates based on test values within each region of Uganda, because current recommendations broadly recommend fertilizer rates for entire regions or soil types irrespective of management history or actual nutrient status.

Nitrogen can be supplied to beans by N fixation following inoculation of seeds with appropriate *Rhizobium* spp., offering a cost effective alternative to N fertilizers (Hardarson and Atkins, 2003) or soil mining. Even with good N fixation, several reports suggest that beans may be nitrogen limited without supplemental nitrogen application (Liebenberg, 2002; Wortmann et al., 1998b). We inoculated seeds prior to planting in HIS and did not apply nitrogen, because beans can fix nitrogen at rates greater than 100 kg ha^{-1} under optimum conditions (Graham and Ranalli, 1997; Hardarson and Atkins, 2003). Optimum conditions generally occur under P fertilization and liming, which is appropriate to ameliorate low pH or Ca deficiency (Giller et al., 1998; Lunze et al., 2012; Wortmann et al., 1998b). Management practices and inputs were done to optimize conditions for N fixation in HIS by applying lime (38% Ca) and P fertilizer. Nitrogen deficiency was only noted in one HIS plot, suggesting nitrogen needs were not limiting following rhizobia inoculation. Even though both improved management systems received P and lime applications, the post-harvest soil results unexpectedly showed no differences in P or Ca concentrations compared to the pre-amendment soil results. This could be attributed to increased plant uptake or P being complexed by reactions in soil (Fungo et al., 2011).

Pests and diseases

Lower yields across management systems, cultivars, and the management system × cultivar interaction were expected in the 2015A season, because our study was conducted on the same plots as the previous season. Disease prevalence was greater in the 2015A season which may have been due to the bean-bean rotation or the greater amounts of rain and increased number of rainy days compared to the 2014B season (Athanase et al., 2013). Increased frequency and amount of rain in the 2015A season may have also been the cause for the decreased presence of aphids (Weisser et al., 1997). Crop rotation can be an effective management practice to decrease disease pressure.

Economic analysis

Although the Economic Return to Land and Management (ERLM) results in this study did not consistently show an increase in net profits by increasing input levels, improved yields document there is great potential for increased profits with improved management systems if input costs decrease and/or grain prices increase. Uganda currently imports many of its agricultural inputs such as synthetic fertilizers, lime, herbicides, and other pesticides resulting in increased costs.

Improved management systems were more labor intensive due to the labor required for applying inputs, and if labor was hired it would represent approximately 50% of the total cost of production in this study. However, there is great variability in labor costs due to the inconsistency of prices between villages, field locations, presence or absence of weeds, relationship with farmers, and seasonal demand. The ERLM does not include the cost of labor in the economic analysis because most labor on smallholder farms in this region of Uganda is provided by members of the family. Furthermore, the opportunity cost for these family members is very low because there are very few opportunities for off-farm employment. Therefore, the ERLM was included in the economic analysis instead of the economic return to management.

A significant portion of the total production costs were from imported and expensive agricultural inputs, especially agricultural lime. With recent bean values, production costs, and production levels it may not always be profitable at this time for smallholder farmers to invest in expensive agricultural inputs such as mineral fertilizers to replenish or maintain soil nutrient reserves or alleviate soil infertility (Nabhan et al., 1999). This is especially important in a region experiencing extensive changes in rainfall patterns in recent years, because these management systems may not recover the value of fertilizer or other inputs (Ojiem et al., 2014).

Regarding cultivar selection, the improved cultivar NABE 14 had the potential for greater returns than other bean cultivars due to its ability to produce higher yields under varying levels of fertility, moisture stress, and pest and disease pressure. Similar to our analysis for profitability, Broughton et al. (2003) compared newly released and older bean cultivars and reported profits increased 300 % or more with the use of improved cultivars in Central and South America. We hypothesized that improved bean cultivars could increase grain yields, especially under greater input levels and management practices. Our production results support conclusions from the Uganda Export Promotion Board (UEPB) (2005), which stated that higher input systems provided greater yields than subsistence bean management systems and low input systems. However, our ERLM results differ from those of the UEPB because we did not consistently show a greater return on investment as input and management levels increased, particularly for bean cultivars with low levels of resistance to diseases.

Conclusions

Increasing management level and planting bean cultivars resistant to common bean diseases improved grain yield in both rainy seasons. The increase in yield was due to in the combination of planting arrangement and density, fertilizer application, and improved N fixation and weed and pest management. All inputs were obtained locally, except the rhizobia inoculant, suggesting that increased yields and profitability are obtainable by farmers, especially when utilizing NABE 14 under HIS. Our production results and economic analysis suggest that common bean production systems with increased use of agricultural inputs and improved pest management strategies are acceptable methods for farmers to alleviate constraints limiting bean production and profitability.

Conflict of Interests

The authors have not declared any conflict of interests.

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