

Variety × Environment × Management Interaction of Diseases and Yield in Selected Common Bean Varieties

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ABSTRACT

Understanding variety × environment interaction (VEI) and variety × management interaction (VMI) are critical for deploying superior crop varieties to responsive environments. We evaluated 15 common bean (*Phaseolus vulgaris* L.) varieties in a split-plot design under two fertilizer regimes, for two seasons, and in six locations in Rakai and Hoima districts, Uganda. We assessed VEI and VMI effects on plant vigor, plant height, number of pods per plant, grain yield, and reaction to angular leaf spot (ALS) (*Pseudocercospora griseola*), common bean rust (CBR), common bacterial blight (CBB) (*Xanthomonas campestris* pv. *phaseoli*), and anthracnose on pods (ANTP) (*Colletotrichum linemuthianum*) under field conditions. The seasons and fertilizer levels were considered as separate environments resulting in 24 environments. Variety × location × season interaction had a significant effect on the reaction to ALS, CBR, and grain yield. The VEI and VMI analysis grouped the 12 environments into two mega-environments based on grain yield in different seasons and fertilizer levels. ROBA1, Masindi Yellow Long, and NABE2 varieties had the highest grain yield in the different mega-environments. The Farmers' variety and varieties KATX69 and KATX56 were stable, whereas NABE2, RWR719, and ROBA1 were unstable in grain yield performance. Genotypic correlations between traits were stronger in Hoima than in Rakai. The diseases correlated negatively with grain yield, and were strong in the second season of Hoima district. The Katumani varieties and landraces were susceptible to disease in the environments. Thus, increased production of landraces, KATX69 and KATX56 could be attained by improving their disease resistance.

Core Ideas

- Varieties were grouped into mega-environments based on the grain yield.
- Farmers' variety, KATX69 and KATX56 were stable in grain yield across environments.
- NABE2, ROBA1, RWR719 and Masindi Yellow Long adapted to specific mega-environments.
- The landraces, and KATX 69 and KATX 56 varieties were susceptible to the diseases.

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COMMON BEAN is one of the important food crops widely consumed and grown by more than 13 million farmers (Buruchara et al., 2011) in eastern, central, and southern Africa (Akibode, 2011). The production is typically subsistence, being grown in less than 1 to 10 ha of land. The actual grain yields are low, about 600 kg ha⁻¹ compared to a potential yield of 2500 kg ha⁻¹ that are recorded on-station in most African countries (Akibode, 2011; Abate, 2012). These low yields are attributed to the cultivation in marginal areas that are associated with low fertility, diseases, pests, and drought (Beebe et al., 2013). In the different bean growing areas in Uganda, diseases such as common bacterial blight, root rot (*Pythium* and *Fusarium* spp.), anthracnose, angular leaf spots, bean common mosaic potyvirus, and bean golden mosaic begomovirus are a major constraint (Ugen et al., 2014). Furthermore, the soils are degraded with low P and N contents, and there are variations in rainfall associated with short seasons (Caffrey et al., 2013), resulting in low productivity or complete crop failure (Mwongera et al., 2014). These production constraints can cause differences in the performance of bean varieties in different environments and under different fertilizer use regimes, phenomena referred to as VEI and VMI.

Understanding the nature of these interactions are relevant when choosing parents for improvement and for identifying stable and highly responsive varieties for growing in different environments and fertilizer management regimes. Varieties that exhibit low VEI or VMI are stable and desired for wide base adaptation whereas the varieties exhibiting high interactions are recommended to specific environments and/or mega-environments. In a mega-environment, explored through genotype and genotype × environment interaction analysis (GGE), minimal interaction effects are experienced enabling

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Abbreviations: ALS, angular leaf spot; AMMI, additive main effects and multiplicative interaction effects, ANTP, anthracnose on pods; CBB, common bacterial blight; CBR, common bean rust; DAP, diammonium phosphate; GGE, genotype and genotype × environment interaction; VEI, variety × environment interaction; VEM, variety × environment × management; VMI, variety × management interaction.

selection of wining genotypes (Gauch, 2013). Additive main effects and multiplicative interaction effects (AMMI) approaches are commonly used in the identification of stable varieties and/or genotypes specifically adapted to a particular environment (Chataika et al., 2010; Gauch, 2006). The bi-plot from AMMI enables a visual comparison of variety, environment, and interaction effects (Bucheyeki and Mmbaga, 2013). Regression approaches proposed by Yates and Cochran (1938) and subsequently modified by Finlay and Wilkinson (1963) are also used in the characterization of genotypic performance. This approach establishes a linear relationship between a genotype and the environment which are used to predict genotypic responses. The estimates could be a good predictive measure of the genotype response to the changes in the quality of the environment when a significant proportion of the interaction are explained by the regression line.

In Uganda, Rakai and Hoima districts are experiencing contrasting climatic conditions; Rakai getting drier and Hoima getting wetter with the soils getting degraded (Förch et al., 2011). These locations represent ideal environments where adaptive studies of different crop varieties for growing in the wet and drier environment could be done. With the changing climatic conditions, change in the spatial differences within the agro-ecologies will likely influence disease pressure and their distribution, and also affect the fertility of the soils due to drainage and/or nutrient loss through evaporation (Beebe et al., 2011). These factors affect the performance of varieties for grain yield, grain yield components, and their reaction to disease (Musaana et al., 2015), necessitating breeding programs to continuously assess the effects of varieties, environments and their VEI on the performance of varieties. Broadening the genetic base is a factor for increasing agricultural systems resilience to climate change. However, introduced genetic materials are not necessarily adapted to the new environments, creating a need for assessment of the VEI effects. In addition, because the fertility of soils in Africa are highly variable and mostly nutrient depleted (Sanchez, 2002), homogenization of the performance of improved varieties for wide adaptation could be improved by assessment of their response to fertilizer management regimes (VMI).

Breeding for yield and diseases resistance constitute major breeding objectives in Uganda. With the existing change of the pattern in climatic condition, the variety or genotype ability to utilize the available soil nutrients in the different environments have also become key components in breeding. Therefore, this study was undertaken to assess the VEI and VMI for grain yield, grain yield components and reaction to diseases in 15 selected common bean varieties. The environment in this study constituted a unique combination of location, season, and fertilizer levels.

MATERIALS AND METHODS

Experimental Sites

Replicated trials were conducted in six locations, two in Rakai and four in Hoima district (Supplementary Table S1) for two seasons, April to July 2013 (season A) and August to December 2013 (season B). Rakai district located in the Kagera Basin (southwestern Uganda) is divided into three major zones; (i) the extensive low-lying swamps, (ii) seasonally

flooded grasslands, and (iii) swamp forest in the South and East of the Kagera flood plain and along the shores of lake Victoria (Zwick and Smith, 2001). The swamp forests are characterized with undulating terrain, ranging from 1402 to 1520 m asl. The soils in the area are mainly ferralitic type; the other types being lithosols, alluvial, and lacustrine that constitutes 25% of the soil types (Kimbugwe, 2013). The annual rainfall range between 850 and 2125 mm, which falls bimodally, peaking from March to May and October to November (Kimbugwe, 2013). However, declines in the amounts of rainfall, and number of rainy days in all months have been reported in the past 10 yr from 2007 (Mubiru et al., 2015). The mean annual temperature is 25°C, with a range of 15 to 27°C (Kimbugwe, 2013), and an increasing trend of about 0.5°C per year (Mubiru et al., 2015).

Hoima district is located in the Albertine Rift valley, central western Uganda. The soil types include acric ferralsol, dystric regosols, and petric plinthosol (Tenywa, 2015). The altitude ranges between 621 and 1158 m asl. The district is characterized among the hottest in Uganda with an annual mean temperature range of 15 to 30°C. Increasing trends in temperatures of 0.8 degrees annually have been observed (Mubiru et al., 2015). Mean annual rainfall is 1270 mm with a range of 800 to 1400 mm, which falls bimodally in March to May and August to November. The district has experienced increasing amounts of rains in January, March, and August with declining trends in certain months (Mubiru et al., 2015).

Study Varieties

Fifteen common bean varieties from East and central African countries were evaluated in this study (Supplemental Table S2). The varieties used included six released varieties from the Uganda National Breeding Program, two local landraces (Farmers' variety and Masindi Yellow Long), four bean varieties released by the Kenya Agricultural Research and Livestock Organization (KARLO)-Katumani center. The remaining three were varieties released by the National Research Programs of Malawi, Tanzania, Ethiopia, Rwanda, and the Democratic Republic of Congo.

Experimental Design

Trials were conducted over two seasons in six locations (two in Rakai and four in Hoima) using a split-plot design of four blocks with two factors; the two levels of management or fertilizer (150 kg ha⁻¹ di-ammonium phosphate [DAP] and no-fertilizer) as main plot (two per site) and the 15 bean varieties planted as subplots in two replicates (30 plots per replication per site). The varieties were randomized within the subplots (3 by 2 m) in each of the main plot (40.5 by 7 m) factors to increase precision in the detection of significant differences among the varieties. Fertilizer was applied in the main plots for ease of practical applicability. Di-ammonium phosphate fertilizer was recommended due to the low soil fertility, especially P observed during a previous common bean evaluation conducted in 2012 by the Centro Internacional de Agricultura Tropical (CIAT) and the bean breeding program in Uganda. Planting was done at a spacing of 50 and 10 cm between and within rows, respectively. Hand weeding was performed at 3 wk after planting and before flowering in the locations, and experiments were done entirely under rain-fed conditions.

Data Collection

For each trial, disease severities for ALS, CBR, CBB, and ANTP were collected at pod filling stage (R8) using a scale of 1 to 9 (Pastor-Corrales, 1994). Plant stand, plant height, plant vigor, pod number per plant (average number of pods from 10 randomly selected plants per plot) and grain yield in grams per plot were recorded at harvest in July for the first seasons' harvest and December for the second seasons' harvest. The grain yield weight was obtained after removal of shrivelled and diseased seeds. Soil analysis was done at the onset of each trial. In each of the four blocks, soil samples were collected from a depth of 0 to 15 cm at the time of planting. The samples were bulked during the analysis for 2013A, whereas for 2013B, the soil samples for blocks where fertilizer was applied in the previous season were composited separately (Supplemental Table S3). The soil analyses were conducted at the National Agricultural Research Laboratory, Kawanda, for soil organic matter (Walkley–Black method), percentage N (micro-Kjeldahl method), available P, Ca, Mg, and K (Mehlich Double Acid method) following procedures by Okalebo et al. (2002). Rainfall data was collected using rain gauges installed at each trial site (Supplemental Table S4). Single rain gauge served a subcounty that had at least one or two experimental locations.

Data Analysis

Differences in disease severities and yield data across the six locations were examined using restricted maximum likelihood (REML) following a split plot design model in GenStat 14th edition (Payne et al., 2011). This model is suitable for unbalanced data and can assume fixed or random effects, thus providing accurate within environment error variance (Smith et al., 2005). Variety, management (DAP fertilizer or none), and their interactions constituted fixed factors whereas replication nested in location and seasons, and their associated interactions were considered as random variables.

The model used for the general analysis of variance over environments was:

$$Y_{ilkhj} = \mu + \alpha_{i(kl)} + \beta_l + \delta_k + (\beta\delta)_{lk} + \gamma_h + (\beta\gamma)_{lh} + (\delta\gamma)_{kh} + (\beta\delta\gamma)_{lkh} + (\alpha\gamma)_{i(kl)h} + \tau_j + (\beta\tau)_{lj} + (\delta\tau)_{kj} + (\gamma\tau)_{hj} + (\beta\delta\tau)_{lkj} + (\beta\gamma\tau)_{lhj} + (\delta\beta\gamma\tau)_{klhj} + \varepsilon_{ilkhj}$$

where

Y_{ilkhj} = trait performance for j th variety, in i th replication, under h th management level in k th location and l th season,

μ = the overall mean of the trials,

$\alpha_{i(kl)}$ = the effect of replication i nested in location k and season l ,

β_l = the effect of the l th season,

δ_k = the effect of the k th location,

$(\beta\delta)_{lk}$ = the interaction effect of the l th season by k th location

γ_h = the effect of the h th management,

$(\beta\gamma)_{lh}$ = the interaction effect of the l th season by h th management level combination,

$(\delta\gamma)_{kh}$ = the interaction effect of the k th location and h th management level combination,

$(\beta\delta\gamma)_{lkh}$ = the interaction of the l th season by k th location by h th management level combination,

$(\alpha\gamma)_{i(kl)h}$ = the interaction effects of the i th replication nested in k th location and l th season by h th management level combination,

τ_j = the effect of j th variety,

$(\beta\tau)_{lj}$ = the interaction effects of the l th season by j th variety combination,

$(\delta\tau)_{kj}$ = the interaction effect of the k th location by j th variety combination,

$(\gamma\tau)_{hj}$ = the interaction effect of the h th management level by j th variety combination,

$(\beta\delta\tau)_{lkj}$ = the interaction effect of the l th season by k th location by j th variety combination,

$(\beta\gamma\tau)_{lhj}$ = the interaction effect of the l th season by h th management level by j th variety combination,

$(\delta\beta\gamma\tau)_{klhj}$ = the interaction effect of the k th location by l th season by h th management level by j th variety combination

ε_{ilkhj} = error associated with genotype j , in i th replication in location k , fertilizer level h , and season.

Although the REML approach provided information on the magnitude of sources of variation, it offered limited insight to the pattern of interactions. Therefore, we used multivariate (AMMI and GGE) and univariate (Finlay and Wilkinson regression) approaches (Smith et al., 2005) to examine the variety $\times$ location $\times$ season and variety $\times$ location $\times$ management interaction effects for grain yield and disease data, respectively (Finlay and Wilkinson, 1963). Thus, AMMI and GGE were used to characterize the varieties and environments for grain yield performance in different seasons and fertilizer management levels. These analyses were performed using the in-built models within the pipeline of the breeding view in the Breeding Management System (Murray et al., 2014). The seasons and the management (DAP fertilizer or none) in each location was each considered as separate environments resulting into 24 environments. To test the appropriateness of the AMMI analysis, we computed the VEI signal. The measure of appropriateness of AMMI analysis depends on the amount of VEI signals rather than the significance levels of the interaction principal components (IPCA's) (Gauch, 2013). The VEI signal was obtained by subtracting the sum of squares of VEI from the sum of squares of VEI noise. The sum of squares of the VEI noise is a product of mean square for the pooled residual at entry mean basis and degree of freedom of VEI (Gauch, 2013). In the AMMI bi-plot, the interaction of the varieties was a product of the cultivars' interaction principal component and the environment scores. Cultivars and environments having the same or different signs on their specific principal component axes were designated by a positive and negative interaction, respectively. The varieties and environments showing large interactions were represented with IPCA scores greater than zero, and positive or negative. Those that exhibited PCA 1 close to zero had minimal interaction.

In the GGE, the season, location, and management levels were delineated into mega-environments, and superior varieties for specific mega-environments were identified. For accuracy in the representation of the variety and environment coordinates, we used a symmetrical scaling model to generate the "Which won where" GGE bi-plot for grain yield for the VEI and VMI data. Genotype scaling model was used in generating the comparison GGE bi-plot for identification of varieties that combine

stability and high grain yield performance in the different environments (VEI) (Yan and Tinker, 2006). Furthermore, box and whisker plots were used to compare the variety performance for grain yield in the different fertilizer management regimes (VMI). The variety $\times$ environment data from Finlay and Wilkinson analysis was summarized by the regression coefficient (β), mean disease severity over all varieties in the environment, each variety's mean severity performance across environments and mean squared deviation from regression. The characterization of sensitivity levels followed Finlay and Wilkinson (1963), where sensitivity value (β) = 1 represented variety consistent in resistance levels, $\beta > 1$ for variety very sensitive to difference in disease pressure, $\beta < 1$ for variety less sensitive to difference in disease pressure. To compare differences in mean disease severity among the varieties, the regression coefficients (response) were assessed against environments disease severity means, a quantitative measure of environment quality. A mean squared deviation was used to judge the degree of linear response in the prediction of the VEI effects.

To determine the phenotypic and genotypic correlations among trait values for each district and season combination, we estimated the variance and covariance using multivariate analysis of covariance (MANCOVA) in GenStat 14th edition (Payne et al., 2011), with disease and yield data averaged across replications and fertilizer levels. Grain yield, plant height, plant vigor, the number of pods per plant, and disease severity of CBB, ALS, CBR, and ANTP were the traits considered. The genotypic and phenotypic correlation coefficients for all possible pairs of trait combinations over the four environments in Hoima and the two environments in Rakai were computed in Microsoft Excel using Kwon and Torrie (1964) formula. The genotypic correlations were obtained by dividing the

variance component for co-variation between traits by the square root of the variance component of variance between the traits under consideration.

RESULTS

General Analysis of Variance on Grain Yield and Disease Severity

There was a significant genotypic difference in the reaction to ALS, CBR, CBB, and grain yield when considered across all the other factors (season, location, and management, Table 1). In addition, there was a significant variety $\times$ location $\times$ season interaction effect for reaction to ALS, CBR, and for grain yield (Table 1). Furthermore, the comparison of selection for varietal reaction to ALS, CBR, and CBB across location was significantly affected by the variety $\times$ location $\times$ season $\times$ management interaction.

AMMI and GGE Bi-plot Analysis

The AMMI model showed that the VEI sum of squares signal (4210,707) was three times larger than VEI noise sum of squares (1310,822) and almost equal the genotypic sum of squares. The interaction principal component analysis IPCA 1, IPCA 2, and IPCA 3 were highly significant (Table 2). The first IPCA captured 73.2% of the total interaction sum of squares in 16% of the interaction degrees of freedom. The second IPCA explained 10.5% of the total interaction sum of squares in 14% of the interaction degrees of freedom and the third IPCA captured 9.1% of the interaction sum of squares and 13% of the interaction degrees of freedom. IPCA 4 to IPCA 9 captured in descending order percent sum of squares of less than 2.9% of the total interaction sum of squares. In summary, IPCA 1 (sum of squares = 4043,928) explained 96.0% of

Table 1. Mean squares from analysis of variance to diseases reaction and grain yield performance of 15 common bean varieties across location, season, and fertilizer management.

Source of variation	df	ALS†	CBR	CBB	Grain yield kg ha ⁻¹
Location	5	17.76	19.16	21.81	20,123,458.0
Season	1	48.36	149.12**	25.77	65,132,305.0
Management	1	0.87	0.37	4.64*	768,977.0
Location $\times$ Season	5	12.46*	9.05***	24.77**	37,977,224.0***
Location $\times$ Management	5	3.57	0.75	1.80	670,151.0
Season $\times$ Management	1	3.66	4.57**	0.55	72,167.0
Replication/(Location, Season)	12	2.94	0.74	3.20	379,005.0
Rep/(Location, Season) $\times$ Management	12	1.95***	0.44	1.28***	476,404.0**
Variety	14	7.65***	1.18**	5.72***	1,388,927.5*
Variety $\times$ Location	70	0.87	1.35	0.90	345,744.0
Variety $\times$ Season	14	1.59	7.00***	1.58	1,426,536.0***
Variety $\times$ Management	14	1.50	1.15*	1.00	381,508.0
Variety $\times$ Location $\times$ Season	70	1.30**	0.99*	1.24	326,832.0**
Variety $\times$ Location $\times$ Management	70	0.53	0.62	0.90	176,239.0
Variety $\times$ Season $\times$ Management	14	0.46	0.27	0.83	259,317.0
Location $\times$ Season $\times$ Management	5	0.67	1.30	1.42	238,647.0
Variety $\times$ Location $\times$ Season $\times$ Management	70	0.66***	0.59***	0.86***	156,605.0
Residual	334	0.30	0.30	0.44	204,284.0

* Significance at $p \leq 0.05$.

** Significance at $p \leq 0.01$.

*** Significance at $p \leq 0.001$.

† ALSL = Angular leaf spot on the leaf, CBR = common bean rust, CBB = common bacterial blight disease.

Table 2. Additive main effects and multiplicative interaction effects ANOVA for variety grain yield averaged across fertilizer treatments in two seasons of 2013.

Source	df	SS	MS	Percent SS explained	Percent df explained
Total	179	105,791,081	591,012***		
Variety	14	11,900,355	850,025***	11.2	
Environment	11	88,369,197	8,033,563***	83.5	
Interactions	154	5,521,529	35,854***	5.2	
IPCA 1	24	4,043,928	168,497***	73.2	15.6
IPCA 2	22	581,608	26,437***	10.5	14.3
IPCA 3	20	503,689	25,184***	9.1	13.0
IPCA 4	18	154,950	8,608***	2.8	11.7
IPCA 5	16	82,611	5,163***	1.5	10.4
IPCA 6	14	66,876	4,777***	1.2	9.1
IPCA 7	12	46,790	3,899***	0.8	7.8
IPCA 8	10	26,152	2,615**	0.5	6.5
IPCA 9	8	10,941	1,368*	0.2	5.2
Residuals	10	3,983	398		
Pooled residuals at entry mean basis	336	2,859,976	8,512		

† SS = sum of squares, MS = mean squares.

the total VE1 signal sum of squares meanwhile the remaining 4% was absorbed in the IPCA 2 axis.

Seasonal Effects on Grain Yield in Different Environments

We found a highly significant difference in grain yield among the 15 varieties and across the 12 environments (AMMI analysis of variance, $P \leq 0.001$, Table 2). Environment, variety, and variety $\times$ environment interaction accounted for 83.5, 11.2, and 5.2% of the total sum of square effects, respectively. The visual display of the variety $\times$ environment relationships (Fig. 1) showed useful characterization of the varieties and environments. Grain yield of above 1100 Kg ha⁻¹ were recorded in environment Gosola 2013B, Kyakamese (2013B and 2013A), and Mpalangasi 2013A. Higher grain yield within a location were registered in Gosola 2013B and Butyamba 2013B in the second season when compared to grain yield in 2013A (first season) (Fig. 1). The IPCA 1 showed the nature of the VEI on variety performance and environments. Varieties NABE 21, Masindi Yellow Long, NABE 15, KAT B1, NABE 17, KATX 69, Farmers' variety associated with environments of 2013A registered positive IPCA 1 scores. Varieties CAL143, NABE 2, NABE 14, ROBA 1, CAL96, RWR 719, and KAT B9 associated with environments of 2013B exhibited negative IPCA 1 scores (Fig. 1). AMMI 2 revealed clearer differentiation for the most interacting environments and varieties (figure not shown). Varieties NABE 2, RWR 719, and ROBA1 showed the highest negative IPCA scores and were regarded as the most unstable in grain yield performance. Farmers' variety and KATX 69 (IPCA 1 scores) and Farmers' variety and KATX 56 (IPCA 2 scores) showed the least IPCA scores and were regarded as the most stable in grain yield performance across environments (both AMMI 1 and AMMI 2 bi-plots). Farmers' variety and KATX69 were associated with average grain yield performances (Fig. 2). Varieties ROBA1, RWR719, and NABE2 were stable and high yielding across environments as observed from their close association to the "ideal" genotype and the average environment coordinate (AEC) abscissa (Yan and Tinker, 2006).

Genotype and genotype $\times$ environment methods are useful for characterization of stable genotypes, mega-environments, and deployment of the winning genotypes to specific subgroups of the environments (Yan and Tinker, 2006). Based on the GGE analysis, the PC1 and PC2 together explained 91.7% (PC1 = 72.9% and PC2 = 18.8%) of the total sum of squares due to variety and VEIs (Fig. 3). All the environments were within the positive PC1 scores, although, the interactions among varieties were observed between environments in 2013A and 2013B. The seasons in the same location were mostly clustered in different mega-environments. Farmers' variety and KATX 69 were the closest to the center of origin of environment vectors and were regarded as the most stable performers in the different environments. The GGE bi-plot identified two mega-environments, varieties ROBA 1, NABE 2, and CAL 143 were the winning varieties in mega-environment I (2013B environments), and variety Masindi Yellow Long won

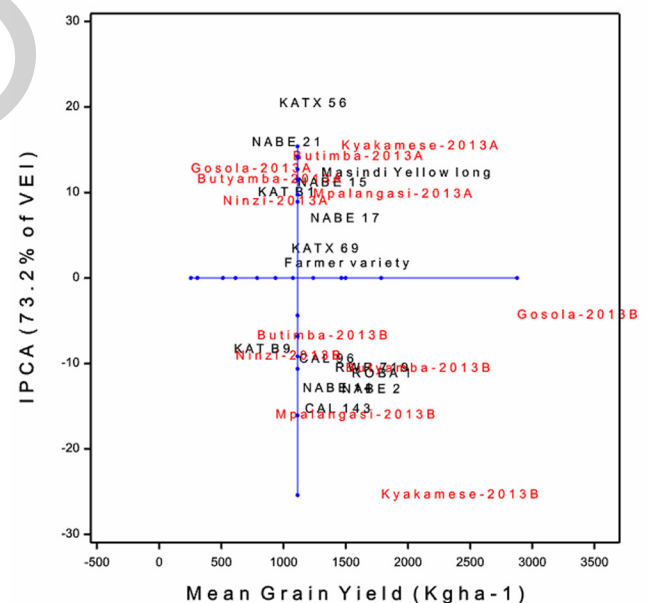


Fig. 1. Additive main effects and multiplicative interaction effects (AMMI)I bi-plot for grain yield of 15 bean varieties averaged across seasons in 12 environments.

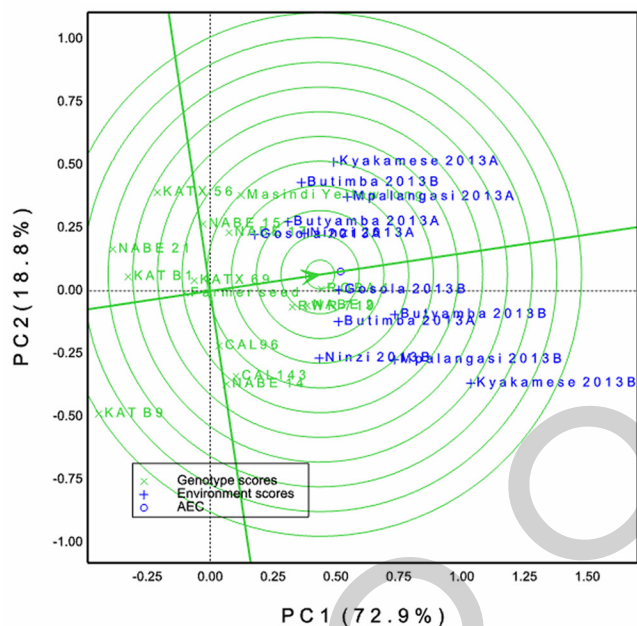


Fig. 2. Comparison bi-plot for grain yield of 15 bean varieties averaged across seasons. Average environment coordinates (AEC) abscissa close to AEC ordinates indicate that the variety is average in performance for grain yield.

in mega-environment II (2013A environments). Environments Ninzi 2013A and Mpalangasi 2013A shared winning varieties with mega-environment II. However, the performance of Masindi Yellow Long was greater than for NABE2 and ROBA1 because the equality line separating the mega-environment II and I are closest to Masindi Yellow Long than to NABE2 or ROBA1. Gosola-2013B with the least PC1 scores and moderate environmental vector length was the most representative environment but moderate in discriminating varietal performance. Environments Kyakamese (2013A and 2013B) and Mpalangasi 2013B were the most discriminating of all environments as shown by their long environment vectors.

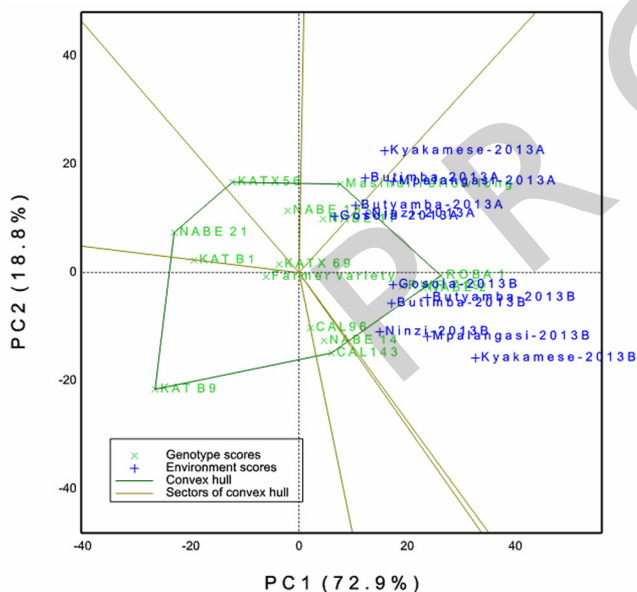


Fig. 3. Genotype and genotype $\times$ environment interaction (GGE) bi-plot for grain yield of 15 bean varieties averaged across seasons.

Effects of Management on Grain Yield in Different Environments

The variety $\times$ environment $\times$ management (VEM) noise sum of square was larger than VEM signal sum of squares and thus AMMI analysis was not recommended. For this reason, the performance for grain yield of the varieties under different management was assessed using boxplot (Fig. 4) and the GGE bi-plot (Fig. 5). Mpalangasi and Butyamba in Hoima district registered higher average grain yield where DAP fertilizer was applied. Kyakamese, Gosola, Butimba, and Ninzi had similar grain yields under both DAP and No-DAP (Fig. 4). Differences in grain yield among the varieties were best observed in Kyakamese, Butyamba, and Mpalangasi environments under both managements as shown by the long interquartile range of the box (Fig. 4).

In the GGE bi-plot, both PC1 and PC2 explained 97.1% (PC1 = 90.5% and PC2 = 6.6%) of the total variation due to variety and VEI (Fig. 5). The environments of DAP and No-DAP in a location were clustered in different mega-environments. Two mega-environments were identified with varieties NABE2 and NABE14 being superior in Mega-environment I (No-DAP environments), with variety NABE 2 and ROBA1 winning in mega-environment II (DAP environments). In location Gosola where minimal management benefits were realized, varieties NABE15, NABE17, CAL96, and ROBA1 registered higher than average grain yields as observed from the angle between the varietal vectors to the Gosola DAP vector being lesser than 45° . According to Yan and Tinker (2006), variety to environment vector angles of lesser than 45° imply that the variety performs better than average, whereas an angle equal to 90° imply that the variety performs near to average. However, if the varietal vector angle is greater than 90° , the variety performs below average of the environment being considered. In location Ninzi, the response of the varieties to fertilizer management was observed on most of the varieties except NABE14, Farmers' variety, NABE2, and NABE21. For these varieties, the varieties' vector angles to the Ninzi No-DAP environmental vector were less than that from the Ninzi DAP environment vectors.

Sensitivity of the Varieties to Differences in Diseases Pressures in the Twelve Environments

There were significant genotypic differences for reaction to ALS, CBR, and CBB across the 12 environments (Finlay and Wilkinson analysis of variance, $P \leq 0.001$, Table 3). The sensitivity values among the varieties were significant ($P \leq 0.05$) for reaction to ALS, CBR ($P \leq 0.001$), and CBB ($P \leq 0.05$) disease. However, the average mean severities scores for reactions of the varieties to the diseases in the different environments (Table 4) were generally high in season 2013B environments for the CBR and ALS. The highest average severity for ALS and CBB were registered in Ninzi 2013B. The varieties KAT B9 and KAT B1, KATX 69, KATX 56, Masindi Yellow Long, and Farmers' variety recorded sensitivity values of above 1.0 for reaction to CBB, ALS, and CBR (Table 5). These varieties also registered high mean severities for the diseases over location and seasons. Varieties RWR 719, ROBA 1, and NABE 2 showed the least mean severities to ALS, CBR, and CBB over the environments (Table 5), and showed low sensitivity to differences in disease pressure in the different environments.

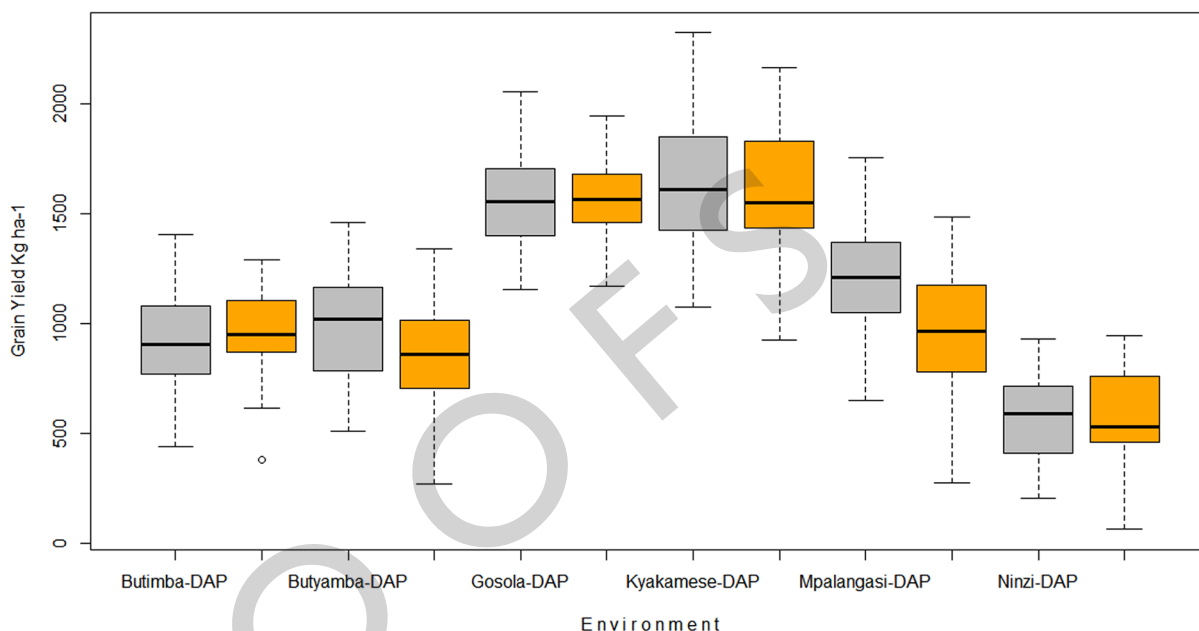


Fig. 4. Boxplot for grain yield for 15 bean varieties averaged over seasons under two management levels in six locations. Di-ammonium phosphate (DAP) fertilizer management is represented by Gray boxplots whereas the non-DAP fertilizer management by orange boxplots.

Phenotypic and Genotypic Correlations among Traits Studied

Genotypic correlations were generally higher than their corresponding phenotypic correlations between most of the pairs of the traits, in Hoima and Rakai districts in both seasons (Tables 6 and 7). The mean genotypic correlation values between the traits in season A in Hoima and Rakai were generally low and nonsignificant. However, there were negative and significant genotypic correlations between the mean values of ALS and mean values for plant height, as well as between ALS and the number of pods per plant in both districts (Table 6). In 2013B, the genotypic correlations among traits in Hoima

were generally higher than that for the Rakai district (Table 7). In both Rakai and Hoima in season B, the mean values of growth parameters (plant height, number of pods per plant, plant vigor) were strongly and positively correlated with each other and with grain yield (Table 7). Negative correlations were observed between grain yield and the mean severities for ALS, ANTP, and CBR (Table 7). With respect to varietal reaction to diseases, there were mostly moderate and strong positive genotypic correlations among the mean severity values for the different pairs of diseases in Hoima (season A) and in both districts (season B), respectively.

DISCUSSION

The 15 common bean varieties showed different reactions to diseases and performance for grain yield across seasons and fertilizer management, suggesting that it is possible to select varieties with resistance to diseases and high grain yield production over the environments. However, the selections of some of the varieties for their reaction to ALS and CBR and their grain yield performance were affected by the significant variety $\times$ location $\times$ season interaction, implying that each variety performs differently and reacts differently to diseases in different locations and seasons. Similar results were found in Kenya where a collection of landraces and elite common bean genotypes showed different reactions to ALS and grain yield in different environments and

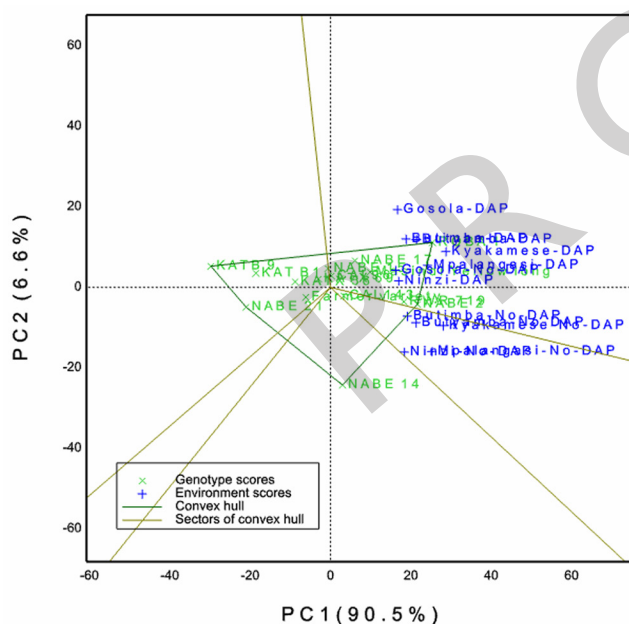


Table 4. Average score for disease reactions of the 15 genotypes in four locations in Hoima and two locations in Rakai district in 2013 A and 2013B.

District	Environments	ALS†			CBR			CBB		
		Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
Hoima	Butimba-2013A	2.8	1.7	4.1	2.1	1.1	3.1	4.2	3.1	5.9
	Butyamba-2013A	3.0	1.9	4.5	2.2	1.1	3.4	2.9	1.9	4.5
	Kyakamese-2013A	2.0	1.3	2.6	1.7	1.0	2.1	2.7	2.0	3.2
	Mpalangasi-2013A	2.0	1.2	2.5	1.5	1.1	3.0	2.3	1.6	3.1
	Butimba-2013B	2.6	2.0	3.5	2.7	1.3	5.1	2.6	2.0	3.6
	Butyamba-2013B	2.7	2.0	3.4	2.6	1.1	4.8	2.5	2.0	3.2
	Kyakamese-2013B	2.5	1.7	3.5	2.3	1.0	4.1	2.3	1.5	3.4
	Mpalangasi-2013B	3.2	2.1	5.0	3.3	1.7	5.2	2.3	1.8	3.0
Rakai	Gosola-2013A	2.5	1.8	3.3	1.1	0.9	1.6	3.4	2.4	4.7
	Ninzi-2013A	2.8	2.2	3.3	1.1	0.9	1.4	2.6	2.0	3.8
	Gosola-2013B	3.3	2.2	4.1	2.1	1.1	3.9	2.5	2.0	3.2
	Ninzi-2013B	3.9	2.9	5.1	2.1	1.0	3.3	3.6	2.8	4.4
	Mean	2.8	1.9	3.7	2.1	1.1	3.4	2.8	2.1	3.8
	p value	1E-05			6E-09			1E-07		
	LSD	0.7			1.1			0.6		
	CV%	20.6			26.1			11.5		

† ALS = Angular leaf spot, CBR = common bean rust, CBB = common bacterial blight.

years (Njoki, 2013). The bi-plot from AMMI allowed us to visually compare variety, environment (location, season), and interaction effects. A large VEI signal that almost equaled the genotypic sum of square found in this study indicated that AMMI was appropriate for analyzing our dataset. In addition, IPCA 1 (96.0%) explained the largest proportions of the VEI signal sum of squares, showing the ability of IPCA 1 to adequately predict useful patterns associated with the varietal adaptations. However, the remaining 4% VEI signal absorbed in the IPCA 2 axis indicated the most interacting varieties, suggesting that supplementary information for the patterns of varietal adaptation could be extracted from IPCA 2. The rest of the six IPCAs, retained sequential genotype $\times$ environment interaction noise

sum of squares that were not relevant in the varietal recommendation (Gauch, 2013).

Results of AMMI analysis indicated that the 12 environments differed in their influence on common bean grain yield, contributing 83.5% to the total sum of squares compared to the variety (11.2%) and VEI effects (5.2%). Season contributed most to the environment response, followed by the location $\times$ season interaction. This suggests that the most important thing farmers can do to improve yield is to choose improved varieties that are stable across a range of weather patterns and soil types. These results corroborate with similar results reported in common bean yield in Malawi (Chataika et al., 2010; Mwale et al., 2008), where environment contributed the largest influence on grain yield.

Table 5. Sensitivity (β), mean severity score and mean square deviation for reaction of 15 bean varieties averaged across two fertilizer levels and seasons.

Variety	CBB†			ALS			CBR		
	β	Mean	Mean square deviation	β	Mean	Mean square deviation	β	Mean	Mean square deviation
CAL143	1.50	2.5	0.08	0.42	2.1	0.09	0.35	1.8	0.30
CAL96 (K132)	1.02	2.5	0.13	0.80	2.8	0.20	0.50	1.9	0.32
Farmer seed	1.68	3.3	0.13	0.99	3.1	0.22	1.23	2.4	0.19
KATBI	1.25	3.3	0.20	1.53	3.6	0.21	2.02	3.2	0.53
KATB9	0.30	2.7	0.35	1.69	3.4	0.28	2.39	2.9	0.40
KATX69	1.22	2.9	0.09	0.96	2.9	0.16	1.63	2.5	0.30
KATX56	1.18	2.9	0.28	0.94	3.2	0.18	1.09	2.3	0.16
Masindi Yellow long	1.40	3.7	0.33	1.29	3.1	0.11	1.65	2.5	0.16
NABE14	0.70	2.4	0.24	0.37	2.2	0.18	0.96	1.9	0.15
NABE15	0.79	2.6	0.24	1.08	2.6	0.10	1.08	2.1	0.18
NABE17	0.76	2.9	0.25	1.36	2.9	0.20	0.41	1.8	0.1
NABE2	0.77	2.4	0.25	0.52	2.1	0.09	0.31	1.3	0.13
NABE21	0.97	2.7	0.15	1.09	2.8	0.06	0.63	2.0	0.14
ROBA1	0.63	2.5	0.19	0.89	2.4	0.51	0.24	1.2	0.07
RWR719	0.70	2.3	0.32	0.96	2.2	0.49	0.16	1.4	0.08
Stand error of the mean	0.271	0.14		0.26	0.14		0.21	0.14	

† CBB—Common bacterial blight, ALS—angular leafspot, CBR—common bean rust, β —sensitivity values.

Table 6. Phenotypic and genotypic correlation coefficients for diseases reaction and agronomic traits for 15 common bean genotypes performance averaged across locations in Hoima 2013A and Rakai 2013A.

Traits	ANTP†		CBR		CBB		Plant vigor		Plant height		Pods plant ⁻¹		Grain yield	
	Hoima	Rakai	Hoima	Rakai	Hoima	Rakai	Hoima	Rakai	Hoima	Rakai	Hoima	Rakai	Hoima	Rakai
ALS	0.60 (0.49)‡		0.84 (0.69)	0.71 (0.57)	0.84 (0.76)	-0.80 (-0.73)	-0.82 (-0.58)	-0.74 (-0.68)	-0.53 (-0.48)	-0.36 (-0.23)	-0.32 (-0.28)	-0.44 (-0.30)		
ANTP		0.00	0.67 (0.42)		0.56 (0.51)	-0.46 (-0.40)	-0.58 (-0.58)	-0.22 (-0.19)	-0.36 (-0.32)		0.27 (-0.23)			
CBR					0.81 (0.62)	-0.77 (-0.63)		-0.81 (-0.67)	-0.65 (-0.53)		-0.46 (-0.36)			
CBB						-0.50 (-0.42)	-0.58 (-0.22)	-0.19 (-0.46)	-0.29 (-0.25)	0.05 (0.13)	0.04 (0.05)	0.32 (0.37)		
Plant vigor								0.80 (0.78)	0.45 (0.44)	-0.17 (0.00)	0.62 (0.60)	0.45 (0.47)		
Plant height									0.73 (0.73)	0.53 (0.55)	0.78 (0.77)	0.71 (0.70)		
Pods plant ⁻¹											0.65 (0.64)	0.54 (0.57)		

† ANTP = anthracnose on pod, CBR = common bean rust, CBB = common bacterial blight, ALS = angular leaf spot on leaf.

‡ Phenotypic correlation are in the parentheses. Phenotypic and genotypic correlations of 0.514, 0.641 and 0.760 are necessary to be significant at 5, 1, and 0.1%, respectively.

Season B was good for grain yield production compared to season A in most locations. The probable explanation for this pattern is that, sufficient and well-distributed rainfall was received in season B than in season A (Supplemental Table S4). According to Manjeru et al. (2007), sufficient water availability results in good pod filling and increased grain yield. Thus, the high rainfall amounts received could have contributed to the high grain yields that were recorded in the environments of Gosola 2013B, Kyakamese 2013B, Butyamba 2013B, and Ninzi 2013B (Fig. 1). In this study, the pod formation and pod-filling growth stage coincided with periods of adequate rains from November through early December which almost certainly contributed to the increased grain weight observed. Pod formation and pod-filling stage are among the most critical growth stage for common bean. Furthermore, the high grain yields in both Kyakamese and Mpalangasi could also be due to their location in the same subcounty and thus experienced similar biophysical and biochemical soil properties. Therefore, for both these locations, the good soil fertility and rainfall pattern could have contributed to the high grain yields observed in those areas. The generally low grain yield that was registered in the location Ninzi could be attributed to the low soil fertility and low rainfall amounts that were recorded in the Rakai district. Compared to the other locations, the percent organic matter and N, Ca (mg kg⁻¹), Mg (mg kg⁻¹) and K (mg kg⁻¹) in Ninzi were the least in both seasons.

In this study, we also show that cultivars NABE2, RWR719, and ROBA1 were unstable in grain weight in the different seasons. These three varieties were positively strongly correlated to environments in Kyakamese (2013A and 2013B), Butyamba in 2013B, and Mpalangasi (2013A and 2013B). However, they showed negative correlations for the 2013A environments. This finding indicates that these varieties are responsive to the difference in environments (seasons and locations). Therefore, better benefits could be attained when they are grown in specific environments. Bernardo (2010) reported that genotypes respond to differences in soil chemical and biophysical conditions present in the different environments. Varieties NABE2, RWR719, and ROBA1 were responsive to the favorable combinations of good organic matter, P content, and reliable rainfall (Supplemental Table S3 and Table 4), that characterized the environments of Kyakamese, Butyamba in 2013B, and Mpalangasi. As shown by the comparison bi-plot (Fig. 2), these varieties displayed dynamic stability in mean grain yield performance. Due to their general adaptation, they can be grown in all environments, but highest grain yield production could be achieved in high-yielding environments (Kyakamese 2013A and 2013B, Butyamba in 2013B, and Mpalangasi 2013A and 2013B). The stability in these varieties being in the order of RWR719 > NABE2 > ROBA1 is an indication that stable grain yield in bean production in those environments could be achieved by growing variety RWR719. A possible reason for the high stability in grain yield for varieties RWR719, NABE2, and ROBA1 in different environments could be attributed to a semi-climbing growth habit. Several previous studies have shown that climbing beans exhibit higher grain yield and stability over a wide range of environments compared to the bush type (White et al., 1992; Beaver et al., 1996). These findings, as well as our study, demonstrate that varieties with climbing

Table 7. Phenotypic and genotypic correlation coefficients for diseases reaction and agronomic traits for 15 common bean varieties performance averaged across locations in Hoima 2013B and Rakai 2013B.

Traits	ANTPT†		CBR		CBB		Plant vigor		Plant height		Pods plant ⁻¹		Grain yield	
	Hoima	Rakai	Hoima	Rakai	Hoima	Rakai	Hoima	Rakai	Hoima	Rakai	Hoima	Rakai	Hoima	Rakai
ALS	0.83 (0.73)‡	0.68 (0.67)	0.92 (0.87)	1.11 (0.70)	0.88 (0.81)	0.96 (0.75)	-0.97 (-0.92)	-0.83 (-0.75)	-0.83 (-0.78)	-0.61 (-0.54)	-0.57 (-0.55)	-0.58 (-0.55)	-0.80 (-0.77)	-0.74 (-0.65)
ANTP			0.61 (0.50)	0.96 (0.72)	0.85 (0.67)	0.71 (0.55)	-1.10 (-0.89)	-0.61 (-0.55)	-0.77 (-0.61)	-0.15 (-0.19)	-0.61 (-0.50)	-0.50 (-0.38)	-0.89 (-0.72)	-0.16 (-0.35)
CBR					0.80 (0.74)	0.96 (0.72)	-0.88 (-0.86)	-0.67 (-0.58)	-0.85 (-0.84)	-0.81 (-0.68)	-0.73 (-0.72)	-0.93 (-0.71)	-0.79 (-0.77)	-1.07 (-0.61)
CBB							-0.70 (-0.67)	-0.87 (-0.75)	-0.51 (-0.49)	-0.48 (-0.45)	-0.54 (-0.51)	-0.83 (-0.69)	-0.58 (-0.54)	-0.63 (-0.45)
Plant vigor									0.90 (0.89)	0.67 (0.70)	0.77 (0.76)	0.49 (0.51)	0.94 (0.93)	0.84 (0.78)
Plant height											0.80 (0.79)	0.80 (0.75)	0.91 (0.88)	0.95 (0.78)
Pods plant ⁻¹													0.80 (0.78)	0.73 (0.64)

† ANTP = anthracnose on pod, CBR = common bean rust, CBB = common bacterial blight, ALS = angular leaf spot on leaf.

‡ Phenotypic correlation are in the parentheses. Phenotypic and genotypic correlations of 0.514, 0.641 and 0.760 are necessary to be significant at 5, 1, and 0.1%, respectively.

growth habits improve their stability in response to differences in conditions in the different environments by adjusting plant height and number of nodes, flowers, and pods per plant.

Farmers' variety and variety KATX 69 that was bred for drought tolerance in Kenya were the most stable in performance for grain yield across seasons (shown by AMMI and GGE bi-plot) and management (GGE bi-plot). According to Becker and Leon (1988), a stable variety is that whose performance remained unchanged irrespective of any variation of the environmental conditions. Therefore, these two varieties could be grown with or without mineral fertilizer and in either season A or season B in both Hoima and Rakai districts. The high stability of Farmers' variety was associated with better adaptation to the environmental conditions of Hoima and Rakai districts suggesting that they have desirable alleles that contribute to its adaptability to changing environmental conditions. Previous studies on bean (Gómez, 2004) and cassava (Turyagyenda et al., 2012) have indicated that local landraces have unique alleles that confer adaptations to local conditions. The high stability of KATX 69 demonstrates the potential of an introduced bean variety in adapting to new environmental conditions. Becker and Leon (1988) reported that improvement against major constraints can result in varietal stability.

In the GGE analysis, bi-plot explained 94.3 and 97.1% of the total sum of squares due to variety and VEI in the seasonal and fertilizer levels, respectively. Due to the singular values being utilized in descending order in the decomposition of a larger variety × environment matrix, PC1 and PC2 explained the most important patterns of the variety × environment data matrix and the remaining PCs' were considered as noise (Yan and Tinker, 2006). The environments for the seasons and fertilizer levels were all within the PC1 scores. The environments being all within positive PC1 scores implied that minimal VEI was experienced by the varieties (Crossa et al., 2002), although, the highest interactions among varieties were observed in Kyakamese and Mpalangasi in the 2013A and 2013B. These environments showed the largest angles, indicating low correlation in the mean yield performance of varieties in these different seasons of the locations (Yan and Tinker, 2006). The seasons and the management levels (fertilizer levels) in the same location, being clustered in different mega-environment implied that some of the varieties were inconsistent in their grain yield in the different seasons and management levels within the same location. Tolessa and Gela (2014) reported similar results, where two different years in Ethiopia were grouped in different mega-environments for the same location. In particular, better grain weight in common bean could be attained by recommendation of different varieties for growing in different seasons and under the different management levels. Season B and season A effects may be repeatable given empirical reports suggesting season B as being longer and reliable compared to season A in the amounts of rainfall received (Caffrey et al., 2013; Mwongera et al., 2014; Mubiru et al., 2015). If so, the level of interaction between season and variety may be large enough to target varieties for shorter and longer seasons separately.

The bi-plot identified two mega-environments for the seasonal and the management (fertilizer level) environments. These imply that the winning varieties could be selected and

deployed for each different season and management. A winning or superior variety that is adapted to the subgroups of environment is one that occurs at the vertices of the polygon (Yan and Tinker, 2006). Our results show that the vertex varieties NABE 2 and Masindi Yellow Long could be recommended for growing in season B and season A, respectively. NABE 2, ROBA 1, and NABE 14 can be recommended for growing under no-DAP management and DAP management, respectively. Additionally, given the close association of environments of 2013A to the equality line (Fig. 3), both NABE 2 and Masindi Yellow long could be grown in the first season. However, since the equality line was closest to Masindi Yellow Long than to NABE 2, it is implied that higher grain yield of common bean could be achieved by growing Masindi Yellow Long in the first season rather than NABE2. Also, the fact that the varieties registered PC1 score on the right of the PC1 axis shows that their grain yields were above the environmental means (Yan and Kang, 2002). Furthermore, varieties NABE17, NABE15, Masindi Yellow Long, CAL96, and ROBA1 had small variety vector angles with the DAP environment, implying that their grain yields might be increased by fertilizer or other soil amendments. For varieties NABE14, RWR719, NABE2, and NABE21, the use of fertilizer might not be realized given that the variety vectors to the No-DAP environment vector were close to each other. According to Yan and Tinker (2006), the angle between specific environments to genotype vector can be used in describing the genotype performance. Regarding wide adaptation, Farmers' variety, CAL143, KATX 56, and KATX69 can be recommended for growing with or without fertilizer management. This is supported by these varieties being closest to the center of origin of the GGE bi-plot and thus they exhibited minimal variation in their performance for grain yield under the different management in the different locations.

Kyakamese (2013A and 2013B) and Mpalangasi 2013B with the longest vectors were the most discriminating environments. These environments can be recommended for selecting varieties or genotypes that are adapted to the environmental conditions of both seasons in the areas with climatic conditions similar to that of Hoima and Rakai district. According to Yan and Tinker (2006), environments' discriminating ability and representativeness are measured by the length of their environment vector and the degree of closeness to PC 2 axis and/or the average environment axis, respectively. The location Kyakamese and Mpalangasi had very fertile soils and received sufficient and well-distributed rainfall that can enhance varietal differentiation. Gosola 2013B showed the least interaction and moderate discriminating ability and therefore was the most representative environment for the selection of genotypes that are adapted to a wide range of environments. However, location Gosola would require improved management like fertilizer application for better varietal differentiation.

The sensitivity of genotypes to differences in the quality of the environments contributes to their adaptability. In the present study, there was generally higher disease pressure registered in the second season (2013B) than in the first season (2013A). The high disease severity observed in the second season could be attributed to the build-up of disease from the previous seasons since the trials were conducted from the same fields.

Diseases are reported to survive in crop residues or volunteer plants resulting in their early establishment in the bean crop in the subsequent season (Kimber et al., 2016). Furthermore, the availability of adequate moisture in the second season could have provided a favorable environment for the development of diseases. Varieties KATB9 and KATB1, KATX69, KATX56, and landraces Masindi Yellow Long and Farmers' variety were highly sensitive to differences in disease pressure for ALS, CBR, and CBB in the different environments. The high sensitivities of these genotypes coupled with high mean severity over environments suggest that these varieties were susceptible to small changes in disease pressure. The Katumani bean varieties, in particular, were bred for drought tolerance in a low rainfall environment and therefore, it is possible that during the breeding process, low priority was given to disease resistance at the different stages of selection. Masindi Yellow Long and Farmers' variety are also regarded as susceptible to diseases. Like in our study, Njoki (2013) also found that the majority of collection of landraces from East African countries was susceptible to ALS disease. The substantial damage due to diseases registered on the leaves of varieties KATB1, KATX56, KATB9, Masindi Yellow Long, and Farmers' variety could have contributed to reduced photosynthetic rate (see also Junior et al., 2001) and affected pod formation, and pod filling. Varieties RWR719, ROBA1, and NABE2 showed the least severities for ALS, CBR, and CBB across environments and sensitivity to differences in disease pressure in the different environments, implying that the varieties were resistant to the diseases.

Understanding of the interrelationships among traits is important in designing an effective strategy for varietal selection for crop improvement. The generally high genotypic correlation coefficient over phenotypic correlations observed in this study suggests that VEI effects less influenced the correlations among traits considered. Our finding corroborates those of Kwon and Torrie (1964) on selected soybean [*Glycine max* (L.) Merr.] crosses where genotypic correlations were higher than phenotypic correlations among the yield component traits. However, the generally low genotypic correlations observed in season A in Rakai compared to seasons A and B in Hoima, respectively, could be due to the influence of the environments on traits expression. Grain yield production and growth parameters were suppressed by the relatively lower rainfall received in Rakai and in season A in Hoima and Rakai district. Experiments conducted under moisture stress studies have been associated with limited genotypic differences and weak genotypic correlations among yield and yield related traits (Ramirez-Vallejo and Kelly, 1998).

The strong and positive genotypic correlations observed between the number of pods per plant and grain yield, and plant height and grain yield in Hoima and Rakai in both seasons suggest that plant height and number of pods per plant contributed to the grain yield of the varieties. The observed relationships between grain yield and the number of pods per plant highlight the possibility of indirect selection for grain yield using pod load for increase grain production. However, in season B, increased production in both districts would require selection of varieties with resistance to the diseases due to the strong and negative genotypic correlations observed with ANTP, ALS, and CBR disease. Furthermore, the negative

genotypic correlations between the disease severity and grain yield suggest that variety that registered low grain yield had high severities for diseases. This finding is consistent with those of Pamela et al. (2014) who reported a reduction in grain yields of common bean due to infection by ALS and CBR in central Uganda. By contrast, however, Njoki (2013) found a weak and nonsignificant correlation between ALS and grain yield in Kenya. In his study, resistant genotypes registered low grain yields and the moderate resistant registered moderate grain yields. The generally high positive genotypic correlations between pairs of the diseases in season B in Hoima and Rakai district is an indication that majority of the varieties were co-infected with a combination of the different diseases. This re-affirms previous observations that under field conditions several bean disease isolates could co-infect susceptible genotypes (Pamela et al., 2014).

To conclude, we showed that variation in the rainfall, soil fertility, and disease pressure influence the yields, stability, and nature of VEI experienced by the common bean varieties. Farmers' variety, KATX69, and KATX56 were stable in seed yield across environments whereas, varieties NABE2, ROBA1, RWR719, and Masindi Yellow Long displayed better responses to specific mega-environments. The landrace Masindi Yellow Long and farmers' variety, and Katumani varieties KATX 69 and KATX 56 were susceptible to ALS, CBR, and CBB, and therefore will require improvement for resistance to the diseases for durable stability. Crossing the landraces and varieties (KATX 69 and KATX 56) with the varieties NABE2, RWR719, and ROBA1 that were responsive in grain yield and resistant to the diseases should contribute to varieties that are resistant and higher yielding, and adaptive to wet and drier environments.

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SUPPLEMENTAL MATERIAL

Table S1. Study sites of the experiment in 2013A and 2013B (PABRA, 2014).

Table S2. Common bean varieties evaluated in Hoima and Rakai district in the first and second 5 season of 2013.

Table S3. Soil characteristics from of the experimental locations in 2013A and 2013B.

Table S4. Rainfall pattern for 2013A and 2013B in the six locations of Hoima and Rakai districts where genotype $\times$ environment trials were conducted.

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