Grouping of Environments for Testing Navy Bean in Ethiopia

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Abstract

Common bean variety selection within its production environment is often challenged by the occurrence of significant genotype-by-environment interactions (GEI) in the variety development process. Grain yield performance of 16 navy bean (Phaseolus vulgaris L.) lines was tested in a multi-environment variety trial during 2010 and 2011 main growing seasons of Ethiopia. Field experiments were conducted in Randomized Complete Block Design (RCBD) with three replications in 14 rainfed environments of the major common bean growing areas. The objectives were to assess the line by environment interactions (LEI), determine stable genotypes, and grouping of test environments. Significant differences were found among the lines for grain yield on each environment and combined over environments. All interactions in relation to L×E showed high significant difference (P<0.01) for grain yield. Statistical methods as AMMI, GGE and some stability...
parameters were used to describe the LE interaction and to define stable lines in relation to their yield. The highest yield (2435 kg ha⁻¹) was obtained from the line ICA BUNSI X SXB 405/1C-C1-1C-87. The stability analysis also identified lines ICA BUNSI X SXB 405/1C-C1-1C-87 and ICA BUNSI X SXB 405/1C-C1-1C-37 as the most stable lines. Lines identified as superior differed significantly from the standard varieties and can be recommended for use by farmers in the bean growing areas of Ethiopia. Cluster analysis, based on grouping of locations showed that Melkassa, Alemtena and Haramaya as potential and high yielding, but Jimma, Bako, Pawe, Areka, Assosa and Sirinka as low to medium yielding locations.

**Introduction**

Common bean is one of the grain legume crops grown in Ethiopia and is being produced on about 3.4 hundred thousand hectares. It is highly produced from lowland to highland areas and also in the warm humid and sub-humid lowlands. The average total crop production per annum is about 2.5 million metric tons. Navy beans are mainly produced for export market and other market class types, as small reds used for local market and human consumption, mainly as cooked grain, or milled for sauce preparation to be eaten with Enjera (Teshale et al., 2008).

The soil and climatic conditions where beans are growing vary in extremes. The considerable variation in soil and climate has resulted in significant variation in annual yield performance of bean cultivars. The environmental variation affects breeding program as selection of genotypes with improved yield performance and yield stability are based on data generated over a number of environments and years (Teshale et al., 2008). Genotype x environment interaction (GEI), which is associated with the differential performance of genetic materials, tested at different locations and in different years and its influence on the selection and recommendation of genotypes has long been recognized (Lin et al. 1986, Becker and Leon 1988, Crossa 1990).

A number of parametric and non-parametric statistical procedures have been developed over the years to analyze genotype x environment interaction and especially yield stability over environments. Lin et al (1986); Becker and Leon (1988), Zobel et al (1986), Crossa (1990) and Huhls (1995) discussed a wide range of methods available for the analysis of GEI and stability. Statistical methods as AMMI (additive main effects and multiplicative interaction) (Gauch, 2006 and Girma Taye et al., 2000) and GGE-biplot (Yan et al., 2000) have been used to analyze the MET data to reveal patterns of GEI. These methods partition the overall variation into G, E and GEI components. GGE-biplot analysis also allowed visual examination of the relationships among the test environments, genotypes and the GEI. The results can be graphically represented in an easily interpretable and informative biplot that shows both main effects and GEI.
AMMI and GGE-biplot model have been used extensively with great success over the past years to analyze and understand genotype x environment interaction in various crops. (Crossa 1990, Gauch & Zobel 1996, Gauch 2006). Therefore, the objectives of this study were: (i) to evaluate navy bean lines (mean performance and stability) under different growing conditions to identify superior lines, (ii) to evaluate the relationships among testing environments, and (iii) to group test locations into mega-environments.

**Materials and Methods**

The trial was carried out during the main cropping seasons of 2010 and 2011 in nine locations (Melkassa, Alemtena, Areka, Haramaya, Jimma, Bako, Pawe, Sirinka and Assossa), which have diverse agro-ecological characteristics such as annual rainfall, temperature and altitude as indicated in Table 1.

**Table 1. Descriptive information of the environments with their codes and climatic characteristics**

<table>
<thead>
<tr>
<th>Environment code</th>
<th>Description</th>
<th>Altitude (m)</th>
<th>Growing season temperature (°C)</th>
<th>Growing season rainfall (mm)</th>
<th>Soil type</th>
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<td>14.6 28</td>
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</table>

* Environment here indicates location by year combination

Sixteen navy bean lines including two released varieties were used in this study. The lines were developed from our crossing program and passed a series of selection procedures to be taken as unique uniform lines. The 16 lines were coded as a sequence of the numbers 1 to 16. Description on the codes is given in Table 2. A randomized complete block design with three replications was used at each location. Each plot consisted of 6 rows of 4m long with total area of 9.6 square meters. The rows in each plot were spaced 40 cm and spacing among bean plants within the row was 10 cm. Recommended agronomic and cultural practices were kept and non-experimental variable applied to all plots. Data were collected from
central four rows (6.4 square meters area) as grain yield per plot from which grain yield per hectare was adjusted to 14% moisture content.

Table 2. Descriptive information on the name and codes of the 16 navy bean lines

<table>
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<tr>
<th>Line Code**</th>
<th>Line Name</th>
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<td>ICA Bunsi x S x B 405/1C-C1-1C-14</td>
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<td>L6</td>
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<td>L8</td>
<td>ICA Bunsi x S x B 405/1C-C1-1C-51</td>
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<td>L15</td>
<td>Awash - 1</td>
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<td>L16</td>
<td>Awash Melka</td>
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</table>

** Represent varieties

Statistical analyses: Before conducting combined analyses of variance and AMMI analysis, the data were subjected to the logarithmic and square root transformations to fix failures of assumptions of ANOVA such as normality and homogeneity of error variances among the different environments. Bartlett’s (1974) test was used to determine the homogeneity of variances between environments to determine the validity of the combined analysis of variance on the data. After the transformation, it was found that square root transformation fixes the problem of the assumption of homogeneity of variance reasonably.

The grain yield data were subjected to AMMI and SREG model analysis using GenStat statistical package (GenStat 15th Ed, 2013). In the analysis, a total of fourteen environments, a combination of location by growing season was treated as an environment.

The AMMI model used for the data was:

$$\bar{y}_{ij} = \mu + \tau_i + \delta_j + \sum_{k=1}^{t} \lambda_k \alpha_{ik} \gamma_{jk} + \bar{e}_{ij}.$$ 

And the SREG linear - bilinear model was:

$$\bar{y}_{ij} = \mu + \delta_j + \sum_{k=1}^{t} \lambda_k \alpha_{ik} \gamma_{jk} + \bar{e}_{ij}.$$ 

Where; $\bar{y}_{ij}$ is the mean of $i^{th}$ genotype in the $j^{th}$ environments; $\mu$ is the overall mean; $\tau_i$ is the genotypic effect; $\delta_j$ is the environment effect; $\lambda_k$ ($\lambda_1 \geq \lambda_2 \geq \cdots \lambda_t$) are scaling constants (singular values) that allow the imposition of orthonormality constraints on the singular vectors for the genotypes, $\alpha_{ik} = (\alpha_{1k}, \ldots, \alpha_{gk})$ and environments, $\gamma_{jk} = (\gamma_{1k}, \ldots, \gamma_{ek})$, such that $\sum_i \alpha_{ik}^2 = \sum_j \gamma_{jk}^2 = 1$ and
\[ \sum_{i} a_{ik} \alpha_{ik}, = \sum_{i} \gamma_{jk} \gamma_{jk}, = 0 \text{ for } k \neq k; \alpha_{ik} \text{ and } \gamma_{jk} \text{ for } k = 1, 2, 3, \ldots, \text{ are called } \text{“primary”}, \text{“secondary”}, \text{“tertiary”}, \ldots \text{ etc effects of genotypes and environments}, \text{ respectively; } \bar{e}_{ij} \text{ is the residual error assumed to be normally and independently distributed } (0, \sigma^2 / r) \text{ (where } \sigma^2 \text{ is the pooled error variance and } r \text{ is the number of replicates)}. \text{List squares estimates of the multiplicative (bilinear) parameters in the } k^{th} \text{ bilinear term are obtained as the } k^{th} \text{ component of the deviations from the additive (linear) part of the model. In the AMMI model, only the GEI term is absorbed in the bilinear terms; whereas in the SREG model, the main effects of genotypes (G) plus the GEI are absorbed in the bilinear terms.} \]

The results of the AMMI model analysis were interpreted on the basis of two AMMI graphs: (a) the graph that showed the main and first multiplicative term (PC1) of both genotypes and environments; and (b) the biplot that used scores of environments and genotypes PC1 against scores of environments and genotypes of the second multiplicative axis term (PC2). The GGE biplots were constructed from the first two principal components (PC1 and PC2) derived by subjecting the environment centered yield data (which contains G and GE) to singular valued composition (SVD) (Yan, 2002 and Yan et al., 2000). GGE biplots were used to: (a) understand the existence of mega-environments (defined as a group of locations that consistently share the best set of genotypes over years (Yan and Rajcan, 2002), (b) relationships between testing environments based on the angels between the vectors of the environments, (c) ranking of genotypes on the basis of yield and stability.

The parametric and univariate non-parametric stability statistics for grain yield were computed by GenStat statistical package (GenStat 15th Ed, 2013). Of the parametric stability estimates, cultivar superiority measure (Pi) of Lin and Binns (1988a) was used. Pi associates stability and productivity and defines a superior genotype as the one with near the maximum in various environments. The smaller the Pi estimate, the more superior the new genotype is.

Among the univariate non-parametric stability statistics rank-based stability parameters Si², Si³, Si⁶ of Nassar and Huhn (1987) were computed. Non-parametric measures for stability are handy for breeders because they are rank based on absolute data and free from stringent statistical assumptions. The non-parametric Si² statistics measures the variance among the ranks over environments. Si³ and Si⁶ represent mean rank of each genotype. The lowest value for each of the statistics represents high stability (Flores et al., 1998; Asrat et al., 2009).

The AMMI Stability Value (ASV) described by Purchase (1997) was use to further investigate the stability of the varieties. The AMMI model does not make provision for a quantitative stability measure, such a measure is essential in order to quantify and rank genotypes according to their yield stability. The following measure was proposed by Purchase (1997):
AMMI Stability Value (ASV) = \[ \left( \frac{\text{IPCA1SumofSquares} - \text{IPCA1score}}{\text{IPCA2SumofSquares}} \right)^2 + [\text{IPCA2score}]^2 \]

In effect the ASV is the distance from zero in a two dimensional scatter gram of IPCA 1 scores against IPCA 2 scores. Since the IPCA 1 score contributes more to G x E sum of squares, it has to be weighted by the proportional difference between IPCA 1 and IPCA 2 scores to compensate for the relative contribution of IPCA 1 and IPCA 2 to the total G x E sum of squares.

**Results and discussion**

**Mean yield performance:** The relative performance of lines based on the mean grain yield over years and locations is presented in Table 3. The general mean yield in the tests ranged from 700 kg ha\(^{-1}\) to 4278 kg ha\(^{-1}\), indicating rather divergent conditions for the lines, due to geographical differences between the sites of evaluation (Table 1). In the combined analysis, all effects were significant, indicating the presence of variability among lines, environments and also a differential response of lines to environments (Table 4). In terms of mean yield of lines, line 13 and line 7 were the most productive, followed by line 12 and line 8 (Table 3). As indicated in table 3 one of the standard checks, Awash-1 was the least performer.
Table 3. Mean yield performance (kg ha\(^{-1}\)) of 16 navy bean lines evaluated at 14 environments for the two periods, 2010 and 2011

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<th>AT11</th>
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<th>JM11</th>
<th>PW10</th>
<th>PW11</th>
<th>SK10</th>
<th>SK11</th>
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AMMI analysis: The combined analysis of variance (ANOVA) of the 16 navy bean lines over the 14 environments is presented in Table 4. AMMI model was used as it gave the best fit for this data set. The ANOVA indicated highly significant differences ($P<0.01$) for environments, lines and line by environment interaction for grain yield data. The IPCA 1 and IPCA 2 axes were also highly significant ($P<0.01$) (Table 4). Variance components of the sum of squares, ranged from 1.79% for lines, 87.98% for environments and 10.23% for LEI. This indicated the overwhelming influence that environments have on the yield performance of navy bean lines in Ethiopia. The importance of the environment component comes from climatic and biological factors as rainfall, temperature, altitude and disease incidence which can result in conditions unique to each year by location combination and that the bean lines respond differently to these conditions. It is important that the L x E variation is five times the variation of lines as main effect (Gauch, 2006 and Girma Taye et al., 2000). The IPCA 1 and IPCA 2 axes explained 39.32% and 24.53% of the total interaction term, respectively.

Table 4. AMMI ANOVA of grain yield for 16 navy bean lines at fourteen environments during 2010 – 2011 main crop seasons

<table>
<thead>
<tr>
<th>Sources of Variation</th>
<th>Degree of freedom</th>
<th>Sum of Squares</th>
<th>Mean Squares</th>
<th>F value</th>
<th>Explained percent of GEI SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td>223</td>
<td>522867290</td>
<td>2344696</td>
<td>16.96**</td>
<td></td>
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<tr>
<td>Environments</td>
<td>13</td>
<td>460020679</td>
<td>35386206</td>
<td>80.88**</td>
<td></td>
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<tr>
<td>Reps within Environment</td>
<td>28</td>
<td>12250577</td>
<td>437521</td>
<td>3.16**</td>
<td></td>
</tr>
<tr>
<td>Line</td>
<td>15</td>
<td>9379070</td>
<td>625271</td>
<td>4.52**</td>
<td></td>
</tr>
<tr>
<td>Variety x Environment</td>
<td>195</td>
<td>53467541</td>
<td>274193</td>
<td>1.98**</td>
<td></td>
</tr>
<tr>
<td>Interaction PCA 1</td>
<td>27</td>
<td>21025671</td>
<td>1060538</td>
<td>5.63**</td>
<td>39.32</td>
</tr>
<tr>
<td>Interaction PCA 2</td>
<td>25</td>
<td>13113741</td>
<td>773422</td>
<td>3.79**</td>
<td>24.53</td>
</tr>
<tr>
<td>Residuals</td>
<td>143</td>
<td>19328128</td>
<td>135162</td>
<td>0.98 ns</td>
<td>36.15</td>
</tr>
<tr>
<td>Pooled error</td>
<td>420</td>
<td>58068413</td>
<td>138258</td>
<td>9.79</td>
<td></td>
</tr>
</tbody>
</table>

** - stands for 1 probability levels; ns – non significant

AMMI biplot: Figure 1 is AMMI biplot where lines and environments are depicted as points on a plane. The abscissa showed the main effects and the ordinate showed the first multiplicative axis term (IPCA1). The horizontal line showed the interaction score of zero and the vertical line indicated the grand mean yield. Displacement along the vertical axis indicated interaction differences between lines and between environments, and displacement along the horizontal axis indicated difference in line and environment main effects. The lines with IPCA1 scores close to zero expressed general adaptation whereas the larger scores indicated more specific adaptation to environments with IPCA1 scores of the same sign (Gauch, 2006). The IPCA scores of a line in the AMMI analysis are an indication of adaptation over environments. The greater the IPCA scores, negative or positive, the more specifically adapted is a line to certain environments. The more the IPCA scores approximate to zero, the more adapted the line is over all the environments sampled.
Looking at the environments it is clear that there is significant variation in the different environments sampled, they are spread from the lower yielding environments in quadrants I and IV to the high yielding environments in quadrants II and III (Figure 1). Most of the higher yielding environments are in quadrants II and III. The high yielding environments are Melkassa and Alemtena, in the Central Rift Valley areas and Haramaya in the eastern zone. Pawe, Bako, Areka and Sirinka are lower yielding environments. Sites representing the south and north-western locations, Jimma and Assossa, respectively were the moderate yielding sites. The lines showed considerably less variation around the mean yield of 2122 kg ha⁻¹ than the environments. Line 13 and line 7 are adapted to almost all environments (Figure 1). Considering only the IPCA 1 scores line 4, line 8, line 12 and the check Awash Melka were the most unstable lines, and also adapted to the higher yielding or more favorable environments.

![Figure 1. IPCA 1 scores for both genotypes and environments plotted against the mean yield for genotypes and environments.](image)

Figure 2 cross-validated the interaction pattern of the 16 bean lines with 14 test environments. The distances from the origin (0,0) are indicative of the amount of interaction that was exhibited by bean lines either over environments or environments over lines. Among environments Melkassa and Alem tena locations in both years (2010 and 2011) Haramaya University in 2011 had higher
values for both IPCA's, depicting high discrimination power and strong role of these locations for the GEI. Similarly, bean lines such as L6, L7, L11 and the check variety Awash melka were also plotted close to these environments (Figure 2) had high values of IPCA1 and IPCA2; and showed high performance in these environments. Assosa is the other location with high IPCA2 score, which specifically contributed to the GE interaction. Bean lines as L1, L9, L10, L14 and the check variety Awash 1 expressed a highly interactive behavior (positively or negatively), in addition L1 and L9 are specifically adapted to Assosa location.

**GGE-biplot analysis of Multi Environment Trial data:**

The GGE refers to the genotype main effect plus the genotype-by-environment interaction (GE), which are the two sources of the site regression model (Yan et al., 2000, 2007). The biplot from this model is used for assessment of multi-environment data provided that a given data set has a high near-perfect correlation ($r = 0.914; P < 0.001$) between IPCA1 and genotype main effects.
Grouping of environments for navy bean testing

(Crossa et al., 2002). The partitioning of line by environment interaction through GGE biplot analysis showed that IPCA1 and IPCA2 accounted for 49.42% and 32.15% of GGE sum of squares, respectively, and both cumulatively explained 81.57% of the LEI variation. This implies that IPCA scores of GGE-biplot better explained the interaction term in this particular experiment.

Visualization of the "which won where" pattern of MET data is necessary for studying the possible existence of different mega-environments in the target environments (Yan et al., 2000) and figure 3 represented a polygon view of genotypes MET data in this investigation. The polygon view of the biplot indicated the best line(s) in each environment and groups of environments (Yan 2002). The polygon is formed by connecting the markers of the lines that are furthest away from the biplot origin such that all other lines are contained in the polygon. The perpendiculars to the sides of the polygon form sectors or mega-environments of lines and sites (Yan 2002, Yan et al 2007). The term mega-environment analysis defines the partition of a crop growing region into different target zones (Gauch and Zobel 1996). The major mega-environments for navy bean testing are enclosed by convex-hull as shown in figure 3. The vertex lines were L3, L4, L8, L9, L12, L13, L15 and L16 and these lines were the best or the poorest yielding lines in some or all of the environments. Among the extreme lines, line 4 and 8 as well as line 3 and 12, respectively were located in pairs indicating their similar response pattern. As indicated in Figure 3, eight sectors of which five had environments and most of the environments fell into two of the sectors or mega-environments. Two small sectors which are located in quadrants I and II, respectively are without environments. And the other big sector with no environments enclosed in it is found in quadrant IV (Figure 3). Four environments, Assossa 2011, Bako 2011, Pawe 2010 and Pawe 2011 fell into a sector found in quadrant II. The highest yielding lines for these four environments are line 13 and Line 9. The second major mega-environment which consisted of environments Melkassa 2010, Melkassa 2011, Alem tena 2010, Alem tena 2011, Sirinka 2010, Sirinka 2011 and Haramaya 2011 was found in a sector located in quadrant III. The third and fourth mega-environments included a single testing site in each, Areka and Jimma locations respectively. The mega-environment which included Jimma environments combined the two sectors in quadrant I. The vector genotypes in these sectors are line 3 and line 12, respectively and they gave the highest yield in Jimma both in 2010 and 2011 (Figure 3, Table 3). And hence, Jimma could be considered as separate mega-location for navy bean evaluation and recommendation.
Relationship among test environments:

Another GGE-biplot, which was based on environment-focused scaling, was depicted to estimate the pattern of environments (Figure 4). Environment IPCA1 and IPCA2 scores had both positive and negative scores which give rise to the crossover non-crossover GEI, leading to disproportionate genotypes yield differences across environments (Yan et al., 2000). A genotype may have large positive interactions with some environments, while it has large negative interactions with some others. Test environments Environment IPCA1 scores correlated with environment yield means ($r = 0.849; P < 0.01$; Table 5). Taking into account such a correlation more than 50% of the environments (like Mk11, Atn11, HU11, Jm10, Jm11, etc.) discriminated sufficiently and they are more representative (Yan et al., 2001). Those environments with short environmental vectors were not discriminated sufficiently because of the incidence of biotic factors (diseases and insect pests) and unpredictable climatic features (distribution and amount of rainfall, high temperature and drought) (Kaya et al., 2006; Kassaye et al., 2013).
Figure 4 provides the summary of the interrelationships among the test environments. The lines that connect the biplot origin and the markers for the environments are called environment vectors. The angle between the vectors of two environments is related to the correlation coefficient between them. The cosine of the angle between the vectors of two environments approximates the correlation coefficient between them (Yan, 2001). Acute angles indicate a positive correlation, obtuse angles a negative correlation and right angles no correlation (Yan and Kang, 2003). The angle between the vectors of two environments is related to its correlation coefficient (Kaya et al., 2006). The correlation coefficients among the 14 environments are presented in Table 5. Of the 91 correlation coefficients contained in Table 5, 47 of them exhibited significant difference. Based on the angles between environment vectors, the highest correlation coefficient observed was between Jm10 and Jm11 which represent the same site (Jimma) in the different years. Jimma location, in general observed loose associations (negative or positive) with most of the environments and negative intermediate relationships with few others (Table 5). Melkassa, Alem tena, Haramaya and Sirinka locations were positively and strongly correlated among each other with high correlation coefficient values. Assosa, Bako, Pawe and Areka locations were also showed strong positive relationships among each other with strong correlation coefficients. Assossa was the other specific location which had loose negative associations with Melkassa, Haramaya and Shrink locations.

Figure 4. GGE-biplot which shows the relationships among the 14 test environments.
Correlation between environments may be used to investigate indirect response to selection (Cooper and Delacy, 1994; Cooper et al., 1997). For example, Melkassa location significantly correlated with Alem tena, Haramaya and Sirinka locations. In the same manner, strong positive associations were observed among Pawe, Bako and Assossa locations (Table 5) Such significant correlation coefficients among locations suggest that indirect selection for grain yield can be practical across locations. For instance, lines adaptable or higher yielding in Melkassa may also show similar responses in Alem tena, Sirinka and Haramaya as well.

**Mean yield and stability performance of lines**

**Cultivar performance measure (Pi):** In terms of mean yield of lines, line 13 and line 7 were the most productive, followed by line 12 (Table 6). However, performance stability of the lines was analyzed by cultivar performance measure. According to the method of Lin & Binns (1988b) cultivar performance measure (Pi) in which lines with the lowest Pi values are considered as the most stable lines. From this analysis, the most stable cultivar ranked first for Pi and mean yield was line 13 followed by line 7 (Table 6). Others with low Pi values and high ranking for mean yield were lines 12 and 8. The ranks of the Pi measure and mean yield are in agreement (Table 6) and this indicated that the Pi value as one of good performance measure in stability analysis (Helton et al 2009). The most unstable lines according to this analysis were Awash-1, line 3 and line 11 (Table 6).
Table 5. Correlation coefficients among test environments.

<table>
<thead>
<tr>
<th>Envts</th>
<th>Ark11</th>
<th>Ass11</th>
<th>Atn10</th>
<th>Atn11</th>
<th>Bk11</th>
<th>HU11</th>
<th>Jm10</th>
<th>Jm11</th>
<th>Mlk10</th>
<th>Mlk11</th>
<th>Pw10</th>
<th>Pw11</th>
<th>Srk10</th>
<th>Srk11</th>
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</thead>
<tbody>
<tr>
<td>Ark11</td>
<td>1</td>
<td>0.588</td>
<td>0.377</td>
<td>0.715</td>
<td>0.712</td>
<td>0.603</td>
<td>-0.557</td>
<td>-0.587</td>
<td>0.189</td>
<td>-0.105</td>
<td>0.958</td>
<td>0.812</td>
<td>0.260</td>
<td>0.106</td>
</tr>
<tr>
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<td>-0.177</td>
<td>-0.106</td>
<td>0.854</td>
<td>-0.165</td>
<td>0.184</td>
<td>0.203</td>
<td>-0.097</td>
<td>-0.551</td>
<td>0.785</td>
<td>0.798</td>
<td>-0.177</td>
<td>-0.573</td>
</tr>
<tr>
<td>Atn10</td>
<td>0.377</td>
<td>-0.177</td>
<td>1</td>
<td>0.791</td>
<td>0.357</td>
<td>0.915</td>
<td>-0.099</td>
<td>-0.208</td>
<td>0.941</td>
<td>0.878</td>
<td>0.160</td>
<td>0.447</td>
<td>0.986</td>
<td>0.905</td>
</tr>
<tr>
<td>Atn11</td>
<td>0.715**</td>
<td>-0.106</td>
<td>0.791**</td>
<td>1</td>
<td>0.275</td>
<td>0.970</td>
<td>-0.672</td>
<td>-0.748</td>
<td>0.545</td>
<td>0.521</td>
<td>0.485</td>
<td>0.432</td>
<td>0.676</td>
<td>0.743</td>
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<tr>
<td>Bk11</td>
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<td>0.854**</td>
<td>0.357</td>
<td>0.275</td>
<td>1</td>
<td>0.297</td>
<td>0.186</td>
<td>0.146</td>
<td>0.423</td>
<td>-0.044</td>
<td>0.792</td>
<td>0.985</td>
<td>0.360</td>
<td>-0.072</td>
</tr>
<tr>
<td>HU11</td>
<td>0.603*</td>
<td>-0.165</td>
<td>0.915**</td>
<td>0.970</td>
<td>0.297</td>
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<td>-0.580</td>
<td>0.728</td>
<td>0.699</td>
<td>0.361</td>
<td>0.437</td>
<td>0.833</td>
<td>0.857</td>
</tr>
<tr>
<td>Jm10</td>
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<td>-0.099</td>
<td>-0.672**</td>
<td>0.186</td>
<td>-0.487*</td>
<td>1</td>
<td>0.994</td>
<td>0.242</td>
<td>0.102</td>
<td>-0.406</td>
<td>0.030</td>
<td>0.068</td>
<td>-0.227</td>
</tr>
<tr>
<td>Jm11</td>
<td>-0.587*</td>
<td>0.203</td>
<td>-0.208</td>
<td>-0.748**</td>
<td>0.146</td>
<td>-0.580*</td>
<td>0.994**</td>
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<td>0.134</td>
<td>0.001</td>
<td>-0.414</td>
<td>-0.018</td>
<td>-0.042</td>
<td>-0.325</td>
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<tr>
<td>Mlk10</td>
<td>0.189</td>
<td>-0.097</td>
<td>0.941**</td>
<td>0.545</td>
<td>0.423</td>
<td>0.728**</td>
<td>0.242</td>
<td>0.134</td>
<td>1</td>
<td>0.884</td>
<td>0.030</td>
<td>0.458</td>
<td>0.984</td>
<td>0.800</td>
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<tr>
<td>Mlk11</td>
<td>-0.105</td>
<td>-0.551*</td>
<td>0.878**</td>
<td>0.521</td>
<td>-0.044</td>
<td>0.699**</td>
<td>0.102</td>
<td>0.001</td>
<td>0.884**</td>
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<td>0.785**</td>
<td>0.160</td>
<td>0.485</td>
<td>0.792**</td>
<td>0.361</td>
<td>-0.406</td>
<td>-0.414</td>
<td>0.030</td>
<td>-0.333</td>
<td>1</td>
<td>0.850</td>
<td>0.063</td>
<td>-0.166</td>
</tr>
<tr>
<td>Pw11</td>
<td>0.812**</td>
<td>0.798**</td>
<td>0.447*</td>
<td>0.432</td>
<td>0.985**</td>
<td>0.437*</td>
<td>0.030</td>
<td>-0.018</td>
<td>0.458*</td>
<td>0.014</td>
<td>0.850**</td>
<td>1</td>
<td>0.424</td>
<td>0.036</td>
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<tr>
<td>Srk10</td>
<td>0.260</td>
<td>-0.177</td>
<td>0.986**</td>
<td>0.876</td>
<td>0.360</td>
<td>0.833**</td>
<td>0.068</td>
<td>-0.042</td>
<td>0.984**</td>
<td>0.911**</td>
<td>0.063</td>
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<td>0.882</td>
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<tr>
<td>Srk11</td>
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<td>-0.573*</td>
<td>0.905**</td>
<td>0.743**</td>
<td>-0.072</td>
<td>0.857**</td>
<td>-0.227</td>
<td>-0.325</td>
<td>0.800**</td>
<td>0.945**</td>
<td>-0.166</td>
<td>0.036</td>
<td>0.882**</td>
<td>1</td>
</tr>
</tbody>
</table>

*, **: Significant at P = 0.05 and P = 0.01 respectively.
Table 6 Lin & Binns’s (1988a) cultivar performance measure ($P$), Rank-based stability parameters $S_i^2$, $S_i^3$, $S_i^6$ of Nassar and Huhn (1987) and AMMI stability value (ASV) for 16 navy bean lines tested at 14 environments, for the years 2010-2011.

<table>
<thead>
<tr>
<th>Line code</th>
<th>Grand mean</th>
<th>Lin and Binns Cultivar Superiority Measure</th>
<th>Rank-based stability parameters $S_i^2$, $S_i^3$, $S_i^6$ of Nassar and Huhn (1987)</th>
<th>AMMI Stability Value (ASV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$P(x10^3)$</td>
<td>Rank</td>
<td>Value</td>
</tr>
<tr>
<td>Line1</td>
<td>2047</td>
<td>196</td>
<td>10</td>
<td>10.43</td>
</tr>
<tr>
<td>Line2</td>
<td>2067</td>
<td>179</td>
<td>6</td>
<td>10.21</td>
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<tr>
<td>Line3</td>
<td>2017</td>
<td>248</td>
<td>15</td>
<td>10.50</td>
</tr>
<tr>
<td>Line4</td>
<td>2153</td>
<td>198</td>
<td>12</td>
<td>7.36</td>
</tr>
<tr>
<td>Line5</td>
<td>2149</td>
<td>173</td>
<td>5</td>
<td>7.71</td>
</tr>
<tr>
<td>Line7</td>
<td>2318</td>
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<td>4</td>
<td>7.86</td>
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<td>Line9</td>
<td>2096</td>
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<td>8</td>
<td>9.43</td>
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<td>Line10</td>
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<td>180</td>
<td>7</td>
<td>10.07</td>
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<td>8.00</td>
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<td>28</td>
<td>1</td>
<td>3.14</td>
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<tr>
<td>Awash-1</td>
<td>1902</td>
<td>367</td>
<td>16</td>
<td>10.86</td>
</tr>
<tr>
<td>A/melka</td>
<td>2106</td>
<td>197</td>
<td>11</td>
<td>8.57</td>
</tr>
</tbody>
</table>
Variances of ranks (Si²), means absolute differences of pairs of ranks (Si³) and mean ranks (Si⁶): The method of Nassar and Huhn (1987) is a non-parametric stability measure based on the ranks of the lines across locations. This gives equal weight to each location or environment. Lines with less change in rank are expected to be more stable. The mean absolute rank difference (Si³) estimates are all possible pair wise rank differences across locations for each line. The Si² estimates are simply the variances of ranks for each line over environments (Nassar and Huhn 1987, Huhn 1990). According to this procedure line 13 was the most stable, with line 3 and Awash-1 the most unstable one (Table 6). Considering mean yield and Si² of the lines the second high yielding line, line 7 was also exhibited good stability. For Si², Si³ and Si⁶ smaller estimates indicate relative stability as indicated in table 5 but often, Si³ and Si⁶ have less power for detecting stability than Si² (Huhn, 1990).

AMMI stability value (ASV): The IPCA scores of lines in AMMI are indicators of the stability of a line over environments (Purchase 1997). The lowest IPCA1 was observed by line1 followed by lines 9 and 13 (Table 6). According to IPCA1 score the three lines were stable but the highest mean yield was exhibited by line 13 (2435 kg ha⁻¹), which is significantly higher than the grand mean (2122 kg ha⁻¹). The highest IPCA1 was recorded by line 8 followed by line 4, Awash Melka, line 12 and line 3. AMMI stability value (ASV) confirms the results of IPCA1 and IPCA2 scores (Table 6). As a result, ASV selected line 13 (ICA Bunsi x SxB 405/1C-C1-1C-87) followed by line 2 (ICA Bunsi x SxB 405/1C-C1-1C-3) with the lowest ASV as stable lines, however only line 13 exhibited the highest mean yield greater than the grand mean (Table 6). Corresponding to ASV, the standard checks (both Awash-1 and Awash Melka), line 8 and line 7 were the most unstable lines although the two lines (7 and 8) had higher mean yield above the grand mean. Helton et al (2009) and Karimzadeh and Mohammadi (2010) reported the same result in rainfed lentil yield trials.

Conclusion

Multi-location trials data is crucial to select and recommend high yielding and stable genotypes for farmers. The genotypes studied in this experiment exhibited both crossover and non-crossover types of GEI. The former substantially led to differential rankings of genotypes across test environments, thereby making genotypic selection difficult for navy bean growing environments under Ethiopian conditions. We exploited the AMMI, GGE-biplot and some stability parameters as statistical methods for evaluating experimental navy bean lines performance data. AMMI-ANOVA and stability analyses revealed similar results in selecting the highest yielding and stable navy bean line as well as in identifying the best test environments. The GGE-biplot model summarized patterns and relationships of lines and environments successfully. It is a very
successful tool in classifying sites into mega-environments and to study the relationships within and between the clustered sites. The highest yielding lines were ICA Buni x SxB 405/1C-C1-1C-87 and ICA Buni x SxB 405/1C-C1-1C-37, and the difference for mean grain yield between these lines and the other lines was significant according to the F test result. Besides, ICA Buni x SxB 405/1C-C1-1C-87 was stable line as depicted in the AMMI biplot figures and stability parameters.

In the case of test environments, we found four possible mega-environments for navy bean testing and therefore, bean improvement program will surely focus on them to foster yield-based selection in multi-environment yield trials. Indirect selection among test environments might also be employed to reduce the number of test environments by eliminating those that are highly correlated with each other thereby economizing and optimizing the conduct of multi-environment yield trials. On the other hand, a low H value might suggest that genotype performance trials should be conducted in a number of population of environments sampled from the target region.

Acknowledgements

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