Selection of common bean (*Phaseolus vulgaris* L.) genotypes using a genotype plus genotype x environment interaction biplot

A.M. Corrêa[1], **P.E. Teodoro**[2], **M.C. Gonçalves**[3], **A. Santos**[4] and **F.E. Torres**[1]

[1]Departamento de Fitotecnia, Universidade Estadual do Mato Grosso do Sul, Aquidauana, MS, Brasil
[2]Departamento de Biologia Geral, Universidade Federal de Viçosa, Minas Gerais, Viçosa, MG, Brasil
[3]Departamento de Estatística, Universidade Federal da Grande Dourados, Dourados, MS, Brasil
[4]Departamento de Melhoramento Genético,
Universidade Estadual do Norte Fluminense Darcy Ribeiro,
Campo dos Goytacazes, RJ, Brasil

Corresponding author: P.E. Teodoro
E-mail: eduteodoro@hotmail.com

ABSTRACT. Recently, the genotype plus genotype x environment interaction (GGE) biplot methodology has been used to investigate genotype x environment interactions in several crop species, but has not been applied to the common bean (*Phaseolus vulgaris* L.) crop in Brazil. The aim of this study was to identify common bean genotypes that exhibit high grain yield and stability in the State of Mato Grosso do Sul, Brazil. We conducted 12 trials from 2000 to 2006 in the municipalities of Aquidauana and Dourados, and evaluated 13

genotypes in a randomized block design with three replications. Grain yield data were subjected to individual and joint analyses of variance. After analyzing the GE interaction, the adaptability and phenotypic stability of the common bean genotypes were analyzed using GGE biplot methodology. The genotypes EMGOPA-201, Xamego, and Aporé are recommended for growing in Mato Grosso do Sul, because they exhibited high grain yield and phenotypic stability.

Key words: *Phaseolus vulgaris* L.; Multivariate analysis; Genotype x environment interaction

INTRODUCTION

Brazil is the largest producer of the common bean (*Phaseolus vulgaris* L.) in the world, with 2.9 million tons estimated to have been produced in 2014 (FAO, 2015) and an average yield of 1.0 Mg/ha per harvest (CONAB, 2015). However, this yield is low considering the crop's potential, which can reach 4.5 Mg/ha. This legume is an important source of protein for the Brazilian population, particularly for low-income groups (Cardoso et al., 2014; Pereira et al., 2014). Therefore, it is necessary to select highly productive genotypes that are adapted to the soil and climatic conditions of particular locations, which will increase the average national yield.

In the State of Mato Grosso do Sul, Brazil, the municipalities of Aquidauana and Dourados are part of the Genetic Breeding Program for the Common Bean, which is conducted by Embrapa Arroz and Feijão. Due to high nighttime temperatures in Aquidauana, cultivation only occurs in the dry season. In Dourados, cultivation only occurs in the spring and autumn, because in the winter the region is subject to frost. The common bean is grown by farmers using subsistence agriculture with little or no technology, and by farmers that use modern production technology.

The diversity of environmental conditions under which the common bean is grown in Mato Grosso do Sul requires genotypes with high yield stability. Because in most cases these environments differ, genotype x environment interactions (GE) occur, i.e., genotype response is a function of the environment. GE interaction analysis allows selection to be properly evaluated, and maximizes yield and other agronomic traits of interest in a particular location or group of environments (Cruz et al., 2014).

However, despite its importance, simple GE interaction analysis does not provide complete and accurate information about the behavior of each genotype under different environmental conditions. Therefore, it is necessary to perform analyses of adaptability and phenotypic stability, in which the identification of genotypes that exhibit predictable behavior and are responsive to environmental variation is possible (Yates and Cochran, 1938). In this context, a methodology has been developed that determines the main effects of genotype and environment and their interaction, which is known as genotype plus genotype x environment interaction (GGE) biplot analysis (Mattos et al., 2013).

A GGE biplot is a graph that interprets the GE interaction in sites regression (SREG) models (Yan et al., 2000), and assumes that the main effect of environment is not relevant in the selection of genotypes (G), because the G effect is treated as a multiplicative GE effect. The axes of the analysis graphs are the first two principal components of a multivariate analysis, which assumes that environmental effects are fixed and other effects are random (Miranda

et al., 2009). Therefore, in cultivar selection and mega-environment training, the adaptive capacity of genotypes is most important in relation to environmental conditions, and changes in the trait under study are only caused by G and GE effects (Yan et al., 2000).

Recently, GGE biplots have been used to investigate GE interactions in several crops, such as cotton (Farias et al., 2016) and sorghum (Teodoro et al., 2016), but not in the common bean in Brazil. Therefore, the aim of this study was to identify common bean genotypes that exhibit high yields and stability in Mato Grosso do Sul, Brazil.

MATERIAL AND METHODS

We conducted 12 Value for Cultivation and Use trials from 2000 to 2006. The environments were chosen based on location, growing season, and agricultural year. In Dourados, trials were conducted at Faculdade de Ciências Agrárias da Universidade Federal da Grande Dourados [22°12'S, 54°48'W, and 452 m above mean sea level (AMSL)]. In Aquidauana, trials were conducted at Unidade Universitária de Aquidauana da Universidade Estadual de Mato Grosso do Sul (20°20'S, 55°48'W, and 207 m AMSL). The climatic characteristics of both environments are presented in Table 1.

Table 1. Environments, sites, climates, agricultural years, monthly rainfalls, and average monthly temperatures of trials conducted in the State of Mato Grosso do Sul, Brazil.

Environment	Code	Site	Climate[1]	Harvest	Agricultural year	Monthly rainfall (mm)	Average monthly temperature (ºC)
1	EA	Dourados	Cwa	Wet	2000/2001	540	26.1
2	EB	Dourados	Cwa	Dry	2000/2001	340	23.4
3	EC	Aquidauana	Aw	Dry	2000/2001	393	23.2
4	ED	Dourados	Cwa	Wet	2001/2002	494	25.9
5	EE	Dourados	Cwa	Dry	2001/2002	403	22.8
6	EF	Aquidauana	Aw	Dry	2001/2002	297	23.4
7	EG	Aquidauana	Aw	Dry	2002/2003	385	23.8
8	EH	Aquidauana	Aw	Dry	2003/2004	280	23.1
9	EI	Aquidauana	Aw	Dry	2004/2005	293	23.6
10	EJ	Dourados	Cwa	Wet	2005/2006	485	26.0
11	EK	Dourados	Cwa	Dry	2005/2006	346	22.6
12	EL	Aquidauana	Aw	Dry	2005/2006	308	24.1

[1]According to the Köppen-Geiger classification.

The experiments included 9 genotypes (Rudá, Aporé, Xamego, Pérola, Ouro Negro, Diamante Negro, IAPAR 14, ENGOPA 201, and IAC-Carioca Eté) and the lines Bambuí, CNF 4999, CNF 4129 A 54, and CNFv. 8025. In Dourados, sowing was conducted in the dry (second half of March) and wet (second half of September) seasons. In Aquidauana, the trials were only conducted in the dry season (between 10 and 20 April). The experimental design was a randomized complete block design with 25 treatments and three replications. The experimental unit consisted of four lines that were 5 m in length, with 0.5 m between rows and 0.1 m between plants within each line. In each experimental unit, grain yield was evaluated in the two central rows, corrected for 13% moisture, and extrapolated to kg/ha.

The grain yield data were subjected to individual analyses of variance (ANOVAs), with the effect of genotype considered fixed and all other effects considered random. The ratio between the largest and smallest mean squares of the residuals from the individual ANOVAs did not exceed 7, allowing a joint analysis of the trials to be conducted (Banzatto and Kronka,

2006). Subsequently, data were subjected to an analysis of adaptability and stability using GGE biplots (Yan et al., 2000). The GGE biplot model used was as follows:

$$Y_{ij} - \mu - \beta_j = y_1 \varepsilon_{i1} \rho_{j1} + y_2 \varepsilon_{i2} \rho_{j2} + \varepsilon_{ij} \qquad \text{(Equation 1)}$$

where Y_{ij} is the mean grain yield of genotype i in environment j; μ is the overall mean of observations; β_j is the main effect of the environment; y_1 and y_2 are the errors associated with the first (PC1) and second (PC2) principal components, respectively; ε_1 and ε_2 are the PC1 and PC2 values, respectively, for the genotype of order i; ρ_{j1} and ρ_{j2} are the PC1 and PC2 values, respectively, for the environment of order j; and ε_{ij} is the error associated with the model of the ith genotype and the jth environment (Yan et al., 2000). The analysis was performed using the GGEGui package in R (R Development Core Team, 2014).

RESULTS AND DISCUSSION

The ANOVAs demonstrated that genotype, environment, and GE interaction effects were significant (Table 2). The genotype effect indicates variability for selection, the environment effect indicates variability between sites, years, and growing seasons (which is important for efficient cultivar selection), and the GE interaction effect indicates differential responses of the genotypes to environmental change. Similar results were obtained by Oliveira et al. (2006), Melo et al. (2007), Pereira et al. (2009), Gonçalves et al. (2009), Rocha et al. (2010), and Corrêa et al. (2016a,b) when evaluating the adaptability and phenotypic stability of common bean genotypes from different locations.

Table 2. Summary of analysis of variance for grain yield (kg/ha) of 13 common bean (*Phaseolus vulgaris* L.) genotypes growing in 12 environments in the State of Mato Grosso do Sul, Brazil.

Source of variation	d.f.	Mean square
Genotype (G)	12	2724.265*
Environment (E)	13	6365.104*
GE	132	606.890*
Error	468	4.209
Coefficient of variation (%)	-	13.12

*Significant at the 1% level of probability according to an F-test.

Figure 1 shows a polygon connecting the genotypes CNF 4129 A 54 (G12), IAC Carioca Ete (G9), EMGOPA-201 (G8), Aporé (G2), Rudá (G1), CNFv 8025 (G13), and Bambuí (G10), which were furthest from the biplot origin. These genotypes had the largest vectors in their respective directions; vector lengths and directions were extensions of the genotypes' responses to the environments. All of the other genotypes in the polygon had smaller vectors, i.e., they were less sensitive to interactions with the environments of each sector (Yan and Rajcan, 2002). Vectors from the center of the biplot (0,0), which were perpendicular to the sides of the polygon, divided the graph into six sectors. Similar results were obtained by Mattos et al. (2013), who also found that the graph divided into six sectors when assessing the stem productivity of sugarcane genotypes.
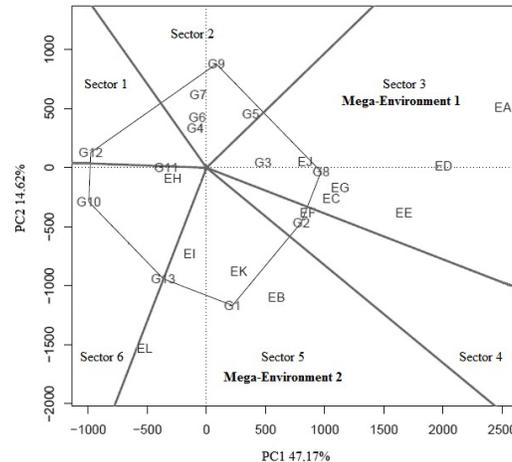
Figure 1. Sectors and mega-environments obtained using a genotype plus genotype x environment interaction (GGE) biplot model of the grain yield (kg/ha) of 13 common bean (*Phaseolus vulgaris* L.) genotypes growing in 12 environments (see Table 1) in the State of Mato Grosso do Sul, Brazil.

Mega-environments contain one or more environments. Therefore, clustered environments within these spaces are considered similar in relation to environmental effects on individuals. The GGE biplot (Figure 1) clustered the EA, EC, ED, EE, EG, and EJ environments into mega-environment 1, where the genotype EMGOPA-201 (G8), present at the vertex, obtained the highest average grain yield in the EA, ED, and EG environments, and the second-highest average among the genotypes (Table 3). If the genotypes gave rise to a polygon vertex but did not contain any clustered environments, they were considered unfavorable because they had low productivity (Yan et al., 2000). Therefore, the genotypes in sectors 1 and 2 were unsuitable.

Mega-environment 1 contained environments that had high rainfall; however, only two genotypes (G8 and G3) were in this mega-environment, indicating that they were among the most productive. Given this result, it can be inferred that these genotypes are well adapted to the environments assessed. Mega-environment 2 included environments with below-average rainfall (Table 3), and was unfavorable for the genotypes used in this study. This was probably due to variations in rainfall in terms of amount and distribution, in addition to differences between these environments in other abiotic factors, such as temperature, which did not favor the expression of genes for grain yield. Only the Rudá (G1) genotype was in this mega-environment, which had a yield that was higher than the overall mean; consequently, this genotype can be recommended for cultivation in unfavorable environments. However, this result should be treated with caution, because its strong GE interaction could be misinterpreted.

Grain yield and genotype stability were evaluated from the coordination of the average environment (CAE). The higher the genotype projection in the axis of the ordinate CAE, the greater the instability of the genotype, which indicates a greater interaction with the environment (Yang et al., 2009). In this regard, Aporé (G2) had high phenotypic stability (Figure 2) and the largest average yield over the environments (Table 3). Rudá (G1), IAC Carioca Ete (G9), and CNFv. 8025 (G13) were the most unstable. When considering both productivity and stability together, Aporé, Xamego, and EMGOPA-201 (G2, G3, and G8, respectively) are recommended.

Table 3. Average grain yields (kg/ha) of 13 common bean (*Phaseolus vulgaris* L.) genotypes growing in 12 environments in the State of Mato Grosso do Sul, Brazil.

Genotype	EA[1]	EB	EC	ED	EE	EF	EG	EH	EI	EJ	EK	EL	Mean
Rudá	1543	2371	1980	2142	2438	2586	2081	2109	2188	1300	2223	3175	2178
Aporé	2768	1841	2461	2494	2347	2582	2521	1887	1969	1900	2052	2872	2308
Xamego	2085	1807	2309	2136	2533	2450	2508	1999	1577	1379	1268	2396	2037
Pérola	1435	1184	1771	1846	2296	1892	1853	2013	1439	732	2018	2084	1714
Ouro Negro	1960	902	3251	1925	2014	3098	2475	2238	1349	811	1488	2052	1964
Diamante Negro	1452	1226	2006	1697	2180	2341	1970	2187	1768	936	1081	2147	1749
IAPAR 14	1618	1153	2390	1923	1158	1832	1868	2901	1682	2414	1298	2168	1867
EMGOPA-201	2864	2008	2910	3074	2500	2587	2572	2810	1436	1031	1429	2447	2306
IAC Carioca Ete	2242	1321	1345	1970	1364	2319	1973	1920	1546	1437	1582	1726	1729
Bambuí	459	827	1662	776	997	2157	1894	3021	2172	630	1984	2972	1629
CNF 4999	1201	1863	2061	1356	1580	2570	2006	2751	1770	533	1107	2360	1763
CNF 4129 A 54	579	1613	1733	1045	1016	1495	1204	1856	1284	598	849	3084	1363
CNFv 8025	818	1941	2576	1452	1342	2534	1985	2482	1962	1275	1926	3285	1965
Mean	1617	1558	2174	1834	1828	2342	2070	2321	1703	1152	1562	2521	1890

[1]Details of the environments are presented in Table 1.

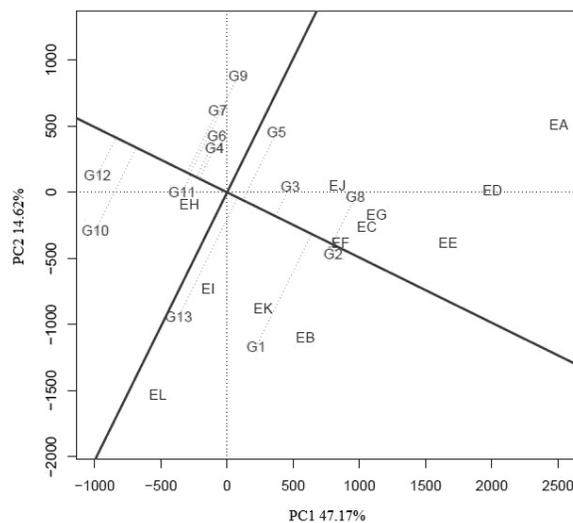**Figure 2.** Mean versus stability according to a genotype plus genotype × environment interaction (GGE) biplot model of the grain yield (kg/ha) of 13 common bean (*Phaseolus vulgaris* L.) genotypes growing in 12 environments (see Table 1) in the State of Mato Grosso do Sul, Brazil.

An ideal genotype should have an average grain yield that is consistently high in all environments. This ideal genotype is graphically defined by the longest vector in PC1 and PC2 without projections, represented by an arrow in the center of the concentric circles (Yan and Rajcan, 2002). Although this genotype is a representative model, it is used as a reference for the evaluation of genotypes. In this way, EMGOPA-201 (G8) and Xamego (G3) in the first and Aporé (G2) in the second concentric circle were the closest to the ideal in terms of high grain yield and phenotypic stability (Figure 3). It can be inferred that these genotypes do not change their average yield over time or location, and are little affected by environmental conditions.
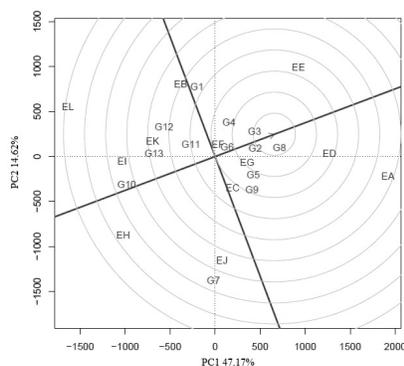
Figure 3. Classification of 13 common bean (*Phaseolus vulgaris* L.) genotypes according to a genotype plus genotype x environment interaction (GGE) biplot model based on grain yield in 12 environments (see Table 1) in the State of Mato Grosso do Sul, Brazil.

Figure 4 shows the relationship between yield and stability from the vectorial viewpoint of environments, in which environments are connected by vectors to the biplot origin. In environments with small vectors, production stability is high (Yang et al., 2009). Therefore, the EH environment contributed little to the GE interaction, while the EA environment was more unstable. The instability of the EA environment may be related to the maximum monthly temperature, because high temperatures result in decreases in the establishment, growth, and development of the crop, and decrease the number of pods per plant, the number of grains per pod, and the grain mass, which together negatively affect grain yield.

According to Yang et al. (2009), ideal environments should have a high PC1 score (with a greater power of discrimination in terms of genotype main effects) and a zero PC2 score (which is the most representative of all of the other environments). In the same way as the ideal genotype, the ideal environment is only an estimate, and serves as a reference for the choice of site for multi-environment testing. Therefore, the ED and EJ environments had the greatest capacity for discriminating between genotypes, and favored the selection of superior genotypes. The EMGOPA-201, Xamego, and Aporé genotypes are recommended for growing in Mato Grosso do Sul because they have high grain yield and phenotypic stability.
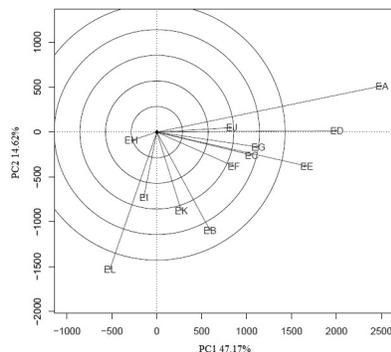

Figure 4. Relationships between environments obtained by a genotype plus genotype x environment interaction (GGE) biplot model based on the grain yield of 13 common bean (*Phaseolus vulgaris* L.) genotypes growing in 12 environments (see Table 1) in the State of Mato Grosso do Sul, Brazil.

Conflicts of interest

ACKNOWLEDGMENTS

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