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Adaptability and yield stability of cowpea genotypes in the Mid-North region of Brazil

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ABSTRACT: This study aimed to evaluate the adaptability and yield stability of 20 erect/semierect cowpea genotypes in the Brazil Mid-North region through three methodologies. The experiments were carried out in 10 environments, corresponding to the Cerrado, Caatinga and Amazon biomes. The research was carried out during the period of 2010 to 2011. The experiments were arranged in a randomized block design, with four replications. The Cerrado biome and the Balsas/MA region were the most suitable locations for cowpea cultivation, comprising the environments with greater yield stability. Theil (1950) methodology showed low sensitivity in genotype discrimination, while those of Lin & Binns modified by Carneiro and AMMI were more sensitive. For unfavorable environments, Lin & Binns (1998) methodology modified by Carneiro (1998) identified the cultivar BRS Tumucumaque with greater stability, whereas the AMMI methodology identified this cultivar with greater adaptation in favorable environments. Both methodologies identified the MNC02-676F-3 strain with better adaptation to favorable environments. The association of methodologies is necessary to complement the interpretation of the adaptability and stability of cowpea genotypes in the Mid-North of Brazil.

Key words: Amazon; Caatinga; Cerrado; genotype × environment interaction; *Vigna unguiculata* (L.) Walp.

Adaptabilidade e estabilidade de produção de genótipos de feijão-caupi na região Meio-Norte do Brasil

RESUMO: Este estudo teve como objetivo avaliar a adaptabilidade e estabilidade de produção de 20 genótipos de feijão-caupi de porte ereto/semiereto na região Meio-Norte do Brasil por meio de três metodologias. Os experimentos foram conduzidos em 10 ambientes, correspondentes aos biomas Cerrado, Caatinga e Amazônia. A pesquisa foi conduzida durante o período de 2010 a 2011. Os experimentos foram arranjados em delineamento de blocos casualizados, com quatro repetições. O bioma Cerrado e a região de Balsas/MA foram os locais mais adequados para o cultivo do feijão-caupi, compreendendo os ambientes com maior estabilidade de produção. A metodologia de Theil (1950) mostrou baixa sensibilidade na discriminação de genótipos, enquanto as de Lin & Binns modificadas por Carneiro e AMMI foram mais sensíveis. Para ambientes desfavoráveis, a metodologia de Lin & Binns (1998) modificada por Carneiro (1998) identificou a cultivar BRS Tumucumaque com maior estabilidade, enquanto a metodologia AMMI identificou esta cultivar com maior adaptação em ambientes favoráveis. Ambas as metodologias identificaram a cepa MNC02-676F-3 com melhor adaptação a ambientes favoráveis. A associação de metodologias é necessária para complementar a interpretação da adaptabilidade e estabilidade de genótipos de feijão-caupi no Meio-Norte do Brasil.

Palavras-chave: Amazônia; Caatinga; Cerrado; interação genótipo × ambiente; *Vigna unguiculata* (L.) Walp.

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Introduction

Aiming at increasing cowpea production in Brazil, large farmers have become interested in the crop in recent years, with cultivation fields conducted in a mechanized way. This has increased the demand for cultivars with modern plant architecture, more compact and erect, facilitating crop practices and mechanized harvesting (Freire Filho et al., 2011; Almeida et al., 2017). Studies have been conducted to evaluate the erect cowpea cultivars yield and quality in various environments and different conditions (Almeida et al., 2017; 2020; 2021).

In addition to superior genotypic performance, the environment is also important in phenotypic expression and may affect plant development (Oliveira et al., 2015; Cruz et al., 2021). Thus, changes in the genotypes performance due to environmental conditions are referred to as genotype × environment (G × E) interaction. Despite being of great importance for breeding, this interaction does not provide detailed information on the behavior of each genotype in the face of environmental variations. Therefore, it is useful to know the estimates of adaptability and stability parameters, which enable the identification of genotypes with behaviors more predictable and responsive to environmental variations (Oliveira et al., 2015; Cruz et al., 2021).

According to Duarte & Zimmermann (1995) and Rocha et al. (2007), it is necessary to have adequate statistical methodologies to estimate and explore the G × E interaction, thus allowing regionalized recommendations. Estimates of phenotypic adaptability and stability can be made based on the level of response to environmental stimulus and on predictability, that is, the maintenance of yield in diverse environments. Studies on adaptability and stability have been conducted using different methodologies, including the Lin & Binns (1998) methodology modified by Carneiro (1998) (Nunes et al., 2014; Santos et al., 2015; Alves et al., 2020) and Theil (1950) methodology (Nascimento et al., 2010). Several studies on this subject have also been reported in the literature using the method of additive main effects and multiplicative interaction - AMMI (Santos et al., 2015; Araméndiz-Tatis et al., 2021; Mbeyagala et al., 2021).

The objective of this study was to evaluate the adaptability and yield stability of 20 erect/semierect cowpea genotypes in the Mid-North region of Brazil, represented by three biomes, through the Lin & Binns methodology modified by Carneiro, Theil and AMMI.

Materials and Methods

Twenty erect/semierect cowpea genotypes from the Embrapa Meio-Norte cowpea breeding program were evaluated. The treatments consisted of 16 lineages or strains (G1-MNC02-675F-4-9, G2-MNC02-675F-4-2, G3-MNC02-675F-9-2, G4-MNC02-675F-9-3, G5-MNC02-676F-3, G6-MNC02-682F-2-6, G7-MNC02-683F-1, G8-MNC02-684F-5-6, G9-MNC02-725F-3, G10-MNC02-736F-7, G11-MNC02-737F-5-1, G12-MNC02-737F-5-4, G13-MNC02-737F-5-9, G14-MNC02-737F-5-10, G15-MNC02-737F-5-11, and G16-MNC02-737F-11) and four cultivars (G17-BRS Tumucumaque, G18-BRS Cauamé, G19-BRS Guariba, and G20- BRS Itaim), used as controls.

Ten trials of value for cultivation and use (VCU) were conducted in the Mid-North region of Brazil, in the states of Piauí and Maranhão, in the agricultural years of 2010 and 2011. The evaluation environments consisted of the combination between location and year, which resulted in 10 environments, distributed in three biomes (Tables 1 and 2).

According to the Köppen classification, the climate of the Amazon-Caatinga Transition biome is classified as Aw, hot and humid with rainfall ranging from 1,000 to 1,800 mm. The Cerrado-Caatinga Transition biome is defined as Aw, hot and humid with rainfall ranging from 1,000 to 1,400 mm. The Cerrado biome is classified as Aw, hot and semi-humid, called savanna climate, with dry winter and maximum rainfall in summer. The Caatinga biome is classified as BShw, semi-arid, with rainfall ranging from 400 to 1,000 mm.

The experimental design used was randomized complete blocks, with 20 treatments and four replicates for each location/agricultural year. Each plot consisted of four 5-m-long rows, spaced apart by 0.5 m and density of 8 plants per linear meter, considering the two central rows as usable area.

The tests were conducted under rainfed conditions, considering the rainy season in each biome in the Mid-North

Table 1. Description of the environments in which the trials were conducted with 20 erect/semierect cowpea genotypes under rainfed conditions in the Mid-North region of Brazil.

Environment	Location	Year	Sowing	Harvest	Cycle (days)
TE10	Teresina-PI	2010	07.15.2010	10.01.2010	75
BJ10	Bom Jesus-PI	2010	02.10.2010	05.21.2010	101
BJ11	Bom Jesus-PI	2011	03.03.2011	06.02.2011	89
SR10	São Raimundo das Mangabeiras-PI	2010	03.04.2010	05.28.2010	84
SR11	São Raimundo das Mangabeiras-PI	2011	03.01.2011	06.01.2011	90
BA10	Balsas-MA	2010	03.03.2010	05.26.2010	83
BA11	Balsas-MA	2011	03.01.2010	06.07.2010	95
BU10	Buriti-MA	2010	05.02.2010	07.13.2010	72
SJ11	São João do Piauí-PI	2011	02.18.2011	05.05.2011	77
CG11	Campo Grande do Piauí-PI	2011	02.09.2011	05.05.2011	84

Table 2. Characterization of the locations where the experiments with erect/semierect cowpea genotypes were conducted in the Mid-North region of Brazil.

Municipalities	Alt. (m)	Lat. (S)	Long. (W)	Type of soil[1, 2]	Biome
Teresina, PI	72	05°54'	42°48'	*Latossolo Vermelho Amarelo* (Oxisol)	Amazon/Caatinga
Bom Jesus, PI	643	09°39'	45°12'	*Latossolo Amarelo* (Oxisol)	Cerrado/Caatinga
São R. Mangabeiras, MA	511	06°53'	45°39'	*Latossolo Amarelo* (Oxisol)	Cerrado
Balsas, MA	324	07°54'	45°96'	*Latossolo Amarelo* (Oxisol)	Cerrado
Buriti, MA	227	03°50'	43°07'	*Latossolo Amarelo* (Oxisol)	Cerrado
São João do Piauí, PI	316	08°20'	42°19'	*Neossolo Quartzarênico* (Quartzipsamment)	Caatinga
Campo G. do Piauí, PI	440	07°07'	41°02'	*Neossolo Quartzarênico* (Quartzipsamment)	Caatinga

[1] Santos et al. (2018); [2] Soil Survey Staff (2014).

region of Brazil. The Teresina-PI 2010 environment was the only one where there was complementation with irrigation. The trials were conducted under conventional soil tillage. Grain yield was evaluated based on the plants of the two central rows of each plot. The adaptability and yield stability were evaluated using the methodologies of Theil (1950), Lin & Binns (1998) modified by Carneiro (1998) and additive main effects and multiplicative interaction (AMMI) (Zobel et al., 1988).

Theil method estimates the response of an individual according to the model: $Y_{ij} = \beta_{0i} + \beta_{li} I_j + \Psi_{ij}$, where: Y_{ij} - average of genotype i in the environment j; β_{0i} - linear coefficient referring to the i-th genotype (intercept); β_{li} - regression coefficient, which measures the response of the i-th genotype to the variation of the environment; I_j - coded environmental index, which is estimated according to the Equation 1.

$$I_j = \left[\sum_j Y_j\right] - \left[\frac{\sum_i \sum_j Y_{ij}}{ge}\right] \quad (1)$$

where: Ψ_{ij} - random errors from a population with a median of zero.

The adaptability, by this methodology, was interpreted through the parameter β_{li}. Genotypes with broad or general adaptability have $\beta_{li} = 1$; genotypes with specific adaptability to favorable environments, $\beta_{li} > 1$; and genotypes with specific adaptability to unfavorable environments, $\beta_{li} < 1$. Stability was analyzed using the coefficient of determination R^2_{Ti} according to the Equation 2.

$$R^2_{Ti} = \frac{(SS_{Total} - SS_{Erros})}{SS_{Total}} \quad (2)$$

which classified genotypes into: genotypes with high stability or predictability, greater than 70%; and genotypes with low stability or predictability, lower than 70%. The intercept β_{0i} was estimated by the median of all: $\beta_{0i} = Y_{ij} - \beta_{lj} I_j$.

The Lin & Binns (1998) methodology modified by Carneiro (1998) adopts as stability estimate the mean square of the distance between the genotype average and the maximum average response for all locations, called the maximum superiority measure (P_i). Thus, the shorter the distance between the response of the genotype and the response of the maximum-yield genotype in the various environments, the lower the P_i and the more stable the genotype. P_i was estimated according to the Equation 3.

$$P_i = \frac{\sum_{j=1}^{a}(Y_{ij} - M_j)}{2e} \quad (3)$$

where: P_i - estimate of the adaptability and stability parameter of genotype “i”; Y_{ij} - yield of genotype “i” in the environment “j”; M_j - maximum response observed among all genotypes in the environment “j”; e - number of environments. Later, Carneiro (1998) made some modifications to the method so that the recommendations were more comprehensive. Thus, P_i was decomposed into P_{if} and P_{iu}, for favorable and unfavorable environments, respectively, which were estimated according to the Equations 4 and 5.

$$P_{if} = \frac{\sum_{j=1}^{f}(Y_{ij} - M_j)}{2f} \quad (4)$$

$$P_{iu} = \frac{\sum_{j=1}^{d}(Y_{ij} - M_j)}{2u} \quad (5)$$

where: f - number of favorable environments; u - number of unfavorable environments.

The additive main effects and multiplicative interaction (AMMI) model (Zobel et al., 1988), which represents a linear and bilinear, unilinear and multivariate model, uses analysis of variance to investigate the additive main effects of genotypes and environments and principal component analysis (PCA) to investigate the multiplicative effect of the G × E interaction. The analysis considered effects of genotypes and environments as fixed and the model according to the Equation 6.

$$Y_{ij} = \mu + g_i + e_j + \sum_{k=1}^{n} \lambda_k \gamma_{ik} \alpha_{jk} + \rho_{ij} + \varepsilon_{ij} \quad (6)$$

where: Y_{ij} - average response of genotype i in environment j; μ - overall average; g_i - fixed effect of genotype i (i =1, 2, ..., g); e_j - fixed effect of environment j (j = 1, 2, ..., e); λ_k - k-th singular value of GE (scalar); γ_{ik} - element corresponding to the i-th genotype in the singular vector γ_k (singular vector column); α_{jk} - element corresponding to the j-th environment in the α_k vector (singular vector row); ρ_{ij} - residual of PCA present in the SS of the G × E interaction (noise portion); ε_{ij} - average experimental error, assumed independently; k - index that refers to the principal components of the PCA applied to the GE matrix. Therefore, k = 1, 2, ..., p, where p is the GE matrix rank, where: p - minimum between (g-1) and (e-1); n - number of principal components selected to describe the pattern of the G × E interaction.

For the selection of the best AMMI model, that is, the number of components to be retained in the model, the posdictive approach was adopted, using Cornelius F_R test (Piepho, 1995), which evaluates the significance of the residual associated with each component of the interaction.

The results of the AMMI analysis are graphically presented in biplot. For cases where the model encompasses only the first component of the principal component analysis of the interaction (PCI1), the AMMI1 biplot is used for interpretation, in which the abscissa axis represents the main effects (averages of genotypes and environments) and the ordinate axis represents the scores of genotypes and environments related to the PCI1. The interpretation of a biplot regarding the G × E interaction is made by observing the magnitude and sign of the scores of genotypes and environments for the component(s) that represent the interaction. Thus, low scores (close to zero) are specific to genotypes and environments that contribute little to the interaction, characterizing them as stable.

The adaptability and stability analyses of Theil (1950) and Lin & Binns (1998) modified by Carneiro (1998) were performed through the computer program GENES (Cruz, 2006), while the AMMI methodology was performed using the computer program SAS, with the routine implemented by Duarte & Vencovsky (1999).

Results and Discussion

The joint analysis of variance for grain yield indicated that the effects of environments and the genotypes × environments interaction (G × E) were significant (Table 3). The existence of significant G × E interaction indicates the need to analyze the adaptability and stability of genotypes in order to identify specific or general adaptations and stability of genotypes and environments.

The effects of environments were responsible for most of the variation (87.77%), followed by the genotypes effects (1.29%) and those of the G × E interaction (10.94%). These results were similar to those reported by Araméndiz-Tatis et al. (2021), who verified that the effects of the environment, genotypes and G × E interaction were responsible for explaining 71.78, 12.02, and 16.20% of the variation. The greater variation of the environmental factor in the present study as compared with the study of Araméndiz-Tatis et al. (2021) is due to the large edaphoclimatic differences between the environments studied here, which encompass three biomes with completely different conditions.

According to Theil (1950) methodology, all genotypes studied showed general or broad adaptability (β_{li} = 1), demonstrating that they can be cultivated in all studied environments (Table 4). This fact may be due to the presence of a simple interaction detected by the method, explained

Table 4. Average grain yield (kg ha^{-1}) and estimates of adaptability (β_{1i}) and stability (R^2_{Ti}) parameters of 20 erect/semierect cowpea genotypes evaluated in ten environments in the Mid-North region of Brazil, according to the methodology of Theil (1950), in the agricultural years of 2010 and 2011.

Genotypes	Average (kg ha^{-1})	B_{1i}	R^2_{Ti} (%)
1-MNC02-675F-4-9	1,149.66	0.93^{ns}	96.67
2-MNC02-675F-4-2	1,188.33	0.92^{ns}	93.16
3-MNC02-675F-9-2	1,140.67	1.02^{ns}	94.00
4-MNC02-675F-9-3	1,182.31	1.04^{ns}	87.53
5-MNC02-676F-3	1,262.27	1.18^{ns}	89.14
6-MNC02-682F-2-6	1,131.33	1.06^{ns}	94.21
7-MNC02-683F-1	1,154.69	0.83^{ns}	90.16
8-MNC02-684F-5-6	1,171.27	0.96^{ns}	94.11
9-MNC02-725F-3	1,058.47	0.97^{ns}	92.83
10-MNC02-736F-7	1,073.00	1.10^{ns}	91.49
11-MNC02-737F-5-1	1,068.09	0.89^{ns}	83.09
12-MNC02-737F-5-4	1,184.30	1.10^{ns}	84.26
13-MNC02-737F-5-9	1,200.95	0.95^{ns}	87.79
14-MNC02-737F-5-10	1,075.30	0.84^{ns}	78.26
15-MNC02-737F-5-11	1,188.33	1.13^{ns}	93.00
16-MNC02-737F-11	1,162.61	0.95^{ns}	88.90
17-BRS Tumucumaque	1,316.96	1.01^{ns}	79.49
18-BRS Cauamé	1,210.04	1.02^{ns}	96.02
19-BRS Itaim	1,122.39	1.04^{ns}	92.10
20-BRS Guariba	1,247.50	1.00^{ns}	90.27
Overall average (kg ha^{-1})	1,164.41		

^{ns} not significant by Student test.

Table 3. Summary of the joint analysis of variance for the grain yield (kg ha^{-1}) trait of erect/semierect cowpea genotypes, evaluated in ten environments of the Mid-North region of Brazil, in the agricultural years of 2010 and 2011.

Sources of variation	Degrees of freedom	Medium square	%$SS_T$$^{(1)}$ or $SS_{GE/PCII}$$^{(2)}$	%SS_{GE}
Genotypes (G)	19	45060.26^{ns}	1.29$^{(1)}$	-
Environments (E)	9	6466028.63**	87.77$^{(1)}$	-
G × E	171	42416.76**	10.94$^{(1)}$	-
PCI1	27	86297.60**	32.12$^{(2)}$	32.12
Residual $_{AMMI}$	144	34189.10^{ns}		67.87
Average error/r$^{(3)}$	322	42916.50		
CV (%)			17.68	

(1) Percentage of the sum of total squares. (2) Percentage of the sum of the genotypes × environments interaction captured by PCI1 (principal component of the interaction). (3) Number of repetitions. **Significant at 1% probability level by F_R test. ^{ns} Not Significant; SS: sum of squares.

by the linear behavior of the genotypes in the environments. Regarding the stability parameter (R^2_{Ti}), the results showed that all genotypes have high yield stability (R^2_{Ti} > 70.0%), hence being predictable for cultivation under different environmental conditions, and that the genotypes behaved linearly under the variations in the environments (Table 4). The genotypes BRS Cauamé and MNC02-675F-4-9 stood out in terms of stability, with the highest estimates of R^2_{Ti}, above 95.0%. This demonstrates the low sensitivity of this method in the differentiation of genotypes for stability and adaptability, as observed by Nascimento et al. (2010).

Stability analyses performed by the Lin & Binns (1998) methodology modified by Carneiro (1998) (Table 5) showed that the genotype MNC02-676F-3 obtained the lowest estimates of the general P_i (49.40) and P_{if} (23.37) parameters, and also had average yield similar to those of the controls BRS Tumucumaque, BRS Guariba and BRS Cauamé. This highlights that this genotype has high yield predictability and responds well to favorable environments, so it can be recommended for farmers who adopt more advanced technologies. In addition to the genotype mentioned above, three others stood out with behaviors also predictable for favorable environments, namely: BRS Cauamé, BRS Guariba and MNC02-736F-7. It is interesting to note that the genotypes MNC02-675F-4-2 and MNC02-737F-5-11 obtained high yields; however, they reached medium levels of general P_i and P_{if} and low level of P_{iu}, probably due to high but positive interactions, which contributed for these genotypes to show specific adaptations to favorable environments. When evaluating the yield of cowpea cultivars under limestone doses, Almeida et al. (2021) observed that the cultivar BRS Guariba had the highest demand in terms of soil fertility to obtain maximum yield. This result is in line with what was observed in the present study, in which BRS Guariba was one of those which had highest adaptability and stability in favorable environments by the Lin & Binns (1998) methodology modified by Carneiro (1998).

Nunes et al. (2014), using the Lin & Binns (1998) methodology modified by Carneiro (1998) to evaluate the adaptability and stability of cowpea genotypes, verified that some strains were more stable and productive in favorable environments compared with the cultivars used as a control, assisting breeding programs to increase cowpea yield. This same result was observed by Alves et al. (2020), who found that several strains showed high adaptability and yield stability both in favorable environments and in unfavorable environments. Cargnelutti Filho et al. (2007) observed that this methodology is sensitive to high yields, indicating cultivars with higher yield, being a more robust and reliable method for the indication of cultivars in favorable environments.

The genotypes with the lowest P_{iu} parameters were: BRS Tumucumaque, MNC02-683F-1 and MNC02-737F-5-4. These also had yields very close to or higher than the overall average of the tests, indicating that they are stable and responsive to environments whose edaphoclimatic factors are limiting. These genotypes, therefore, represent a good option for production in systems with lower technological levels or under more limiting environmental conditions, as in the Caatinga biome. Santos et al. (2015) and Alves et al. (2020) also verified, through the Lin & Binns (1998) methodology modified by Carneiro (1998), that the cultivar BRS Tumucumaque was

Table 5. Average grain yield (kg ha^{-1}) and estimates of the general superiority (P_i), superiority in favorable environments (P_{if}) and superiority in unfavorable environments (P_{iu}) parameters of 20 erect/semierect cowpea genotypes evaluated in ten environments in the Mid-North region of Brazil, in rainfed cultivation, according to the Lin & Binns (1998) methodology modified by Carneiro (1998).

Genotype	Average (kg ha^{-1})	General P_i	Order (General P_i)	P_{if}	Order P_{if}	P_{iu}	Order P_{iu}
1-MNCO2-675F-4-9	1,149.66	103.18	7	167.33	10	60.42	11
2-MNCO2-675F-4-2	1,188.33	104.70	9	149.45	8	74.88	15
3-MNCO2-675F-9-2	1,140.67	108.63	13	132.50	7	92.72	18
4-MNCO2-675F-9-3	1,182.31	103.59	8	188.47	13	47.01	9
5-MNCO2-676F-3	1,262.27	49.40	1	23.37	1	66.74	13
6-MNCO2-682F-2-6	1,131.33	95.43	6	120.53	5	78.70	16
7-MNCO2-683F-1	1,154.69	105.56	10	226.07	15	25.22	2
8-MNCO2-684F-5-6	1,171.27	87.07	5	166.08	9	34.39	5
9-MNCO2-725F-3	1,058.47	145.94	18	231.14	16	89.13	17
10-MNCO2-736F-7	1,073.00	131.68	17	115.49	4	142.48	20
11-MNCO2-737F-5-1	1,068.09	172.91	19	337.43	19	63.24	12
12-MNCO2-737F-5-4	1,184.30	129.89	16	280.97	18	29.16	3
13-MNCO2-737F-5-9	1,200.95	108.22	12	225.51	14	30.03	4
14-MNCO2-737F-5-10	1,075.30	186.70	20	404.06	20	41.80	8
15-MNCO2-737F-5-11	1,188.33	112.11	14	170.39	11	73.26	14
16-MNCO2-737F-11	1,162.61	121.16	15	241.96	17	40.63	7
17-BRS Tumucumaque	1,316.96	75.73	4	171.04	12	12.20	1
18-BRS Cauamé	1,210.04	65.79	3	76.60	2	58.58	10
19-BRS Itaim	1,122.39	105.89	11	125.30	6	92.95	19
20-BRS Guariba	1,247.50	61.61	2	98.75	3	36.85	6
Overall average (kg ha^{-1})	1,164.41						

one those which had the greatest stability and adaptability in unfavorable environments. This indicates the high tolerance of this genotype to environmental stress conditions.

For the AMMI method (Table 6 and Figure 1), although the G × E interaction was decomposed into nine principal components of the interaction (PCI), only the first component (PCI1) had its residual not significant by Cornelius F_R test, suggesting the selection of the AMMI1 model. PCI1 explained 32.12% of the sum of squares of the G × E interaction ($SS_{G \times E}$). This denotes that the entire pattern adjacent to the G × E interaction was concentrated in the first component. As 32.12% of the $SS_{G \times E}$ corresponds to the pattern adjacent to the G × E interaction and of agronomic importance, the remainder (67.88%) of the $SS_{G \times E}$ represents noise, which is negligible and, therefore, can be discarded when estimating the responses of genotypes in the environment. Thus, the graphical interpretation of adaptability and stability was performed considering only PCI1, via AMMI1 biplot (Figure 1).

As for the additive main effects of genotypes and environments, shown by the horizontal dispersion of the AMMI1 biplot (Figure 1), it was observed that the genotypes varied less than the effects of environments and G × E interaction, the latter being shown in the vertical of the AMMI1 biplot. This indicates that the effects of environments interacted strongly with macro-environmental or micro-environmental factors; consequently, the multiplicative effect of the G × E interaction was also quite dispersed. This same pattern was observed by Araméndiz-Tatis et al. (2021), who verified that, by the AMMI methodology, environmental effects were the main responsible for the variation.

The variation observed in the environments probably occurred due to the strong interaction between years and locations, caused mainly by the occurrence of abiotic stresses, with predominance of rainfall irregularities and presence of dry spells. In the present study, this condition occurred mainly in the environments of the Caatinga biome. Similar behavior was verified by Rocha et al. (2007), when evaluating other cowpea genotypes in northeastern Brazil.

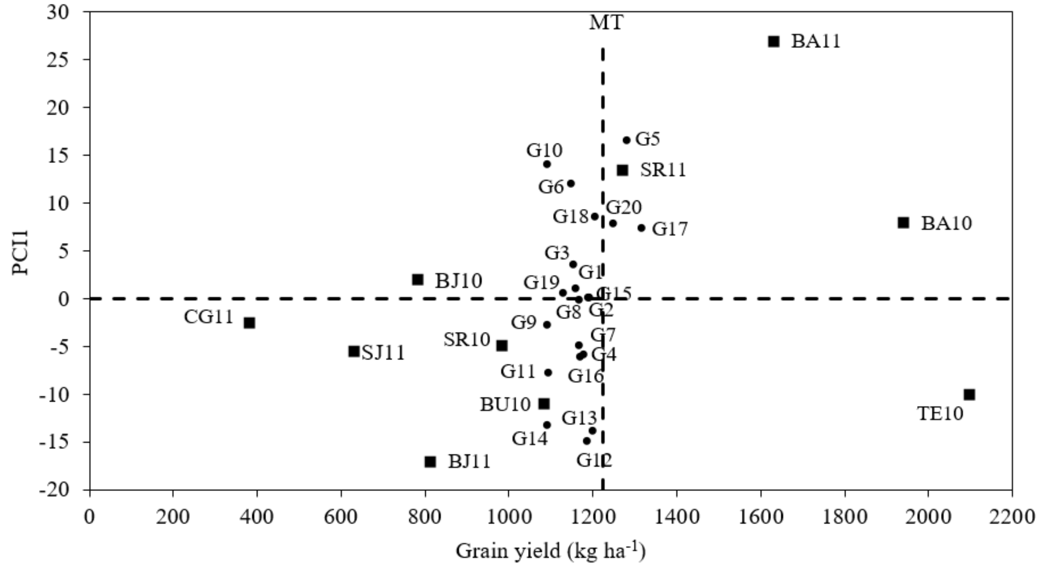
The most stable genotypes (5 and -5) were: G1-MNC02-675F-4-9, G2-MNC02-675F-4-2, G3-MNC02-675F-9-2, G9-MNC02-725F-3, G15-MNC02-737F-5-11 and G19-BRS Itaim; however, they had averages slightly below that of the controls (1,224 kg ha^{-1}) (Table 6 and Figure 1). These genotypes, for having low interactions with the environments, can be indicated for all biomes studied. G2-MNC02-675F-4-2 and G15-MNC02-737F-5-11 stand out because they had averages closer to the controls average and, at the same time, were predictable. The most unstable genotypes were G5-MNC02-676F-3, G12-MNC02-737F-5-4, G13-MNC02-737F-5-9, and G14-MNC02-737F-5-10, with G5-MNC02-676F-3 being the only one with a average above the controls average.

Genotypes G5-MNC02-676F-3, G17-BRS Tumucumaque and G20-BRS Guariba showed averages above the controls average, and among these, BRS Tumucumaque had the highest adaptability and yield stability (Table 6 and Figure 1). The cultivars BRS Guariba and BRS Tumucumaque showed specific

Table 6. Predicted averages for grain yield (kg ha^{-1}) by the AMMI1 model, considering only the first component of the interaction (PCI1) obtained from the evaluation of 20 cowpea genotypes in ten environments in the Mid-North region of Brazil.

Code	Genotype	Environment[(3)]										Overall average
		TE10	BJ10	BJ11	SR10	SR11	BA10	BA11	SJ11	BU10	CG11	
G1	MNCO2-675F-4-9[(1)]	2,042.93	771.42	789.47	955.62	1,264.31	1,966.75	1,693.02	636.18	1,013.57	363.31	1,149.66
G2	MNCO2-675F-4-2[(1)]	2,096.26	806.70	855.56	1,002.14	1,280.82	1,991.60	1,688.20	684.51	1,070.72	406.77	1,188.33
G3	MNCO2-675F-9-2[(1)]	2,017.90	766.15	750.47	938.03	1,279.58	1,972.89	1,731.63	616.63	984.37	349.07	1,140.67
G4	MNCO2-675F-9-3[(1)]	2,140.96	788.95	944.42	1,023.31	1,198.12	1,937.79	1,531.74	711.90	1,128.61	417.34	1,182.31
G5	MNCO2-676F-3[(1)]	2,023.10	914.68	654.32	997.25	1,577.19	2,204.19	2,198.54	661.55	959.29	432.61	1,262.27
G6	MNCO2-682F-2-6[(1)]	1,935.40	773.73	604.28	889.49	1,380.86	2,032.49	1,939.31	559.10	882.85	315.82	1,131.33
G7	MNCO2-683F-1[(1)]	2,104.86	763.28	900.95	991.15	1,183.30	1,918.15	1,529.24	678.70	1,090.32	386.94	1,154.69
G8	MNCO2-684F-5-6[(1)]	2,084.15	788.49	847.78	987.74	1,256.26	1,969.87	1,656.44	670.72	1,059.91	391.33	1,171.27
G9	MNCO2-725F-3[(1)]	1,993.14	670.65	775.74	886.62	1,110.51	1,836.54	1,479.00	572.27	974.56	285.65	1,058.47
G10	MNCO2-736F-7[(1)]	1,858.50	719.69	511.22	821.20	1,350.59	1,991.65	1,936.04	488.54	801.11	251.41	1,073.00
G11	MNCO2-737F-5-1[(1)]	2,045.55	670.37	865.40	919.17	1,055.45	1,805.84	1,361.70	610.08	1,038.10	309.26	1,068.09
G12	MNCO2-737F-5-4[(1)]	2,224.20	772.13	1,098.43	1,068.85	1,077.22	1,853.18	1,292.63	767.42	1,233.01	445.89	1,184.30
G13	MNCO2-737F-5-9[(1)]	2,228.42	791.66	1,091.81	1,078.84	1,112.69	1,891.57	1,346.21	775.88	1,233.98	458.48	1,200.95
G14	MNCO2-737F-5-10[(1)]	2,096.63	667.43	954.68	949.90	996.31	1,771.70	1,238.75	646.19	1,100.60	330.83	1,075.30
G15	MNCO2-737F-5-11[(1)]	2,093.90	807.24	851.16	1,000.88	1,284.38	1,993.83	1,695.20	682.96	1,067.75	406.00	1,188.33
G16	MNCO2-737F-11[(1)]	2,124.70	768.44	931.17	1,005.45	1,173.19	1,914.83	1,501.80	694.47	1,113.25	398.76	1,162.61
	Average of strains	2,069.41	765.06	839.18	969.73	1,223.80	1,941.43	1,613.72	653.57	1,047.00	371.84	1,149.47
G17	BRS Tumucumaque[(2)]	2,156.00	951.27	855.32	1,093.86	1,513.62	2,185.17	2,021.21	767.77	1,112.54	512.88	1,316.96
G18	BRS Cauamé[(2)]	2,036.18	847.34	724.28	980.02	1,426.20	2,090.40	1,952.55	652.35	989.36	401.74	1,210.04
G19	BRS Itaim[(2)]	2,020.80	742.96	771.82	931.10	1,229.26	1,934.63	1,650.49	612.30	992.78	337.72	1,122.39
G20	BRS Guariba[(2)]	2,080.94	883.10	775.39	1,021.39	1,452.62	2,120.98	1,968.35	694.61	1,036.02	441.58	1,247.50
	Average of controls	2,073.48	856.17	781.70	1,006.59	1,405.43	2,082.80	1,898.15	681.76	1,032.68	423.48	1,224.22
	Overall Average	2,070.22	783.28	827.68	977.10	1,260.12	1,969.70	1,670.60	659.21	1,044.14	382.17	1,164.42
	CV (%)	15.03	29.18	28.27	28.74	30.47	25.32	29.71	21.19	11.63	24.81	24.43

[(1)] Strains; [(2)] Controls; [(3)]TE10: Teresina-PI 2010; BJ10: Bom Jesus-PI 2010; BJ11: Bom Jesus-PI 2011; SR10: São Raimundo das Mangabeiras-MA 2010; SR11: São Raimundo das Mangabeiras-MA 2011; BA2010: Balsas-MA 2010; BA11: Balsas-MA 2011; SJ11: São João-PI 2011; BU10: Buriti-MA 2010 and CG11: Campo Grande-PI 2011.



Genotypes: G1 = MNC02-675F-4-9, G2 = MNC02-675F-4-2, G3 = MNC02-675F-9-2, G4 = MNC02-675F-9-3, G5=MNC02-676F-3, G6=MNC02-682F-2-6, G7=MNC02-683F-1, G8=MNC02-684F-5-6, G9=MNC02-725F-3, G10 = MNC02-736F-7, G11 = MNC02-737F-5-1, G12 = MNC02-737F-5-4, G13 = MNC02-737F-5-9, G14 = MNC02-737F-5-10, G15 = MNC02-737F-5-11, G16 = MNC02-737F-11, G17 = BRS Tumucumaque, G18 = BRS Cauamé, G19 = BRS Itaim and G20 = BRS Guariba. Environments: TE10 = Teresina-PI 2010, BJ10 = Bom Jesus-PI 2010, BJ11 = Bom Jesus-PI 2011, SR10 = São Raimundo das Mangabeiras-MA 2010, SR11 = São Raimundo das Mangabeiras-MA 2011, BA10 = Balsas-MA 2010, BA11 = Balsas-MA 2011, BU10 = Buriti-MA 2010, SJ11 = São João do Piauí-PI 2011 and CG11 = Campo Grande do Piauí-PI 2011. MT = Average of controls.

Figure 1. AMMI1 biplot for grain yield data of 20 erect/semierect cowpea genotypes, evaluated in ten environments of the Mid-North region of Brazil, in the agricultural years of 2010 and 2011.

adaptation to favorable environments (BA10, BA11, and SR11) (positive scores). The highest yields of these cultivars have been obtained in Cerrado biome environments, where cultivation has higher technological level. Rocha et al. (2007), studying the adaptability and stability of cowpea genotypes in northeastern Brazil, also pointed to the cultivar BRS Guariba as more adapted to favorable environments. Almeida et al. (2017), evaluating the effect of sowing times on the grain yield of cowpea cultivars in the Cerrado of Minas Gerais, observed that BRS Tumucumaque was, on average, the cultivar with the highest grain yield. Santos et al. (2015) also observed that the cultivars BRS Tumucumaque and BRS Guariba were the most productive in the Brazilian Midwest region (Cerrado).

Different AMMI methodology classifications were observed for G5-MNC02-676F-3 and G17-BRS Tumucumaque by the Lin & Binns (1998) methodology modified by Carneiro (1998), which considered the former as of general adaptability, denoting high stability, and the latter as of better adaptability to unfavorable environments. For G5-MNC02-676F-3, the results between the two methodologies were similar regarding the fact that this genotype showed better adaptation to favorable environments.

Regarding the behavior of the environments, the most stable were BJ10, SR10, and CG11, but were associated with low yields, hence being considered environments not indicated for cultivation. TE10, BA10, and BA11 environments had the highest averages; however, TE10 was relatively more unstable than BA10 and BA11 (Table 6 and Figure 1). It can be concluded that, among the biomes and experiments locations, the Cerrado and Balsas/MA are the most indicated for cowpea in the Mid-North region of Brazil. Regarding the specific adaptation between genotypes and environments, G5-MNC02-676F-3 showed specific adaptation to the environment SR11, G9-MNC02-725F-3 to SR10 and the genotypes G11-MNC02-737F-5-1 and G14-MNC02-737F-5-10 to BU10 (Figure 1).

A possible explanation for the differences in terms of results between the Lin & Binns (1998) methodology modified by Carneiro (1998) and Theil (1950) methodology, as compared with the AMMI methodology, is that they explore the entire sum of squares of the interaction, while AMMI explores only one pattern part, which in the case of the present study corresponds to 32.0% (Table 3), that is, the majority (68.0%) is considered as noise by this methodology.

Conclusions

The association of methodologies, especially that of Lin & Binns (1998) methodology modified by Carneiro (1998) and AMMI, is necessary to complement the interpretation of the adaptability and stability of cowpea genotypes in the Mid-North region of Brazil, assisting in decision making.

In the Lin & Bins (1998) methodology modified by Carneiro (1998), the MNCO2-676F-3 strain was identified with greater general stability and for favorable environments, while for unfavorable environments the cultivar BRS Tumucumaque stood out.

Using the AMMI methodology, the genotypes with greater yield stability were the cultivars BRS Tumucumaque and BRS Guariba and the strain G5-MNC02-676F-3, showing specific adaptation to favorable environments.

Theil (1950) methodology has low sensitivity in evaluating the adaptability and stability of cowpea genotypes. Using this methodology, the BRS Cauamé and MNC02-675F-4-9 genotypes were the most predictable and presented the highest yield stability.

Among the biomes and locations, the Cerrado and Balsas/MA are the most suitable for the cultivation of cowpea in the Mid-North region of Brazil, presenting the highest yields and comprising environments with the greatest yield stability.

Compliance with Ethical Standards

Author contributions: Conceptualization: CLCS, MMR, KJDS, LBL; Data curation: CLCS, MMR, FLCM; Formal analysis: CLCS, MMR, KJDS; Investigation: CLCS, MMR, KJDS, APC; Methodology: CLCS, MMR, KJDS; Project administration: MMR, LBL; Resources: MMR, KJDS; Supervision: MMR, LBL; Validation: MMR, KJDS, APC; Writing – original draft: CLCS, FLCM; Writing – review & editing: MMR, KJDS, APC, LBL.

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