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Adaptability and stability with multivariate definition of macroenvironments for wheat yield in Rio Grande do Sul

Abstract – The objective of this work was to evaluate the adaptability, stability, and environmental stratification of wheat (*Triticum aestivum*) grown in 20 environments, in the state of Rio Grande do Sul, Brazil. The experiments were performed during four crop years, in five wheat growing regions, considering 20 distinct growing environments. In the presence of genotype x environment (GxE) interaction, the additive main effects and multiplicative interaction analysis (AMMI) method was used. This method combines variances of additive effects of genotypes and environments with the multiplicative effects of GxE interaction, and the obtained scores are displayed in biplot graphs, using the principal component analysis. The environments stratified by the factor analysis, and the macroenvironments were defined according to grain yield behavior. The patterns of adaptability and phenotypic stability for genotypes 'BRS 327', 'BRS 331', 'Fundacep Raízes', 'BRS 328', and 'BRS Guamirim' were obtained through the multivariate biometric approaches AMMI and the factor analysis. The definition of macroenvironments is intrinsic to peculiarities of the crop year in the state of Rio Grande do Sul, and there is similarity between the municipalities of Santo Augusto, Cachoeira do Sul, and São Luiz Gonzaga, as well as between Cachoeira do Sul and São Gabriel.

Index terms: *Triticum aestivum*, AMMI method, genotype x environment interaction, multiplicative model, principal component analysis.

Adaptabilidade e estabilidade com definição multivariada de macroambientes para o rendimento de trigo no Rio Grande do Sul

Resumo – O objetivo deste trabalho foi avaliar a adaptabilidade, a estabilidade e a estratificação ambiental de trigo (*Triticum aestivum*) em 20 ambientes, no estado do Rio Grande do Sul, Brasil. Os experimentos foram realizados durante quatro anos agrícolas, em cinco regiões de cultivo, tendo-se considerado 20 ambientes distintos. Na presença da interação genótipo x ambiente (GxA), utilizou-se o método “additive main effects and multiplicative interaction analysis” (AMMI). Este método combina as variâncias dos efeitos aditivos dos genótipos e dos ambientes com os efeitos multiplicativos da interação GxA, e os escores obtidos são mostrados em gráficos biplot, com uso de análise de componentes principais. A estratificação dos ambientes foi obtida com análise fatorial, e os macroambientes foram definidos de acordo com o comportamento do rendimento de grãos. Os padrões de adaptabilidade e estabilidade fenotípica dos genótipos 'BRS 327', 'BRS 331', 'Fundacep Raízes', 'BRS 328' e 'BRS Guamirim' foram obtidos por meio dos métodos biométricos multivariados AMMI e análise de fatores. A definição de macroambientes é

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intrínseca a peculiaridades dos anos agrícolas, no estado do Rio Grande do Sul, e há similaridade entre os municípios de Santo Augusto, Cachoeira do Sul e São Luiz Gonzaga, bem como entre Cachoeira do Sul e São Gabriel.

Termos para indexação: *Triticum aestivum*, método AMMI, interação genótipo x ambiente, modelos multiplicativos, análise de componentes principais.

Introduction

The wheat (*Triticum aestivum* L.) production in Brazil does not meet the internal demand, as the country depends on importing more than five million tonnes of grain per year. In the crop season of 2016-2017, the state of Rio Grande do Sul produced more than 6.8 million tonnes of grains, which represent 37% of the national production, with an average yield of 3,214 kg ha^{-1} (Oliveira Neto & Santos, 2017). According to Szareski et al. (2017), this state has a great variation of grain production due to effects of growing environments (88%), genotypes (12%) and genotype x environment (GxE) interactions (26%).

Field trials in multiple environments may quantify the effects of the GxE interaction, which not only can abruptly modify the genotype performance in response to the growing environments (Ayalneh et al., 2013; Mohamed, 2013; Bornhofen et al., 2017; Carvalho et al., 2017; Szareski et al., 2018a), but also define which environments are favorable or unfavorable for cropping (Carvalho et al., 2014; Szareski et al., 2018b). Therefore, for the proper recommendation of broadly or specifically adapted cultivars to particular environments, it is necessary to identify the nature and magnitude of the GxE interaction (Bornhofen et al., 2017; Possato Junior et al., 2017; Szareski et al., 2018c). In order to minimize the interaction effects, it is possible to subdivide heterogeneous regions into specific environments with smaller and homogeneous cropping areas. This is suited to the new genetic breeding tendency of developing genotypes for specific environments with peculiar features (Mohammadi et al., 2007; Munaro et al., 2014; Nardino et al., 2018). Nonetheless, strategies regarding the selection of stable and widely adapted genotypes for the tested environments (Eberhart & Russell, 1966) are still common.

Studies on the adaptability, stability, and environmental stratification are required to identify superior wheat genotypes and macroenvironments (Albrecht et al., 2007; Condé et al., 2010; Franceschi et al., 2010; Carvalho et al., 2018).

The objective of this work was to evaluate the adaptability, stability, and environmental stratification of wheat grown in 20 environments in the state of Rio Grande do Sul, Brazil.

Materials and Methods

The experiments were carried out for four years (2012, 2013, 2014, and 2015), in five regions of the state of Rio Grande do Sul, Brazil. Isolated situations were considered as 20 growing environments (Table 1). The experimental design was randomized complete block with three replicates, in a factorial arrangement, with 20 growing environments and 12 wheat genotypes, recommended for Rio Grande do Sul: G_1, 'Ametista'; G_2, 'BRS 327'; G_3, 'BRS 328'; G_4, 'BRS 331'; G_5, 'BRS Guamirim'; G_6, 'CD 123'; G_7, 'FPS Nitron'; G_8, 'Fundacep 52'; G_9, 'Fundacep Bravo'; G_{10}, 'Fundacep Cristalino'; G_{11}, 'Fundacep Nova Era'; and G_{12}, 'Fundacep Raízes'.

The experimental units consisted of five rows of 5.0 m length, 0.2 m apart. Seeding was carried out in the first half of June (standard for all growing environments). The population density used was 330 viable seed m^{-2}, and the base fertilization, applied at the full-tillering stage, consisted of 250 kg ha^{-1} N-P_2O_5-K_2O (08-25-20), at sowing, and 50 kg ha^{-1} N topdressing (urea at 46% N). The control of weeds, pest insects, and diseases was carried out to minimize the biotic effects in the experiment. Grain yield was measured by harvesting the useful area of each experimental unit (5 m^2), and grain mass was adjusted to 13% humidity.

The analyses of variance were performed individually for each growing environment to verify the assumptions of the model (Ramalho et al., 2000). Subsequently, a joint analysis of variance was done to identify the presence of interaction between environments and wheat genotypes. In the presence of GxE interaction, the AMMI method (additive main effects and multiplicative interaction analysis) was used. This method combines the variances of additive effects of genotypes and growing environments with the multiplicative effects of GxE interaction, and the obtained scores are displayed in biplot graphs suitable for principal component analysis (Zobel et al., 1988).

The statistical model was

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

in which: Y_{ij} is the i[th] genotype average response (i = 1, 2, 3, ..., g) at the j[th] growing environment (j = 1, 2, 3, ..., e); μ is the mean of genotypes in all environments (overall mean); g_i is, the main effect of the i genotype; e_j is the main effect of the j environment; λ_k, y_{ik}, and α_{jk} are the terms of singular decomposition of the GE matrix gxe={[(ge)ij]}, which express and capture the pattern associated to the interaction between I genotype and j environment, being (ge)ij the data additivity deviation (Y_{ij}) in relation to g_i and e_j principal effects; ρ_{ij} is the additional error to be eliminated from the GxE interaction analysis; and ε_{ij} is the experimental error (Duarte &Vencovsky, 1999).

Afterward, the factorial analysis was carried out with the objective of stratifying the growing environments and defining the macroenvironments. This method follows the model:

$$X_j = I_{j1}F_1 + I_{j2}F_2 + ... + I_{jm}F_m + \varepsilon_j,$$

in which: X_j refers to the trait of interest (j = 1,2,... v); I_{jk} refers to the source of variation environments (j[th]) associated to the trait of interest and the number of factors (k[th]), when k = 1,2,... m (number of common factors); F_k refers to the j[th] common factor; and ε_j refers to the error associated to a specific factor (Murakami & Cruz, 2004). The statistical analysis was performed with the software Genes (Cruz, 2013) and R (R Core Team, 2015).

Results and Discussion

The analysis of variance showed significant interactions between growing environments and wheat genotypes for grain yield, at 5% of probability (Table 2). The experiment evidenced a coefficient of variation of 11.7%. The AMMI method showed the variance estimates for genotypes, environments, and GxE interaction, which allows of the selection and indication of the best genotypes for specific environments (Yokomizo et al., 2013). The closeness of scores to the first axis of the principal component analysis (EPCA) allows the AMMI method to explain the total variation of the character. This method

Table 1. Description of the growing environments evaluated in 20 locations of Rio Grande do Sul state, Brazil.

Initials	Growing season	Environment	Coordinates	Altitude (m)	Type of soil[1]
E_1	2012	Cachoeira do Sul	30º17'52" S, 52º57'54" W	113 m	Haplic Eutrophic Planosol
E_2	2012	Passo Fundo	28º13' 17" S, 52º19'39" W	709 m	Dystrophic Red Latosol
E_3	2012	Santo Augusto	27º54'47" S, 53º49'04" W	503 m	Dystroferric Red Latosol
E_4	2012	São Gabriel	30º20' 09" S, 54º10'21" W	159 m	Haplic Eutrophic Planosol
E_5	2012	São Luiz Gonzaga	28°24'42" S, 54°45'45" W	270 m	Dystrophic Red Latosol
E_6	2013	Cachoeira do Sul	30º17'52" S, 52º57'54" W	113 m	Haplic Eutrophic Planosol
E_7	2013	Passo Fundo	28º13' 17" S, 52º19'39" W	709 m	Dystrophic Red Latosol
E_8	2013	Santo Augusto	27º54'47" S, 53º49'04" W	503 m	Dystroferric Red Latosol
E_9	2013	São Gabriel	30º20' 09" S, 54º10'21" W	159 m	Haplic Eutrophic Planosol
E_{10}	2013	São Luiz Gonzaga	28°24'42" S, 54°45'45" W	270 m	Dystrophic Red Latosol
E_{11}	2014	Cachoeira do Sul	30º17'52" S, 52º57'54" W	113 m	Haplic Eutrophic Planosol
E_{12}	2014	Passo Fundo	28º13' 17" S, 52º19'39" W	709 m	Dystrophic Red Latosol
E_{13}	2014	Santo Augusto	27º54'47" S, 53º49'04" W	503 m	Dystroferric Red Latosol
E_{14}	2014	São Gabriel	30º20' 09" S, 54º10'21" W	159 m	Haplic Eutrophic Planosol
E_{15}	2014	São Luiz Gonzaga	28°24'42" S, 54°45'45" W	270 m	Dystrophic Red Latosol
E_{16}	2015	Cachoeira do Sul	30º17'52" S, 52º57'54" W	113 m	Haplic Eutrophic Planosol
E_{17}	2015	Passo Fundo	28º13' 17" S, 52º19'39" W	709 m	Dystrophic Red Latosol
E_{18}	2015	Santo Augusto	27º54'47" S, 53º49'04" W	503 m	Dystroferric Red Latosol
E_{19}	2015	São Gabriel	30º20' 09" S, 54º10'21" W	159 m	Haplic Eutrophic Planosol
E_{20}	2015	São Luiz Gonzaga	28°24'42" S, 54°45'45" W	270 m	Dystrophic Red Latosol

[1]Source: created with data of Streck et al. (2008) and Santos et al. (2013).

prioritize the maximization of the understanding of the data standard fraction, minimizing the effects of errors in the experimental conditions (Oliveira et al., 2003; Carvalho et al., 2016).

The first axis ($EPCA_1$) represented 45.4% (Figure 1) of the general effects of GxE interaction. When estimating adaptability and stability of *Triticum durum* L. genotypes, De Vita et al. (2010) achieved representativeness of 42% for GxE interaction effects by $EPCA_1$. Considering that interaction effects are abrupt on grain yield phenotypic expression, this result is justified by the large number of genes responsible for its expression, their low heritability, the continuous nature of the trait, and the great effect of environment (Yokomizo et al., 2013). Studies with 10 growing environments and 42 wheat genotypes showed representativeness of 86.2% for GxE interaction effects through $EPCA_1$ (Szareski et al., 2017). Hagos & Abay (2013) achieved 68% of representativeness by the $EPCA_1$ for wheat cropped in Northern Ethiopia.

When considering the contribution of the other axes of principal component, the significance was 5% of probability for $EPCA_2$ (15.3%), and $EPCA_3$ (10.9%), which makes it necessary to understand them for a greater reliability of inferences. For an adequate graphical representation of scores at the $EPCA_1$, $EPCA_2$, and $EPCA_3$ axes, the independence of these axes is necessary to provide smaller biases, and to maximize the correct interpretation of the inferences on growing environments and genotypes (Silveira et al., 2016).

The number of principal components required to explain and graphically represent the standard fraction of GxE interaction is variable and depends on the nature of the interaction, the number of observations associated to the experiment, and the magnitude of the mean square error in relation to interaction effects (Carvalho et al., 2016). Researches on *T. durum* evidenced the need of four principal components to explain the interaction effects (Rharrabti et al., 2003). Studies on *Trifolium repens* L. required three principal components (Tarakanovas & Sprainaitis, 2005). Campbell & Jones (2005) used three principal components for studying the fiber production of *Gossypium hirsutum* L.

Four situations may distinguish the tested genotypes with the AMMI method. The first one allows to join stable genotypes with grain yield above the experiment general average, with minimal contribution to GxE interaction. The second allows to group stable genotypes with grain yield below the general average. The third groups are unstable and specifically adapted genotypes with high grain yield. The fourth groups are unstable and specifically adapted genotypes with low grain yield (Carvalho et al., 2019; Szareski et al., 2019). Genotypes or growing environments closely located to the axe origin of the biplot graph are considered phenotypically stable. In contrast, when this distance increases (Table 3), the genotypes are considered unstable and highly influenced by GxE interaction.

The $AMMI_1$ biplot graph (Figure 1 A) represented 45.4% of the GxE interaction, evidencing stability in the environments E_{15} (São Luiz Gonzaga, 2014), E_5 (São Luiz Gonzaga, 2012), E_2 (Passo Fundo, 2012), E_7 (Passo Fundo, 2013), E_{18} (Santo Augusto, 2015), and E_{11} (Cachoeira do Sul, 2014), whose scores minimally contributed to GxE interaction. The environments E_7 (Passo Fundo, 2013), E_{11} (Cachoeira do Sul, 2014), and E_{18} (Santo Augusto, 2015) provided stability and also favored a high grain yield.

The genotypes G_1 ('Ametista'), G_2 ('BRS 327'), G_3 ('BRS 328'), G_4 ('BRS 331'), G_{10} ('Fundacep Cristalino'), and G_{12} ('Fundacep Raízes') suffered minor GxE

Table 2. Summary of the general analysis of variance and results for the AMMI method concerning 20 growing environments in the state of Rio Grande do Sul, Brazil, and 12 wheat (*Triticum aestivum*) genotypes.

Source of variation	DF	Sum of square	Square of means
Environment (E)	19	785,826,779.20	41,359,304.2*
Genotype (G)	11	55,271,813.40	5,024,710.30*
G x E interaction	209	160,892,327.90	769,819.80*
Blocks/Environment (E)	40	17,791,015.90	494,775.40
CV (%)		11.75	
R^2		0.91	
AMMI			
Source of variation	DF	Sum of square	Square of means
Environment (E)	19	18,692,633.00	1,699,330.27*
Genotype (G)	11	257,565,173.20	13,556,061.75*
G x E interaction	209	60,852,929.30	291,162.34*
$EPCA_1$	29	27,630,433.80	952,773.58*
$EPCA_2$	27	9,360,763.80	346,694.96 *
$EPCA_3$	25	6,661,846.30	266,473.85*
Error	672	62,664,028.40	93,250.04

DF, degree of freedom; CV, coefficient of variation; R^2, coefficient of determination; *Significant at 5% probability.

interaction effects. Genotypes with high stability do not necessarily have high grain yields (Franceschi et al., 2010; Bornhofen et al., 2017). Duarte & Vencovski (1999) reported that unstable genotypes with high grain yields should not be discarded due to their specific adaptability to certain growing environments. This is the case for G_1 ('Ametista'), G_2 ('BRS 327'), G_3 ('BRS 328'), G_5 ('BRS Guamirim'), G_7 ('FPS Nitron'), and G_8 ('Fundacep 52'), in the environments E_8 (Santo Augusto, 2013), E_9 (São Gabriel, 2013), E_{10} (São Luiz Gonzaga, 2013), E_{11} (Cachoeira do Sul, 2014), E_{13} (Santo Augusto, 2014) and E_{20} (São Luiz Gonzaga, 2015) (Figure 1 A).

The $AMMI_2$ biplot graph represented 15.3% of the effects attributed to GxE interaction (Figure 1 B), evidencing stability in the environments E_9 (São Gabriel, 2013), E_{14} (São Gabriel, 2014), and E_{10} (São Luiz Gonzaga, 2013). As to genotypes, minor GxE interaction effects were observed for G_9 ('Fundacep Bravo') and G_2 ('BRS 327'), and this last one had a grain yield greater than the overall mean. Specific adaptability was observed for G_4 ('BRS 331') in the

Table 3. Principal component scores of genotype x environment interactions using the AMMI method for the three explanatory axes (EPCA1, EPCA2, and EPCA3), regarding grain yield of 12 wheat (*Triticum aestivum*) genotypes grown in 20 environments in the state of Rio Grande do Sul, Brazil.

Initial	Genotype		Average (kg ha^{-1})	$EPCA_1$	$EPCA_2$	$EPCA_3$
G1	Ametista		4,151.1	2.0	-17.1	-2.4
G2	BRS 327		4,535.8	9.3	5.6	-14.7
G3	BRS 328		3,990.5	2.9	5.6	-14.9
G4	BRS 331		3,642.2	12.0	23.9	13.3
G5	BRS Guamirim		4,253.5	20.4	-28.0	22.4
G6	CD 123		3,506.4	20.1	-11.9	2.4
G7	FPS Nitron;		4,161.4	23.0	9.0	10.9
G8	Fundacep 52		4,236.4	-5.6	27.5	13.9
G9	Fundacep Bravo		3,860.7	-35.4	5.3	0.1
G10	Fundacep Cristalino		3,836.2	1.8	-11.6	-22.9
G11	Fundacep Nova Era		3,769.9	-48.7	-13.4	13.2
G12	Fundacep Raízes		3,902.2	-1.7	5.0	-21.2
Initial	Growing season	Environment	Average (kg ha^{-1})	$EPCA_1$	$EPCA_2$	$EPCA_3$
E_1	2012	Cachoeira do Sul	2,968.4	16.6	-28.1	3.4
E_2	2012	Passo Fundo	1,693.4	-1.8	-1.4	1.4
E_3	2012	Santo Augusto	2,202.5	-9.5	-14.1	-10.9
E_4	2012	São Gabriel	4,095.3	-5.1	-14.8	-11.7
E_5	2012	São Luiz Gonzaga	3,343.8	-1.3	-12.6	-2.8
E_6	2013	Cachoeira do Sul	5,279.6	-20.3	17.7	0.4
E_7	2013	Passo Fundo	4,935.3	-1.8	-4.0	8.7
E_8	2013	Santo Augusto	5,891.2	19.4	9.1	13.9
E_9	2013	São Gabriel	4,679.9	14.9	0.6	9.6
E_{10}	2013	São Luiz Gonzaga	4,279.1	6.2	3.3	-11.0
E_{11}	2014	Cachoeira do Sul	4,189.3	3.3	9.1	20.3
E_{12}	2014	Passo Fundo	3,300.7	-8.9	9.3	12.2
E_{13}	2014	Santo Augusto	4,844.1	4.7	-6.1	-13.0
E_{14}	2014	São Gabriel	4,252.0	-9.3	-1.8	-6.8
E_{15}	2014	São Luiz Gonzaga	3,480.3	0.9	3.3	12.0
E_{16}	2015	Cachoeira do Sul	4,451.3	-19.3	9.8	-11.3
E_{17}	2015	Passo Fundo	2,801.4	-28.2	-18.1	11.1
E_{18}	2015	Santo Augusto	4,787.2	-2.1	11.1	7.4
E_{19}	2015	São Gabriel	3,458.0	-7.4	21.4	-21.5
E_{20}	2015	São Luiz Gonzaga	4,811.2	48.8	6.3	-11.4

environments E_8 (Santo Augusto, 2013), E_9 (São Gabriel, 2013), E_{10} (São Luiz Gonzaga, 2013), E_{11} (Cachoeira do Sul, 2014), E_{15} (São Luiz Gonzaga, 2014), and E_{20} (São Luiz Gonzaga, 2015).

The $AMMI_3$ showed 10.9% of GxE interaction effects (Figure 1 C), evidencing stability in the environments E_6 (Cachoeira do Sul, 2013) and E_1 (Cachoeira do Sul, 2012). Minor effects of GxE

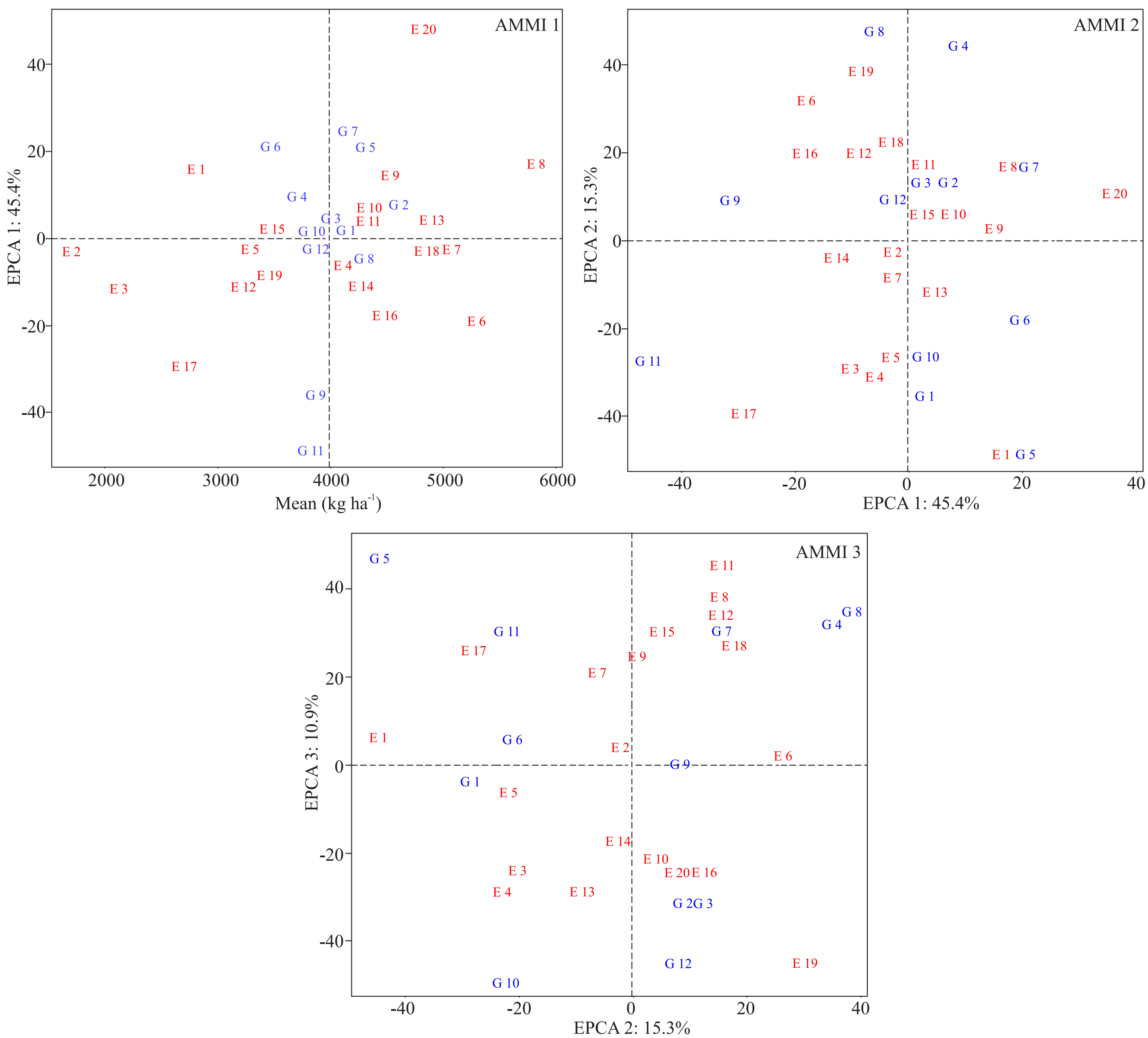

Figure 1. Biplots of the principal component scores of genotype x environment interactions, obtained with the AMMI method for grain yield (kg ha^{-1}), representing 12 wheat (*Triticum aestivum*) genotypes and 20 environments in Rio Grande do Sul state, Brazil. Genotypes: G1, 'Ametista'; G2, 'BRS 327'; G3, 'BRS 328'; G4, 'BRS 331'; G5, 'BRS Guamirim'; G6, 'CD 123'; G7, 'FPS Nitron'; G8, 'Fundacep 52'; G9, 'Fundacep Bravo'; G10, 'Fundacep Cristalino'; G11, 'Fundacep Nova Era'; and G12; 'Fundacep Raízes'. Environments: Cachoeira do Sul (E1, 2012; E6, 2013; E11, 2014; and E16, 2015), Passo Fundo (E2, 2012; E7, 2013; E12, 2014; and E17, 2015), Santo Augusto (E3, 2012; E8, 2013; E13, 2014; and E18, 2015), São Gabriel (E4, 2012; E9, 2013; E14, 2014; and E19, 2015), and São Luiz Gonzaga (E5, 2012; E10, 2013; E15, 2014; and E20, 2015).

interaction were evidenced for G_6 ('CD 123'), and specific adaptability was verified for the genotype G_9 ('Fundacep Bravo'), in the growing environments E_6 (Cachoeira do Sul, 2013), E_{12} (Passo Fundo, 2014), E_{16} (Cachoeira do Sul, 2015), E_{18} (Santo Augusto, 2015), and E_{19} (São Gabriel, 2015).

Factorial loads greater than or equal to 0.7 indicate highly correlated environments, which are grouped in the same factor (macroenvironment). Factorial loads with magnitudes between 0.5 and 0.7 do not fit in the definition of groups that represent a macroenvironment, and magnitudes smaller than 0.5 preclude macroenvironment formation (Carvalho et al., 2016). This statistical method supports the stratification of environments and, in a multivariate way, it graphically allows to differentiate which genotypes have wide adaptability to macroenvironments (quadrant I), which ones show specific adaptability to X and Y macroenvironments (quadrant II and IV), and which ones are likely to be disregarded, or do not provide a trustworthy indication to determine macroenvironments (quadrant III). This methodology reliably defines and fragments correlated crop environments (Murakami & Cruz, 2004).

In order to represent the largest standard fraction of the GxE interaction, the factors were rotated (Johnson & Wichern, 1992), and five final factors provided representativeness of 83.3%. For a reliable explanation of this method, the eigenvalues should represent at least 80% of the trait's total variation (Carvalho et al., 2016). Thus, representativeness is evident for factor I (31.13%), factor II (18.26%), factor III (14.63%), factor IV (11.01%), and factor V (8.11%). After the rotation of the eigenvalues, each factor was considered a macroenvironment responsible for gathering the most correlated growing environments.

The environmental index (EI) is achieved through the difference between the average of a given environment in relation to the average of all environments. Therefore, it was possible to identify the environments E_4 (São Gabriel, 2012), E_6 (Cachoeira do Sul, 2013), E_7 (Passo Fundo, 2013), E_8 (Santo Augusto, 2013), E_9 (São Gabriel, 2013), E_{10} (São Luiz Gonzaga, 2013), E_{11} (Cachoeira do Sul, 2014), E_{13} (Santo Augusto, 2014), E_{14} (São Gabriel, 2014), E_{16} (Cachoeira do Sul, 2015), E_{18} (Santo Augusto, 2015), and E_{20} (São Luiz Gonzaga, 2015) as favorable for the evaluated wheat genotypes (Table 4). However, the fact that these environments have positive or negative indexes does not define that they are correlated (Cruz & Carneiro, 2003).

The macroenvironment-I was formed by E_8 (Santo Augusto, 2013), E_{11} (Cachoeira do Sul, 2014), E_{12} (Passo Fundo, 2014), E_{15} (São Luiz Gonzaga, 2014), and E_{18} (Santo Augusto, 2015). The environments E_8, E_{11}, and E_{18} were considered favorable, while E_{12} and E_{15}, unfavorable. The macroenvironments-II gathered the environment E_{17} (Passo Fundo, 2015) which was unfavorable, and the environment E_{20} (São Luiz Gonzaga, 2015) which was considered favorable. In the macroenvironment-III, the environments E_3 (Santo Augusto, 2012), E_4 (São Gabriel, 2012), and E_5 (São Luiz Gonzaga, 2012) were grouped, but only the environment E_4 was considered favorable (Table 2). The macroenvironment-IV was formed only by the environment A_2 (Passo Fundo, 2012), which was unfavorable. Macroenvironment-V gathered the environment E_6 (Cachoeira do Sul, 2013), which was favorable, and the environment E_{19} (São Gabriel, 2015), unfavorable.

The macroenvironment-I combined the environments E_8 and E_{18} (2013 and 2015), since they were correlated by edaphoclimatic characteristics, which allowed of similar responses of genotypes to GxE interaction (Table 4). The presence of only one environment in the macroenvironment-IV was due to the low grain yield in the environment A_2 (1,693.3 kg ha^{-1}). The environments E_1 (Cachoeira do Sul, 2012), E_7 (Passo Fundo, 2013), E_9 (São Gabriel, 2013), E_{10} (São Luiz Gonzaga, 2013), E_{13} (Santo Augusto, 2014), E_{14} (São Gabriel, 2014), and E_{16} (Cachoeira do Sul, 2015) were not grouped by any multivariate factor. The ability to group environments through factor analysis was reported by Mendonça et al. (2007), Garbuglio et al. (2007), and Carvalho et al. (2016), in specific studies on the adaptability, stability, and stratification of cropping environments for soybean and maize in Southern Brazil.

The commonalities (Φ) for the environments E_3 (Santo Augusto, 2012), E_5 (São Luiz Gonzaga, 2012), E_6 (Cachoeira do Sul, 2013), E_7 (Passo Fundo, 2013), E_{10} (São Luiz Gonzaga, 2013), E_{12} (Passo Fundo, 2014), E_{14} (São Gabriel, 2014), E_{15} (São Luiz Gonzaga, 2014), E_{16} (Cachoeira do Sul, 2015), E_{17} (Passo Fundo, 2015), E_{18} (Santo Augusto, 2015), E_{19} (São Gabriel, 2015), and E_{20} (São Luiz Gonzaga, 2015) were higher than 80% (Table 4), allowing the method to reliably represent the standard fraction of GxE interaction. The factor analysis grouped 13 growing environments, in five macroenvironments, which biometrically represents 65% of the wheat cropping scenario of Rio Grande do Sul state. A similar study with carrots grouped environments that represented 47% of the cropping scenario (Carvalho et al., 2014).

The factor analysis was expressed by the multivariate graph (Figure 2 A), which represents the scores of macroenvironment-I (E_8, Santo Augusto, 2013, E_{11}, Cachoeira do Sul, 2014; E_{12}, Passo Fundo, 2014; E_{15}, São Luiz Gonzaga, 2014; and E_{18}, Santo Augusto, 2015) and macroenvironment-II (E_{17}, Passo Fundo, 2015 and E_{20}, São Luiz Gonzaga, 2015). Thus, the quadrant I grouped the genotypes G_7 ('FPS Nitron'), G_2 ('BRS 327'), and G_4 ('BRS 331'), which showed broad adaptability for both macroenvironments. The quadrant II brought together the genotypes G_6 ('CD 123'), G_{12} ('Fundacep Raízes'), G_{10} ('Fundacep Cristalino'), and G_3 ('BRS 328'), which showed specific adaptability to macroenvironment-II. The quadrant III showed that the genotypes G_1 ('Ametista') and G_9 ('Fundacep Bravo') did not allow of inferences to be made in the conditions of the present study. Regarding the quadrant IV, the genotypes G_5 ('BRS Guamirim'), G_8 ('Fundacep 52'), and G_{11} ('Fundacep Nova Era') showed specific adaptability to macroenvironment-I (E_8, E_{11}, E_{12}, E_{15}, and E_{18}).

The biplot represents the scores of macroenvironment-II (E_{17}, Passo Fundo, 2015, and E_{20}, São Luiz Gonzaga, 2015) and macroenvironment-III (E_3, Santo Augusto, 2012, E_4, São Gabriel, 2012, and E_5, São Luiz Gonzaga, 2012) (Figure 2 B). In the quadrant I, the genotypes G_4 ('BRS 331'), G_6 ('CD 123'), and G_7 ('FPS Nitron') had broad adaptability in the macroenvironments II and III. The quadrant II pointed the genotypes G_8 ('Fundacep 52') and G_9 ('Fundacep Bravo') as of specific adaptability for macroenvironment-III, while in the quadrant III no inferences could be made for genotype G_{11} ('Fundacep Nova Era').

The biplot (Figure 2 C) represents the scores of macroenvironment-III (E_3, Santo Augusto, 2012; E_4, São Gabriel, 2012; and E_5, São Luiz Gonzaga, 2012) and macroenvironment-IV (E_2, Passo Fundo, 2012). Quadrant I shows broad adaptability of genotypes G_9

Table 4. Factor analysis for 12 wheat (*Triticum aestivum*) genotypes grown in 20 environments of the state of Rio Grande do Sul, Brazil.

λ(1)	Environment	Growing season	Factorial loads after rotation					Φ (2)	EI(3)
			Factor 1	Factor 2	Factor 3	Factor 4	Factor 5		
6.23	E_1	2012	0.533	0.327	-0.571	0.172	-0.099	0.757	-930.083
3.65	E_2	2012	0.019	-0.003	-0.068	0.876	0.112	0.786	-2311.767
2.92	E_3	2012	0.004	-0.330	-0.857	-0.146	0.131	0.884	-1802.642
2.22	E_4	2012	-0.133	-0.069	-0.837	0.144	0.164	0.771	90.174
1.62	E_5	2012	0.235	0.002	-0.865	0.230	-0.032	0.859	-661.350
1.50	E_6	2013	0.226	-0.474	-0.003	0.104	0.722	0.808	1274.449
0.66	E_7	2013	0.562	-0.177	-0.298	0.609	0.045	0.810	930.174
0.44	E_8	2013	0.728	-0.074	-0.228	0.206	0.048	0.634	2062.524
0.39	E_9	2013	0.650	0.506	-0.192	-0.071	-0.135	0.740	674.724
0.22	E_{10}	2013	0.250	0.457	-0.434	0.331	0.557	0.882	273.966
0.10	E_{11}	2014	0.807	0.171	-0.015	-0.133	0.110	0.712	184.124
0.00	E_{12}	2014	0.725	-0.433	0.119	-0.027	0.386	0.879	-704.475
0.00	E_{13}	2014	0.153	0.373	-0.696	-0.245	0.212	0.753	838.924
0.00	E_{14}	2014	0.344	-0.210	-0.558	-0.554	0.316	0.883	246.849
0.00	E_{15}	2014	0.905	0.054	-0.104	0.110	0.123	0.862	-524.850
0.00	E_{16}	2015	0.139	-0.393	-0.226	-0.583	0.586	0.910	446.174
0.00	E_{17}	2015	0.142	-0.860	-0.409	-0.087	-0.052	0.953	-1203.742
0.00	E_{18}	2015	0.743	0.009	0.134	-0.443	0.281	0.846	782.057
0.00	E_{19}	2015	0.096	0.077	-0.201	-0.040	0.947	0.954	-547.125
0.00	E_{20}	2015	0.218	0.944	-0.083	-0.013	-0.153	0.971	881.891

(1)Eigenvalues. (2)commonality. (3)Environmental index.

('Fundacep Bravo'), G_7 ('FPS Nitron'), G_6 ('CD 123'), and G_4 ('BRS 331') in the macroenvironments-III and IV. Quadrant II shows specific adaptability of genotypes G_1 ('Ametista'), G_5 ('BRS Guamirim'), and G_{10} ('Fundacep Cristalino') to macroenvironment-IV. Quadrant III shows that genotypes G_2 ('BRS 327') and G_3 ('BRS 328') did not allow of inferences regarding macroenvironments.

In the biplot (Figure 2 D, inferences were made for macroenvironment-IV (E_2, Passo Fundo, 2012) and macroenvironment-V (E_6, Cachoeira do Sul, 2013, and E_{19}, São Gabriel, 2015), in which the quadrant I shows

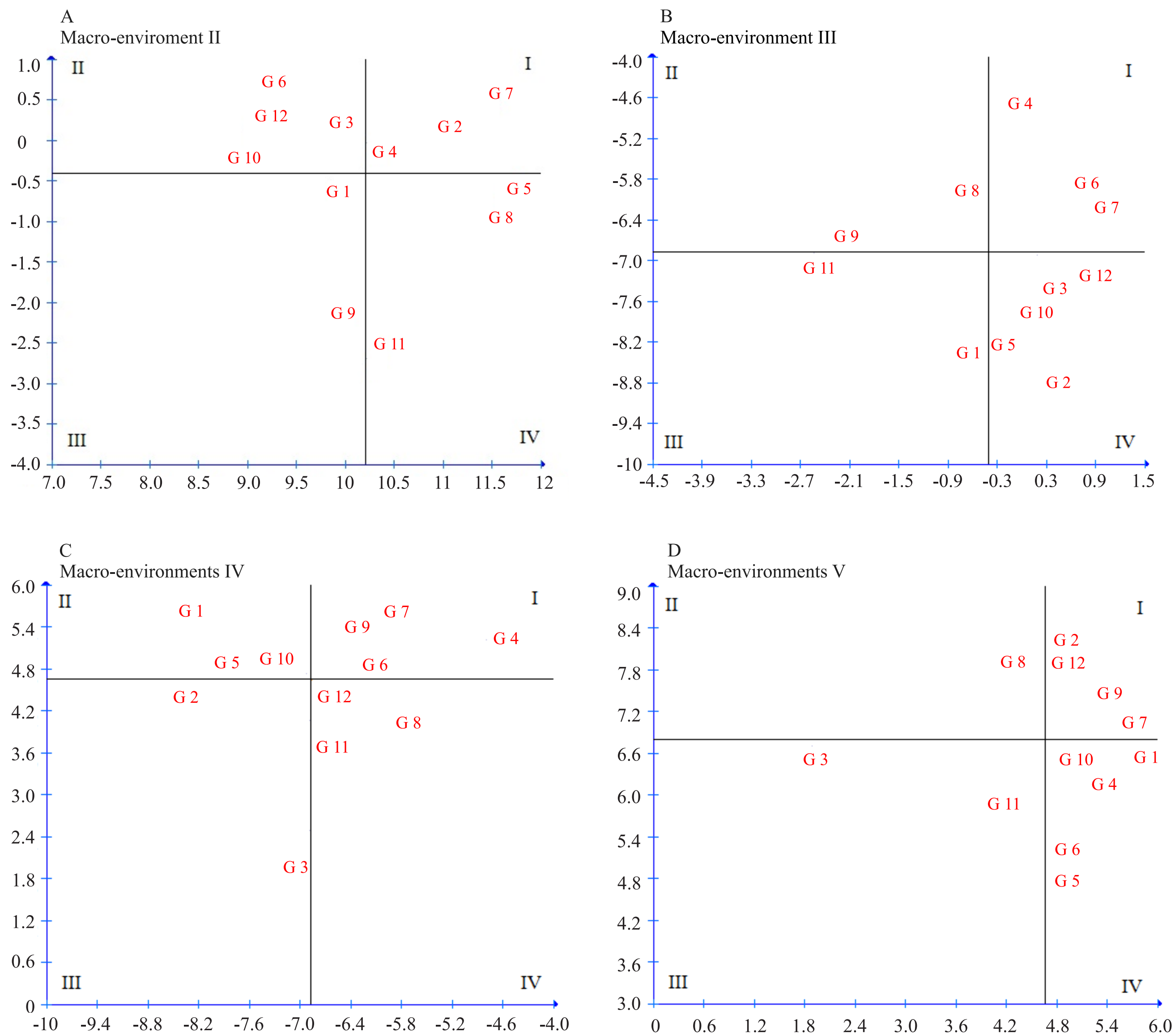

Figure 2. Plots of factor scores considering the factors I, II, III, and IV, obtained by the factor analysis of 12 wheat (*Triticum aestivum*) genotypes evaluated in 20 environments, during 2012, 2013, 2014, and 2015 growing seasons, in Rio Grande do Sul state, Brazil. Genotypes: G1, 'Ametista'; G2, 'BRS 327'; G3, 'BRS 328'; G4, 'BRS 331'; G5, 'BRS Guamirim'; G6, 'CD 123'; G7, 'FPS Nitron'; G8, 'Fundacep 52'; G9, 'Fundacep Bravo'; G10, 'Fundacep Cristalino'; G11, 'Fundacep Nova Era'; and G12; 'Fundacep Raízes'. Environments: Cachoeira do Sul (E1, 2012; E6, 2013; E11, 2014; and E16, 2015), Passo Fundo (E2, 2012; E7, 2013; E12, 2014; and E17, 2015), Santo Augusto (E3, 2012; E8, 2013; E13, 2014; and E18, 2015), São Gabriel (E4, 2012; E9, 2013; E14, 2014; and E19, 2015), and São Luiz Gonzaga (E5, 2012; E10, 2013; E15, 2014; and E20, 2015).

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the broad adaptability for genotypes G_2 ('BRS 327'), G_{12} ('Fundacep Raízes'), G_9 ('Fundacep Bravo'), and G_7 ('FPS Nitron') for both macroenvironments. The quadrant II shows that genotype G_8 ('Fundacep 52') had specific adaptability in the macroenvironment, while quadrant III evidenced that genotypes G_3 ('BRS 328') and G_{11} ('Fundacep Nova Era') did not allow of trustworthy inferences.

Both multivariate biometric approaches aimed to better represent the effects of adaptability and phenotypic stability of genotypes (AMMI) and environmental stratification (factor analysis), which shows the source of variation in the growing environments. There were 30% accordant responses regarding favorability for wheat yield for environments of E_8 (Santo Augusto, 2013), E_9 (São Gabriel, 2013), E_{10} (São Luiz Gonzaga, 2013), E_{11} (Cachoeira do Sul, 2014), E_{13} (Santo Augusto, 2014), and E_{20} (São Luiz Gonzaga, 2015). The agreement between multivariate approaches evidences the phenotypic stability of the genotypes G_2 ('BRS 327'), G_4 ('BRS 331'), and G_{12} ('Fundacep Raízes'). Regarding specific adaptability, the concordance was verified for genotype G_3 ('BRS 328'), in the environments E_{20} (São Luiz Gonzaga, 2015) and G_5 ('BRS Guamirim') in the environments E_8 (Santo Augusto, 2013) and E_{11} (Cachoeira do Sul, 2014).

Conclusions

1. The multivariate biometric approaches AMMI and factor analysis efficiently define patterns of adaptability and phenotypic stability for the evaluated wheat (*Triticum aestivum*) genotypes .
2. The definition of macroenvironments is intrinsic to the peculiarities of the crop year in Rio Grande do Sul state, Brazil.
3. There is similarity between the growing environments in the municipalities of Santo Augusto, Cachoeira do Sul, and São Luiz Gonzaga, as well as in Cachoeira do Sul and São Gabriel.

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