Determination of Genotypic Stability and Adaptability in Wheat Genotypes Using Mixed Statistical Models

M. M. D. Coan¹*, V. S. Marchioro², F. de A. Franco², R. J. B. Pinto¹, C. A. Scapim¹, and J. N. C. Baldissera¹

ABSTRACT

The objective of this study was to evaluate the adaptability and stability of wheat genotypes simultaneously in unbalanced Multi-Environment Trials (MET) in four different regions of Brazil, using the method of harmonic means of the relative performance of genetic values. Mixed model was applied to the analysis of Genotype-Environment Interaction (GEI) in wheat. Grain yield data were obtained from a network of MET carried out at seven locations from 2008 to 2010. A joint of experiments in complete randomized blocks design with some common treatments was used in all 21 experiments. Adaptability and stability parameters were obtained by several different methodologies, based on prediction, Harmonic Mean, and of the Relative Performance of Genotypic Values (HMRPGV). These methodologies ranked in a very similar way the studied genotypes and indicated the genotypes CD0950, CD0857, CD0667, CD0915, CD0914, CD0669, CD0859, and CD0851 as the superior ones for grain yield, adaptability, and stability in all environments. Dourados-MS (2010) was the worst environment with lowest mean (1,560.26 kg ha⁻¹) and São Gotardo–MG (2008) was the best environment with highest mean (5,687.08 kg ha⁻¹). The genotype more stable by HMRPGV across 21 environments tested was CD085; in the best environment, it was ranked the sixth (6,319.30 kg ha⁻¹), but changed your values in the worst environment and was ranked the fifth (2,051.53 kg ha⁻¹). The HMRPGV proved to be a practical and useful statistical tool in the determination of the Value for Cultivation and Use (VCU), particularly in the selection of genotypes’ reliability when genotypes are selected for the environments evaluated. This method has the advantage of providing results that are directly interpreted as breeding values for yield, stability, and adaptability.

Keywords: Genetic values, REML/BLUP, Triticum aestivum L. Interblock.

INTRODUCTION

Multi-Environment Trials (MET) are assays to assess variation in relative performance of genotypes in different environmental conditions and frequently show significant fluctuation in yield performance resulting from Genotype-by-Environment interaction (GE). The nature of GE can be assessed by partitioning the total GE variability into two components: (i) Change in scale of a trait measured in different environments, that is, heterogeneity of variances, and (ii) Imperfect genetic correlation of the same trait across environments (or genotypes) (Yang and Baker, 1991).

The use of cultivars with wide adaptability and stability is an alternative to overcome some problems arising from the GE interaction in breeding programs. Adaptability is the ability of the material to
be high-yielding with respect to a given environment or given conditions. Stability is related to the maintenance of performance and to the production predictability in different environments (Annicchiarico et al., 2005; Ceccarelli, 1989; Khalili and Pour-Aboughadareh, 2016; Lin and Binns, 1988). There are various methods to analyze the genetic stability and adaptability, which differ in conceptual terms and biometric procedures (Khalili and Pour-Aboughadareh, 2016; Mohammadia et al., 2015; Sayar et al., 2013).

The number of genotypes included in MET for recommending superior cultivars in relation to stability and adaptability tends to be very large. Under these conditions, it may be difficult to ensure a correct distribution of genotypes in the experimental area, due to the effect of soil heterogeneity within the blocks, which increases the experimental error (Cochran and Cox, 1957). METs also are used in the process of crop cultivar registration for assessing the Value for Cultivation and Use (VCU). In MET, it is common that breeders add, remove, or replace certain genotypes over the years. This causes an unbalance of genotypes in the experimental network.

Estimation methodologies based on the least square method, as those applied in the analysis of variance, are not very recommendable when the experiments are unbalanced or in experiments with different number of treatments or replications (Piepho et al., 2003; Piepho and Möhring, 2006).

The processing of experimental data by mixed models provides great flexibility in analysis and can usually overcome these difficulties by the estimation of variance components through the Restricted Maximum Likelihood (REML) method (Patterson and Thompson, 1971). They are able to handle complicated data structures and they possess the properties of consistency and asymptotic normality of the estimators desirable for hypothesis testing (Searle et al., 1992).

New methodologies based on mixed models are being used for a better understanding of the GE interaction. However, the use of methods based on mixed models (REML/BLUP - Best Linear Unbiased Prediction) in the study of adaptability and stability is still relatively rare (Piepho and Möhring, 2006; Viana et al., 2011).

The use of HMRPGV proposed by Resende (2007a) is an alternative analysis based on mixed models for adaptability and stability studies. The HMRPGV method provides information on adaptability, stability, and yield in the same measured unit and on the same scale as the assessed trait. According to Resende (2007a), the lower the standard deviation of the genotypic behavior at the locations, the greater will be the harmonic mean of their genotypic values across locations. Thus, selection for the highest values of HMGV allows a simultaneous selection for yield and stability.

Studies using HMRPGV methodology have been carried out for grain yield with various species such as sorghum (Almeida-Filho et al., 2014), corn (Mendes et al., 2012; Rodovalho et al., 2015), and upland rice (Colombari-Filho et al., 2013).

The aim of this study was to apply mixed models in the analysis of groups of experiments in randomized blocks with common treatments at unbalanced multi-environment trials, in order to study the GE interaction with proper methodologies to analyze wheat adaptability and stability genotypic.

**MATERIALS AND METHODS**

**Experiments**

In this work, all the analysis were performed with the grain yield data obtained from the VCU experiments carried out by the wheat breeding program of Coodetec (Central Cooperative of Agricultural Research), Cascavel - Paraná, Brazil. Unbalanced Multi-Environment (MET)
Trials were performed between 2008 and 2010 at seven locations, thus adding up to 21 environments. Wheat map and geographic data of adaptation regions for the VCU trial and location and altitudes of the environments were evaluated (Supplementary Figure 1).

All the experiments were statistically designed in joint of experiments in complete randomized blocks with some common treatments (Pimentel Gomes and Guimarães, 1958), with three replications (Supplementary Figure 2). In 2008, three groups of experiments with 3 replications and 21 genotypes per test resulted in 63 regular genotypes, with three cultivars in common in all experiments. In 2009, four experimental groups with 21 genotypes each were carried out, resulting in 84 regular genotypes and 3 cultivars present in all experiments. In 2010, two groups of experiments with 22 genotypes each were carried out, with 44 regular genotypes and two cultivars in common per group.

**Statistical Procedures**

The mathematical model for experimental groups in randomized blocks with common treatments in several environments in scheme 3 is given by Equation (1). Statistical procedures for the mixed modeling consisted of deviance analysis of data. The parameters $b$, $g$ and $ge$ were considered random, and the matrix form of the mathematical model was represented by:

$$y = X\alpha + Zg + Wb + Ti + \varepsilon$$

Where, $y$: Is the data vector; $\alpha$: Vector of experiment $\lambda$ at environment effects (assumed as fixed) plus the overall mean,

![Brazil - VCU Wheat Map](image_url)

**Figure 1.** Adaptation regions for the Value for Cultivation and Use (VCU) trial and location and altitudes from environments evaluated. State Abbreviations: PR- Paraná, MG- Minas Gerais, MS- Mato Grosso do Sul, SP- São Paulo. (*Irrigated only until germination; Source: Cunha et al., 2006).
Figure 2. Resume diagram of an experiment group in randomized block design with common treatments with three replications. The letters represent the treatments in common given by (c) and the numbers represent the regular treatments (regular treatments are not repeated between experiments) given by (z), all assigned randomly within the blocks.

The vector \( \alpha \) includes all experiments of all environments (fits experiments-environments combinations); \( g \): Vector of genotypic effects (assumed as random); \( b \): Vector of block within experiment within environment effects (assumed as random); \( i \): Vector of genotype-environment interaction effects \( ge \) (assumed as random), and \( \varepsilon \): The error or residue vector, random effect of experimental error, assuming \( NID(0, \sigma^2) \).

In the above model (2), the capital letters \( X, Z, W, \) and \( T \) represent the incidence matrices for the effects of \( \alpha, g, b \) and \( i \), respectively. We used model 52 Software Selegen REML/BLUP (Resende, 2007b) to represent this model, for the incomplete block design for groups of experiments, with GE interaction to study the stability and adaptability by the HMRPGV method.

The means and variances were structured and distributed as follows:

\[
\begin{align*}
\frac{y}{r} &\sim N(X\alpha, V) \\
g &\sim N(0, I\sigma^2_g) \\
b &\sim N(0, I\sigma^2_b) \\
i &\sim N(0, I\sigma^2_i) \\
\varepsilon &\sim N(0, I\sigma^2_e)
\end{align*}
\]

The mixed model equations provided the genetic values:

\[
\begin{bmatrix}
X'X & X'Z & X'W & X'T \\
Z'X & Z'Z + I\sigma^2_g & Z'W & Z'T \\
W'X & W'Z & W'W + I\sigma^2_e & W'T \\
T'X & T'Z & T'W & T'T + I\sigma^2_e
\end{bmatrix}
\begin{bmatrix}
\hat{\alpha} \\
\hat{g} \\
\hat{b} \\
\hat{i}
\end{bmatrix}
= 
\begin{bmatrix}
X'y \\
Z'y \\
W'y \\
T'y
\end{bmatrix}
\]

Solution Model

The model effects were estimated by analysis of deviance. The statistical significance of the model was tested by the Likelihood Ratio Test (LRT). The deviances were obtained by both analysis, with and without the effects of \( b, g, \) and \( ge \). Each effect was subtracted from the deviance of the full model and compared with the chi-square value with one degree of freedom, at 1% probability by the \( LRT \). Thus \( \mu \) was obtained, which refers to the general mean in all environments; \( g \): predicted genotypic values, \( g+ge \): Genotypic effects with interaction; \( \mu+g+ge \): Genotypic values with mean interaction, and \( \mu+g+ge_m \): Genotypic
Genotypic Stability and Adaptability

The genotypic values of stability were obtained from the Harmonic Mean of Genotypic Values (HMGV), according to Equation (2). Adaptability was evaluated based on the Relative Performance of Genotypic Values (RPGV), by Equation (3). In the next step, Equation (4) was used for the simultaneous evaluation of stability, adaptability, and yield, by calculating the harmonic mean of the relative performance of genotypic values (HMRPGV) for all genotypes.

The Equations (2), (3), and (4) are:

\[ HMGV = \frac{1}{l} \sum_{i=1}^{l} \frac{GV_{ij}}{GV_{ij}} \]  
\[ RPGV = \frac{1}{l} \left( \sum_{i=1}^{l} \frac{GV_{ij}}{\mu_j} \right) \]  
\[ HMRPGV = \frac{1}{l} \left( \frac{1}{\sum_{i=1}^{l} \frac{1}{RPGV_{ij}}} \right) \]

Where, \( \mu_j \) is the general mean for each environment \( j \); \( l \)- Number of environments; \( GV_{ij} \): \( u_j + g_i + ge_{ij} \) In which \( GV_{ij} \) genotypic value of genotype \( i \) in a specific environment \( j \). \( u_j \) represents the mean of environment \( j \), and \( g_i \) and \( ge_{ij} \) are the BLUP values of genotype \( i \) and the interaction between genotype \( i \) and or environment \( j \), respectively.

Correlations

The degree of association between the estimated mean and the parameters of adaptability and stability from the different methods was checked by Spearman’s rank correlation coefficient \( (r) \). The assumption of normality for each environment and data analysis by mixed modeling were checked using software SAS (SAS Institute, 2003).

RESULTS

Genotype-Environment Interaction

The results of the combined analysis of deviance, coefficients of variation, and the general mean are shown in Table 1. The variance of genotype effect was highly significant \( (P< 0.01) \) by the Chi-square test for the Likelihood Ratio (LTR), indicating significant differences among the tested cultivars.

Similarly, as for the effect of genotypes, the variance of the GE interaction was also highly significant, showing a different behavior of genotypes in the tested environments. Thus, there were changes in the ranking of genotypes or changes in the magnitude of differences between them at the studied locations.

The values of genotype-environment correlation \( (ge = 0.25) \) indicate the predominance of a complex correlation and that genotypic performance of genotypes was not exactly the same over the environments.

The estimated accuracy value was relatively high \( (\hat{r}_g = 0.87) \), which maximizes selection of the best genotypes tested across many environments.

Genotypic Values Recommendation

The genotypes with highest predicted genotypic values \( (\mu + g) \) free from any interaction with environments and the mean genotypic value \( (\mu + g + ge) \) in different environments were CD0857, CD0667, CD0914, and CDI0809 and had high genotypic values, which exceeded the best check (Quartzo) (Table 2). The predicted genotypic value for the best line (CD0857) was 3843.0 kg ha\(^{-1}\), with a gain of 372.2 kg
Table 1. Combined analysis of deviance in 21 environments involving 118 genotypes, which were tested for three years (2008-10).

<table>
<thead>
<tr>
<th>Effects</th>
<th>21 Environments</th>
<th>Estimated parameters$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Deviance$^b$</td>
<td>LRT ($x^2$)</td>
</tr>
<tr>
<td>Blocks/Exp/environments (E)</td>
<td>59015.17</td>
<td>285.9**</td>
</tr>
<tr>
<td>Genotypes (G)</td>
<td>60010.78</td>
<td>1281.51**</td>
</tr>
<tr>
<td>GE</td>
<td>59939.31</td>
<td>1210.04**</td>
</tr>
<tr>
<td>Complete model</td>
<td>58729.27</td>
<td>282046.35</td>
</tr>
</tbody>
</table>

CV$^e\%$: 5.88  
CV$^e\%$: 9.11  
$\bar{\mu}_\cdot$: 3470.88

$^a$ Components of variance, coefficients of determination and correlations.  
$^b$ Deviance from the adjusted model without the corresponding effects. * and **: Significant by the Chi-square test with 1 degree of freedom: At 5% (3.84) and 1% (6.63) respectively.

Effects corresponding to:

- Component of block variance ($\delta^2_G$)
- Error variance ($\delta^2_E$)
- Correlation of genotypes with environment ($\rho_{ge}$)
- Coefficient of determination of the GEI ($R^2_{ge}$)
- General mean ($\bar{\mu}_\cdot$)

$\mu + g$: Genotypic effects, interaction free ($\mu + g$), prediction of genotypic values, capitalizing on the mean interaction ($\mu + g + ge_m$).  
$\bar{\mu}_\cdot$: General mean of all environments; the parameters are expressed in grain yield (kg ha$^{-1}$).

Table 2. Ranking of the genotypes in all environments evaluated for the genotypic prediction of wheat genotypes assessed in 21 environments at 7 locations (2008-10).

<table>
<thead>
<tr>
<th>Or</th>
<th>Gen</th>
<th>$g$</th>
<th>$\mu + g$</th>
<th>Gain</th>
<th>$N$ Mean</th>
<th>$\mu + g + ge_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CD0857</td>
<td>372.2</td>
<td>3843.0</td>
<td>372.2</td>
<td>3843.1</td>
<td>3895.1</td>
</tr>
<tr>
<td>2</td>
<td>CD0667</td>
<td>323.2</td>
<td>3794.0</td>
<td>347.7</td>
<td>3818.5</td>
<td>3839.2</td>
</tr>
<tr>
<td>3</td>
<td>CD0914</td>
<td>304.2</td>
<td>3775.1</td>
<td>333.2</td>
<td>3804.1</td>
<td>3817.6</td>
</tr>
<tr>
<td>4</td>
<td>CD10809</td>
<td>296.4</td>
<td>3767.3</td>
<td>323.9</td>
<td>3794.9</td>
<td>3808.7</td>
</tr>
<tr>
<td>5</td>
<td>Quartzo</td>
<td>288.7</td>
<td>3759.5</td>
<td>316.9</td>
<td>3787.8</td>
<td>3799.9</td>
</tr>
<tr>
<td>6</td>
<td>CD0950</td>
<td>272.9</td>
<td>3743.8</td>
<td>309.6</td>
<td>3780.5</td>
<td>3781.9</td>
</tr>
<tr>
<td>7</td>
<td>CD0915</td>
<td>262.6</td>
<td>3733.5</td>
<td>302.9</td>
<td>3773.8</td>
<td>3770.2</td>
</tr>
<tr>
<td>8</td>
<td>CD0513</td>
<td>228.3</td>
<td>3699.1</td>
<td>293.5</td>
<td>3764.4</td>
<td>3731.0</td>
</tr>
<tr>
<td>9</td>
<td>CD0959</td>
<td>227.8</td>
<td>3698.7</td>
<td>286.3</td>
<td>3757.1</td>
<td>3730.5</td>
</tr>
<tr>
<td>10</td>
<td>CD0814</td>
<td>227.8</td>
<td>3698.6</td>
<td>280.4</td>
<td>3751.3</td>
<td>3730.5</td>
</tr>
<tr>
<td>11</td>
<td>CD0647</td>
<td>217.2</td>
<td>3688.0</td>
<td>274.7</td>
<td>3745.5</td>
<td>3718.4</td>
</tr>
<tr>
<td>12</td>
<td>CD0669</td>
<td>214.1</td>
<td>3684.9</td>
<td>269.6</td>
<td>3740.5</td>
<td>3714.9</td>
</tr>
<tr>
<td>13</td>
<td>CD154</td>
<td>213.7</td>
<td>3684.6</td>
<td>265.3</td>
<td>3736.2</td>
<td>3714.5</td>
</tr>
<tr>
<td>14</td>
<td>CD10902</td>
<td>203.1</td>
<td>3673.9</td>
<td>260.9</td>
<td>3731.7</td>
<td>3702.3</td>
</tr>
<tr>
<td>15</td>
<td>CD0910</td>
<td>201.9</td>
<td>3672.8</td>
<td>256.9</td>
<td>3727.8</td>
<td>3701.0</td>
</tr>
<tr>
<td>118 CD0817</td>
<td>-512.7</td>
<td>2958.1</td>
<td>0</td>
<td>3470.8</td>
<td>2886.5</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Or: Increasing Order; Gen: Genotype ranking. Genotypic effects, interaction free ($\mu + g$), prediction of genotypic values, capitalizing on the mean interaction ($\mu + g + ge_m$).  
$^b$ General mean of all environments; the parameters are expressed in grain yield (kg ha$^{-1}$).
The new mean was 3,843.1 kg ha\(^{-1}\) and its mean genotypic value in all environments reached 3,895.1 kg ha\(^{-1}\). The worst genotype was CD0817, whose predicted genotypic value was only 2,958.1 kg ha\(^{-1}\) (\(u + g\)). The gain of this genotype was zero and its new mean reached 3,470.8 kg ha\(^{-1}\), with a mean genotypic value for all environments of 2,886.5 kg ha\(^{-1}\).

The cultivar Quartzo was the best check, with a mean genotypic value of 3,799.9 kg ha\(^{-1}\) in all environments. As Quartzo occupied the fifth position, the results indicated a certain number of genotypes suitable for recommendation, since the new genotypes were able to perform better than the check cultivars. The genotypic values of these four genotypes were higher than those of the best control in all environments and their yield stability was considered high.

The patterns of stability and adaptability identified in the genotypic analysis using mixed models are shown in Figure 3. It should be noted that even those genotypes with a high phenotypic mean might have negative prediction estimates; the reason for which plant breeders should not use the phenotypic mean as the only criterion for recommending genotypes.

Genotype CD0857 and CD0914 were tested in 21 and 14 environments, respectively. Their genotypic values in relation to the mean effect of the environment (\(\mu + g + ge_m\)) exceeded the general mean of all genotypes in all environments (Figures 3a and b). Genotypes CD0857 and CD0914 were regarded as stable and adaptable, for their capacity to respond to the environmental improvement and because they maintain stable yields under environmental alterations. The genotypes CD0911 and Onix had variations in the predicted genotypic values (\(g + ge\)), both in a positive and in a negative direction across environments. Thus, the genotypic mean values advantage of the environmental effect (\(\mu + g + ge_m\)) is offset by the general phenotypic mean \(\mu\) (Figures 3-c and -d). The standard values of \(\mu + g + ge_m\) below the line of the general mean \(\mu\), are presented by genotypes CD0844 and CD0913 (Figures 3-e and -f), in which the values prediction (\(g + ge\)) were negative in most environments.

The method (HMRPGV\(_{\mu\mu}\)) offers simultaneously genotypic stability and adaptability. The results of its application to experimental data were highly consistent in the ranking of genotypes, when compared to the results from the methods (\(\mu + g + ge_m\)), HMGV and RPGV\(_{\mu\mu}\). (Supplementary Table 3).

The estimated values of coefficients had a high positive and significant correlation (0.99*) with Spearman’s correlation coefficients, at a probability level of 1%. The high Spearman’s correlation coefficient for comparing HMRPGV\(_{\mu\mu}\) with HMGV (0.84*) shows the small difference in the ranking of these methods, due to the stricter ranking of HMGV, which penalizes instability of the genotypes.

Based on the results of the measure of stability and adaptability (HMRPGV) (Table 4), the top four genotypes that performed better than check Quartzo were CD0950,
Figure 3. Genotypic values of grain yield at seven locations, genotypes that have positive BLUP values, high stability and adaptability: (A) Genotype CD0857 (2008, 2009 and 2010); (B) Genotype CD0914 (2009 and 2010). Genotypes that have intermediate ranking with positive, negative and null BLUP values: (C) Genotype CD0911 (2009 and 2010); (D) Genotype Onix (2008, 2009 and 2010); genotypes without stability with negative BLUP values; (E) Genotype CD0913 (2009 and 2010), (F) Genotype CD0844 (2008 and 2009). $\mu_{..}$, $g+ge$, $\mu+g+ge$, and $\mu+g+ge_m$ are defined in the text.

CD0857, CD0915, and CD0914. The products of $HMRPGV$ and the general mean ($HMRPGV*H..$) of these four genotypes were 3905.47, 3,902.42, 3,869.54 and 3,841.64 kg ha$^{-1}$, respectively. Assuming the selection of the four best-ranked genotypes for grain yield, an increase of 11.78% over the general mean should be expected for this trait (in this case 3,470.88 kg ha$^{-1}$). It is important to measure $HMRPGV$ because it expresses both stability and adaptability, indicating the capacity of a positive genotypic response to environmental improvements and the stability of genotypes over the tested environments.
Genotypic Stability and Adaptability

Genetic Value Recommendation in Contrasting Environments

The adjusted means of the 21 environments with the ranking of the 10 best genotypes in contrasting environments are shown in Table 5. São Gotardo-MG was considered the best environment in 2008, with the highest mean (5,687.08 kg ha⁻¹). It should be noted that wheat is produced at high technological level in that location, growing under irrigation and in a no-tillage system.

Dourados-MS was the worst environment in 2010, with the lowest mean (1,560.26 kg ha⁻¹) considered. In 2008, the environment was below the general mean again. In fact, Dourados is a location where wheat is produced under low technical level and dry spells commonly occur during the crop cycle. However, Dourados was regarded as the second best environment in 2009.

For the sub-region (Dourados–MS in year 2010), the best genotypes recommended were CD0914, CD0647, CD0854, CD0803 and CD0857 by exploitation of specific adaptation in rainfed condition. Moreover, these genotypes were stable in all environments tested (Table 4).

Genotypes CD0647, CD0857, and CD0854 had high genotypic means (μogenesis), and ranked among the top 10 genotypes in both the best and in the worst environment (São Gotardo in 2008 and Dourados in 2010, respectively). This result allows indicating them as highly stable and adaptable genotypes.

The genotype tested in the best and worst environments and considered stable by HMRPGV across 21 environments tested was CD0857, which, in the best environment, was ranked the sixth (6,319.30 kg ha⁻¹) and changed your values in worst environment that was ranked the fifth (2,051.53 kg ha⁻¹).

The stability of genotype CD0803 was

Table 4. Ranking of the genotypes in all environments evaluated for adaptability parameters of genotypic values for the trait grain yield of wheat genotypes evaluated in 21 environments.a

<table>
<thead>
<tr>
<th>Or</th>
<th>Gen</th>
<th>HMGV</th>
<th>Gen</th>
<th>RPGV</th>
<th>RPGV*μ.</th>
<th>Gen</th>
<th>HMRPGV</th>
<th>HMRPGV*μ.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CD0669</td>
<td>3758.22</td>
<td>CD0857</td>
<td>1.1318</td>
<td>3928.46</td>
<td>CD0950</td>
<td>1.1252</td>
<td>3905.47</td>
</tr>
<tr>
<td>2</td>
<td>CD0667</td>
<td>3748.57</td>
<td>CD0950</td>
<td>1.1294</td>
<td>3919.96</td>
<td>CD0857</td>
<td>1.1243</td>
<td>3902.42</td>
</tr>
<tr>
<td>3</td>
<td>CD0857</td>
<td>3656.09</td>
<td>CD0914</td>
<td>1.1186</td>
<td>3882.57</td>
<td>CD0915</td>
<td>1.1149</td>
<td>3869.54</td>
</tr>
<tr>
<td>4</td>
<td>CD0859</td>
<td>3633.16</td>
<td>CD0915</td>
<td>1.1182</td>
<td>3881.21</td>
<td>CD0914</td>
<td>1.1068</td>
<td>3841.64</td>
</tr>
<tr>
<td>5</td>
<td>CD0851</td>
<td>3594.05</td>
<td>CD0667</td>
<td>1.1131</td>
<td>3863.45</td>
<td>QUARTZO</td>
<td>1.1045</td>
<td>3883.42</td>
</tr>
<tr>
<td>6</td>
<td>CD0668</td>
<td>3563.97</td>
<td>QUARTZO</td>
<td>1.1092</td>
<td>3849.74</td>
<td>CD0667</td>
<td>1.1012</td>
<td>3822.11</td>
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<td>CD0810</td>
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<td>CD0959</td>
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<td>3826.77</td>
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<td>CD0669</td>
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<td>CD0814</td>
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<td>3467.88</td>
<td>CD0918</td>
<td>0.8302</td>
<td>2881.36</td>
<td>CD0913</td>
<td>0.8047</td>
<td>2792.96</td>
</tr>
</tbody>
</table>

Or: Increasing Order; Gen: Genotype ranking. Performance Genetic Value (RPGV); RPGV*μ.; Stability of Genotypic Values (HMGV). Adaptability and stability of Genotypic Values (HMRPGV); (HMRPGV*μ.).

a General mean of all environments; the parameters are expressed in kg ha⁻¹, except for RPGV and HMRPGV.
Table 5. General means of the genotypes evaluated in each environment and rank of the 10 best genotypes with high genotypic values in contrasting environments.

<table>
<thead>
<tr>
<th>Location</th>
<th>2008 (Mean rainfall (mm) (RCy/RHFM))</th>
<th>2009 (Mean rainfall (mm) (RCy/RHFM))</th>
<th>2010 (Mean rainfall (mm) (RCy/RHFM))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Campo Mourão-PR</td>
<td>3585.44 (687 /317 )</td>
<td>2549.25 (933 /300 )</td>
<td>4759.82 (422 /150 )</td>
</tr>
<tr>
<td>Cascavel - PR</td>
<td>3821.07 (665 /224 )</td>
<td>3040.87 (747 /240 )</td>
<td>4127.40 (840 /158 )</td>
</tr>
<tr>
<td>Dourados – MS</td>
<td>2456.35 (340 /26 )</td>
<td>3278.47 (509 /210 )</td>
<td>1560.26 (245 /57 )</td>
</tr>
<tr>
<td>São Paulo-SP</td>
<td>3696.31 (377 /80 )</td>
<td>2939.13 (644 /282 )</td>
<td>3206.31 (401 /95 )</td>
</tr>
<tr>
<td>Palotina-PR</td>
<td>2694.42 (403 /133 )</td>
<td>2761.75 (512 /128 )</td>
<td>3530.95 (551 /234 )</td>
</tr>
<tr>
<td>Rolândia-PR</td>
<td>3579.70 (550 /209 )</td>
<td>2669.85 (776 /340 )</td>
<td>3047.48 (446 /120 )</td>
</tr>
<tr>
<td>São Gotardo-MGb</td>
<td>5687.08 (750 /250 )</td>
<td>5461.85 (750 /250 )</td>
<td>5417.51 (750 /250 )</td>
</tr>
<tr>
<td>São Gotardo-MG</td>
<td>5461.85 (750 /250 )</td>
<td>5417.51 (750 /250 )</td>
<td>5417.51 (750 /250 )</td>
</tr>
</tbody>
</table>

Best environment (São Gotardo-MG 2008) 5461.85 (750 /250 )
Worst environment (Dourados – MS 2010) 1560.26 (245 /57 )

OrdGen g+ge μ+g+ge OrdGen g+ge μ+g+ge
1CD0667 1498.04 7185.13 1CD0914 782.27 2342.54
2CD151 961.18 6648.27 2CD0647 776.89 2337.16
3CD0647 897.82 6584.91 3CD0854 631.91 2192.18
4CD0809 725.96 6413.05 4CD0803 603.46 2163.73
5CD0668 708.04 6395.13 5CD0857 491.26 2051.53
6CD0857 632.21 6299.34 6CD0911 411.68 1971.90
7CD0809 612.25 6299.34 7CD0961 321.59 1881.86
8CD0854 578.03 6265.12 8CD0953 307.87 1868.13
9CD0845 549.45 6236.54 9CD0908 199.50 1759.77
10CD0858 549.41 6236.50 10CD0960 198.05 1758.32

\( a \) Adjusted by the recovery of inter-block information-kg ha\(^{-1}\). RCy: Rainfall total Cycle; RHFM= Rainfall wheat stage Heading, Flowering and Milk. \( b \) Condition: Irrigated.

Considered to be high in all 21 environments (Table 3), with a HMRPGV of 1.0565, showing a 5.6% increase in grain yield over the general mean, and ranked 20th among the 118 genotypes. CD0803 had a high genotypic value in the most unfavorable environment (Dourados-MS 2010), where it ranked fourth. However, this genotype did not show a high grain yield in response to the best environment (São Gotardo-MG 2008), where it ranked 31st. Our results suggest that a continuous evaluation of genotypes for several years at the same locations should be appropriate.

**DISCUSSION**

**Genotype-Environment Interaction**

Genotype\times Environment Interaction (GEI) is very important for plant breeding.
programs (Yang and Baker, 1991; Mortazavian et al., 2014; Sayar and Han, 2015). GEI stemmed from changing of ranking of genotypes because of changing environmental conditions (Kendal, 2015). The assessment of genotypes in many locations and years could increase the reliability of plant breeding programs (Sayar et al., 2013; Sayar and Han, 2016; Kendal and Sayar, 2016). The GE interaction often causes some concern because it contributes to some mistakes during the selection of superior genotypes, especially when breeders work with pure lines, since the inbred lines do not behave in a similar way in different environments (Yang and Baker, 1991; Viana et al., 2011; Kendal, 2015). The low correlations can occur when a type performance of genotypes in a certain environment cannot be seen in other conditions, preventing a reliable recommendation (Yang and Baker, 1991; Mortazavian et al., 2014). The low value found in this study for correlation was considered complex and indicated some changes in rank order of genotypes.

Genotype-environment correlations are commonly reported in the literature. Rodovalho et al. (2015) found a GE correlation of $\rho_{g e} = 0.47$ when studying genotypic stability and adaptability for selecting corn hybrids. Working with grain yield corn, Mendes et al. (2012) found a correlation of 45%, which was reported as a result of a complex interaction, confirming the different genotypic behavior over the environments.

The assessment of genotypes in potential strategic environments across randomly occurring cycles of normal and extreme conditions and the analysis of stability parameters allows the identification of promising materials from the experimental network where they are evaluated. Genotypes identified to be stable in dynamic sense can have wide adaptation if they show simultaneously high yield potential (high mean yield across environments), or they do not show this agronomic attribute if they do not have high yield potential (Khalili and Pour-Aboughadareh, 2016).

Accuracy in the Genotype Ranking

The accuracy indicates the precision of the inferences concerning genotypic means because the higher it is, the more accurate will be the ranking of cultivars for selection purposes (Piepho et al., 2008; Resende, 2002; Viana et al., 2011). Thus, accuracy measures the correlation between the predicted value and the true genotypic value. According to Piepho et al. (2008), the lower the value of the Predicted Error Variance (PEV), the greater will be the accuracy and precision. Therefore, in the class of unbiased estimators/predictors, the strategy of minimizing PEV also results in maximized accuracy. In general, the reduction of the residual mean square is important since the residues quantify the differences between the genetic parametric values and the predicted values used in plant breeding. The high accuracy value that was found in this study indicates an excellent experimental quality and a high reliability in the selection of genotypes with more stability and adaptability (Thomason and Phillips, 2006).

The BLUP is a predictor with maximum correlation with the true genotypic value ($g$), fulfilling the assumption that there are no departures from trait normality, while $\mu$ is the major criterion of selection, for its role in the ranking of the genotypes that maximize the genotypic population mean (Duarte et al., 2001; Searle et al., 1992). For Resende (2007a), the use of predicted genotypic values ($\mu + g$) for the evaluated genotypes allows their recommendation even in not-yet-evaluated environments, i.e., out of the network and maybe with a different GE interaction pattern. The predicted genotypic values are also useful in case of environmental heterogeneity, since genotypes are ranked based on genotypic values free of GE interaction. These aspects
show the great advantage of using the proposed methodology.

For balanced tests in randomized complete blocks, in which means are not adjusted by the recovery of inter-block information, the genotypic values obtained by BLUP can differ from those of phenotypic means due to the shrinkage effect. However, the ranking of treatments will be the same as the one based on BLUP or on phenotypic means (Duarte and Vencovsky, 2001). If the heritability is taken as a regression function, the predictions of random effects start to be targeted towards the general average, by the effect of shrinkage, and this compromises the predictions made from small samples.

**Genotypic Stability and Adaptability Recommendation**

The breeder can select a genotype for the higher ranking of genotypic values, without comparing means. With the acceptance of the treatment effects as random and/or use of shrinkage estimators, multiple-comparison tests between treatment means are not recommended because such tests are designed under the assumption of fixed treatment effects (Resende, 2007a).

The importance of adaptability in plant breeding justifies the effort of breeders to identify this desirable behavior in the new developing cultivar (Ceccarelli, 1989). According to Resende (2007a), the HMRPGV method is similar to that of Lin and Binns (1988). However, unlike the method of Lin and Binns, which is based on phenotypic results, the HMRPGV method processes simultaneously grain yield, adaptability, and stability data, in a genotypic context. Stability is important to allow the identification of those genotypes less affected by the environmental variation, which may be recommended for a wide range of environments (Ceccarelli, 1989; Thomason and Phillips, 2006; Sayar et al., 2013).

According to Smith et al. (2001) and Resende (2007a), as the genotypic values of cultivars cannot be observed, they are unknown random variables. On the other hand, the future performance of these random variables can be predicted when the genotypic effects are regarded as random. Thus, the results of this conception are more consistent during the growing seasons.

The observation from Table 4 assumes that stability is associated with higher grain yield and a greater tolerance to environmental changes (Annicchiarico et al., 2005). However, plant breeders may eventually eliminate stable genotypes when such materials have a homogeneous performance in different environments, but fail to express a high grain yield in response to environmental improvements.

The Dourados-MS environment had high contrast of means between years, forming a sub-region across years: considered as favorable in 2010 and unfavorable in 2008 and 2009. Ceccarelli (1989) defined an environment “favorable” when characterized by low stress and high mean yield and “unfavorable” with high stress and low yield. This difference is explained by the variation of the weather conditions during the evaluation time. According to Fietz et al. (2005), the water stress is a major cause of crop losses in Dourados (MS), where droughts are frequent due to the irregular rainfall distribution. Sub-regions may be defined for genotype recommendation, in which each sub-region coincides with a recommendation domain, grouping those environment with the same best-performing genotypes (Gauch and Zobel, 1997). The definition of sub-regions is not just geographical, but may also encompass farming practices (e.g. irrigated or rainfed cropping).

The predicted genotypic value for the mean of the 21 environments is useful not only to take advantage of the mean effect of the (μ+g+ge) interaction, but also to indicate genotypes in other environments, provided that they have the same pattern of GE interaction verified on the test network (Resende, 2004). The indication based on the general phenotypic mean (Figure 3)
usually favors those genotypes with high behavior in the best environments, but does not discriminate genotypes particularly adapted to a better or worse environmental condition. Knowledge about the behavior or adaptability of genotypes to certain environments is essential for the agronomic evaluation of cultivars (Ceccarelli, 1989; Lins and Binns, 1988).

According to Piepho and Möhring, (2006), the values of BLUP obtained from all environments are more accurate than those from the individual analysis of each environment, due to the quality of information generated from the entire experimental network.

The methods adopted in this study had a high correlation in the ranking of genotypes across environments. The use of one or more stability parameters obtained by different methodologies for the study of the effect of environmental variations on genotypic performance requires a level of association between such estimates (Duarte and Zimmermann 1995).

The predicted genotypic values can be used in relation to the environments with the same pattern of GE interaction observed in the experimental network, otherwise the superior genotypes should be selected based on their genotypic means (u+g), a safer procedure for being free of the GE-interaction.

CONCLUSIONS

The mixed models proved to be adequate to analyze GE-interaction and genotypic adaptability and stability study. Wheat genotypes CD0950, CD0857, CD0667, CD0915, CD0914, CD0669, CD0859 and CD0851 had the best grain yield performance, adaptability, and stability. The HMRPGV method has the advantage of providing results that are directly interpreted as breeding values for yield, stability, and adaptability. The high value of accuracy ($\hat{g}_g$), over 87%, revealed a satisfactory experimental quality and a higher reliability when genotypes were selected for each environment.

The grain yield obtained in this study was determined at which intervals among all of the 21 environments tested the most stable by HMRPGV was CD0857 (3,902.42 kg ha$^{-1}$), in the best environment, was ranked the sixth (6,319.30 kg ha$^{-1}$) and changed your values in the worst environment that was ranked the fifth (2,051.53 kg ha$^{-1}$). Dourados-MS (2010) was the worst environment with lowest mean yield (1,560.26 kg ha$^{-1}$) and São Gotardo–MG (2008) was the best environment with highest mean yield (5,687.08 kg ha$^{-1}$). The classification of genotypes resulting from the application of the methods (u+g+ge$_m$), HMGV, RPGV, and HMRPGV was very similar in all the evaluated environments. The predicted genotypic values based on genotypic means (u+g), can be used in relation to the environments with the same pattern of GE interaction observed in the experimental network, for being free of the GE-interaction.

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Appendix A. Supplementary data
Supplementary data related to this article can be found at...LINK FROM JAST

REFERENCES


گرفته شد. داده‌های عملکرد دانه از شبکه‌ای از MET که در هفت محل در سال‌های ۲۰۰۸ تا ۲۰۱۰ اجرا شده بود به دست آمده. در تمامی ۲۱ آزمایش، از آزمایش‌های گیاهی به هم پوسته (experiments) با طرح بلک های کاملاً تصادفی و برخی تیمارهای مشترک استفاده شد. پارامترهای سازگاری و پایداری با چند روش متغیر سنجی بر پیش بینی، میانگین هارمونیکا، و عملکرد نسبی ارزش زنوتیبی (HMRPGV) به دست آمده. با این روش‌ها، زنوتیبی های آزمون شده به طور مشابهی رده بندی شده و از نظر عملکرد، سازگاری و پایداری، برتری زنوتیب‌های کد CD0950، CD0855، CD0859 و CD0669 و ۱۵۴۰ تا ۸۸۵۱ در تمام محیط‌های آزمایش. میانگین عملکرد (HMRPGV) با روش CD0857 (۵۶۸۷.۰۸ kg ha⁻¹) زنوتیب ۸۸۸۵۱ بهترین میانگین عملکرد در دارای پایداری بیشتر در ۲۱ محیط مطالعه شده بود و در بهترین محیط، این زنوتیب از نظر عملکرد (۶۳۱۹.۳۰ kg ha⁻¹) رده‌بندی داشت و در دو بندی محیط، با تغییر ارزش‌ها به رده پنج عملکرد HMRPGV، روسیه شد که در هر عملی و ازار (۲۰۵۱.۵۳ kg ha⁻¹) آماری مفیدی است در تعیین ارزش کاشت و مصرف (VCU)، به ویژه برای انتخاب قابلیت اطمینان زنوتیب‌ها در مواردی که زنوتیب‌ها برای محیط‌های ارزیابی شده انتخاب می‌شوند. مزیت این روش در آن است که تاییدی را به دست می‌دهد که از نظر ارزش به‌نهاگری مستقیما برای عملکرد، پایداری و سازگاری قابل تفسیر است.