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# Effects of years, locations and sowing date on the spring wheat yield performance

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Understanding the environmental factors that influence genotype performance is an important step in a breeding program because large interactions can complicate the identification and recommendation of superior cultivars. The objective of this study was to evaluate the effects of years, locations and sowing dates on the performance of wheat genotypes in two growing regions of the State of Paraná, Brazil. The grain yield data for 17 wheat genotypes at two locations (Cascavel and Palotina, PR) over five years (2007 to 2011) for three sowing dates at each location in each year were used. Analyses of joint variance were performed, and the repeatability, adaptability and stability statistics of the genotypes were calculated for the different sowing dates. The effects of years (24.3%) and locations (12.5%) had greater contributions to the genotype-by-environment interaction (GEI), and the effect of the sowing dates contributed less (7.0%) to the GEI. To identify superior wheat genotypes with regard to grain yield with 80% precision, a total of 21 trials distributed across different years, locations and sowing dates must be used. The trials for the evaluation of wheat genotypes must include a greater number of years and lower numbers of sowing dates and locations. The CD 105, CD 114 and CD 150 cultivars at Cascavel and the CD 150, Onix and CD 119 cultivars at Palotina were shown to be stable and broadly adapted across different sowing dates, with high grain yield.

**Key words:** *Triticum aestivum* L, Genotype-by-Environment Interactions, Repeatability, Adaptability and Stability.

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Entender os fatores ambientais que influenciam o desempenho dos genótipos é um importante passo para os programas de melhoramento, uma vez que a presença de interação dificulta a identificação e recomendação de cultivares superiores. O objetivo deste trabalho foi avaliar os efeitos de anos, locais e datas de semeadura sobre o desempenho de genótipos de trigo, em duas regiões de cultivo do estado do Paraná. Foram usados os dados de produtividade de grãos de 17 genótipos de trigo em dois locais (Cascavel e Palotina, PR), cinco anos (2007 a 2011) e três datas de semeadura em cada local e ano. Foram realizadas as análises de variância conjunta e calculadas as estatísticas de repetibilidade e adaptabilidade e estabilidade dos genótipos às diferentes datas de semeadura. A interação ambiente x genótipo tem maiores contribuições dos efeitos de anos (24,3%) e locais (12,5%) e menor contribuição do efeito de datas de semeadura (7,0%). Para identificar genótipos de trigo superiores em relação à produtividade de grãos, com 80% de exatidão no prognóstico de seu valor real, devem ser utilizados um total de 21 ensaios distribuídos em diferentes anos, locais e datas de semeadura. Os ensaios de avaliação de genótipos de trigo devem ser executados em ambientes que incluam maior frequência de anos e menor frequência de datas de semeadura e locais. As cultivares CD 105, CD 114 e CD 150 em Cascavel e CD 150, Onix e CD 119 em Palotina, são estáveis, amplamente adaptadas em diferentes datas de semeadura e apresentam alta produtividade de grãos.

**Palavras-chave:** *Triticum aestivum* L, Interação genótipo x ambiente, Repetibilidade, Adaptabilidade e Estabilidade.

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## INTRODUCTION

The grain yield trials on spring wheat, normally involve testing of cultivars in several locations, years and sowing dates. The response of each genotype to environmental variations results in different patterns of genotype-by-environment interaction (GEI) (Zhang et al., 2006; Benin et al., 2013; Munaro et al., 2014). The assessment of the relative importance of these sources of variations is required to take advantage of the GEI.

In wheat, the contributions of the location, year, and sowing dates are proportionally greater than the main effect of the genotype and interactions (Zhang et al., 2006). The appropriate sowing date may impact in several factors, such as physiology, phenology, and environmental conditions, which may result in increases in yield performance of 10 to 80% (Coventry et al., 2011; Silva et al., 2011).

The number of trials required to produce consistent evaluations can be determined from the repeatability coefficient. The repeatability coefficient indicates the correlation between measurements for the same individual which the evaluations were repeated in time or space (Dovale et al., 2011). The necessary number of measurements to predict the real value of the individual is that tends to eliminate the temporary effects of the environment on its characteristics (Mohammadi & Pourdad, 2009). Thus, groups from heterogeneous environments may exhibit different patterns of interaction with genotypes, thus demanding different numbers of trials to achieve adequate precision for evaluation.

The identification of highly productive and stable genotypes in various environments has been a continuous challenge for plant breeders globally. An interaction that is complex in nature with a high number of genotypes and environments renders this task more difficult. In this context, genotype and genotype-by-environment (GGE) analysis is highlighted as enabling inferences regarding the identification of adapted and stable genotypes with ease in the visualization of the results in graphical outputs (Benin et al., 2012; Silva & Benin, 2012; Pande et al., 2013).

The objective was to determine the number of trials (measurements) required to predict the performance of wheat genotypes in environments (years, locations, and sowing dates) with regard to grain yield and to identify genotypes adapted to different sowing dates in two Brazilian growing regions.

## MATERIALS AND METHODS

The experiments were performed at two representative sites of the Value for Cultivation and Use (VCU) regions 2 and 3 in the State of Paraná (Brazil) as follows: Cascavel (latitude 24°95'60" and longitude 53°45'50"; altitude 720 m; average annual rainfall of 1248mm and average temperature of 26°C), with soil classified as a Distroferric Red Latosol, and Palotina (latitude 24°28'40" and longitude 53°84'00"; altitude 340 m; average rainfall of 1508mm and average temperature of 20°C), with soil classified as a Eutrudox Red Latosol. These sites were chosen because they represent the regions of VCU 2 and 3 respectively, which are part of the main wheat producing areas in Brazil.

The grain yield data from 17 wheat genotypes (CD 104, CD 105, CD 108, CD 113, CD 114, CD 115, CD 116, CD 117, CD 118, CD 119, CD 120, CD 121, CD 122, CD 123, CD 150, IPR 85 and ONIX) were evaluated in trials performed over five years (2007 to 2011) for three sowing dates at each site in each year. The cultivars named 'CD' were developed by the breeding program of the Central Cooperative of Agricultural Research (Coodetec) and IPR 85 and Onix cultivars were developed by Agronomic Institute of Paraná (IAPAR) and OR Seeds and Biotrigo Genetics, respectively. These cultivars have low relatedness and were chosen to be representative of the cultivars used in the VCU 2 and 3 regions. At Cascavel, the three sowing dates were 4/25 (S1), 5/10 (S2) and 5/25 (S3), and at Palotina, the three sowing dates were approximately 4/20 (S1), 5/5 (S2) and 5/20 (S3). The sowing may have been early or delayed by two or three days to allow the experiments to be started under optimal soil moisture conditions.

The field experiments were performed in a completely randomized block design with three replications. Each plot consisted of six lines, 5 m in length, with 0.20 m spacing between the lines, making an area of 5.0 m². Crops were handled according to the agricultural technical recommendations. Grain yield was measured by harvesting the whole area of each plot, then corrected to 13% moisture (wet basis) and converted to kg ha$^{-1}$.

The joint analysis of variance and the F-test, using datas from 17 genotypes in different years, locations and sowing dates, was done as the model in the annex. Considering that the effect of the environment is composed of the combination of the effects of years (Y), locations (L) and sowing dates (S), the relative contribution of the environmental effects (Y, L and S) was estimated as follows: $SQ_{YmG} = SQ_{LG} + SQ_{YG} + SQ_{SG} + SQ_{LYG} + SQ_{LSG} + SQ_{YSG} + SQ_{LYSG}$ resulting in $R^2_{(LG)} = SQ_{LG} / SQ_{YmG}$, $R^2_{(YG)} = SQ_{YG} / SQ_{YmG}$, $R^2_{(SG)} = SQ_{SG} / SQ_{YmG}$, $R^2_{(LYG)} = SQ_{LYG} / SQ_{YmG}$, $R^2_{(LSG)} = SQ_{LSG} / SQ_{YmG}$, $R^2_{(YSG)} = SQ_{YSG} / SQ_{YmG}$, and $R^2_{(LYSG)} = SQ_{LYSG} / SQ_{YmG}$.

The 17 genotypes for three sowing dates in each year at each location were grouped together into test groups, resulting in 10 groups of three measurements. Moreover, the 17 genotypes in three sowing dates over five years at each location were also grouped together into trial groups, resulting in two groups of 15 measurements. Another grouping was across the two locations and three sowing dates in each year, forming five groups of six measurements. Finally, one group of 30 measurements was formed from the two locations, five years and three sowing dates. For each group of trials, the estimates of the coefficients of repeatability ( $\hat{\rho}$ ) were calculated using the analysis of variance method with the respective averages of the genotypes (Cruz, 2006) and considering the environment (location, year and sowing dates) as repeated measurements in time for the same genotypes. The minimum number of measurements (J) necessary to predict the real value of the genotypes with basis in the pre-established coefficients of determination ($R^2$ = 0.80 and $R^2$ = 0.90) was calculated as described by Cruz (2006).

The GGE (*Genotype and Genotype-by-Environment*) biplot methodology (Yan et al., 2000) was used to evaluate the genotypes' adaptability and stability with respect to the studied sowing dates. The GGE methodology used the unique shared value for the genotype (SVP = 1) for the analysis of the "ideal genotype". The single-arrow vector indicates the largest average, and the double-arrow vector indicates the largest instability. The concentric circles indicate the best genotypes based on their average and stability, giving equal weight to the two factors (Yan & Tinker, 2006).

For each of the statistics, the averages obtained in each group of tests were compared using a bootstrap t test with 5000 simulations with a 5% probability of error using BioEstat 5.0 software. The GGE analysis was performed using the GGE biplot application. The other analyses were performed using the Genes computational application (Cruz, 2006) and Excel spreadsheets.

## RESULTS AND DISCUSSION

The joint analysis of variance of the grain yield (Table 1) showed that there was no variance among the locations and years and there was no difference among sowing dates and genotypes. The absence of significant differences among the genotypes may have been due to the effects of the significant interactions (p-value < 0.01) observed among the environmental variables (year and location) and the genotypes. For example, the genotypes interacted significantly (p-value < 0.01) with year and location but not with the sowing dates.

Different patterns of genotypes responses across sites, year, location and sowing dates have also been observed by Silva et al. (2011) and Tapley et al. (2013). The interactions among the environmental factors (year and location) provided little information because they did not involve the individual responses of the genotypes. However, it is important to identify which environmental factor (year or location) was proportionally more important for the interaction with the genotypes. Thus, the $R^2$ statistics (Table 1) indicated that the years ($R^2_{(YG)}$ = 24.3%) were more important in the interactions with the genotypes than were the locations ($R^2_{(LG)}$ = 12.5%). The combinations of years, locations and sowing dates ($R^2_{(YLSG)}$ = 22.5%) were also important for the determination of the magnitude of the interaction with the genotypes, which may have been due to the greater effect of the year and location than the sowing dates. Thus, the effect of sowing dates was relatively unimportant for the occurrence of the interaction ($R^2_{(SG)}$ = 7.0%), and sowing dates may be a candidate for use as an environmental measurement for the analysis of repeatability.

The year x sowing dates x genotype interaction was not meaningful, with a p-value close to unity (0.972), but this interaction was important because it indicated that the order of the genotypes (from the lowest to the most productive) was maintained (there was repeatability) through the different year x sowing dates combinations. In contrast, the location x year x genotype interaction and the location x sowing dates x genotype interaction showed lower p-values (0.488 and 0.323, respectively), which may have been due to the effect of the location, which was responsible for the significant quadruple interaction. Thus, it was observed that the location

*Table 1. Sources of variation (SV), degrees of freedom (DF), contribution of the environmental variables (year, location and sowing dates) to the interaction with the genotypes ($R^2$), mean square (MS), F-value (Fc) and numerator (DFn) and denominator (DFd) DF and p-values for the different SV for the joint analysis of variance of grain yield (t $ha^{-1}$) of wheat at Cascavel and Palotina in PR, Brazil. * according to the expressions in annex table.*

| SV | DF | $R^2$ (%) | MS | Fc* | DFn | DFd | p-value |
|---|---|---|---|---|---|---|---|
| Location (L) | 1 | | 36.481 | 1.75 | 2 | 5 | 0.243 |
| Year (Y) | 4 | | 55.825 | 1.90 | 6 | 8 | 0.210 |
| Sowing date (S) | 2 | | 5.022 | 1.57 | 10 | 12 | 0.234 |
| Genotype (G) | 16 | | 3.315 | 1.39 | 20 | 33 | 0.194 |
| L x Y | 4 | | 25.578 | 1.93 | 4 | 9 | 0.199 |
| L x S | 2 | | 0.956 | 0.10 | 4 | 9 | 0.979 |
| Y x S | 8 | | 9.690 | 0.76 | 9 | 8 | 0.648 |
| L x G | 16 | 12.5 | 1.795 | 2.57 | 24 | 82 | 0.001 |
| Y x G | 64 | 24.3 | 0.875 | 1.85 | 124 | 150 | 0.000 |
| S x G | 32 | 7.0 | 0.504 | 1.23 | 90 | 78 | 0.179 |
| L x Y x S | 8 | | 13.045 | 15.28 | 8 | 156 | 0.000 |
| L x Y x G | 64 | 11.3 | 0.405 | 1.00 | 64 | 128 | 0.488 |
| L x S x G | 32 | 6.3 | 0.452 | 1.12 | 32 | 128 | 0.323 |
| Y x S x G | 128 | 16.0 | 0.288 | 0.71 | 128 | 128 | 0.972 |
| L x Y x S x G | 128 | 22.5 | 0.404 | 2.74 | 128 | 960 | 0.000 |
| Block/(L Y S) | 60 | | 0.459 | 3.10 | 60 | 960 | 0.000 |
| Residue | 960 | | 0.148 | | | | |
| Environment x G | 464 | 100 | | | | | |

was an important factor (type of environment) in classifying the environments and that the selection of genotypes must be performed preferentially by location, thereby allowing the year and sowing date to be used as measurements of the common environment (more homogeneous). Additionally, whether the genotypes were statistically evaluated for four years with two sowing dates, two years with four sowing dates or one year with eight sowing dates, the same type of information was generated because the predictability of the climate conditions among the years was the same as among the different sowing dates.

The average grain yield and the differences showed among the years from 2007 to 2011 at Cascavel and Palotina (Table 2) indicated the complexity of the phenotypic manifestation of grain yield with stimuli from the environment. However, the amplitude of the response variability of grain yield was similar to that observed for other groups of environments and genotypes (Caierão et al., 2006; Franceschi et al., 2010; Silva et al., 2011; Benin et al., 2013).

The coefficients of repeatability ($\hat{\rho}$), the coefficients of determination ($R^2$), the number of trials for $R^2$ = 0.80 (J80) and $R^2$ = 0.90 (J90) for each year and in the set of years for the two locations (Cascavel and Palotina) and the sum of the locations for the different years are shown in Table 2.

The two locations did not differ (p-value = 0.05) in the averages of yield per test, the coefficient of repeatability for the sowing dates ($\hat{\rho}$), the coefficient of determination ($R^2$) or the number of trials (sowing dates) for $R^2$ = 0.80 (J80) and $R^2$ = 0.90 (J90), which may have been due to the variation in these estimates among years. These results indicated that on average, the two locations could have their evaluation trials of genotypes planned in a similar manner with regard to the number of trials per year and/or per sowing dates.

However, through the joint repeatability analysis (Table 2) using the five years x three sowing dates (15 repeated measurements) as a repeated measurement, the coefficient of repeatability ($\hat{\rho}$) was greater at Cascavel ($\hat{\rho}$=0.268) than at Palotina ($\hat{\rho}$=0.206). Thus, the number of trials necessary at Cascavel (J80 = 10.9) was equivalent to 0.70 (10.9/15.4 = 0.70) of the number of trials used at Palotina (J80 = 15.4) for the same coefficient of determination.

At Cascavel, the number of trials necessary for $R^2$ = 0.80 (J80) for a given year was greater than the number of sowing dates evaluated in the majority of the five years. With the average of J80 equal to 11.7 sowing dates per year, 58.5 trials (five years of trials; 5 x 11.7) would be necessary, that is, 3.9 times more than what is practiced. The same result occurred at Palotina. This large number of sowing dates with few days between

*Table 2. Number of trials measured (N), average grain yield of wheat (Prod; t ha$^{-1}$), repeatability coefficient for sowing dates ($\hat{\rho}$), coefficient of determination ($R^2$), number of trials required for $R^2$ = 0.80 (J80) and $R^2$ = 0.90 (J90) to be obtained by the analysis of variance method, F-test estimate for the GxE interactions (Fc) and the probability of significance (p-value) by year and in total for the two locations separately and grouped together. [(1)]Locations with averages not connected by the same letter differ by a bootstrap t-test (p-value = 0.05).*

| Year | N | Prod | $\hat{\rho}$ | $R^2$ | J80 | J90 |
|---|---|---|---|---|---|---|
| | | | | Cascavel, PR | | |
| 2007 | 3 | 3,696 | 0.560 | 79.2 | 3.1 | 7.1 |
| 2008 | 3 | 4,038 | 0.480 | 73.4 | 4.3 | 9.8 |
| 2009 | 3 | 3,070 | 0.136 | 32.1 | 25.4 | 57.1 |
| 2010 | 3 | 4,315 | 0.231 | 47.4 | 13.3 | 29.9 |
| 2011 | 3 | 3,117 | 0.245 | 49.4 | 12.3 | 27.7 |
| Average | - | 3,647a[(1)] | 0.330a | 56.3a | 11.7a | 26.3a |
| Total | 15 | 3,647 | 0.268 | 84.6 | 10.9 | 24.6 |
| | | | | Palotina. PR | | |
| 2007 | 3 | 3,642 | 0.112 | 27.4 | 31.8 | 71.6 |
| 2008 | 3 | 2,895 | 0.309 | 57.3 | 8.9 | 20.1 |
| 2009 | 3 | 2,766 | 0.338 | 60.5 | 7.8 | 17.7 |
| 2010 | 3 | 3,841 | 0.634 | 83.8 | 2.3 | 5.2 |
| 2011 | 3 | 3,549 | 0.486 | 73.9 | 4.2 | 9.5 |
| Average | - | 3,338a | 0.376a | 60.6a | 11.0a | 24.8a |
| Total | 15 | 3,338 | 0.206 | 79.5 | 15.4 | 34.7 |
| | | | | Cascavel + Palotina. PR | | |
| 2007 | 6 | 3,668 | 0.294 | 71.4 | 9.6 | 21.6 |
| 2008 | 6 | 3,467 | 0.296 | 71.6 | 9.5 | 21.4 |
| 2009 | 6 | 2,918 | 0.144 | 50.2 | 23.8 | 53.6 |
| 2010 | 6 | 4,078 | 0.213 | 61.9 | 14.7 | 33.2 |
| 2011 | 6 | 3,333 | 0.329 | 74.7 | 8.1 | 8.3 |
| Average | - | 3,493a | 0.255a | 65.9a | 13.1a | 27.6a |
| Total | 30 | 3,493 | 0.159 | 85.0 | 21.1 | 47.4 |

sowing dates was not justified from a practical or biological perspective. However, in grouping the three sowing dates and the five years to form the 15 environmental measurements, the J80 values were lower (10.9 trials at Cascavel) and similar (15.4 trials at Palotina) to the number of environments evaluated (15 measurements). The repeatability of sowing dates was not similar for the different years of evaluation. Thus, at Cascavel and at Palotina, the genotypes must be evaluated in various years and sowing dates, avoiding evaluations of only a few years, for which the J80 results were more variable.

The option to group the two locations and the three sowing dates (Table 2, lower block) into six measurements of environment resulted in a J80 higher than the number of environments evaluated in all years. However, this option was better than analyzing the two locations independently because the J80 (13.1) for five years resulted in 65.5 trials, which is 2.2 times more than that practiced, and this value was less than the 3.9 times of the analysis by location. In this condition, grouping the locations and the sowing dates resulted in better prediction of the genotypic values. Thus, the genotypes must be evaluated in different locations and sowing dates in addition to including the measurements of the variation across years.

Considering a group of trials composed of the 30 measurements of environment (three sowing dates x five years x two locations), the J80 value was 21 trials or 70% of the total number of trials evaluated. Therefore, this group was the most economical option, for which lower financial and human resources would be employed. These 21 trials must be distributed across the different locations, sowing dates and years, with greater frequency of years due to the greater heterogeneity among the years.

Repeatability estimates to assess the representativeness of trials (Annicchiarico et al., 2000), traits (Hakizama et al., 2000) or genetic parameters measurements (Jalaluddin & Harrison, 1993) are available for wheat. However, with regard to spring wheat, there was no documented assessment of the effects of years, locations and sowing dates to determine the optimal number of tests required to predict the grain yield performance, with a view to selecting and recommending cultivars. Our results point that it is possible to reduce the number of tests of evaluations without losing the level of informativeness.

Sowing date is one of the most important management factors affecting cereal production (McLeod et al., 1992). The most indicated sowing dates to achieve the highest yield are those that shows the best compromise among the demands for environmental resources (photoperiod, radiation, temperature and water availability) for the various phenophases of development of the wheat plant (Subedi et al., 2007; Bassu et al., 2009; Silva et al., 2014). At both Cascavel and Palotina, the ideal genotypes for cultivation on the evaluated sowing dates were identified.

The “ideal cultivar” is defined based on the following two criteria: high yield and stability (Yan & Kang, 2003). The “ideal genotype” is defined graphically by the vector with the largest length in the first principal component (PC1) and without projections in the second principal component (PC2); that is, it must be closer to the smallest central concentric circle. In the first sowing date at Cascavel, the CD 105 cultivar was the closest to the ideal genotype, followed by the CD 113, CD 114 and CD 117 cultivars (Figure 1). The CD 105, CD 114, CD 115 and CD 150 cultivars were highlighted as the closest to the ideal genotype in the second sowing date at Cascavel, followed by the Onix and CD 119 cultivars (Figure 1). In the third sowing date at Cascavel, the CD 105 and CD 114 cultivars were highlighted, followed by the CD 150, CD 121, CD 122 and Onix cultivars. In the first sowing date at Palotina, Onix was the cultivar closest to the ideal, followed by the CD 117 and CD 119 cultivars. For the second and third sowing dates at Palotina, the CD 150 cultivar was highlighted, followed by the Onix and CD 119 cultivars.

One group of cultivars was highlighted for stability and yield for all of the sowing dates at Cascavel (CD 105, CD 114 and CD 150; the latter with the exception of the first sowing date) and Palotina (CD 150, Onix and CD 119). Silva et al. (2011) and Tapley et al. (2013) also identified productive and stable cultivars adapted to different cultivation locations and sowing dates. Thus, the identification of the minimum number of trials so that evaluations are consistent and the adoption of the sowing dates that provide the climate conditions required by the wheat cultivars was revealed to be of extreme importance for the good productive performance of the crops.

## CONCLUSIONS

To identify superior wheat genotypes with respect to grain yield with 80% precision, a total of 21 trials distributed in different years, locations and sowing dates must be used.

The evaluation trials for genotypes of wheat must be executed with a greater number of years and lower numbers of sowing dates and locations.

The CD 105, CD 114 and CD 150 cultivars at Cascavel and the CD 150, Onix and CD 119 cultivars at Palotina were shown to be stable and widely adapted across different sowing dates, with high grain yield.

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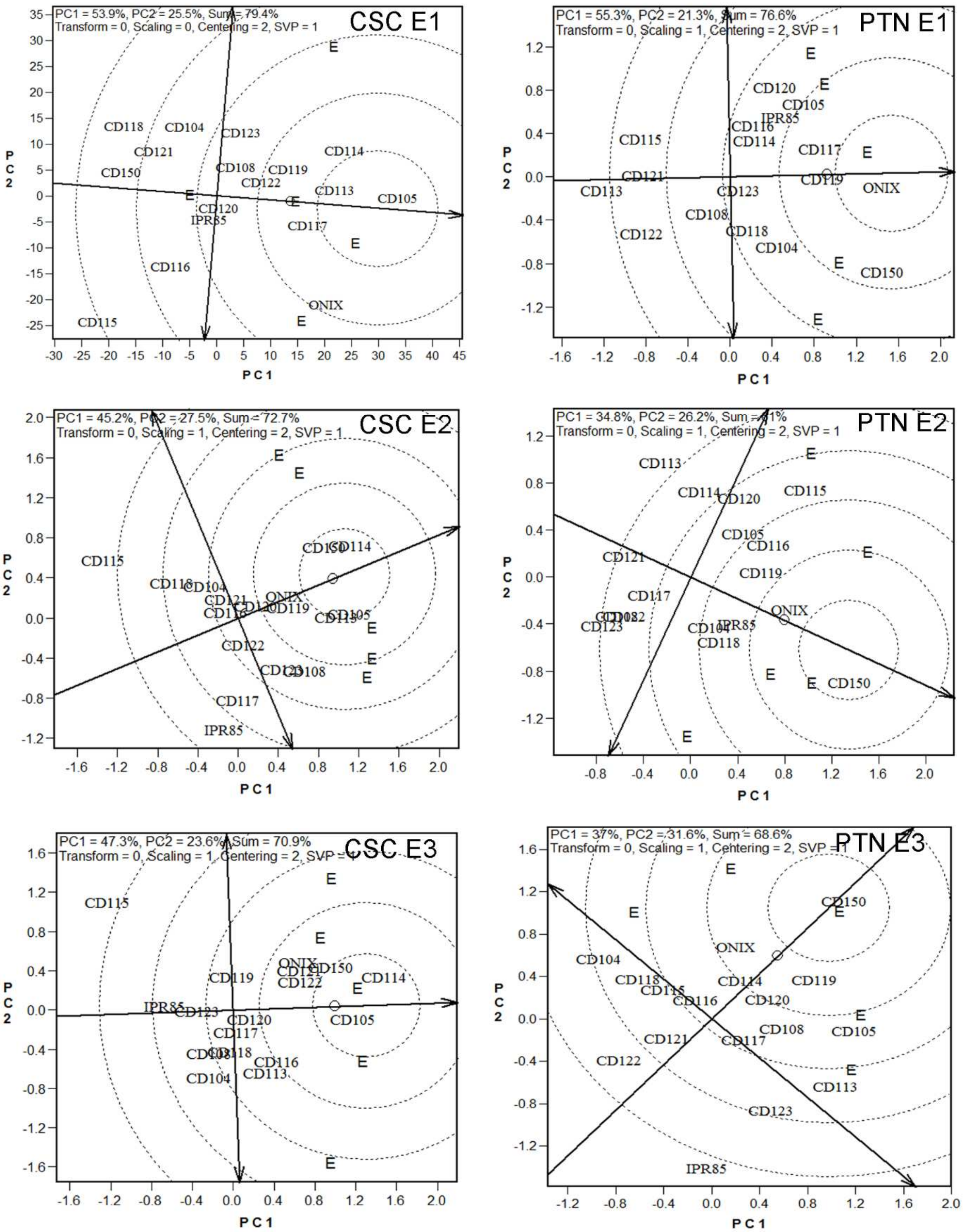


*Figure 1. Plots of the scores of the principal components according to the GGE biplot model for the identification of the ideal genotype based on grain yield characteristics of the 17 and 16 genotypes of wheat evaluated at Cascavel (CSC) and Palotina (PTN), respectively, for three sowing dates (S1, S2 and S3) in the years from 2007 to 2011 (average of 5 years).*

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**Annex**

Joint analysis of variance, using genotypes data from different years, locations and sowing dates, as the model:

$Y_{ijklm} = m + L_j + Y_i + S_k + G_l + LY_{ij} + LS_{jk} + YS_{ik} + LG_{jl} + YG_{il} + SG_{kl} + LYS_{ijk} + LYG_{ijl} + LSG_{jkl} + YSG_{ikl} + LYSG_{ijkl} + B_{m(ijk)} + R_{ijklm}$,

where:

$L_j$ is the random effect of the j-th location (j = 1,2,...J) - $L_j \cap N(0; \sigma_l^2)$;

$Y_i$ is the random effect of the i-th year (i= 1,2,... I) - $Y_i \cap N(0; \sigma_y^2)$;
$S_k$ is the fixed effect of the k-th sowing date (k= 1,2,... K);
$G_l$ is the fixed effect of the l-th genotype (l = 1,2,...L);

$LY_{ij}$ is the random effect of the i-th year in the j-th location – $LY_{ij} \cap N(0; \sigma_{ly}^2)$;

$LS_{jk}$ is the random effect of the interaction between the location j and the sowing date k –$LS_{jk} \cap N(0; \sigma_{ls}^2)$;

$YS_{ik}$ is the random effect of the interaction between the year i and the sowing date k –$YS_{ik} \cap N(0; \sigma_{ys}^2)$;

$LG_{jl}$ is the random effect of the interaction between the location j and the genotype l – $LG_{jl} \cap N(0; \sigma_{lg}^2)$;

$YG_{il}$ is the random effect of the interaction between the year i and the genotype l - $YG_{il} \cap N(0; \sigma_{yg}^2)$;
$SG_{kl}$ is the fixed effect of the k-th sowing date and the l-th genotype;

$LYS_{ijk}$ is the random effect of the interaction location x year x sowing date - $LYS_{jik} \cap N(0; \sigma_{lys}^2)$;

$LYG_{ijl}$ is the random effect of the interaction location x year x genotype - $LYG_{jil} \cap N(0; \sigma_{lyg}^2)$;

$LSG_{jkl}$ is the random effect of the interaction location x sowing date x genotype - $LSG_{jkl} \cap N(0; \sigma_{lsg}^2)$;

$YSG_{ikl}$ is the random effect of the interaction year x sowing date x genotype - $YSG_{ikl} \cap N(0; \sigma_{ysg}^2)$;

$LYSG_{ijkl}$ is the random effect of the interaction location x year x sowing data x genotype - $LYSG_{jikl} \cap N(0; \sigma_{lysg}^2)$;
$B_{m(ijk)}$ is the random effect of the m-th block (m = 1,2...M) within each sowing date, location and year - $B_{m(ijk)} \cap N(0; \sigma_b^2)$;

and $R_{ijklm}$ is the error associated with the observation ijklm ($R_{ijklm} \cap N(0; \sigma^2)$).

For this model, the degrees of freedom, the expected mean squares of the sources of variation and the numerator and denominator of the F-test for the hypotheses related to the sources of variation in the model are shown in annex table. The degrees of freedom for the F-test composed of two mean squares were calculated using the Satterthwaite expression.

Annex table. Sources of variation (SV), degrees of freedom (DF), mean square (MS), expectations of the MS and expressions for the F-tests (Fc) for the effects of fixed sowing dates, genotype and sowing dates x genotype, with the other effects being random in a randomized block design with three repetitions per test (year and location)

| SV | DF | MS | Expectations (MS) | Fc |
|---|---|---|---|---|
| Location (L) | 1 | V1 | $\sigma^2 + L\sigma_b^2 + M\sigma_{lysg}^2 + JM\sigma_{lsg}^2 + KM\sigma_{lyg}^2 + LM\sigma_{lys}^2 + JKM\sigma_{lg}^2 + JLM\sigma_{ls}^2 + KLM\sigma_{ly}^2 + IKLM\sigma_{l}^2$ | (V1+V11+V12+V13)/ (V5+V6+V8+V15) |
| Year (Y) | 4 | V2 | $\sigma^2 + L\sigma_b^2 + M\sigma_{lysg}^2 + IM\sigma_{ysg}^2 + KM\sigma_{lyg}^2 + LM\sigma_{lys}^2 + IKM\sigma_{yg}^2 + ILM\sigma_{ys}^2 + KLM\sigma_{ly}^2 + JKLM\sigma_{y}^2$ | (V2+V11+V12+V14)/ (V5+V7+V9+V15) |
| Sowing dates (S) | 2 | V3 | $\sigma^2 + L\sigma_b^2 + M\sigma_{lysg}^2 + IM\sigma_{ysg}^2 + JM\sigma_{lsg}^2 + LM\sigma_{lys}^2 + IKM\sigma_{yg}^2 + ILM\sigma_{ys}^2 + JLM\sigma_{ls}^2 + \varphi(s)$ | (V3+V11+V12+V14)/ (V6+V7+V9+V15) |
| Genotype (G) | 16 | V4 | $\sigma^2 + M\sigma_{lysg}^2 + IM\sigma_{ysg}^2 + JM\sigma_{lsg}^2 + KM\sigma_{lyg}^2 + IKM\sigma_{yg}^2 + JKM\sigma_{lg}^2 + \varphi(g)$ | (V4+V2)/(V8+V9) |
| L x Y | 4 | V5 | $\sigma^2 + L\sigma_b^2 + M\sigma_{lysg}^2 + KM\sigma_{lyg}^2 + LM\sigma_{lys}^2 + KLM\sigma_{ly}^2$ | (V5+V15)/(V11+V12) |
| L x S | 2 | V6 | $\sigma^2 + L\sigma_b^2 + M\sigma_{lysg}^2 + JM\sigma_{lsg}^2 + LM\sigma_{lys}^2 + JLM\sigma_{ls}^2$ | (V6+V15)/(V11+V13) |
| Y x S | 8 | V7 | $\sigma^2 + L\sigma_b^2 + M\sigma_{lysg}^2 + IM\sigma_{ysg}^2 + LM\sigma_{lys}^2 + ILM\sigma_{ys}^2$ | (V7+V15)/(V11+V14) |
| L x G | 16 | V8 | $\sigma^2 + M\sigma_{lysg}^2 + JM\sigma_{lsg}^2 + KM\sigma_{lyg}^2 + JKM\sigma_{lg}^2$ | (V8+V15)/(V12+V13) |
| Y x G | 64 | V9 | $\sigma^2 + M\sigma_{lysg}^2 + IM\sigma_{ysg}^2 + KM\sigma_{lyg}^2 + IKM\sigma_{yg}^2$ | (V9+V15)/(V12+V14) |
| S x G | 32 | V10 | $\sigma^2 + M\sigma_{lysg}^2 + IM\sigma_{ysg}^2 + JM\sigma_{lsg}^2 + IJM\sigma_{sg}^2$ | (V10+V15)/(V13+V14) |
| L x Y x S | 8 | V11 | $\sigma^2 + L\sigma_b^2 + M\sigma_{lysg}^2 + LM\sigma_{lys}^2$ | (V11+V17)/(V15+V16) |
| L x Y x G | 64 | V12 | $\sigma^2 + M\sigma_{lysg}^2 + KM\sigma_{lyg}^2$ | V12/V15 |
| L x S x G | 32 | V13 | $\sigma^2 + M\sigma_{lysg}^2 + JM\sigma_{lsg}^2$ | V13/V15 |
| Y x S x G | 128 | V14 | $\sigma^2 + M\sigma_{lysg}^2 + IM\sigma_{ysg}^2$ | V14/V15 |
| L x Y x S x G | 128 | V15 | $\sigma^2 + M\sigma_{lysg}^2$ | V15/V17 |
| Block/(L Y S) | 60 | V16 | $\sigma^2 + L\sigma_b^2$ | V16/V17 |
| Residue | 960 | V17 | $\sigma^2$ | - |