Agronomic performance of transgenic and isogenic corn hybrids in the state of Mato Grosso do Sul[1]

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ABSTRACT

Theoretically, isogenic hybrids should not present any differences in their genetic makeup due to recombinant DNA technology. However, these materials may behave differently in relation to adaptability and stability. This study aimed at evaluating the agronomic performance of transgenic corn and their isogenic hybrids in two locations in Mato Grosso do Sul, Brazil. Three isogenic simple hybrids and two transgenic varieties of each hybrid were evaluated. The first and second corn crop of 2013/14 were simultaneously analyzed in Dourados and Caarapó, two locations in the State of Mato Grosso do Sul, totaling four environments x season conditions that were evaluated. A randomized complete block design with three replicates per location was used, and the treatments were arranged in a 3 × 3 factorial design (three genetically modified and three conventional hybrids), with three replicates per site. Characteristics such as plant height, ear height, male flowers, female flowers, and grain yield were evaluated. The parameters adaptability and stability were estimated using the Eberhart and Russell model. In all environments, transgenic hybrids showed higher average grain yield. Considering the environments, AG 7000, a conventional isogenic hybrid, obtained the highest average grain yield. The most stable and productive hybrids were DKB 390 VT PRO and AG 7000 YG, both transgenic. All assessed hybrids exhibited greater average plant height, ear height, and grain yield in Caarapó during the second corn crop, demonstrating that the environment at that site and time was more favorable.

Key words: *Zea mays*; grain yield; transgenics; *Bt*-corn; genotype-environment interaction.

RESUMO

Desempenho agronômico de híbridos de milho transgênicos e respectivos isogênicos avaliados no estado de Mato Grosso do Sul

Plantas isogênicas, teoricamente, não deveriam apresentar modificação alguma advinda da tecnologia do DNA recombinante na sua base genética. Entretanto, acredita-se que haja comportamento diferenciado destes materiais em relação a adaptabilidade e estabilidade. Objetivou-se com este trabalho avaliar o desempenho agronômico de híbridos de milho transgênico e seus respectivos isogênicos em dois locais de Mato Grosso do Sul. Foram avaliados três híbridos simples isogênicos e duas versões transgênicas de cada híbrido. O ensaio foi instalado na primeira e segunda safra 2013/14, simultaneamente, em duas localidades do Estado de Mato Grosso do Sul, Dourados e Caarapó, totalizando quatro ambientes. O delineamento experimental utilizado foi de blocos ao acaso com três repetições e os tratamentos foram dispostos no esquema fatorial 3 x 3 (três híbridos transgênicos e três convencionais), com três repetições por local. Foram avaliadas as características altura de planta, altura de espiga, florescimento masculino, florescimento feminino e produtividade de grãos. Os parâmetros de adaptabilidade e estabilidade foram estimados pelo método proposto por Eberhart e Russell. Em todos os ambientes as maiores médias de produtividade de grãos foram dos

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híbridos transgênicos. O híbrido que obteve a maior média de produtividade de grãos em relação aos ambientes foi o isogênico, convencional, AG7000. Os híbridos mais estáveis e produtivos foram DKB 390VTPRO e AG 7000YG, ambos transgênicos. A segunda safra em Caarapó apresentou maiores médias de altura de planta, altura de espiga e produtividade de grãos para todos os híbridos avaliados, demonstrando ser, consequentemente o ambiente mais favorável.

Palavras-Chave: *Zea mays*; produtividade de grãos; transgenia; milho *Bt*; interação genótipos x ambientes.

INTRODUCTION

Corn (Zea mays L.) is one of the oldest domesticated plants and is now the most produced grain in the world accounting for 38% of all grain produced, followed by wheat (29%) and rice (21%) (Conab, 2014). Currently, corn is the second largest transgenic crop grown in Brazil, occupying about 12.5 million hectares considering both summer and winter corn crops (Celeres, 2014).

According to Embrapa (2013), 253 transgenic and 214 conventional corn cultivars were made available to farmers during the corn crop of 2013/14. Transgenic cultivars currently available are the result of five genetic modification events to control caterpillars, some of which include YieldGard® MON 810 and MON 89034 YieldGard VT PRO®. Genetically modified organisms were made available for trading and planting in Brazil in 2005 (Mapa, 2013).

Transgenic plants are products obtained from the genetic modification or transformation of plants, the creation of which involves inserting DNA into the genome at one or more sequences of nucleotide pairs, usually isolated from one or more particularly arranged species, to ensure gene expression of one or more genes of interest (Lerayer *et al*., 2006). Transgenics derive from conventional cultivars by classical breeding methods and are known as isogenic hybrids. In this manner, theoretically, isogenic hybrids should not present any differences in their genetic makeup due to the recombinant DNA technology used to create them. However, transgenics may interfere with the adaptability and stability of these materials.

Pest-resistant transgenic corn plants, such as those with the Cry1Ab gene (e.g., Yield Gard® MON810), reduce losses caused by pests thereby reducing insecticide use (James, 2005). The management of these pests may reduce production costs and increase corn grain yield (Carneiro *et al*., 2009). Transgenics have remarkably become a technological advance primarily used for corn crops, and they are extremely important for farmers, agribusiness, and consumers.

The genotype-environment interaction may be simple when the relative merit of the genotype is not altered by different environments and complex when it denotes the lack of correlation between measurements of the same genotype in distinct environments, indicating inconsistency between the superiority of certain genotypes and environmental variation. Breeding is difficult only when complex interactions occur (Cruz & Regazzi, 2001). Besides the difficulty of widely recommending adaptable cultivars, this type of interaction requires that more environments be analyzed.

Cruz & Carneiro (2004) define adaptability as the ability of a genotype to respond advantageously to improvements in the environment, which is an advantage from the point of view of grain yield. Stability is defined as the ability of genotypes to show highly predictable performance according to environmental variation.

Data on the performance of genetically modified corn hybrids are sparse thus necessitating studies in several regions and field conditions to assess whether the technology sold by companies that produce transgenics is improving or worsening the stability of organisms to which they has been incorporated, that is, whether the conventional (isogenic) hybrid is improved or worsened. This study aimed at assessing the agronomic performance of transgenic and isogenic corn hybrids at two locations in Mato Grosso do Sul, Brazil.

MATERIALS AND METHODS

The experiments were carried out in two seasons during the first and second corn crop 2013/14in the municipalities of Caarapó and Dourados, both located in the state of Mato Grosso do Sul, Brazil, totaling four location×crop environments, herein referred to as environments. The climate of both regions was classified as Cwa according to the Köppen climate classification. Both locations have hot summers and dry winters, maximum temperatures during December and January, minimum temperatures from May to August, rainfall surpluses in spring-summer, and water shortages in autumn-winter (Fietz & Fisch, 2008). The weather data in Caarapó during the first corn crop indicated 410 mm rainfall, 60.5% relative humidity, and 23 °C average temperature, and in Dourados, there was 390.2 mm rainfall, 63.7% relative humidity, and 23.4 °C average temperature. The weather data in Caarapó during the second corn crop included 640 mm of rainfall, 75.4% relative humidity, and

33.6 ºC average temperature, all of which were higher than the values observed in Dourados: 632 mm rainfall, 74.4% relative humidity, and 30.6 ÚC average temperature (Embrapa, 2015).

Three commercially available conventional (isogenic) hybrids, namely, AG 7000, DKB 390, P 30K73, and their transgenic versions, AG 7000 YG, AG 7000 VT PRO, DKB 390 YG, DKB 390 VT PRO, P 30K73 YG, and P 30K73 VT PRO were used. A randomized complete block design with three replicates per location was used, and the treatment conditions were arranged in a 3 × 3 factorial design (three transgenic and three conventional hybrids). The plots comprised four rows of five meters in length. The first corn crops of 2013/14 were grown on October 23, 2013 in Dourados and on November 6, 2013 in Caarapó. The second corn crops were grown on March 7, 2014 in Dourados and on March 9, 2014 in Caarapó. Both were given 300 kg/ha^{-1} 8-20-20 (NPK) fertilizer and 100 kg/ha^{-1} urea.

Cultural practices were carried out whenever necessary according to the technical recommendations for the corn crop. During the crop cycle, insecticide applications were carried out twice in all treatments and during both corn crop periods (Galvão & Miranda, 2004).

Characteristics such as plant height (PH), ear height (EH), male flowers (MF), and female flowers (FF) were assessed. Grain yield was determined after threshing and weighing the ears of each plot; the moisture content was adjusted to 13%, and expressed in kg ha^{-1}.

The plant height and ear height of randomly selected competitive plants were measured in centimeters using a millimeter ruler. Both the distance from the soil to the insertion of the flag leaf and the distance from the soil to the point of insertion of the stem of the first formed ear were considered, respectively. The male and female flowers were assessed regarding the number of days after sowing, the time at which 50% of plants had tassels, and the time at which 50% of plants presented stigma and style.

Grain yield was found after threshing and weighing the ears in each plot. The water content was determined immediately after harvesting, and the yield was measured in kg, adjusted to 13%, and expressed in kg ha^{-1}.

Initially, an individual analysis of variance was conducted to determine the performance of each genotype in each environment. After verification of the homogeneity of residual variance, a joint analysis of variance was performed comparing the four environments. The statistical model used for each individual analysis of variance was as follows: $y_{ij} = \mu + G_i + \beta_j + \varepsilon_{ij}$, where y_{ij} was the observed performance of the jth replicate of the ith genotype, μ was the overall average performance, $\hat{a}_j$ was the effect of the ith block, G_i was the effect of the ith genotype, and ε_{ij} was the random error associated with jth replicate of the ithgenotype.

A joint analysis was performed considering the fixed effects of genotypes and environments, according to the following model: $Y_{ijk} = \mu + (\beta / A)_{jk} + G_i + A_j + GA_{ij} + \varepsilon_{ijk}$, where Y_{ijk} was the observed performance of the i^{th} genotype in the k^{th} block and the j^{th} environment, μ : was the overall average performance, $B / A)_{jk}$: was the effect of block k within environment j,G_i: was the effect of the i^{th} genotype, A_j: was the effect of the j^{th} environment GA_{ij}: was the effect of the interaction between the ith genotype, in the jth environment, and ε_{ijk}: was the random error associated with the i^{th} genotype, in the k^{th} block and the j^{th} environment observed. The Scott-Knott's test ($p < 0.05$) was used to group the averages of each genotype within each environment (location × crop), and significant environments were compared with a Tukey's test ($p < 0.05$).

The parameters of adaptability and stability were estimated using the Eberhart & Russell model (1966), which is based on simple linear regression analysis. According to the model, $Y_{ij} = \beta_{0i} + \beta_{1i} I_j + \delta_{ij} + \varepsilon_{ij}$, where was the average of the i_{th} genotype in the j^{th} environment, β_{0i} was the overall average of the i^{th} genotype, β_{1i} was the linear regression coefficient, which measured the response of the i^{th}genotype to variation in the environment, I_j was the coded environmental index ($E^I_J = I_J = 0$), where: $I_J = Y_j - Y_\infty$, ε_{ij}: was the regression deviation of the i^{th} genotype in the j^{th} environment, and was the average experimental error associated with the observed Y_{ij}.

Adaptability (β_i) was estimated according to the following expression: $\beta i = \Sigma^{n}_{j=1} \frac{Y_{ij} I_j}{\Sigma^{n}_{j=1} I^2_j}$, where was the average of the i^{th} genotype in the j^{th} environment, was the environmental index in which $Ij = (Yj/p) - (Y_\infty/pn))$, Ij was the average of all genotypes in the j^{th} environment was the overall average, *n:* was the number of genotypes, and *p:* was the number of environments. The estimates for β_i were tested according the null hypothesis H_0: $\beta_i = 1$ and the alternative hypothesis H_1: $\beta_i \neq 1$ and assessed by the t-statistic.

Stability (S^2d_i) was estimated according to the following expression: $S^2d_i = (QMD_i - QMR/r)$, where was the average square of the regression deviationat the i^{th} genotype. *QMR* was the averagesquare of the residue, and was the number of repetitions. The estimates for (S^2d_i) were tested according to the null hypothesis H_0: (S^2d_i) = 0 and the alternative hypotheses H_1: (S^2d_i) $\neq$ 0 and assessed by an F-test according to the following expression: QMD_i / QMR.

According to Cruz *et al*. (2004), genotypes with higher average yields and a δ^2_{ij} statistically different from zero may occur, and selection of some genotypes with low stability from the group may be required. In such cases, the coefficient of determination R^2 was used as an ancillary measure to compare genotypes. R^2 was obtained according

Table 1: Summary of the analysis of individual variance and respective averages of nine corn genotypes obtained in four environments in the state of Mato Grosso do Sul, 2013 e 2014

			PH				
Caarapó Crop		**Dourados Crop**		**Caarapó 2ª Crop**		**Dourados 2ª Crop**	
P 30K73 VT PRO	161,66 aB	P 30K73 VT PRO	169,33 aB	P30K73	194,00 aA	AG 7000 VT PRO	140,33 aB
P 30K73 YG	157,00 aB	P 30K73 YG	163,83 aB	P 30K73 VT PRO	189,66 aA	AG 7000 YG	138,00 aB
DKB 390	154,33 aB	P30K73	158,50 aB	P 30K73 YG	186,66 aA	DKB 390 YG	135,16 aB
P30K73	146,33 bB	DKB 390	154,66 aB	DKB 390 VT PRO	178,66 bA	DKB 390 VT PRO	135,00 aB
AG 7000 VT PRO	145,66 bB	DKB 390 YG	149,83 bB	DKB 390 YG	177,66 bA	P 30K73 YG	134,00 aC
DKB 390 YG	143,66 bB	DKB 390 VT PRO	149,66 bB	DKB 390	173,16 cA	P 30K73 VT PRO	123,16 bC
DKB 390 VT PRO	139,33 bB	AG 7000 VT PRO	148,66 bB	AG 7000 VT PRO	166,66 cA	AG 7000	123,00 bB
AG 7000 YG	125,33 cB	AG 7000	140,33 cB	AG 7000 YG	161,66 cA	DKB 390	119,66 bC
AG 7000	135,00 cBC	AG 7000 YG	130,33 cB	AG 7000	157,33 cA	P30K73	107,16 cC
			EH				
Caarapó Crop		**Dourados Crop**		**Caarapó 2ª Crop**		**Dourados 2ª Crop**	
DKB 390	103,00 aA	DKB 390	101,66 aA	DKB 390	104,16 aA	DKB 390 YG	74,66 aC
AG 7000 VT PRO	90,00 bA	DKB 390 VT PRO	92,66 bA	DKB 390 YG	102,33 aA	DKB 390 VT PRO	74,66 aB
DKB 390 VT PRO	89,66 bA	AG 7000 VT PRO	91,66 bA	P 30K73	99,33 aA	P 30K73 YG	68,66 bB
P 30K73 VT PRO	88,00 bA	DKB 390 YG	89,33 bB	P 30K73 VT PRO	98,16 aA	AG 7000 VT PRO	62,83 bB
DKB 390 YG	85,5 bBC	P 30K73 VT PRO	88,50 bA	DKB 390 VT PRO	98,00 aA	AG 7000 YG	62,66 bB
AG 7000	83,00 bA	AG 7000	87,33 bA	AG 7000 VT PRO	95,33 aA	AG 7000	57,33 cB
P 30K73	82,16 bB	P 30K73	84,66 bB	AG 7000 YG	90,00 bA	DKB 390	49,33 cB
P 30K73 YG	77,33 bAB	P 30K73 YG	81,16 bB	P 30K73 YG	88,33 bB	P 30K73 VT PRO	49,00 cB
AG 7000 YG	60,66 cB	AG 7000 YG	63,83 cB	AG 7000	86,00 bA	P 30K73	47,16 cC
			FF				
Caarapó Crop		**Dourados Crop**		**Caarapó 2ª Crop**		**Dourados 2ª Crop**	
AG 7000VTPRO	66,33 aB	AG 7000YG	65,00 aB	DKB 390	66,00 aB	AG 7000	72,66 aA
PIONNER 30K73	65,66 aB	DKB 390	64,33 aB	AG 7000VTPRO	65,66 aB	DKB 390	71,33 aA
AG 7000	65,66 aB	DKB 390VTPRO	64,00 aB	DKB 390YG	64,66 aB	P 30K73	71,33 aA
P 30K73VTPRO	65,00 aB	P 30K73YG	64,00 aB	DKB 390VTPRO	64,66 aB	DKB 390VTPRO	71,00 aA
P 30K73YG	64,66 aB	P 30K73VTPRO	64,00 aB	AG 7000YG	64,66 aB	P 30K73 YG	70,66 aA
DKB 390YG	64,00 aB	P 30K73	64,00 aB	AG 7000	64,00 aB	DKB 390YG	70,33 aA
AG 7000YG	64,00 aB	DKB 390YG	63,66 aB	P 30K73VTPRO	63,00 aB	AG 7000VTPRO	70,33 aA
DKB 390	64,00 aB	AG 7000VTPRO	63,33 aB	P 30K73YG	62,33 aB	AG 7000YG	70,00 aA
DKB 390VTPRO	61,66 aB	AG 7000	62,66 aB	P 30K73	62,00 aB	P 30K73VTPRO	69,66 aA

Continua...

Continuação

MF							
Caarapó Crop		**Dourados Crop**		**Caarapó 2ª Crop**		**Dourados 2ª Crop**	
AG 7000	68,33 aB	DKB 390VTPRO	65,66 aB	DKB 390	65,00 aB	AG 7000	72,33 aA
AG 7000VTPRO	68,00 aA	AG 7000YG	65,33 aB	DKB 390YG	64,66 aB	DKB 390	71,66 aA
DKB 390	67,00 aB	P 30K73YG	65,33 aBC	DKB 390VTPRO	64,66 aB	P 30K73	71,33 aA
P 30K73YG	66,66 aAB	DKB 390YG	65,00 aB	AG 7000VTPRO	64,66 aB	DKB 390YG	70,00 aA
DKB 390YG	66,00 bB	P 30K73	64,66 aB	AG 7000YG	63,66 aB	DKB 390VTPRO	70,00 aA
DKB 390VTPRO	65,33 bB	AG 7000	64,00 aC	P 30K73YG	62,33 bC	P 30K73VTPRO	70,00 aA
P 30K73VTPRO	65,33 bB	DKB 390	64,00 aB	AG 7000	62,33 bC	AG 7000VTPRO	70,00 aA
AG 7000YG	64,00 bB	P 30K73VTPRO	63,66 aB	P 30K73VTPRO	62,33 bB	P 30K73 YG	69,66 aA
PIONNER 30K73	63,33 aB	AG 7000VTPRO	63,66 aB	P 30K73	61,00 bC	AG 7000YG	69,66 aA
PROD							
Caarapó Crop		**Dourados Crop**		**Caarapó 2ª Crop**		**Dourados 2ª Crop**	
DKB 390VTPRO	5.635,53 aA	AG 7000VTPRO	4.393,56 aB	AG 7000VTPRO	8.091,73 aA	DKB 390YG	5.209,26 aBA
P 30K73YG	5.570,30 aBA	P 30K73VTPRO	4.166,70 aAB	AG 7000YG	6.958,53 aA	DKB 390VTPRO	4.754,80 aBA
P 30K73VTPRO	5.531,13 aA	P 30K73YG	4.099,76 aB	DKB 390YG	6.845,93 aA	AG 7000	4.157,80 aB
DKB 390YG	5.137,50 aB	AG 7000	4.015,13 aB	P 30K73YG	6.567,20 bA	P 30K73 YG	3.997,06 aB
PIONNER 30K73	4.313,43 bA	AG 7000YG	3.735,40 aB	DKB 390VTPRO	6.364,80 bA	P 30K73	3.971,50 aA
DKB 390	4.309,86 bB	P 30K73	3.671,56 aA	DKB 390	6.321,86 bA	AG 7000YG	3.871,50 aB
AG 7000	3.935,56 bB	DKB 390	3.601,46 aB	AG 7000	6.160,00 bA	DKB 390	3.589,63 aB
AG 7000VTPRO	3.870,23 bB	DKB 390YG	3.422,96 aC	P 30K73VTPRO	5.446,26 bA	P 30K73VTPRO	3.436,30 aB
AG 7000YG	3.582,46 bB	DKB 390VTPRO	3.191,86 aB	P 30K73	5.267,40 bA	AG 7000VTPRO	3.314,83 aB

PH: plant height; EH: ear height; FF: female flowering; MF: male flowering; PROD: grain yield. Means followed by the same lowercase letter in the column and upper case in the row do not differ by Scott-Knott test ($p < 0.05$) and Tukey ($p < 0.05$), respectively.

to the following expression: $R^2_i = (SQRLinear_i / SQ(A/G_i) \times 100$, where *SQRLinear* was the sum of linear regression squares of the i^{th} genotype and $SQ(A/G_i$ was the sum of environment squares within the i^{th} genotype. All statistical analyses were performed using the GENES software (Cruz, 2013).

RESULTS AND DISCUSSION

Initially, each experiment was analyzed individually within each environment, and plant and ear height were significantly different ($p<0.05$) in all environments analyzed (Table 1).

Concerning individual plant height averages in each environment, 30K73 P YG excelled in all environments, while AG 7000 exhibited poor results in all environments analyzed. Comparing the transgenics to their isogenic hybrids in Dourados (first corn crop) and Caarapó (second corn crop), the P 30K73 and GM hybrids showed similar results and higher character averages. Likewise, AG 7000 and its transgenic hybrids grew to similar heights in Caarapó during the second crop. The other transgenics and their isogenic hybrids displayed great heterogeneity in this character (Table 1).

It is worth noting that when location was assessed, the second corn crop in Caarapó experienced superior conditions for the development of genotypes, both for the transgenic and isogenic hybrids. This result may be related mainly to the 640 mm rainfall, 75.4% relative humidity, and average temperature of 33.6 ÚC, all of which were superior to the conditions in Dourados during the second corn crop (632 mm rainfall, 74.4% relative humidity, and 30.6 °C). Concerning the first corn crop, the following weather data was observed in Caarapó and Dourados: 410 mm rainfall, 60.5% relative humidity, and 23 °C, and 390.2 mm rainfall, 63.7% relative humidity, and 23.4 °C, respectively (Embrapa, 2015).

The lowest growth was observed in Dourados during the second crop; this may be related to the late sowing of the hybrids, that is, at the end of the recommended period for southern Mato Grosso do Sul, since decreasing temperatures over time reduced plant height. Average heights ranged from 107.16 to 140.33 cm among the hybrids studied, which were below the recommended height for the region. A study by Figueiredo *et al*. (2009) at Embrapa Cpao found that 42 commercially available corn genotypes exhibited an average plant height of 190 cm in southern Mato Grosso do Sul, which was taller than the heights observed in this study.

Conventional hybrids and the isogenic hybrid DKB 390 had higher average ear height than those in three of the environments (first and second crop in Caarapó and first crop in Dourados). The AG 7000 YG hybrid's ears grew less in the corn crop in both environments. The highest averages were found in Caarapó during the second corn crop, and the lowest were found in Dourados also during the second corn crop. Ear height of isogenic hybrids, such as P 30K73, was not significantly different when compared to that of their transgenic hybrids in Caarapó and Dourados during the first corn crop; likewise DKB 390 in Caarapó during the second crop was not significantly different from its transgenic hybrids. The remaining transgenic and isogenic hybrids were all statistically different from each other ($p < 0.05$) in all environments (Table 1).

Female flowers were not statistically significantly different among environments; the averages were 64.55 days (Caarapó, first crop), 63.88 days (Dourados, first crop), 64.10 days (Caarapó, second crop), and 70.80 days (Dourados, second crop), indicating that transgenic and isogenic hybrids were equal among all environments (Table 1). The importance of assessing the cycle of a plant within a production system is considered crucial, since the number of days from sowing or emergence until the initial presence of male and/or female inflorescences signifies the completion of the cultivar cycle and is the recommendation for sowing. Since this cycle depends on several environmental factors, especially temperature, total growing degree days and days from sowing to early flowering have been used to make the data quantifiable (Russell & Stuber, 1985). Likewise, Diniz (2011) found no significant differences between transgenic and isogenic hybrids in terms of days to early flowering.

Comparing the male flowers in Caarapó during the first corn crop, transgenic hybrids differed from isogenic hybrids ($p < 0.05$). On the other hand, DKB 390 and PIONNER 30K73 and their transgenic hybrids were not significantly different during the second corn crop. Only AG 7000 differed from its transgenic hybrids although neither environment was statistically significantly different from each other in Dourados.

Magg *et al*. (2001) assessed male flowers of the Bt corn hybrid of both transgenic and isogenic hybrids in Dourados as well and found no statistically significant difference between them.

Regarding male and female flowers in each environment, the cycle of hybrids assessed in Dourados during the second corn crop was regular since they flowered later than in other environments: between 69 and 72 days after sowing, which differed statistically from the other environments that flowered between 61 and 68 days. This may be related mainly to variations in the climates as hybrids were sowed later than what is recommended for Mato Grosso do Sul. Therefore, hybrids received uneven rainfall, primarily from the period of emergence until preflowering when less than half the total rainfall fell. This period of drought, coinciding with when the crop began to germinate, caused hybrids to blossom later. The remaining rainfall in Dourados occurred from the postflowering period until maturation when the hybrids were able to recover from the dry period during the initial phase of the crop.

When sown late, hybrids are influenced by water shortages and low temperatures during critical periods of the crop, which affect grain yield and contribute to the increase of time required for flowering and production (Landau *et al*., 2010).

The grain yield differed ($p < 0.05$) in Caarapó only in both crops, especially for the transgenic hybrid DKB 390 YG, which was among the most productive across all environments assessed (Table 1).

Between transgenic and isogenic hybrids in Caarapó, the conventional hybrid AG performed similarly to transgenic hybrids during the first crop. In Dourados, none of the hybrids was significantly different during the first crop. In Caarapó during the second crop, PIONNER 30K73 was not different from its genetically modified hybrids. This demonstrated that transgenic hybrids are not always advantageous over a conventional hybrid. In other words, in the case of infestation, some Bt hybrids were unable to prevent infestation in such a way that they could fully express their productive potential. Higher grain yields were obtained in Caarapó during the second crop, since, as previously mentioned the environment presented better conditions for the development of both transgenic and isogenic genotypes, which may be primarily due to the amount of rain that fell while this study was carried out in this environment.

Since caterpillars were prevented in all treatments, transgenic hybrids exhibited higher average yield in all environments due to the new technology implemented where damage caused by infestation was lower. This may be because conventional hybrids have served as a refuge for caterpillars, resulting in lower agronomic performance. Waquil *et al*. (2002) found that transgenic hybrids produced 32% more than susceptible varieties.

Benício & Hanauer (2010) assessed grain yield in Bt transgenic and isogenic corn hybrids in the region of Ituiutaba, Minas Gerais, and verified that transgenic hybrids exhibited superior performance compared with isogenic hybrids with a 26.5% greater yield. Fagioli *et al*. (2010) and Magg *et al*. (2001) found similar results.

On the other hand, Zamariola *et al*. (2010) also assessed grain yield in transgenic and isogenic corn hybrids and found no difference concerning this character.

The joint analysis indicated that genotypes significantly affected plant height (PH), ear height (EH), and grain yield (GY) ($p < 0.05$), demonstrating that these characters performed differently in the environments analyzed. Both plant height and ear height were significantly affected ($p < 0.05$) in transgenic and isogenic hybrids when the factor was unfolded, indicating divergence in the response of these traits in transgenic and isogenic hybrids (Table 2).

Female and male flowers showed no differences among hybrids signifying that they belong to the same group in terms of flowering (early flowering), which indicates that the environment had no influence on the cycle of transgenic and isogenic hybrids when the data were jointly analyzed (Table 2).

Diniz (2011) studied various commercially available hybrids and found that transgenic and isogenic hybrids were significantly different regarding plant and ear height, male and female flowering, and grain yield evidencing the differential performance of these characters in the environments studied.

However, in contrast, transgenic vs isogenic hybrids had significant effects on plant height and grain yield indicating that hybrid performance is dependent on their type (transgenic or isogenic), that is, differences between transgenics and their isogenic hybrids pertaining to these two characteristics were found. Differences regarding grain yield may be related to minor damage caused by caterpillars, specifically Spodopterafrugiperda, because the damage this caterpillar causes to leaves reduces the leaf area index therefore reducing the plant's productive potential.

In comparing transgenic and isogenic hybrids, both exhibited great heterogeneity regarding plant height, which is in accord with the significant effect observed on this character. It is noteworthy that smaller plants, besides having greater tolerance to lodging, in general still withstand the sowing of a greater number of plants per area, which may contribute to higher grain yield (Cardoso *et al*., 2011).

A significant effect on all characters was observed due to both the environment alone and to genotype-environment interactions (G × E), demonstrating the heterogeneity of the environmental conditions in which the experiments were performed. In this manner, this study found differences in the plants grown in the environments assessed; that is, hybrids presented different phenotypic manifestations from one location to another due to environmental variations making it difficult to select or recommend genotypes that are widely adaptable. In other words, the response of genotypes is different, considering changes in the environments (Ramalho *et al*., 2008).

Another factor to be taken into account in the study of genotype interactions considering environments is the nature of these interactions. Interactions are caused by two factors: the first, also known as the simple part, is due to the magnitude of the difference in variability between the genotypes; the second, known as the complex part, is dependent on the correlation of genotypes within environments (Cruz & Castoldi, 1991).

This study exemplified predominance of the complex part (Table 3) since the genotypes that present similar environments are those that exhibited a complex percentage of interaction below 50%. Therefore, the predominance of the complex part, which is more expressive, makes the selection and/or recommendation of specific genotypes more difficult as some genotypes are more adaptable to specific environments (Cruz & Castoldi, 1991).

When the G × E interactions were evaluated, it was found that genotype-location interactions (G × L) significantly affected ear height ($p < 0.01$), plant height ($p < 0.01$), and grain yield ($p < 0.05$), indicating that the genotypes assessed responded differently when in different locations.

Genotype-season interactions (G × S) significantly affected ear height ($p < 0.01$), plant height ($p < 0.01$), and grain yield ($p < 0.05$), signifying that the performance of transgenic and isogenic hybrids was different between the first and second crops. This indicates that the associations between location and crop are different among environments.

The triple interaction genotype-location-season (G × L × S) significantly affected grain yield ($p < 0.05$), therefore demonstrating that the assessed genotypes responded differently when assessed in different environments. These data demonstrate that interactions and their decomposition in the different environments were relevant factors in the performance of genotypes, evidencing the importance of evaluating environments when assessing corn cultivars.

Because the locations were in the same microregion and homogeneity between locations was present, significant differences in the effects of G × L × S interactions on the plants demonstrated the value of the

Table 2: Summary of the analysis of joint variance of nine corn genotypes obtained in four environments in the state of Mato Grosso do Sul, Brazil, 2013 and 2014

S.V	D.F	Medium Square				
		EH (cm)	PH (cm)	FF (days)	MF (days)	PROD (kg há$^{-1}$)
Blocks	2	340,12	137,90	0,70	2,06	800.671,06
Genotypes (G)	(8)	517,97**	725,27**	2,23^{ns}	3,31^{ns}	1.071.662,02**
Transgenic (T)	5	628,79**	796,47**	2,05^{ns}	2,72^{ns}	702.037,35^{ns}
Isogenic (I)	2	498,79**	585,27**	1,44^{ns}	4,08^{ns}	206.066,13^{ns}
T *vs* I	1	2,24^{ns}	649,30**	4,74^{ns}	4,74^{ns}	4.650.977,12**
Environments(E)	3	6.035,07**	1.0541,59**	298,75**	263,32**	38.552.246,67**
G x E	(24)	219,29**	305,54**	4,34*	4,32*	2.539.146,04**
G x Local (L)	8	117,67**	175,86**	1,92^{ns}	2,46^{ns}	898.576,09*
G x Seasons (S)	8	87,64**	138,75**	1,35^{ns}	0,96^{ns}	876.456,10*
G x L x S	8	13,98^{ns}	9,06^{ns}	1,07^{ns}	0,90^{ns}	764.113,85*
Resíduo	64	29,81	44,89	2,15	2,12	576.827,20
CV%	-	6,67	4,45	2,23	2,20	16,03
General average	-	81,89	150,42	65,84	66,20	4.736,41
Average (A)	-	81,79	152,15	65,69	66,05	4.883,15
Average (I)	-	82,09	146,95	66,13	66,5	4.442,94

S.V: Source of variation; D.F: degrees of freedom; **, *, ^{ns}: significative a ($p < 0,01$), significative ($p < 0,05$) e not significative, respectively by test F; CV%: coefficient of variation.

Table 3: Pairs of environments and percentage of the complex and simple part resulting from the decomposition of the interaction between genotypes and environmental pairs, according to Cruz & Castoldi methodology (1991), in maize hybrids trials in the state of Mato Grosso do Sul, 2012 and 2013

Pairs of environments	Complex part (C%)	Simple part (S%)
Caarapó (Crop) x Dourados (Crop)	80,95	19,05
Caarapó (Crop) x Caarapó (2ª Crop)	99,97	0,03
Caarapó (Crop) x Dourados (2ª Crop)	96,44	3,56
Dourados (Crop) x Caarapó (2ª Crop)	70,55	29,45
Dourados (Crop) x Dourados (2ª Crop)	92,68	7,32
Caarapó (2ª Crop) x Dourados (2ª Crop)	91,83	8,17

genotypes from one environment to another (Table 1) indicating significant differences in grain yield across genotypes when compared between locations and crops.

The G × L × S interaction and the complex effect of decomposition may be reduced by either using specific hybrids recommended for each location and season, using hybrids with wide adaptability and good stability, or dividing the region into subregions based on similar environmental characteristics causing the interaction to no longer be significant (Ramalho *et al*., 1993).

As previously mentioned, the differences in grain yield due to G × L × S interactions were defined by genotypic differences in which transgenic hybrids exhibited superior performance in certain environments when compared to isogenic hybrids. This contributed to the interaction effect, in which all environments produced a higher average yield since the technology allows the transgenic hybrids to withstand minor damages caused by infestation.

The study of adaptability and stability was necessary due to G × L × S interaction, even considering a few locations or seasons, contributing only to differentiate GM from isogenic hybrids, according to their performance.

Therefore, according to the Eberhart & Russell model (1966), the effect of environment on grain yield was 71.75%; thus, it was more important than the effect of the G × E interaction (22.23%), which was in turn higher than the effect of genotypes (6.02%). These results reveal that the environment was the determining factor regarding variability in the results between transgenic and isogenic hybrids (Table 4).

Concerning the adaptability and stability estimated for each hybrid, average grain yield (β_0) ranged from 4172.18 to 5128.31 kg.ha^{-1}; the highest average grain yield was produced by AG 7000, while the lowest was produced by P 30K73 VT PRO. The overall average was 4736.00 kg.ha^{-1}, indicating that isogenic hybrids can produce an average grain yield greater than that of the transgenic hybrids (Table 5).

The estimated regression coefficients () indicated that AG 7000, DKB 390 VT PRO, PIONNER 30K73 YG, and PIONNER 30K73 responded to improvements in the environment, and they were considered responsive and adaptive to favorable environments (> 1,0). AG 7000YG (=1,0), which did not produce significantly different yields, contained a genotype exhibiting great adaptation. The regression coefficients (< 1,0) for DKB 390 YG, DKB 390, AG 7000 VT PRO, and PIONNER 30K73 VT PRO were significant indicating that these hybrids are tolerant to adverse condition; that is, they can withstand adverse conditions and maintain their average yield at similar to the overall average thus responding to unfavorable environments.

When assessing the performance predictability of the hybrids (, DKB 390 VT PRO, AG 7000 YG, PIONNER 30K73,

Table 4: Summary of the joint variance analysis according to Eberhart and Russell methodology, regarding grain yield (kg ha^{-1}), of nine corn genotypes obtained in four environments in the state of Mato Grosso do Sul, 2012 and 2013

SV	DF	MS	% ofvariation
Environments(E)	3	38.552.246,67**	71,75
Genotypes (G)	8	1.071.662,02**	6,02
G x E	24	1.539.146,04**	22,23
TOTALE	35	41.163.054,73	100,00

**,*: Significative (p < 0,01) e significative (p < 0,05), respectively by test F.

Table 5: Eberhart and Russell methodology, regarding grain yield (kg ha^{-1}) of 9 corn genotypes obtained in 4 environments in the state of Mato Grosso do Sul, 2012 and 2013

Genotypes	$\hat{\beta}_{0i}$	$\hat{\beta}_{1i}$	$\hat{\sigma}^2_{di}$	R^2
AG 7000	5128,32	1,52**	742562,30*	84
DKB 390VTPRO	5040,29	1,11**	126054,10^{ns}	89
AG 7000YG	5027,18	0,99**	120931,10^{ns}	87
DKB 390YG	4857,01	0,80**	484689,30*	67
P 30K73YG	4797,30	1,08**	462204,70*	79
AG 7000VTPRO	4614,73	0,62^{ns}	683707,80*	49
P 30K73	4561,97	1,25**	318937,30^{ns}	87
DKB 390	4425,09	0,92*	20329,49^{ns}	90
P 30K73VTPRO	4172,18	0,66^{ns}	-129795,00^{ns}	94
Overall average		4736,00		

Overall average ($\hat{\beta}_{0i}$); Regression coefficient estimates ($\hat{\beta}_{1i}$); Regression deviations ($\hat{\sigma}^2_{di}$); Coefficients of determination (R^2); **,*, ^{ns}: significative (p < 0,01), significative (p < 0,05) e not significative, respectively, Significance by the test F.

DKB 390, and PIONNER 30K73 VT PRO did not significantly differ in their regression deviations (= 0), indicating that these were more stable and suggesting that their average yield may not vary over time and location with little environmental influence. Alternatively, the regression deviations (0), for AG 7000, DKB 390 YG, PIONNER 30K73 YG, and AG 7000 VT PRO significantly differed demonstrating that they were more unstable than others.

Regarding the coefficients of determination (R2), hybrids without significant regression deviations had higher coefficients indicative of low data dispersion and high reliability in terms of environmental response as determined by the regressions (Raizer & Vencovsky, 1999). This value should be used as a regression reference to satisfactorily explain the performance of a genotype due to a specific environment (Cruz & Regazzi, 2004). Thus, hybrids that had significant regression deviations had lower coefficients. The genotypes assessed showed significant stability since more than 60% had R2 values greater than 80%. Moreover, each group of GM and isogenic hybrids contained at least two genotypes with R2 values greater than 80% signifying that regardless of which group the hybrids belonged to, the genotypes may be more or less stable.

Therefore, the isogenic hybrid AG 7000, which had the highest average grain yield, was considered unstable when considering the coefficient of determination, while the transgenic hybrid AG 7000 YG was considered stable and produced a higher average grain yield. On the other hand, the isogenic hybrids DKB 390 and P30K73 were considered stable, although with lower grain yield, which is explained by Bt hybrids' greater resistance to infestation. Phenotypic stability for grain yield is dependent on several plant characteristics, such as the grain yield, resistance to insects, and environmental pests present where the hybrid is planted (Kang & Magari, 1996). However, when the Bt gene is inserted into the genome of corn plants, these hybrids are expected to be able to withstand massive infestation and produce the same grain yield when compared to plants without this gene. Blanche *et al*. (2006) found similar results to this study when they compared Bt transgenic cotton cultivars with their isogenic hybrids, concluding that Bt hybrids were more stable than the conventional cultivars.

As to the indices for each environment, the hybrids grown in Caarapó during the second crop had a higher yield than the overall average, and, as previously mentioned, this was the environment where transgenics stood out over their isogenic hybrids. In this manner, this environment may be classified as favorable for developing the assessed hybrids. In other words, these hybrids could take advantage of the good environmental conditions, such as rainfall, among others, and express their yield potential; this was confirmed by the positive environmental index here (Table 6).

The average grain yields were lower than the overall average, and the environmental indices were negative; thus, the conditions in Caarapó and Dourados during the first crop and in Dourados during the second crop were unfavorable to the hybrids. This was probably due to uneven rainfall in terms of quantity and distribution as well as to differences between these environments and other abiotic factors such as soil and temperature. It is worth noting that the hybrids used are recommended for the regions where they were evaluated.

Table 6: Eberhart and Russell (1966), referring to grain yield (kg ha^{-1}) of nine corn genotypes obtained in four environments in the state of Mato Grosso do Sul, Brazil, in 2013 and 2014

Environments	**Average**	**Index**
Caarapó /Crop	4.652,40	-83,60
Dourados/Crop	3.810,93	-925,07
Caarapó /2ª crop	6.447,07	1110,07
Dourados /2ª crop	4.033,61	-702,39

CONCLUSION

The transgenic DKB 390 VT PRO and AG 7000 YG hybrids exhibited superior agronomic performance due to greater stability. The conventional hybrid P 30K73 VT PRO showed both stability and tolerance to adverse conditions. The hybrids exhibited greater average plant and ear height as well as grain yield in Caarapó during the second corn crop demonstrating this environment to be more favorable.

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