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AGRONOMIA

EVALUATION OF HALF-SIB MAIZE PROGENIES THROUGH THE RECURRENT SELECTION METHOD

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Abstract: Maize is a globally significant cereal, with Brazil ranking among top producers and exporters. Maize's genetic variability enables its cultivation across diverse regions, positioning it as an excellent candidate for genetic improvement programs. This study aimed to evaluate the potential genetic gain in a population of half-sib maize progenies derived from the crossing of commercial hybrids over two cycles of intrapopulation recurrent selection. The experiment was conducted at the Federal Institute of Education, Science, and Technology of Triangulo Mineiro – *Campus* Uberlandia. The agronomic traits evaluated included plant height (PH), ear insertion height (EIH), stem diameter (SD), ear length (EL), ear diameter (ED), and grain weight (GW). The results indicated significance for the traits EL and ED in the first cycle and ED in the second cycle. A low experimental coefficient of variation (CVe) was achieved, demonstrating the experiment's precision. In the first cycle, EL showed a high genetic variation coefficient (CVg), while ED showed a CVg/CVe ratio greater than one, leading to the conclusions that only the ED trait benefited from the selection process. The heritability for ED decreased in the second cycle due to reduced genotypic variance, suggesting a decline in available genetic variability. Path analysis revealed a significant direct effect of ear diameter on grain weight in the second cycle, however, direct selection did not result in weight gains due to low genetic variance.

Keywords: Correlation. Biometric models. *Zea Mays L*.

AVALIAÇÃO DE PROGÊNIES DE MEIOS-IRMÃOS DE MILHO PELO MÉTODO DE SELEÇÃO RECORRENTE

RESUMO: O milho é um cereal de importância econômica global, com o Brasil se destacando como um dos principais produtores e exportadores. A variabilidade genética da espécie permite seu cultivo em diversas regiões, aspecto que favorece seu estudo em programas de melhoramento genético. Este estudo objetivou avaliar o potencial de ganho genético em uma população de meios-irmãos de milho, oriunda do cruzamento de híbridos comerciais, ao longo de dois ciclos de seleção recorrente intrapopulacional. O experimento foi conduzido no Instituto Federal de Educação, Ciência e Tecnologia do Triângulo Mineiro – *Campus* Uberlândia. Foram avaliados os caracteres agronômicos: altura de planta (AP), altura de inserção de espiga (AIE), diâmetro de colmo (DC), comprimento de espiga (CE), diâmetro de espiga (DE) e peso de grãos (PG). Os resultados indicaram significância para os caracteres CE e DE no primeiro ciclo, e DE no segundo ciclo. Obteve-se baixo coeficiente de variação experimental (CVe), observando precisão no experimento. No primeiro ciclo, o caractere CE apresentou alto coeficiente de variação genético (CVg) enquanto que DE, no mesmo ciclo, apresentou valor acima da unidade para a razão CVg/CVe, concluindo que apenas a característica DE foi favorecida pelo processo de seleção. A herdabilidade para diâmetro de espiga diminuiu no segundo ciclo devido à redução da variância genotípica, indicando menor variabilidade genética disponível. A análise de trilha mostrou efeito direto significativo do diâmetro da espiga sobre o peso de grãos no segundo ciclo, mas a seleção direta não resultou em ganhos de peso devido à baixa variância genética.

Palavras-chave: Correlação. Modelos biométricos. *Zea Mays* L.

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INTRODUCTION

Maize is one of the most important cereal crops worldwide. In Brazil, the corn harvest is projected to cover more than 21.2 million hectares in the 2023/2024, highlighting its economic significance to the country (CONAB, 2023). According to the United States Department of Agriculture (USDA, 2024), Brazil emerged as the third-largest producer of maize and the world's leading exporter during the 2022/23 growing season.

Maize exhibits substantial genetic variability, allowing it to be cultivated in diverse regions worldwide. This variability, coupled with its economic importance and widespread distribution, encourages genetic improvement efforts aimed at achieving higher yields in smaller cultivation areas. Among maize cultivars, varieties stand out as groups of plants that possess higher variability compared to commercial hybrids while sharing common characteristics. These varieties are genetically stable and can be reused without compromising their yield potential. Typically, they are produced by public institutions through research and distribution in seed programs. The use of maize varieties is appealing due to their lower cost and the ability to be cultivated without the need for advanced technology (Cruz *et al*., 2010).

Maize's extensive genetic variability enables its cultivation across diverse global regions. In Mexico, this diversity is preserved through traditional farming and germplasm banks like CIMMYT, which has maintained about 28,000 maize accessions since 1943, supporting both conservation and sustainable use (Orozco-Ramírez *et al*., 2017; Leyva-Madrigal *et al*., 2020; Alvarado-Beltrán *et al*., 2019; Taba *et al*., 2005). The economic importance and adaptability of maize drive breeding programs focused on higher productivity in limited areas. Public institutions often develop and distribute genetically stable traditional varieties for small-scale farming, with Brazil's EMBRAPA leading efforts in seed programs and technical support to enhance yield in family farms and agroecological systems (Cruz *et al*., 2010; Meirelles *et al*., 2014).

One prominent method for generating these varieties is recurrent selection, performed both among and within families of half-sibs. As described by Borém *et al*. (2021), this method involves four fundamental steps: obtaining progenies, evaluating the progenies, selecting superior progenies, and recombining them to form the next generation. Generally, this breeding method aims to develop a population with satisfactory levels of desirable alleles, which can then be utilized as a new variety after the selection cycle is complete. Recurrent selection is a cyclical breeding method used to raise the frequency of favorable alleles in a population until they reach desired levels. In cross-pollinated plants, this process may require multiple cycles, often between 5 and 10 cycles of selection.

Therefore, the objective of this study was to investigate the potential genetic gain of a population of half-sib maize progenies, derived from the crossing of commercial hybrids, over two cycles of intrapopulation recurrent selection. Additionally, we aimed to evaluate the relationships between agronomic traits through path analysis.

MATERIALS AND METHODS

The experiment was conducted at the Federal Institute of Education, Science, and Technology of Triangulo Mineiro – Campus Uberlandia. According to Köppen (1948), the climate of the location is classified as tropical, hot, and humid, with an average annual precipitation of 1500 mm and an average temperature of 21ºC.

In March 2023, six commercial maize hybrids — DKB360, AS1868, P3551, P3808, GNZ7720, and GNZ7750— were sown, serving as the parental lines for the populations under evaluation. These hybrids were used in the first selection cycle and subjected to random crossings, resulting in the formation of six half-sib families by the end of the cycle. In this experiment, each treatment corresponds to a half-sib family. The seeds obtained from different blocks representing the same family were homogenized and sown in September 2023 to initiate the second selection cycle.

The experiment followed a randomized block design (RBD) with four replicates. The experimental units consisted of plots with two 5-meter-long rows. During the first cycle, the row spacing was 0.9 meters; however, for the second cycle, it was reduced to 0.7 meters, with 0.2 meters between plants within each row, totaling 50 plants per plot. This adjustment in spacing aimed to increase plant density, mirroring practices adopted by farmers to optimize land use.

Climate data, including precipitation, were collected from the campus weather station located approximately 700 meters from the experimental area. During drought periods, a sprinkler irrigation system was installed to ensure the water levels necessary for maize growth, with a prior uniformity test conducted to assess water distribution. The installation and technical guidance for the system were carried out with support from the institute's hydraulics department.

Fertilization was based on soil chemical analysis, which indicated low phosphorus and potassium availability. At planting, 40 kg/ha of NPK 4-14-8 fertilizer was applied in the furrow. Topdressing fertilization was split into two applications, following the recommendations of Boletim 100 (2022) for maize cultivation. The first application took place at the V4 phenological stage, involving a mixture of 15 kg of urea and 10 kg of potassium chloride to supply nitrogen and potassium. The second application, conducted at the V10 stage, consisted of 12 kg of urea. All other cultural practices were carried out according to standard technical recommendations for maize cultivation.

The traits evaluated were: plant height (PH), measured in centimeters using a graduated ruler from the soil level to the point of insertion of the flag leaf. This measurement was taken with the plant at physiological maturity, a stage that minimizes variations due to active growth; ear insertion height (EIH), measured in centimeters from the soil level to the insertion of the first productive ear; stem diameter (SD), measured in millimeters using a precision digital caliper positioned just below the first ear to standardize the measurement location; ear length (EL), measured in centimeters with a precision ruler from the peduncle to the upper end of the ear. Ears were randomly selected within each plot to represent the experimental unit average; ear diameter (ED), measured at the central region of the ear using a digital caliper; and grain weight (GW), obtained by weighing all the shelled seeds from each ear using a previously calibrated precision scale to ensure measurement reliability. For the GW trait, humidity was corrected to 14% according to the formula:

$$W14\% = Wf(1 - H)/0.86 \quad (1)$$

where W14% is the weight corrected to 14% humidity; Wf is the field weight of the trait per plot; e H is the grain humidity in each plot, expressed in decimals (RAS, 2009).

The variance components and genetic parameters were estimated using the Genetics and Statistics Software - GENES (CRUZ, 2013), applying the following model:

$$Yij = \mu + ti + Bj + eij \quad (2)$$

where Yij is the response variable value of treatment i in replication j, µ is the overall mean, ti is the effect of treatment i, Bj is the effect of block j, and eij is the error of plot ij.

Analysis of variance (ANOVA) was performed to obtain the mean squares and coefficients of variation for the analyzed variables. Residual normality was verified using the Shapiro-Wilk test, and at a 5% significance level. The residuals were deemed normally distributed. Subsequently, the variance components were obtained, where the significance of the model was evaluated by the F-test at 1% and 5% probability levels. The genetic parameters and their estimators were analyzed for each trait using the following expressions (CRUZ, 2006):

- Average genotypic variance:

$$\sigma_G{}^2 = (QM_g - QM_r)/r \quad (3)$$

where QM_g is the mean square of families, QM_r is the mean square of the residual and r is the number of replications.

- Average environmental variance:

$$\sigma_A{}^2 = QM_r/r \quad (4)$$

where QM_r is the mean square of the residual and r is the number of replications.

- Phenotypic variance:

$$\sigma_F{}^2 = QM_g/r \quad (5)$$

where QM_g is the mean square of families and r is the number of replications.

- Average heritability - h^2:

$$(QM_g - QM_r)/QM_g \quad (6)$$

where QMg is the mean square of families and QMr is the mean square of the residual.

- Genetic coefficient of variation - CVg%:

$$100\ (\sqrt{\sigma_g^2}/m) \quad (7)$$

where σ_G^2 is the genotypic variance and *m* is the overall mean of the trait under study.

- Ratio:

$$CV_g/CV_e \quad (8)$$

where CV_g is the genetic coefficient of variation and CV_e is the experimental coefficient of variation.

- Direct selection gain:

$$GS = i\ .\sigma_G{}^2.\sqrt{h^2} \quad (9)$$

where i is the selection intensity, $\sigma_G{}^2$ is the genotypic variability and $\sqrt{h^2}$ is the square root of heritability or accuracy.

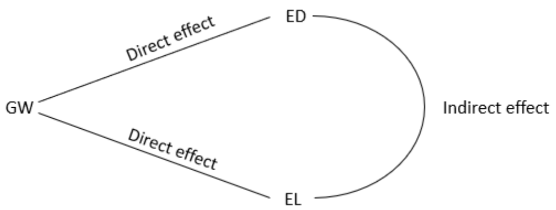
- The indirect selection gain in Y, when selection is practiced on X ($SG_{Y(x)}$) was calculated using the formula:

$$SG_{y(x)} = i\ .\sqrt{h^2}\ .rg\ .S_{gy} \quad (10)$$

where i is the selection intensity, is the square root of heritability or accuracy, rg is the genotypic correlation between traits X and Y, and S_{gy} is the genotypic standard deviation for trait Y.

The relationship between the dependent variable and the explanatory variables is illustrated in the diagram in Figure 1. Path analysis, proposed by Wright (1921), is used to understand these relationships by considering both the direct and indirect effects of the explanatory variables (EL and ED) on the dependent variable (GW). Path analysis allows for the quantification of these influences through path coefficients, which are obtained from standardized multiple regressions (Cruz; Carneiro; Regazzi, 2014).

Figure 1: Illustrative causal diagram showing the effects of explanatory variables (ED and EL) on the dependent variable GW.



Source: Prepared by the authors (2024).

RESULTS AND DISCUSSION

Significance was observed through analysis of variance for the agronomic traits: ear diameter (ED) and ear length (EL) (Table 1) in the first selection cycle, and only for ED in the second cycle. In the first cycle, the analysis did not reveal significant differences in grain yield – a trait of high importance for this breeding program – among the families. Therefore, the material harvested after the first cycle was homogenized and replanted for the second cycle. The presence of genetic variability for significant traits indicates the potential for genetic gains in future cycles.

Table 1: Mean squares and coefficients of variation from the ANOVA for traits that showed significance in two cycles of intrapopulation recurrent selection in maize.

	First Cycle		**Second Cycle**
Source of variation	ED	EL	ED
Block	1.96	0.50	0.14
Treatment	23.26**	3.87*	7.80*
Error	4.13	0.93	2.25
Total	29.36	5.31	10.20

*and ** Significant at 5% and 1% probability by the F-test, respectively.

Source: Prepared by the authors (2024).

The other productive traits, such as plant height (PH), ear insertion height (EIH), stem diameter (SD), and grain weight (GW), were not significant according to the analysis of variance for both selection cycles. This finding diverges from that observed by Cintra *et al*. (2023), who, when analyzing half-sib progenies of fresh maize over five cycles of recurrent selection, identified significance for plant height and ear insertion height in the first two cycles. Similarly, Modesto *et al*. (2014) also observed significance regarding ear weight when studying phenotypic recurrent selection aimed at obtaining a synthetic maize variety.

This divergence suggests that while some traits may be consistently improved over successive cycles, others may be more influenced by environmental factors or the genetic structure of the populations under study. Similar findings were reported by Coelho (2019), who observed variations in the behavior of these populations when examining the same progenitors.

The experimental coefficients of variation (CVe) for the significant traits showed low values, indicating high experimental precision (Table 2). Experimental precision is crucial for achieving genetic progress in breeding programs, especially for traits highly influenced by environmental factors. The study by Santos Junior (2023) on reciprocal recurrent selection in popcorn corroborates the observed results, as the author reported experimental coefficients of variation of 4.43% and 3.31% for EL and ED, respectively, demonstrating experimental precision similar to the present study.

Table 2: Estimates of genetic parameters for the evaluated traits, with variance values: genotypic (σ_G^2) and environmental (σ_A^2), average heritability (h^2), genetic coefficient of variation (CVg%), environmental coefficient of variation (CVe%), ratio CVg/CVe, and the means of ear diameter (ED) and ear length (EL) in two cycles of intrapopulation recurrent selection in maize.

	First Cycle		**Second Cycle**
Description	ED	EL	ED
σ_G^2	4.78	0.73	1.39
σ_A^2	1.03	0.24	0.56
σ_F^2	5.82	0.97	1.95
h^2%	82.23	75.87	71.05
CVg %	5.60	5.81	2.72
CVe (%)	5.20	6.54	3.47
CVg/CVe	1.08	0.89	0.78
Mean	39.03	14.76	43.22

Source: Prepared by the authors (2024).

In genotype selection, the use of heritability is fundamental for obtaining individuals with traits that promote genetic improvement of the crop, as its values represent the heritable genetic fraction in the expression of the phenotype (Borém *et al*., 2021). Understanding heritability in a broad sense is crucial in plant breeding, as it addresses the proportion of observed variability caused by genetic effects (Carvalho *et al*., 2001).

In the first selection cycle, the highest heritability (h^2) values were observed for ear diameter (ED) and ear length (EL), respectively, while the heritability value for ED decreased in the subsequent cycle. As observed, the estimated heritability percentages for the ED trait in the first and second cycles were higher than the 76% and 51% values, respectively, reported by Almeida *et al*. (2024) in their study with two maize recurrent selection populations.

The heritability observed for the EL variable in the first cycle was lower than the estimates of 95.63% and 85.85%, as reported by Bernini *et al*. (2021) in their study with different maize progenies. However, this same variable showed a heritability estimate higher than the 55% and 70% values described by Almeida *et al*. (2024) in their study with different maize populations. The average ear length is one of the traits that can directly influence the number of kernels per row and, consequently, the productivity of maize (Kappes *et al*., 2009). This trait can be targeted for selection in maize breeding programs aimed at increasing the number of kernels per ear (Nascimento *et al*., 2023).

The analyses indicate that the reduction in heritability for ear diameter (ED) in the second cycle was primarily due to the decrease in genotypic variance (Table 2), suggesting that the genetic variability available for ED was significantly reduced after the first selection cycle. Decreases in variability over selection cycles have also been highlighted in other studies involving half-sib progenies (Carvalho *et al*., 2003).

In the study, the mean for the ear diameter (ED) trait was 39.03 mm in the first cycle and 43.22 mm in the second cycle. This increase in the mean ED occurred because, despite the drop-in heritability between cycles, it remained high, favoring direct gains for this trait. These results corroborate the study by Cintra *et al*. (2023), who also observed gains in ear diameter in their study of five cycles of intrapopulation recurrent selection in fresh maize half-sib progenies. Thus, even with the reduction in genetic variability, selection at this stage still provides significant gains in ED.

These findings are particularly relevant for maize breeding programs, as the varieties developed will benefit family farming. Farmers who adopt these varieties tend to consume the product or sell it on a small scale, with larger ears often being preferred by consumers (SILVA *et al*., 2015). Therefore, the gains in ear diameter not only enhance production efficiency but also meet market demands.

In the present study, the trait ear diameter (ED) in the first cycle exhibited the highest genotypic variance (4.78), a value higher than that observed by Santos Junior (2023). Conversely, the genotypic variance for the ear length (EL) trait in the first cycle was lower compared to ED. According to the study by Silveira (2021) on maize genotype selection in the semi-arid region, the observed genotypic variance for EL was 2.07, while the environmental variance was 1.79, both of which were higher than the values observed in the present study.

Genotypic variance directly influences the potential genetic gain achievable through selection, also affecting heritability values (Borém *et al*., 2021). These results obtained regarding genotypic variance suggest that selection based on these traits will be effective, enabling significant genetic gains in subsequent cycles. It was observed that the trait ED was more affected by environmental conditions in both selection cycles, as also reported by Nascimento *et al*. (2023), where the author noted a greater environmental influence on ED than on EL. However, there is still a favorable situation for improvement, as it is possible to select genotypes whose phenotypic values of the traits are more influenced by genetic factors than by environmental ones (Tucker *et al*., 2020). Environmental variance (σA^2) refers to the part of phenotypic variation caused by differences in environmental conditions and is crucial for understanding how these factors influence trait expression. The means of genotypic, environmental, and phenotypic variances are extremely important as they allow for a precise analysis of the sources of phenotypic variation, facilitating the selection of superior individuals and the prediction of the success of breeding programs.

The genetic coefficient of variation (CVg), being directly proportional to genetic variance, allows breeders to gauge the relative magnitude of changes that can be achieved through selection, as it is expected that the higher the CVg estimate, the greater the genetic variability. According to Pandey *et al*. (2017), CVg values above 5% are considered high. The trait with the highest CVg was observed for EL and ED, respectively, in the first cycle, with values of 5.81 and 5.60, indicating high genetic variability for these traits. In the second cycle, the observed genetic coefficient of variation for ED was 2.72, resulting in a decrease in genetic variability for this trait.

Through the CVg/CVe ratio, it is possible to identify which traits have variation predominantly influenced by genetic factors rather than environmental ones. According to Faleiro *et al*. (2002), the closer this ratio is to 1.0, the greater the proportion of variation attributable to genetic causes. In the first cycle, the ratio value for ear diameter (ED) was higher than that observed in the second cycle, indicating that, in the second generation of recurrent selection, there was a decline in both genetic and environmental variance. Considering that values close to or above 1.0 suggest the predominance of genetic variance over environmental variance, it is concluded that only the ED trait in the first cycle benefited from the selection process.

Understanding the correlation between grain yield components is crucial, especially when selecting based on one trait to effect changes in other agronomically important traits correlated with each other. In the first cycle, a high direct effect of ear length (EL) on grain weight (GW) was observed, and theoretically, a higher indirect correlation in GW through selection for EL (0.54) than through ear diameter (ED) (0.52) can be expected. In contrast, in the second cycle, a high direct effect of ED on GW was observed, with a higher indirect correlation in GW through selection for ED (0.81) compared to EL (0.03), which corroborates the results obtained by Barbosa *et al*. (2019) (Table 3).

Table 3: Path analysis of the direct and indirect effects of ear length (EL) and ear diameter (ED) on grain weight (GW) in two cycles of intrapopulation recurrent selection of maize.

First Cycle		
Variable	**EL**	
Direct effect on GW	0.60	
Indirect effect on ED	-0.06	
Total		0.54
Variable	**ED**	
Direct effect on GW	0.59	
Indirect effect on EL	-0.06	
Total		0.52
Second Cycle		
Variable	**EL**	
Direct effect on GW	0.44	
Indirect effect on ED	-0.41	
Total		0.03
Variable	**ED**	
Direct effect on GW	0.99	
Indirect effect on EL	-0.18	
Total		0.81

Source: Prepared by the authors (2024).

In the first cycle, a positive correlation between ear length (EL) and grain weight (GW) was observed, which is supported by the studies of Grespan *et al*. (2023) and Lopes *et al*. (2007), who also indicated a positive correlation between ear length and the productive aspects of ears.

Considering direct gains, ear diameter (ED) in the second cycle shows a high positive correlation with GW, making it more advantageous for direct gains. This suggests that in the second cycle of recurrent selection, the direct influence of ED on GW became more dominant, while the influence of EL decreased, possibly indicating changes in the relationships between these variables across selection cycles.

Regarding selection gains, a 4.70% and 3.55% gain in GW can be expected when practicing direct selection through EL and ED, respectively, in the first cycle, using a selection intensity of 16% (Table 4). These secondary components (EL and ED) are efficient for use in direct selection for PG (Nascimento Júnior; Môro; Môro, 2021).

For EL and ED in the second cycle, however, no direct gains in GW were observed with this level of selection intensity. Even though path analysis showed a high direct effect of ear diameter on grain weight in the second cycle, direct selection on this trait does not result in gains in grain weight due to null genetic variance. According to Cruz *et al*. (2003), the absence of genetic variance prevents any potential gains, even when the genetic correlation between traits is high.

Table 4: Selection gain (%) in grain weight (GW) through direct selection of significant traits in the first cycle of recurrent selection.

First Cycle	
	SG% in GW
Direct Selection on EL	4.70%
Direct Selection on ED	3.55%

Source: Prepared by the authors (2024).

CONCLUSIONS

In the first selection cycle, ear length (EL) and ear diameter (ED) were significant, with high coefficients of genetic variation. However, in the second cycle, only ED remained significant, showing a reduction in genetic variation. Path analysis indicated the potential for indirect gains in grain weight (GW) through the selection of EL in the first cycle, with expected gains of 4.70% for EL and 3.55% for ED, but no gains were observed in the second cycle due to a lack of genetic variance.

These results reinforce the viability of the breeding program and the need to introduce new genetic materials to increase variability. The continuous selection of superior families will facilitate the development of a new variety adapted to local conditions, particularly benefiting family farming and small producers by ensuring productivity and reducing costs compared to hybrid seeds.

After two cycles of selection, the results indicate a positive potential for maize productivity, making this research relevant for small farmers, research entities, and breeding companies. Strengthening genetic variability is crucial for developing new cultivars that meet the sector's needs.

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