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Correlations and path analysis of second-crop corn hybrids for maximum grain yield performance

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Abstract

The aim was to estimate the correlation coefficients and their direct and indirect effects through path analysis between agronomic traits that modulate the grain yield of second-crop corn hybrids. The hybrids SYN7G17 TL, 30F53VYHR, B2433PWU and AG 8700 PRO3 were employed. The following agronomic traits were evaluated: leaf nitrogen content, ear height, ear length, ear diameter, number of rows of grains per ear, number of grains per row, mass of a thousand grains, grain yield and grain protein content. Estimates of phenotypic correlation of all combinations of traits were calculated, and then the development of phenotypic correlations in direct and indirect effects was evaluated through path analysis, where grain yield was considered the main variable and the others were considered explanatory variables. Grain yield correlated strongly and positively with thousand-grain mass (0.83) and ear diameter (0.72). In the path analysis to tested conditions, no significant indirect effect was observed. However, the mass of a thousand grains and the ear diameter had a significant direct effect on the grain yield of corn, indicating that the selection of these characteristics can help to improve the grain yield in lines of corn.

Keywords: Productivity; Multicollinearity*; Zea mays*.

Abbreviations: Aw - Köppen classification is the tropical rainy type; DAE - days after emergence; NTS - no-tillage system; N - leaf nitrogen content; EIH - ear height; EL - ear length; ED - ear diameter; NRE - number of grain rows per ear; NGR - number of grains per row; M1000 - thousand-grain mass; GY - grain yield; GPC - grain protein content.

Introduction

Corn (*Zea mays* L.) is one of the most important and productive cultures in the world. Culture is very associated with the world's food security by the enormous products that are obtained from this plant to support population increase (Gao et al., 2023). The production of corn grains is increased enormously in the twentieth century, with one of the highest rates of increased production among cereals (Zhang et al., 2017). Therefore, corn crop optimization is a great challenge for all corn researchers in the Atuis times (Liu et al., 2020).

The inference of phenotypic, morphological, productive and energetic-nutritional characteristics of corn is used for the early identification of characteristics indicative of the nutritional quality of the grain (Alves et al., 2017). The characteristics are formed by the genotypic and environmental interactions that shape the phenotype of the hybrids, and these generate direct and indirect consequences on the productivity and quality of the grains (Begum et al., 2016; Aman et al., 2020; Parsons et al., 2020).

Corn yield is dependent on the characteristics determined by the interaction between the gene of the hybrids and the environment where it is inserted due to the existence of a linear dependence between the morphological and energy-nutritional characters (Alves et al., 2017; Aman et al., 2020).

To enhance the productive performance and implementation of the culture, it is necessary to adopt technologies such as the implantation of hybrids adapted to regional ecoclimatic conditions and the strategic use of soil fertilization that directly participate in the biosynthesis of proteins in relation to the requirements of the plants (Eckardt et al., 2022; Zuffo et al., 2022).

In breeding programs, environmental stratification and identification of cultivars with high adaptability and stability are common, with the aim of reducing the effect of genotype-environment interactions (He et al., 2023; Matova et al., 2023). Some authors have demonstrated that corn hybrids cultivated in different environments generate similar behavior regardless of location, sowing date and N dose, with or without genetic modification (Eckardt et al., 2022).

The tools used are based on phenotypic, genetic and/or metabolic correlations. Although the correlation coefficients are useful in quantifying the magnitude and direction of the influence that the variable has in the determination of complex traits, they are not capable of providing the exact relative importance of the direct and indirect effects of the variables (Cruz et al., 2012). Thus, it is necessary to use path analysis, which makes it possible to more accurately interpret the direct effect of one character on the other and the interference of other characters in this association (Crevelari et al., 2018).

Thus, the aim was to estimate the correlation coefficients and their direct and indirect effects through path analysis between agronomic traits that modulate the grain yield of second-crop corn hybrids.

Results and discussion

Correlations between variables

Correlations between most variables were weak, with the exception of grain yield, which correlated strongly and positively with thousand-grain weight (0.83) and ear diameter (0.72) (Figure 1). According to Yousaf et al. (2018), grain yield is positively correlated with the weight of a thousand grains, corroborating the results of the present study, suggesting that the greater the mass of a thousand grains is, the greater the grain productivity tends to be. Rafiq et al. (2010) also obtained a significant positive correlation between grain yield and ear diameter. The increase in ear diameter consequently results in an increase in the number of rows (Nemati et al., 2009), as seen in the positive correlation between the number of grain rows per ear and the ear diameter (Figure 2e), resulting in increased grain yield**.**

Grain yield is controlled by morphological and physiological traits; thus, the genetic control of yield is influenced by traits that correlate with yield. The increase in productivity and the improvement of genetic characteristics is a function of morphological and physiological characteristics (Mousavi and Nagy, 2021).

Significant correlations between agronomic traits can be used as an indication of indirect selection of important traits (Oliveira et al., 2010). Thus, with the study of relationships between plant traits, it is possible to direct selection, enabling the choice of more correlated productivity and quality traits (Gomes et al., 2004).

Knowledge of the correlations between the traits that favor greater grain yield in plant breeding programs is essential, as it helps in choosing favorable hybrids and directs the selection methodology (Crevelari et al., 2018). The selection of corn hybrids with high grain yield is a difficult task, as the relationship between the traits that contribute to this trait is complex. Thus, it is necessary to develop correlations through direct and indirect effects when assessing the degree of importance of each explanatory variable in relation to the main variable (Crevelari et al., 2018).

Path analysis for maximum grain yield performance

The coefficient of determination of the model in the path analysis (R_2) showed a magnitude of 0.926, indicating that the 92.6% variation in the dependent variable, grain yield, in the model was explained by means of the independent variables (Figure 2). The multicollinearity was weak (68.61), not causing problems for the analysis. Ear diameter (Figure 2d) and thousand-grain mass (Figure 2g) with magnitudes of 0.476 and 0.524, respectively, were the only variables that had a significant positive direct effect on second-crop corn grain yield, as they surpassed the effect of the residual variable whose magnitude was 0.271.

Azad et al. (2012) also observed that ear diameter was one of the variables that most contributed to corn grain yield. Studies report that the weight of a thousand grains has a positive and significant correlation with grain yield (Kandel and Shrestha, 2020), as observed in the present study.

According to Crevelari et al. (2018), these results show that the explanatory variables are the main determinants of variations in the main variable, grain yield, and it is now possible to predict the effectiveness of indirect selection. Thus, ear diameter and thousand-grain mass stand out as the variables most associated with grain yield. These variables are of great importance if you want to obtain responses correlated to the main variable (Crevelari et al., 2018). Therefore, selecting hybrids that have the highest ear diameter and thousand-grain mass means indirectly selecting hybrids capable of providing higher grain yield.

Regarding the indirect effect, there was no significant positive or negative correlation between the variables. In the correlation analysis, some characteristics do not have a significant relationship with yield (Mousavi and Nagy, 2021).

Although the other characters did not have a significant direct or indirect effect, they had positive and negative correlations, such as the content of leaf N, which correlated negatively with the ear diameter (ED) and with the mass of a thousand grains (M1000) and positively with the number of grains per row (NGR) (Figure 3a). Nitrogen is one of the most important nutrients in corn grain yield. The negative correlation between ear diameter and thousand-grain mass with leaf N content shows that N was used by plants to increase their ear diameter and thousand-grain mass. N acts directly on photosynthesis, in addition to being a constituent of carbohydrates, vitamins, nucleic acids and proteins (Ata-Ul-Karim et al., 2016; Ning et al., 2022), which are associated with ear development and the mass of a thousand grains.

The ear diameter had a positive correlation with the mass of a thousand grains and a negative correlation with the

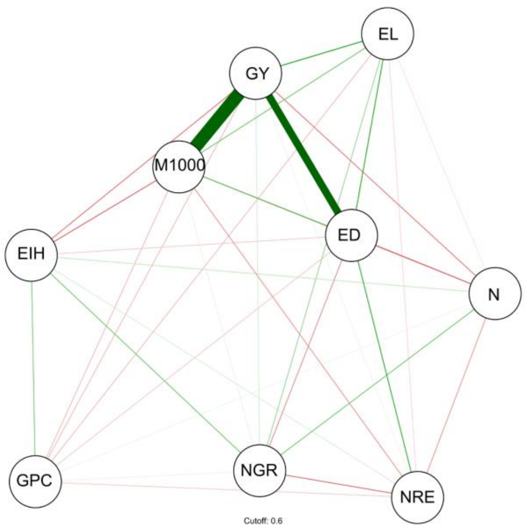

Figure 1. Pearson correlation network between leaf nitrogen content (N), ear height (EIH), ear length (EL), ear diameter (ED), number of grain rows per ear (NRE), number of grains per row (NGR), thousand-grain mass (M1000), grain yield (GY) and grain protein content (GPC).

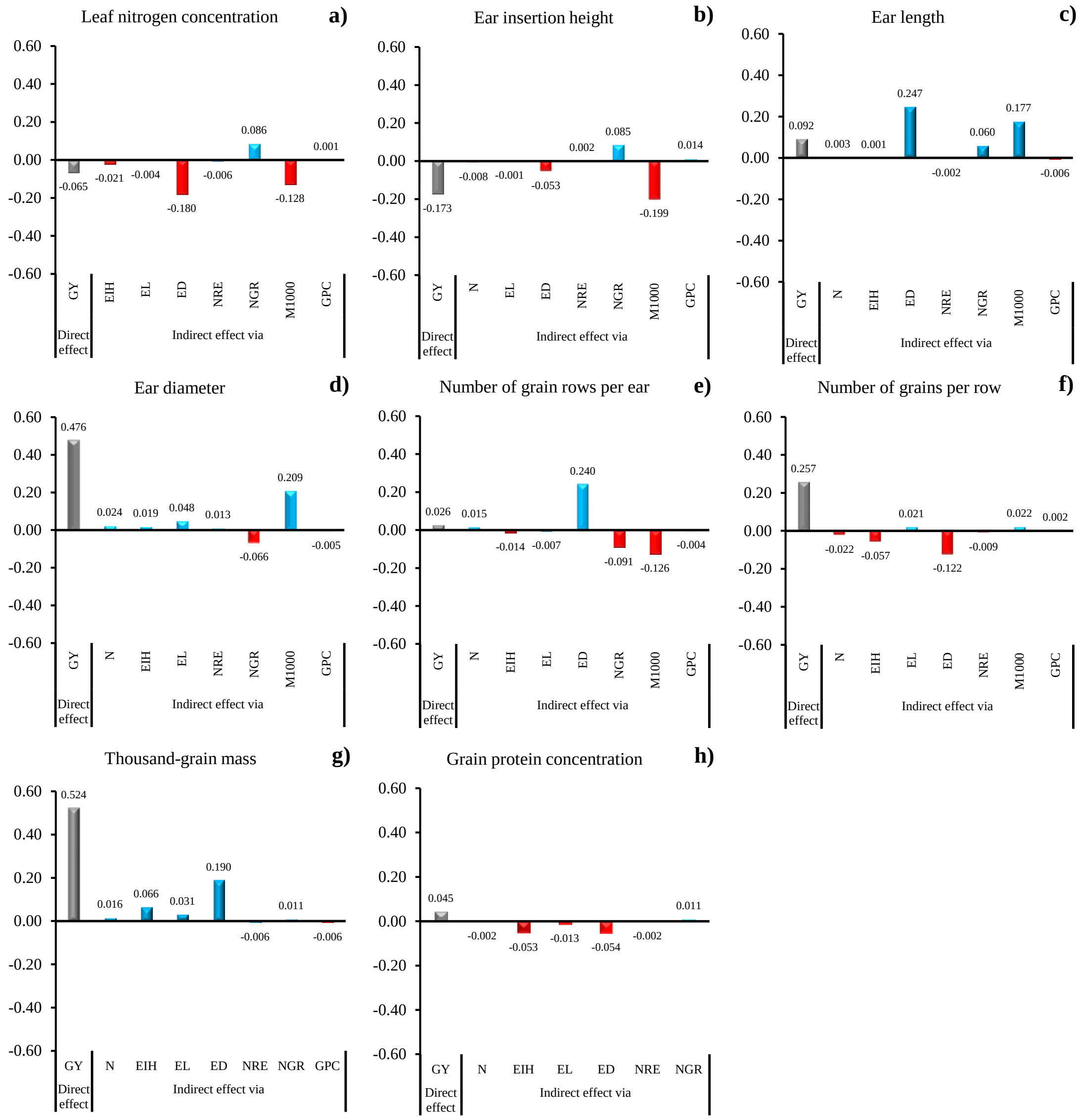

Figure. 2. Direct and indirect effects of seven traits on corn second crop grain yield as a function of environment, corn cultivars and nitrogen levels during the 2020 season. Chapadão do Sul, MS, Brazil. Coefficient of determination of the causal model (R2): 0.926. Effect of the residual variable (EVR): 0.271. Multicollinearity test of explanatory variables: weak (NC<100). NC Value: 68.61. Abbreviations: N: leaf nitrogen content; EIH: ear height; EL: ear length; ED: ear diameter; NRE: number of grain rows per ear; NGR: number of grains per row; M1000: thousand-grain mass; GPC: grain protein content.

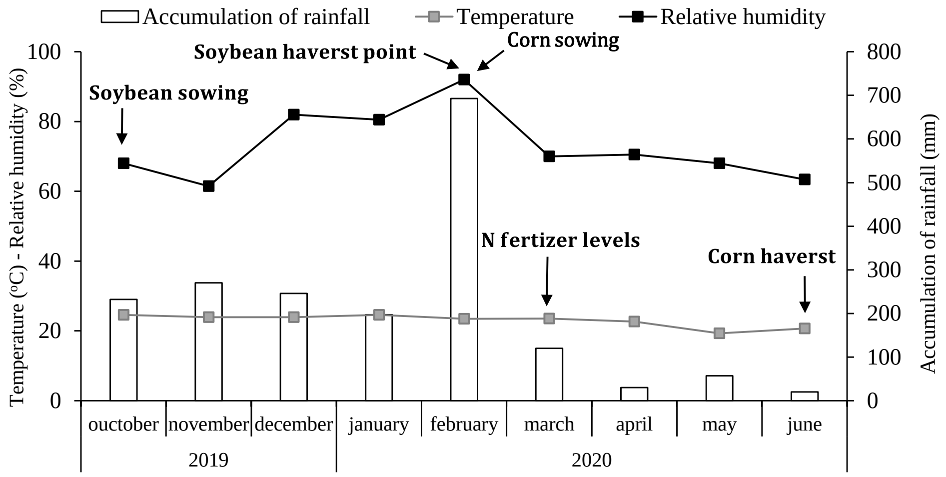

Figure 3. Average monthly temperature, relative humidity, and monthly cumulative rainfall during the experiments in Chapadão do Sul, MS, Brazil, in the 2019/20 cropping season. Source: National Institute of Meteorology.

number of grains per row (Figure 3d). The number of rows of grains per ear (NRE) was positively correlated with ear diameter and negatively correlated with the number of grains per row and the mass of a thousand kernels (Figure 3e). Increasing the ear diameter causes an increase in the number of rows per ear, consequently resulting in an increase in the number of rows per ear (Nemati et al., 2009).

Material and methods

Study site description

Data on averages of variables previously published by Zuffo et al. (2022) were employed to carry out the analyzes proposed in this work. The field experiments were conducted in two experimental areas of the Federal University of Mato Grosso do Sul, called UFMS 1 and UFMS 2, in Chapadão do Sul, MS, Brazil (18°46'18"S, 52°37'25"W with an altitude of 810 m), during the 2019/20 growing season. The climate of the region according to the Köppen classification is the tropical rainy (Aw) type, with rainy summers and dry winters. The rainfall, average annual temperature, and relative air humidity are 1,261 mm, 24.0 °C, and 64%, respectively. Rainfall data gathered during the experiments are shown in Figure 3.

The soils of the experimental areas were classified as Rhodic Hapludox (Soil Survey, 2015) and "Latossolo Vermelho" by the Brazilian soil classification (Santos et al. 2018) and are cited in this paper as Oxisol. Before starting the experiments, the soils were sampled from the 0–0.20 m layer. The main chemical properties are presented in Table 1.

Experimental design and treatments

The data used were obtained by Zuffo et al. (2022) in an experiment where treatments were arranged as split-split plots in a randomized complete block design with three replicates. In the main plots, two agricultural production areas with distinct levels of fertility were established. The first production area had medium-fertility soil and was named UFMS 1, while the second production area had high-fertility soil and was named UFMS 2 (see Table 1). The subplots were represented by the cultivation of four corn cultivars [SYN7G17 TL (early cycle single hybrid), 30F53VYHR (early cycle single hybrid), B2433PWU (super early cycle single hybrid), and AG 8700 PRO3 (early cycle simple hybrid). In the subsubplots, five N fertilization rates (0, 40, 80, 120, and 160 kg ha^{-1} of N) were applied at 30 days after

emergence (DAE). Nitrogen fertilizer topdressing was carried out at the V_4 growth stage when the corn plants had four fully expanded leaves with visible collar. Urea (45% N) was used as the N source. The experimental units consisted of seven 5.0-m long rows, with 0.45 m between rows. The useful area comprised the three central rows of each subsubplot, disregarding 1.0 m of each edge (i.e., 4.05 m^2). This experimental dising permeated collecting data and averages for the evaluated characteristics were employed in the present work.

Experiment implementation and conduction

At phenological stage $R_{7.2}$ (70% pods with brown coloring), the soybeans were desiccated with 2 L ha^{-1} Gramoxone 200® (paraquat 200 g active ingredient (a.i.)/L). However, soybeans were not harvested. However, the average soybean yield was estimated to be approximately 3,544 kg ha^{-1}. Approximately 15 days after the application of the desiccant in the soybean, sowing of corn trials was performed on the no-tillage system (NTS). The corn crop was mechanically sown on February 20, 2020, at a depth of 3 cm, in rows 0.45 cm apart at a density of four seeds per meter to reach a final stand of 70,000 to 75,000 plants per hectare. The base fertilization consisted of 230 kg ha^{-1} MAP (11% N-ammoniacal and 52% P_2O_5; 22 kg/N ha and 104 kg/P_2O_5 ha) at the sowing furrow. Corn seeds were previously treated with 70 g de i.a. ha^{-1} de ciantraniliprole + 70 g de i.a. ha^{-1} + 0.6; 4.5 e 0.75 g de i.a. ha^{-1} de metalaxil-M + tiabendazol + fludioxonil, respectively.

At 30 DAE of corn plants (V_4 - four fully expanded leaves), the N application in topdressing was performed according to the preestablished treatments. At 40 DAE (V_6 – six fully expanded leaves), foliar fertilization was applied using 1 L ha^{-1} of Actilase ZM (Zn 50 g L^{-1}; S 42 g L^{-1}; Mn 30 g L^{-1}). Fertilization was carried out according to technical recommendations for cultivation in Cerrado soils (Sousa and Lobato 2004).

Weed control was performed at 20 DAE of corn plants using 1.5 L a.i. ha^{-1} of the herbicide atrazine + 101 a.i. ha^{-1} of the tembotriona. When the two herbicides were sprayed, 0.5% mineral oil (v/v) was also added. At the beginning of corn flowering, the fungicide pyraclostrobin + epoxiconazole was applied at a rate of 99.7 ± 37.5 g a.i. ha^{-1}. The insecticides

Table 1. Chemical properties of the soils used in the experiment.

Environment	pH	OM	$P_{Mehlich-1}$	H+Al	Al^{3+}	Ca^{2+}	Mg^{2+}	K^{+}	CEC	V
	$CaCl_2$	g dm^{-3}	mg dm^{-3}	------------------- $cmol_c$ dm^{-3} ---------------------						%
UFMS 1	5.3	27.3	14.1	3.70	0.20	2.70	0.80	0.30	7.50	51
UFMS 2	5.7	35.3	41.6	3.90	0.05	4.20	1.60	0.45	10.15	62

OM: organic matter. CEC: cation exchange capacity at pH 7.0. V: soil base saturation.

Metomil and Acetamiprido + Bifentrine were also applied at rates of 129 and 30 + 30 g a.i. ha^{-1}, respectively.

Measurement of corn agronomic traits

At the flowering stage, after the emergence of corn female inflorescence, a total of 10 leaves opposite and below the ear were collected per experimental unit for the determination of N content. The leaf samples were dried in an oven at 60 °C for 72 h and then ground in a Wiley mill equipped with a 40-mesh sieve. After digestion with sulfuric acid, the leaf N content was determined by the semimicro Kjeldahl method (Silva et al., 2011).

At physiological maturity (R_6 growth stage), plant height and ear height were measured in ten plants per subsubplot. The plant height (cm) was measured from the soil surface to the insertion of the last leaf using a tape measure. The ear height (cm) was determined from the soil surface to the insertion of the first ear using a tape measure.

The ears of corn in the subsubplots useful area were manually harvested on June 30th, 2020, and then threshed in a Wintersteiger Classic Plot Harvester. The grain yield and agronomic traits were then measured. The ear length, the number of grain rows per ear, the number of grains per row, and ear diameter were determined in twenty ears chosen at random. The mass of one thousand grains (g) was determined by the average of five measurements of 100 grains taken at random. The grain yield (kg ha^{-1}) was estimated after the correction of grain weights to 13% moisture. The grain protein content was determined by the semimicro Kjeldahl method as recommended by Silva (Silva et al., 2011).

Statistical analysis

The means of the variables obtained by Zuffo et al. (2022) were submitted to tests to verify the assumptions of normality and homogeneity and with them the subsequent analyzes were carried out. Statistical correlations were performed based on Pearson's correlation networks (threshold set at 0.60, $p < 0.05$) between the different agronomic traits evaluated. A correlation network was used to graphically illustrate Pearson's correlation analyses, in which the proximity between nodes is proportional to the absolute correlation values between morphological characters. The relative thickness of the bands and the color density will indicate the strength of the Pearson correlation coefficients, and the color of each band indicates a positive or negative correlation (red for negative and green for positive). These analyses were performed using Rbio software version 140 for Windows (Rbio Software, UFV, Viçosa, MG, BRA). Then, path analysis was performed, verifying the direct and indirect effects on productivity according to the method proposed by Wright (1921). Statistical analyses were performed using Genes software (Cruz, 2013). Before the path analysis, the diagnosis of multicollinearity was performed, as detailed in Cruz et al. (2013).

The degree of multicollinearity of the correlation matrix between the independent variables of the regression model was established based on its number of conditions, which is the ratio between the highest and lowest eigenvalues of the phenotypic correlation matrix. Thus, when the number of conditions is less than 100, multicollinearity is weak and does not cause problems for the analysis; when it is between 100 and 1,000, multicollinearity is moderate to strong; and when it is greater than 1,000, multicollinearity is severe (Montgomery et al., 2006).

Conclusion

Thousand-grain mass and ear diameter were the only variables with a significant positive correlation with grain yield, with coefficients of 0.83 and 0.72, respectively, also being the traits that had a significant positive direct effect on the yield of corn grains, indicating that the selection of these traits can help grain yield in corn lines.

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