SARTURI, M. V. R.; TEIXEIRA, C. A. M. B., CARVALHO, I. R.; DEMARI, G. H.; LORO, M. V.; PRADEBON, L. C.; PORT, E. D. Prediction of corn grain yield according to the altitude and plant population. **Revista de Agricultura Neotropical**, Cassilândia-MS, v. 9, n. 4, e7070, oct./dec. 2022. ISSN 2358-6303. DOI: https://doi.org/10.32404/rean.v9i4.7070.

Prediction of corn grain yield according to the altitude and plant population

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Received: 09/08/2022; Accepted: 27/10/2022.

ABSTRACT

This study aimed to evidence the best arrangement of plants according to altitudes to potentialize corn grain yield. An information survey was performed in the 2019/20 harvest, using 144 producers responsible for corn grain production fields totaling 2,301.3 hectares in 144 environments of Rio Grande do Sul. Within 144 environments, 14 corn hybrids were arranged: DKB 240 PRO, DOW 2A620, AG 9045 PRO3, AS1555 PRO3, AS1572 PRO2, AS1656, BIOGENE 7046, DKB 250 PRO2, DKB 290 PRO3, DKB 330RR, NS56, P1630HX, P30F53HX, and SH7910. Yield, morphological, and phenological variables were measured, and geographic and meteorological information was collected. There is a positive influence on grain yield according to altitude and plant population characteristics. At lower altitudes, increasing plant population is essential to enhance grain yield.

Keywords: *Zea mays,* Geographic variables, Principal components, Linear association.

Previsão da produtividade de grãos de milho em função da altitude e da população de plantas

RESUMO

O objetivo deste trabalho foi evidenciar o melhor arranjo de plantas em função das altitudes para potencializar a produtividade de grãos de milho. Foi realizado um levantamento de informações na safra 2019/20, utilizando 144 produtores, responsáveis pelos campos de produção de grãos de milho, que totalizaram 2,301.3 hectares, em 144 ambientes do Rio Grande do Sul. Dentro de 144 ambientes, foram dispostos 14 híbridos de milho, os quais: DKB 240 PRO, DOW 2A620, AG 9045 PRO3, AS1555 PRO3, AS1572 PRO2, AS1656, BIOGENE 7046, DKB 250 PRO2, DKB 290 PRO3, DKB 330RR, NS56, P1630HX, P30F53HX e SH7910. Variáveis produtivas, morfológicas e fenológicas foram mensuradas, bem como informações geográficas e meteorológicas coletadas. Há uma influência positiva da produtividade de grãos em função da altitude e das características da população de plantas. Em altitudes mais baixas, o aumento da população de plantas é essencial para aumentar o rendimento de grãos de milho.

Palavras-chave: *Zea mays,* Variáveis geográficas, Componentes principais, Associação linear..

1. Introduction

The corn crop is one of the oldest cultures in the world, one of the most important for its many ways of use, and one of the few economic native species from the Americas (Silva et al. 2021). Over the last few decades, corn has become the largest agricultural crop, the only one to have exceeded 1 billion tons, surpassing other plant species, such as rice and wheat. Grain yield is the result of the interaction of three important factors, the genotype and the variability of biotic and abiotic factors in the physiological process of plants. However, the reduction in yield is more linked to abiotic factors related to climate (soil water availability, air temperature, relative humidity, and solar irradiation) (Souza and Barbosa, 2015).

According to Bergamaschi and Matzenauer (2014), corn has high efficiency in the use of solar radiation and, thus, high grain yield due to its C4 metabolism. Renato et al. (2018) observed that, in general, the highest photosynthetic rates in C4 plants occur at temperatures between 30 and 40°C and that for corn gross photosynthesis, the increase in temperature is favorable; however, this implies other factors, such as an increase in the rate of respiration and a decrease in the cycle.

The air temperature usually decreases with increasing altitude in a proportion of approximately 1ºC/100m (adiabatic gradient of dry air). This cooling rate occurs because a rising dry air mass is subject to less and less pressure, increasing its volume and decreasing its temperature (Fritzsons et al., 2016). Maldaner et al. (2014) conclude that climatic effects define the success of the crop, and the main factors affecting grain yield are solar radiation, precipitation, and temperature, affecting individuals or jointly; thus, the greatest losses when they act in critical periods of development, to reduce the probability of decreasing production, an important tool is agricultural zoning.

The corn plant supports night temperatures up to 30ºC for long periods; however, high temperatures at night cause a decrease in production since there is a consumption of metabolic products produced during the day. For temperatures below 10ºC, there is practically no development; finally, the temperature must oscillate between 10 and 30ºC (Maldaner et al., 2014). Water deficiency limits corn yield, especially when it occurs in critical phases of the crop. The average needs are from 412 to 648 mm of water during its cycle, but in places of Rio Grande do Sul, there is a need for supplementary irrigation to obtain acceptable production increment (Köpp et al., 2015).

For Caron et al. (2017), corn (*Zea mays* L.) has greater productive potential when positioned at altitudes above 700 meters, while at lower altitudes, there is lower potential, and this is due to temperatures, and radiation is available in smaller quantities, directly affecting growth, flowering, water balance, nutrient absorption, and respiration processes. For Bernini et al. (2020), altitudes below 300 m and above 1300 m bring the suitability for grain yield becomes medium to low. It is necessary a search to know the effects of altitude on corn yield, as well as to evaluate possible management to increase grain yield. Thus, this study aimed to evidence the best arrangement of plants according to altitudes to potentialize corn grain yield.

2. Material and Methods

The present study presents itself as a survey of information carried out in the 2019/20 harvest, using 144 producers who are responsible for corn grain production fields, which totaled 2,301.3 hectares, in the locations (Table 1) of Barra do Guarita, Braga, Derrubadas, Esperança do Sul, Miraguaí, Redentora, Santo Augusto, Tenente Portela, and Vista Gaúcha, Rio Grande do Sul.

The 144 producers were grouped in their locations, forming nine environments. The nine environments include 14 corn hybrids: DKB 240 PRO, DOW 2A620, AG 9045 PRO3, AS1555 PRO3, AS1572 PRO2, AS1656, BIOGENE 7046, DKB 250 PRO2, DKB 290 PRO3, DKB 330RR, NS56, P1630HX, P30F53HX, and SH7910 (Table 2).

Table 1. Altitude, soil type, climate, and total precipitation of the locations of northern Rio Grande do Sul: Barra do Guarita, Braga, Derrubadas, Esperança do Sul, Miraguaí, Redentora, Santo Augusto, Tenente Portela, and Vista Gaúcha.

Environments	Alt[3]	Soil type	Climate	Total prec. (mm)[4]
Barra do Guarita	194 m	Latossolo Vermelho Distrófico	*Cfa* Subtropical	724.16
Braga	572 m	Latossolo Vermelho Distrófico	*Cfa* Subtropical	743.71
Derrubadas	430 m	Latossolo Vermelho Distrófico	*Cfa* Subtropical	704.72
Esperança do Sul	387 m	Latossolo Vermelho Distrófico	*Cfa* Subtropical	696.98
Miraguaí	488 m	Latossolo Vermelho Distrófico	*Cfa* Subtropical	743.71
Redentora	680 m	Latossolo Vermelho Distrófico	*Cfa* Subtropical	743.71
Santo Augusto	528 m	Latossolo Vermelho Distrófico	*Cfa* Subtropical	724.16
Tenente Portela	390 m	Latossolo Vermelho Distrófico	*Cfa* Subtropical	710.82
Vista Gaúcha	497 m	Latossolo Vermelho Distrófico	*Cfa* Subtropical	708.61

[1]Alt – Altitude, [2]Total prec. – Total precipitation

Hybrid characteristics took into account: hybrid class (HYB), cycle (Cl, days), the color of stigma and anthocyanin (CSA), type of grain (TG), and technology (transgenic event) present in the plant (TEC). In the crops (environments), were collected the data relative to plant population per ha (PO), grain yield (GY), grain humidity at harvest (HU, %), size of the sown area (AR, ha), altitude (AL) and location (MUN). The meteorological information, average (Tavg, °C), minimum (Tmin, °C), and maximum air temperature (Tmax, °C), precipitation (Prec, mm), and relative air humidity (RH, $g.kg^{-1}$), were expressed to understand better the results obtained (Nasa Power, 2022).

Data submission occurred to descriptive analysis to understand which variables influenced grain yield per hectare. Linear correlation analyses occurred with significance based on Student's t-test at 5% probability. The principal component analysis was applied to establish the expression trends of the evaluated traits for hybrids and cultivation environments. The packages used in the R software were ggplot 2, metan, patchwork, stats, factoextra, and neuranet. Based on the evidence, plant population per hectare and the altitude determined variables for the dependent variable grain yield. In this context, these interrelationships proved themselves through multiple regression and an algorithm of artificial neural networks (Figure 1).

Table 2. Hybrid, type of grain, the color of stigma and anthocyanin, and technology (transgenic event) cultivated the northern Rio Grande do Sul: Barra do Guarita, Braga, Derrubadas, Esperança do Sul, Miraguaí, Redentora, Santo Augusto, Tenente Portela, and Vista Gaúcha.

Hybrid	Type of grain	CSA	Technology
BG7046	Semi-flint	Present	Conventional
NS 56	Semi-dent	Present	Conventional
SHS 7910	Semi-dent	Present	Conventional
30F53H	Semi-flint	Present	Herculex
P1630H	Semi-dent	Present	Herculex
2A620 PW	Semi-dent	Present	PowerCore
DKB 330RR2	Semi-dent	Present	Roundup Ready 2
DKB 240PRO	Dent	Present	VT PRO
AS1656PRO	Semi-flint	Absent	VT PRO
AS1572PRO2	Dent	Present	VT PRO 2
DKB250PRO2	Semi-dent	Present	VT PRO 2
AS1555PRO3	Flint	Present	VT PRO 3
AG9045PRO3	Semi-flint	Present	VT PRO 3
DKB290PRO3	Semi-flint	Present	VT PRO 3

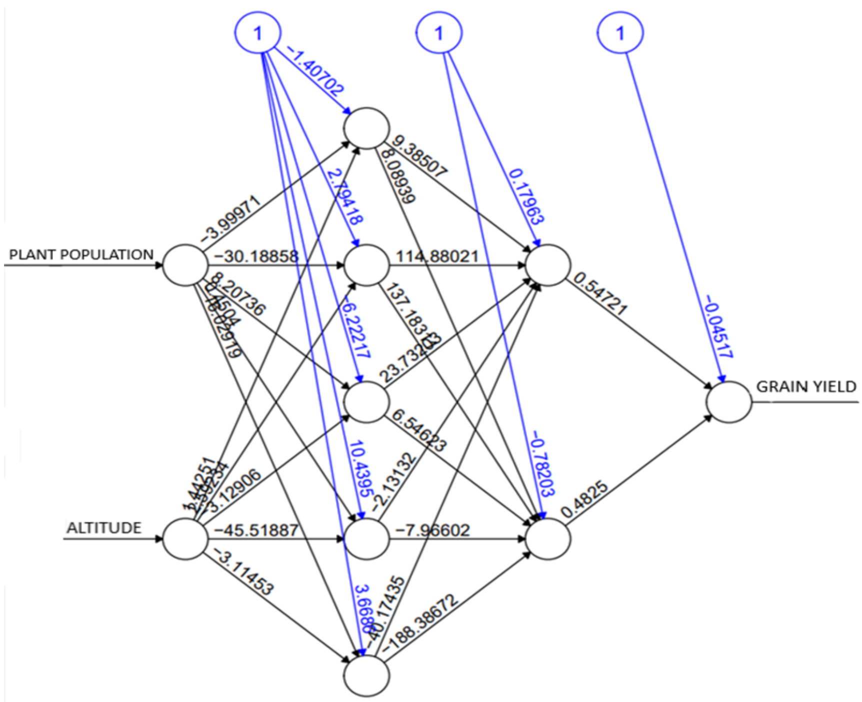

Figure 1. Artificial neural network, with grain yield output layer.

The network building used 80% of the original data and 20% for validation. A coefficient of determination (R^2) above 0.70 was considered for the neural network. Based on the predictions, a polynomial linear regression analysis occurred with significance in the t-test with a 5% probability. The predicted grain yield variable was considered as a dependent variable and altitude as an independent variable. Based on the angular, quadratic, and linear coefficients, the maximum technical efficiency (MTE) was estimated, revealing the maximum altitude of the environment and its potential theoretical grain yield.

3. Results and Discussion

The accumulated precipitation for the environments, as well as maximum and minimum temperatures (Figure 2) in the northern region of the state of Rio Grande do Sul, show that during the cultivation of corn in the municipalities, there was, in August, rainfall lower than 100 mm. in all locations, with an average close to 50 mm for all environments. August was the month with the lowest average temperatures, especially Vista Gaúcha, with an average of 15.61 ºC. September presented a scenario of lower rainfall in all locations, with an average of 89.94 mm in the environments. In September, the lowest average temperatures were in Tenente Portela and Vista Gaúcha (19.5 ºC), and the highest average temperature was in Barra do Guarita (30.54 ºC). The precipitations in October were the highest, with an average of 174.68 mm for the environments. Tenente Portela and Vista Gaúcha maintain the lowest average temperatures at 23.35 ºC, and the highest average temperature is in Barra do Guarita at 31.7 °C.

In November, the highest accumulated were in Barra do Guarita and Santo Augusto (158.54), and the lowest was in Braga, Miraguaí, and Redentora (127.31 mm), with an average of 135.98 mm, considering all locations. The temperatures with the lowest averages were Tenente Portela and Vista Gaúcha, with 26.69 ºC, and the highest average temperature is in Derrubadas at 34.45 ºC. The rainfall in December had 81.71 mm per location. Higher average temperatures mark December, but three locations have different averages from the others, Tenente Portela and Vista Gaúcha (25.51º C) and Barra do Guarita (24.42º C); the other municipalities maintain an average close to 32º C.

In January, average rainfall and temperature were 125.15 mm and 30.53 ºC, respectively. February, there was average rainfall of 98.50 mm, and an average temperature of 30.37 ºC. In March, the average rainfall was 4.53 mm during the first 15 days, and the average temperature was 32.9 ºC. With the data exposed (Figure 2), it is evident that there were periods with lower rainfall, October and March, but in the other periods, the rainfall and temperatures were consistent for the corn crop.

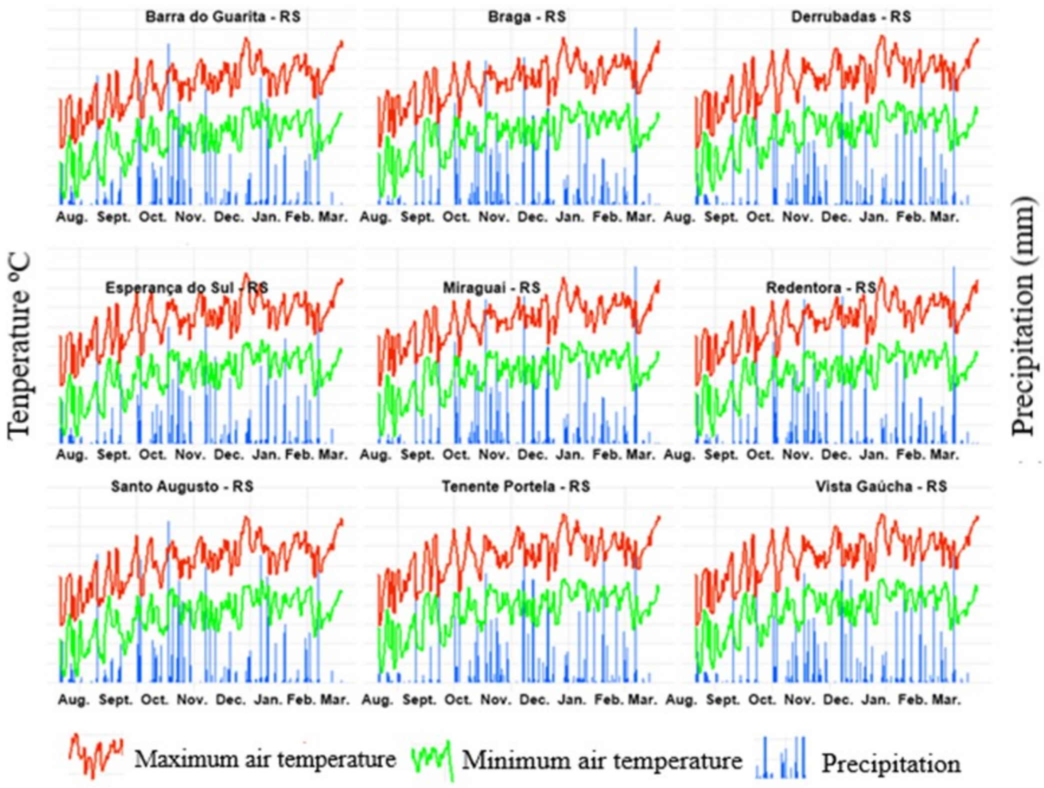

Figure 2. Maximum and minimum temperatures (ºC) and total precipitation (mm).

Pearson correlation analysis has been used in studies with corn (Carvalho et al., 2021; Barbosa et al., 2019) to show linear relationships between agronomic and meteorological characteristics. According to the Pearson correlation (Figure 3), in the association of 16 variables, it was possible to verify that for higher grain yields, there is a strong correlation (0.61) of altitude (AL) with grain yield (GY); similarly, the population (PO) obtained a medium magnitude correlation (0.43) with grain yield (GY).

There was a negative correlation of the mean magnitude of the cycle (Cl) with the minimum (Tmin) (-0.32), maximum (Tmax) (-0.32), and average (Tavg) (-0.32) temperatures, as well as with precipitation (Prec) (-0.31). This can be explained because the cycle duration is based on accumulated degree days, in such a way that the crop will reach its requirement earlier to complete the cycle, with a decrease in this (Minuzzi and Lopes, 2015). Relative air humidity (RH) obtained a positive correlation of medium magnitude with the size of the area (AR) (0.48). It was also correlated with the location (MUN), with 0.49, and with the population (PO) (0.33).

The reason is the different characteristics of each location, and the population (PO) size since each population composes a different microclimate due to smaller or larger interceptions of solar radiation and high air humidity conditions for corn plants for optimal development when combined with optimal temperatures. There was a positive correlation of mean magnitude between the population (PO) and the cycle (Cl) (0.32), which explains the fact that the greater this per hectare, the greater the occurrence of variation for water vapor in the atmosphere—favoring the increase of the cycle since the plants will have a less photosynthetic interception and greater concentration of humidity.

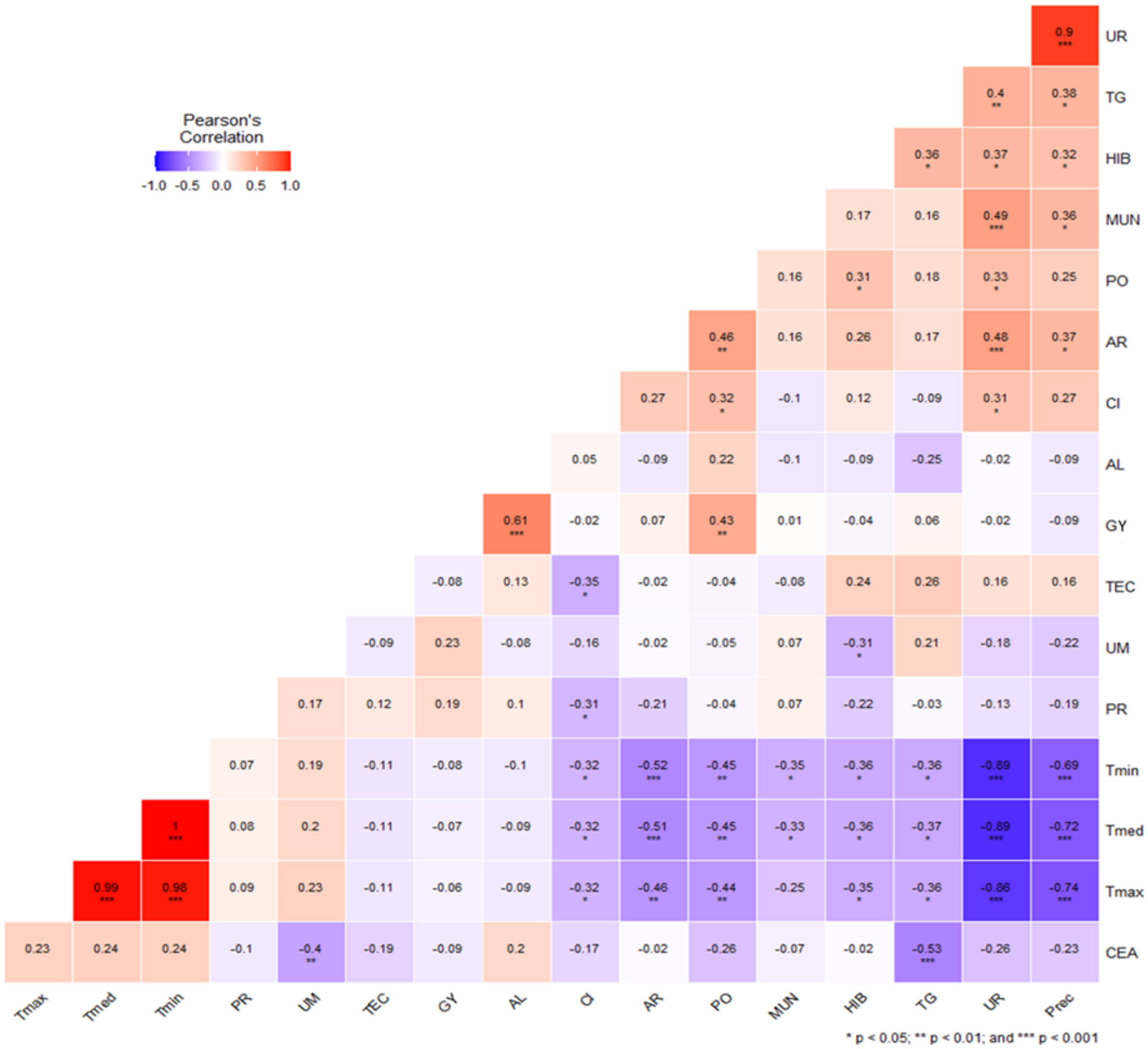

Figure 3. Pearson correlation between yield traits, plant population (PO), grain yield (GY), grain humidity at harvest (HU, %), size of the sown area (AR, ha), altitude (AL), and location (MUN); meteorological factors, average (Tavg,°C), minimum (Tmin,°C), and maximum (Tmax,°C) air temperature, precipitation (Prec, mm), relative air humidity (RH, $g.kg^{-1}$), and hybrid characteristics, hybrid (HYB), cycle (Cl, days), the color of stigma and anthocyanin (CSA), type of grain (TG) and technology present in the hybrid (TEC).

With a greater arrangement of plants, according to Almeida Júnior et al. (2018), there may be greater competition between plants for light, water, CO_2, and nutrients, thus harming the final yield and the availability of the first two factors favoring greater limitation for the use of large populations of corn. The choice of hybrid is negatively influenced by temperature conditions, minimum (-0.36), maximum (-0.35), average (-0.37), and precipitation (-0.31).

There is a positive influence of medium magnitude with the population (0.31), and these results may have a link to daily thermal units, such as degree-days (DD), which it is from the thermal accumulation that there are changes in the phenological cycle of the culture, thus having adaptations of cultivars with the environment. There is a negative correlation of mean magnitude between population (PO) and minimum (-0.45), maximum (-0.44), and average (-0.45) temperatures, being related to the correct decision-making concerning the population of plants per hectare in this way, in places where there are lower temperatures, the greater the productive response of populations.

Based on average character estimates, biplot dispersion (Figure 4) explained 76.1% (Dim1, 57.4%; Dim2, 18.7%) of the total variability of the data in the first two principal components. Redentora, in Quadrant 1, showed higher yields kg/ha and showed an affinity with the variables altitude (AL), grain yield (GY), population (PO), and size of the area (AR), demonstrating that they are determinants characteristics for high grain yield in the case of Redentora.

It is observed (Quadrant 2) affinity of the color of stigma and anthocyanin (CSA) and grain humidity at harvest (HU) with the locations of Santo Augusto and Derrubadas. In Quadrant 4, the types of hybrids and relative air humidity (RH) showed a contribution in Miraguaí. Precipitation (Prec), type of grain (TG), and the cycle (Cl) were consistent with the municipality of Braga, as well as with Tenente Portela and Miraguaí. In Biplot analysis (Figure 5), it had an explainability of 55.1% (Dim1, 38.4%; Dim2, 16.7%). For the traits with a slight affinity with the color of stigma and anthocyanin (CSA), the hybrid DKB290 PRO3 (9) showed consistency with the color of stigma and anthocyanin (CSA) and with maximum temperatures (Tmax) and minimum temperatures (Tmin), as well as the hybrids AS1656 (6) and AS1572 (5).

In Quadrant 2, there is an affinity of the hybrid AS1555 (4) with precipitation (Prec), type of grain (TG), and size of the area (AR). In Quadrant 3, there is an affinity of the hybrid P1630HX (12) with relative humidity (RH), cycle (Cl), and technology (TEC), as well as a lower affinity with the population (PO), the hybrid DKB 250 PRO2, showed consistency with the population (PO), as well as technology (TEC), cycle (Cl), and relative humidity (RH).

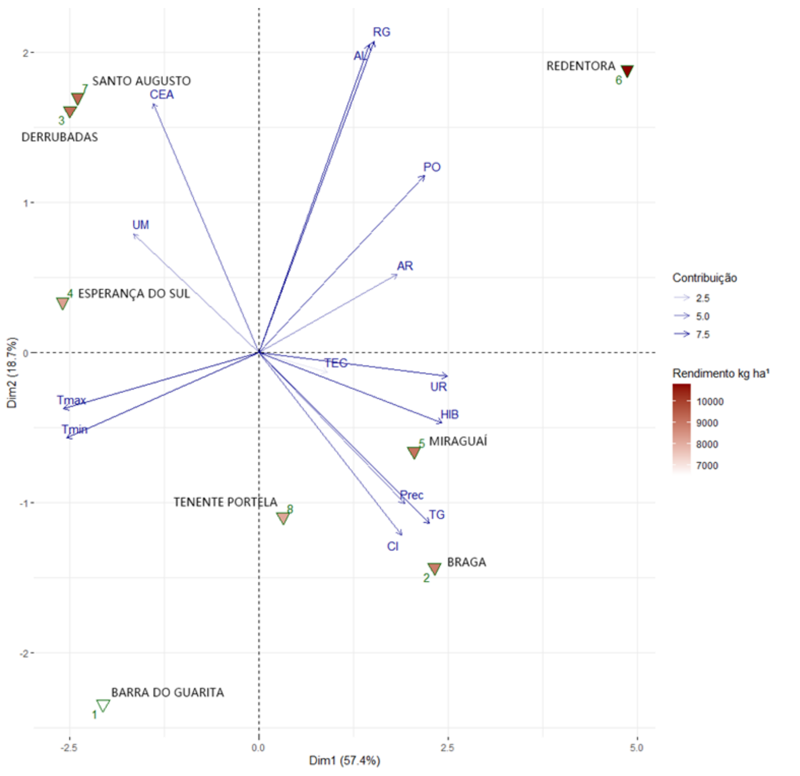

Figure 4. Distribution of locations (Barra do Guarita, Braga, Derrubadas, Esperança do Sul, Miraguaí, Redentora, Santo Augusto, Tenente Portela), considering the contribution of the main components. Relative Humidity (RH), Type of Grain (TG), Hybrid (HYB), Population (PO), Area (AR), Cycle (Cl), Altitude (AL), Grain Yield (GY), Technology (TEC), Humidity at Harvest (HU), Precipitation (Prec), Minimum Temperature (Tmin), Maximum Temperature (Tmax), Color of Stigma and Anthocyanin (CSA).

In Quadrant 4, based on the characters, it is evident that the hybrids DKB240 (1), AG9045 (3), and BIOGENE 7046 (7) have an affinity with grain humidity at harvest (UM). DOW 2A60 (2) exhibits affinity for altitude, as well as grain yield (GY) and grain humidity at harvest (HU). The hybrid P30F53HX (13) had a higher affinity with grain yield (GY) and with altitude (AL), as well as harvest humidity (HU). The hybrid DKB330RR (10) has a consistent similarity with grain yield (GY), altitude (AL), and harvest humidity (HU).

The different populations at different altitudes corroborate that there are different levels of productivity per hectare; in this way, the maximum technical efficiency (MTE) analyses demonstrate the maximum efficiency of each population per hectare according to the altitude (Table 3). Note that when the population is equal to 50 thousand plants per hectare, the corn plant has a productive potential of 3.95 tons at sea level (0 meters) (Figure 6A).

It reaches its maximum productive potential at 1698.9 meters of altitude (11.9 tons), this being its maximum technical efficiency (MTE), with an increase of 4.68 kg of productive potential per meter. For a population of 60,000 plants per hectare (Figure 6B), there is a maximum productive potential of 4,426 kg at sea level and a maximum potential at 1,521.9 meters of altitude, with a gain of 5.04 kg per meter, totaling 12,100 kg per hectare.

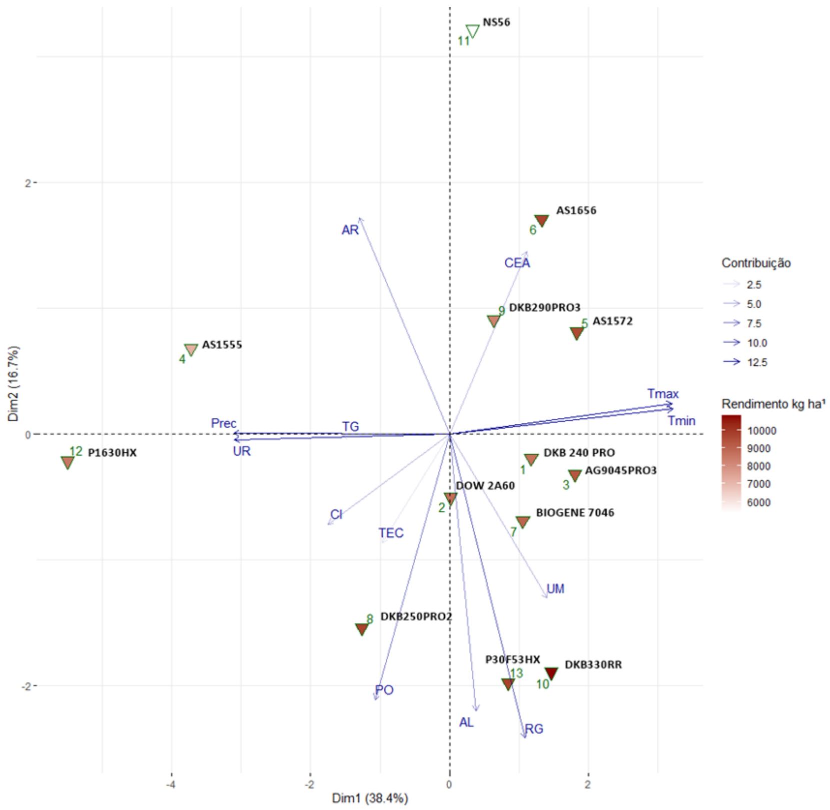

Figure 5. Distribution of hybrids, which are called genotypes (numbered from 1 to 13). The contribution of the main components is considered. Relative Humidity (RH), Type of Grain (TG), Hybrid (HYB), Population (PO), Area (AR), Cycle (CI), Altitude (AL), Grain Yield (GY), Technology (TEC), Humidity at Harvest (HU), Precipitation (Prec), Minimum Temperature (Tmin), Maximum Temperature (Tmax), and Color of Stigma and Anthocyanin (CSA).

Table 3. Regression analysis between grain yield (tons) and altitude (meters) according to the different populations per hectare. Rio Grande do Sul, Brazil, 2020.

PH	Mathematical model	R^2	MTE	PY	IM
50	3.945e+00 + 9.446e-03x – 2.780e-06x²	0.96	1698.90	11.90	4.68
60	4.426e+00 + 1.020e-02x – 3.351e-06x²	0.96	1521.90	12.10	5.04
70	5.300e+00 +9.926e-03x – 3.485e-06x²	0.95	1463.40	12.30	4.78
80	6.498e+00 + 8.661e-03x – 3.163e-06x²	0.92	1369.10	12.40	4.31
90	7.803e+00 + 6.828e-03x – 2.549e-06x²	0.88	1339.30	12.30	3.35
100	8.939e+00 + 5.050e-03x – 1.908e-06x²	0.84	1323.30	12.20	2.46
110	89.781e+00 + 3.671e-03x – 1.397e-06x²	0.84	1313.80	11.30	1.76
120	1.037e+01 + 2.679e-03x – 1.025e-06x²	0.80	1306.80	12.10	1.32

PH: population per hectare; MTE: maximum technical efficiency; PY: Potential yield; IM: Increment per meter.

With a population of 70 thousand plants per hectare, there is a potential yield of 5.3 tons per hectare (Figure 6C). At zero meters of elevation, the maximum potential is at 1,463.4 meters, 12.3 tons/ha, a gain of 4.78 kg per meter of elevation from 0 meters. With 80 thousand plants per hectare (Figure 6D), it is possible to reach 6.45 tons at zero meters of altitude, and the maximum potential at 1369.1 meters (12,400 kg), a gain of 4.31 kg per meter. Using a population of 90 thousand plants, the maximum yield occurs at 1339.3 meters of altitude, 12.3 tons (gain of 3.35 kg/m), already at sea level, 7,803 tons (Figure 6E). With 100,000 plants per hectare, there is a trend toward a maximum yield at sea level of 8.94 tons, and the maximum potential reaches 1323.3 meters above sea level, with a potential gain of 2.46 kg per meter (Figure 6F).

When considering a density of 110 thousand plants, there is a potential yield of 8,978 tons at sea level, while at 1,313.8 meters, it is 11.3 tons (MTE), with 1.76 kg per meter, the increase in yield potential (Figure 6G). Using a population of 120,000 plants without considering the effect of altitude, there is the greatest possible potential for grain yield under these conditions, being 10.37 tons, the maximum is 12.1 tons at an altitude of 1306.8 meters, an increase in the yield potential of 1.32 kg per meter (Figure 6H).

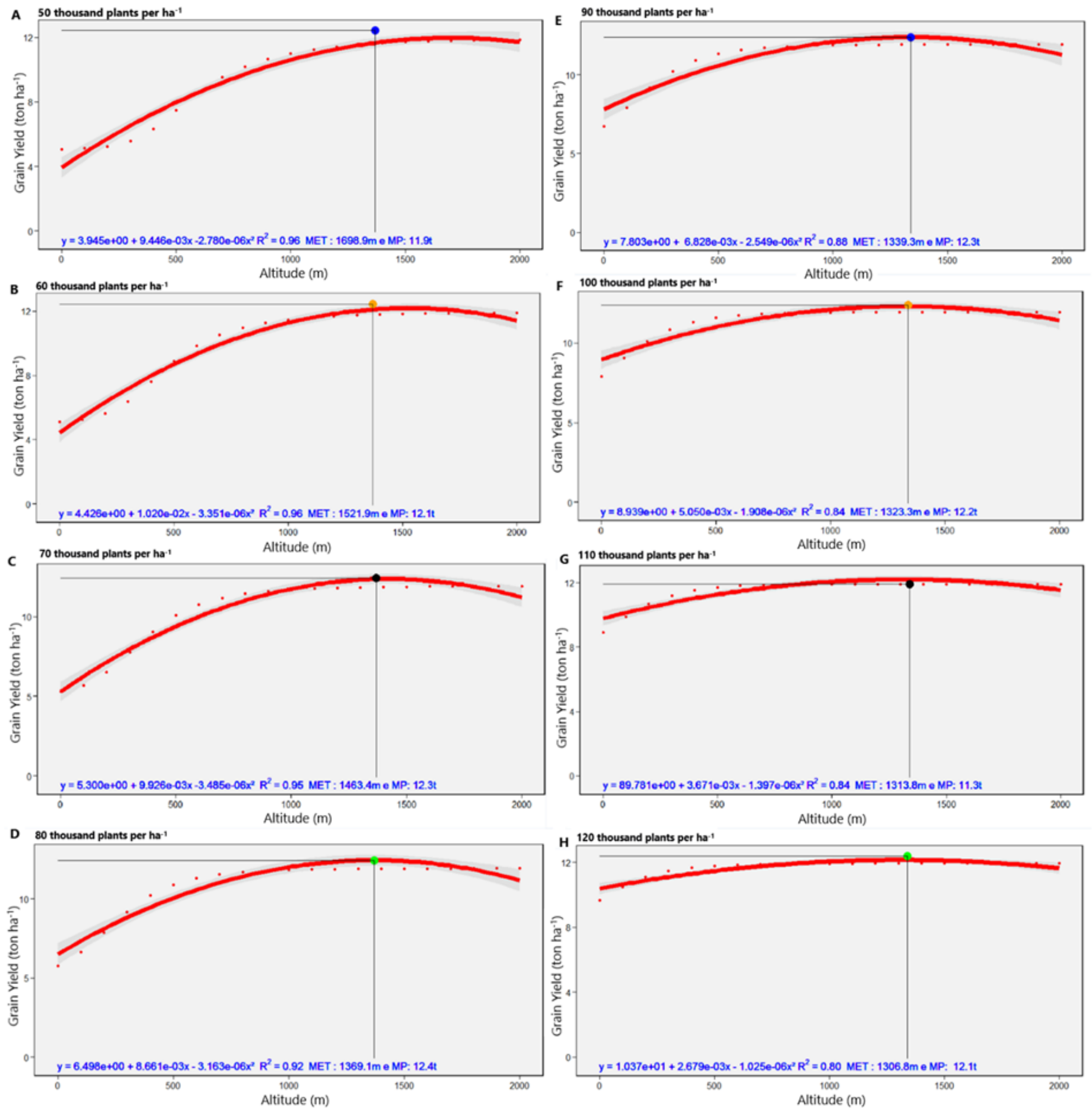

Figure 6. Regression between grain yield (ton ha^{-1}) and altitude (m), considering a population of 50 (A), 60 (B), 70 (C), 80, (D), 90 (E), 100 (F), 110 (G), and 120 (H) thousand plants per hectare.

4. Conclusions

There is a positive influence on grain yield according to altitude and plant population characteristics. Increasing plant population is essential to enhance the corn grain yield at lower altitudes.

Authors' Contribution

Marlon Vinicius da Rosa Sarturi, Ivan Ricardo Carvalho and Gustavo Demari contributed to the installation of the experiments, evaluations, data collection, tabulation and writing of the manuscript. Murilo Vieira Loro, Leonardo Cesar Pradebon e Eduarda Donadel Port contributed with the writing and correction of the manuscript.

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