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Agronomic optimal plant density for corn in subtropical environments

Abstract – The objective of this work was to determine the agronomic optimal plant density (AOPD) for corn (*Zea mays*) in environments with a high, medium, and low grain yield, as well as to define which yield component is the most sensitive to variations in plant density. On-farm experiments were conducted in the municipalities of Júlio de Castilhos, in the 2018/2019 growing season, and of Entre-Ijuís, Jóia, Agudo, and Júlio de Castilhos, in the 2019/2020 growing season, in the state of Rio Grande do Sul, Brazil. The production environments were classified as having a low (< 10 Mg ha^{-1}), medium (from 10 to 16 Mg ha^{-1}), and high (> 16 Mg ha^{-1}) grain yield. Júlio de Castilhos was identified as a site of high yield; Jóia and Entre-Ijuís, as of medium yield; and Agudo, as of low yield. The AOPDs ranged from 60,000 to 140,000 plants per hectare in the different production environments. The AOPD was of 110,300 to 116,200 plants per hectare for the high-yield environment, 101,000 plants per hectare for the medium-yield environment, and 60,000 plants per hectare for the low-yield environment. The number of grains per row is the yield component that is the most sensitive to variations in plant density in all production environments.

Index terms: *Zea mays*, on-farm experiments, plant arrangement, yield potential.

Densidade agronômica ótima de milho em ambientes subtropicais

Resumo – O objetivo deste trabalho foi determinar a densidade agronômica ótima de plantas (DAOP) para o milho (*Zea mays*), em ambientes de alta, média e baixa produtividade de grãos, bem como definir qual componente da produtividade é mais sensível às variações de densidade de plantas. Experimentos em fazenda foram conduzidos nos municípios de Júlio de Castilhos, na safra de 2018/2019, e de Entre-Ijuís, Jóia, Agudo e Júlio de Castilhos, na safra de 2019/2020, no estado do Rio Grande do Sul, Brasil. Os ambientes de produção foram classificados como de baixa (< 10 Mg ha^{-1}), média (de 10 a 16 Mg ha^{-1}) e alta (> 16 Mg ha^{-1}) produtividade. Júlio de Castilhos foi identificado como ambiente de alta produtividade; Jóia e Entre-Ijuís, como de média produtividade; e Agudo, como de baixa produtividade. As DAOPs variaram de 60.000 a 140.000 plantas por hectare nos diferentes ambientes de produção. A DAOP foi de 110.300 a 116.200 plantas por hectare para o ambiente de alta produtividade, de 101.000 plantas por hectare para o ambiente de média produtividade e de 60.000 plantas per hectare para o ambiente de baixa produtividade. O número de grãos por fileira é o componente de rendimento mais sensível às variações de densidade de plantas, em todos os ambientes de produção.

Termos para indexação: *Zea mays*, experimentos de lavouras, arranjo de plantas, potencial de produtividade.

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Introduction

One of the main challenges of modern agriculture is to increase crop yield by intensifying the use of resources (Hoang & Kanemoto, 2021). The predictions for the growth of the world population are worrying in what concerns the supply of corn demand by the year 2050. Corn production will have to increase by 124%, by 2050 (Sadras et al., 2015). Adjusting plant density is one of the most effective measures to maximize corn yield and reduce environmental impact of greenhouse gases (GHG) emissions (Liu et al., 2017).

Some studies associate the greater yield potential of modern corn hybrids – which have the ability to tolerate stresses – with their increase of plant density (Schwalbert et al., 2018; Rizzo et al., 2022). From the 1980s to 2016, the plant density increase at 24% allowed the average increase of 3 Mg ha^{-1} in the United States corn yield (Assefa et al., 2018). The plant density that provides the highest yield by the environment can be defined as the agronomic optimal plant density (AOPD) (Xu et al., 2017). This denomination can also be interpreted as the smallest amount of plants needed to maximize the yield (Carciochi et al., 2019; Ferreira et al., 2020). The AOPD is achieved when there is a balance between the yield decrease of a single plant and the yield rise of the plant community (Schwalbert et al., 2018).

Studies seeking AOPD have already been carried out for corn (Assefa et al., 2018), soybean (Carciochi et al., 2019), and wheat (Fischer et al., 2019). Maximum yield of 14 Mg ha^{-1} at plant density of 93,000 plants ha^{-1} were reported by Assefa et al. (2018). In the main corn producing regions of China, the AOPD was defined as 80,000 plants ha^{-1}, in the Southwest, and as 105,000 plants ha^{-1} in the Northwest of the country (Luo et al., 2020). The maximum yield found in Brazil was 15.3 Mg ha^{-1} with a plant density of 88,000 plants ha^{-1} (Schwalbert et al., 2018). However, corn yield potential in Brazil is higher than this value, which indicates the need for more studies on the AOPD for production environments where potential corn yields are greater than 15.3 Mg ha^{-1}.

Plant density is related to production environments because when density exceeds the ideal level for a given environment, there is a negative impact per plant, which reduces crop yield (Assefa et al., 2018). This occurs because the number of plants per area is related to a greater efficiency in the use of available resources (Schwalbert et al., 2018). From the sowing date, we can define the environmental conditions during the growing season that drive yield potential, such as temperature, solar radiation, and water availability (Lobell et al., 2009). The AOPD is associated with plant arrangement and determines the radiation interception efficiency, as the leaf area index (LAI) is directly influenced. Therefore, it is necessary to define AOPD for the main yield environments in Brazil, according to the available resources in each environment and production system, as well as to identify the AOPD for environments with yields higher than 16 Mg ha^{-1}, especially with modern and more efficient hybrids in the use of resources.

The objective of this work was to determine the agronomic optimal plant density for corn in environments with a high, medium, and low grain yield, as well as to define which yield component is the most sensitive to variations in plant density.

Materials and Methods

Field experiments were conducted during two growing seasons in farms located in several municipalities in the state of Rio Grande do Sul (RS), Southern Brazil, as follows: Júlio de Castilhos (JC) in the 2018/2019 growing season; and in Entre-Ijuís (EI), Jóia (JO), Agudo (AG), and Júlio de Castilhos (JC) in the 2019/2020 growing season (Table 1). Each site is an environment with distinct yield potential, and the sites were chosen because they represent the main climatic zones where corn is produced in the state of Rio Grande do Sul (Global Yield Gap Atlas, 2022). According to the Köppen-Geiger's classification, the climate of these sites is humid, subtropical with hot summer, and no defined dry season (Cfa) (Alvares et al., 2013). From the average yield achieved in AOPD in the experiments, it was possible to establish a classification in three yield potential ranges. Thus, the yield environments were classified as low (<10 Mg ha^{-1}), medium (between 10 and 16 Mg ha^{-1}), and high (> 16 Mg ha^{-1}) potential yield. The JC environment was identified as high-yield (HY), JO and EI as medium yield environments (MY), and AG as low-yield environments (LY). The yield environments are classified as a function of yield in response to plant density with basis on the classification used for corn in the United States (Assefa et al., 2016) and

Brazil (Schwalbert et al., 2018). After classifying the environments, we evaluated the influence of the plant density increase in the experiments classified as HY and LY.

The experiments maintained the standard management performed in commercial corn crops by farmers, thus representing the technical and socioeconomic conditions of each environment. In Júlio de Castilhos (HY), in the 2018/2019 harvest, we used the densities of 60,000, 80,000, 100,000, 120,000 and 140,000 plants ha^{-1} and the hybrid AG9025 (super-early cycle); in the 2019/2020 harvest, we used the same plant densities and the AG9025 (super-early cycle) and DKB230 (hyper-early cycle) hybrids. In Entre-Ijuís (MY), the densities used were 70,000, 90,000, and 110,000 plants ha^{-1}, and the hybrids used were AS1666 (super-early cycle), AG9025 (super-early cycle), P2501 (super-early cycle), and P3016 (early cycle). In Jóia (MY), the densities used were 70,000, 80,000, 90,000 and 100,000 plants ha^{-1}, and the hybrids were AG9025 (super-early cycle) and AS1666 (super-early cycle). In Agudo (LY), the densities used were 60,000, 80,000, 100,000, 120,000, and 140,000 plants ha^{-1}, and the hybrids were AG9025 (super-early cycle) and P30F53 (early cycle) (Table 1). The hybrids and cycles were chosen because they are representative of the study regions and because they are the most used crops where the experiments were conducted. Each treatment consisted of a combination of hybrid and plant density. The experiments were carried out in a completely randomized block design, with four replicates. In all sites, each replicate was a plot with 8 plant rows, spaced at 0.5 m apart and with 5 m long, totaling 20 m².

Fertilizer was applied in accordance with the technical recommendations for the crop and with the expected yield of each location, which was 15, 12, 12, and 7.2 Mg ha^{-1}, respectively for JC, JO, EI, and AG. Irrigation was carried out according to plant's water demand, and setting the irrigation depth was based on the soil water balance, using the daily water balance model of Thornthwaite & Mather (1955). In JC, EI, and JO, irrigation was performed through a center pivot sprinkler irrigation system, and in AG by conventional sprinkler.

Sowing was carried out at a high seeding rate and plants were thinned at the V1-V2 stages (Ritchie et al., 1993), to achieve uniform spacing between plants and target plant densities in each treatment. At that time, an 5 m² area in each of the four replicates of each treatment in all sites was demarcated for the harvest, in order to avoid the interference of external factors in the estimation of grain yield. After plants reached the R6 stage (Ritchie et al., 1993), in all sites, the yield components were measured on five plants per plot. These five plants, which were representative of the plot, were outside the harvest area, but were also previously marked. Before harvesting, the yield components were evaluated in the ears of these five plants, for the following parameters: stem diameter at the first internode; ear insertion height; and plant height up to the flag leaf. The ears of these five plants were collected to determine the

Table 1. Experimental areas, sowing dates, hybrids [and maturity in accumulated growing degree days (ADD) from emergence to physiological maturity], and corn (*Zea mays*) plant densities in the experiments in four locations, in the state of Rio Grande do Sul, Brazil, during the 2018/2019 and 2019/2020 growing seasons.

Municipality	Geographic coordinate	Altitude (m)	Sowing date	Hybrid (maturity)	Plant density (x 1000 ha^{-1})	Soil taxonomy	
						Type	Textural class
Júlio de Castilhos (JC)	29º11'S, 53º36'W	513	09/07/2018 08/24/2019	AG9025(1564 ADD) AG9025 (1564 ADD), DKB230 (1488 ADD).	60, 80, 100, 120,140	Oxisols	Clay loam
Entre-Ijuís (EI)	28º31'S, 54º22'W	339	08/16/2019	AS1666 (1564 ADD), AG9025 (1564 ADD), P2501 (1564 ADD), P3016 (1710 ADD).	70, 90, 110	Oxisols	Clay
Jóia (JO)	28°46'S, 53°58'W	332	10/01/2019	AG9025(1564 ADD), AS1666 (1564 ADD).	70, 80, 90, 100	Oxisols	Clay
Agudo (AG)	29º40'S, 53º14'W	81	12/07/2019	AG9025(1564 ADD), P30F53 (1710 ADD).	60, 80, 100, 120,140	Ultisols	Sand clay loam

other components, the grain number per row, the grain rows per ear, and 1000-grain weight. Grain yield was measured (corrected to 15.5% moisture) for each plot, in the previously demarcated area.

In every production environment, the relations among stem diameter, plant height, ear height, rows per ear, grains per row, 1000-grain weight, plant density, and grain yield were calculated using the Pearson correlation coefficient (r). The significance of coefficients from the p-value was tested at 10%, 5%, and 1% probability. Pearson's correlation coefficient and p-value were calculated with the aid of Microsoft Office Excel software.

Results and Discussion

In the average of environments and harvests, we found that AOPD in the HY environment was 111,000 plants ha^{-1} for 19 Mg ha^{-1} yield, and in the LY environment, AOPD was 60,000 plants ha^{-1} for the yield of 9 Mg ha^{-1}. Yield follows a quadratic curve as a function of plant density in the HY environment, and a negative linear regression in the LY environment (Figure 1). Regardless of cultivar and year, in the HY environments, the average increase for yield at the plant density of 60,000 plants ha^{-1} until AOPD was 3.4 Mg ha^{-1}, which is 45.0 kg ha^{-1} for every thousand increase in plants ha^{-1}; and in LY environments, the average decrease was 9.9 kg ha^{-1} for every thousand additional plants ha^{-1} (Table 2).

When analyzing the differences for years and hybrids, the AOPD in the HY environment cultivated in 2019-2020 was 116,200 plants ha^{-1}, with 20.9 Mg ha^{-1} yield (Figure 1). In the 2018-2019 growing season, the AG9025 hybrid reached maximum yield (17.8 Mg ha^{-1}) at a density of 110,300 plants ha^{-1}, resulting in 43.7 kg ha^{-1} average increase for each additional 1000 plants ha^{-1} (Table 2), which means an increase of 20% less than in the 2019-2020 growing season (Figure 1). For the same growing season, considering the hyper-early hybrid P1630, the agronomic optimum density found was 121,800 plants ha^{-1}, with 18.0 Mg ha^{-1} yield, and 2.5 Mg ha^{-1} increase concerning the 60,000 plants ha^{-1} density.

Yield penalty in LY for the AG9025 (super-early) and P30F53 (early) hybrids was 5.9 kg ha^{-1} and 14.0 kg ha^{-1}, respectively, with the addition of 1000 plants ha^{-1} (Table 2). The higher loss in the longer-cycle hybrid is related to genetics and earlier hybrids, such as those with a hyper-early cycle, which are more responsive to high densities. The lower yield of the hybrid P30F53, in comparison with the hybrid AG9025 (Figure 1), was also related to the late sowing date, since the hybrid P30F53 has a longer cycle and, therefore, its reproductive stages coincide with a period of lower air temperature and solar radiation. For this reason, the hybrid was exposed to adverse conditions for a longer period (Tsimba et al., 2013; Yang et al., 2019).

Results presented here indicate that not only the agronomic optimal density depends on the hybrid, but also on whether or not the environment is favorable. The same result was found in Greece and Romania, where 7 cultivars were tested in two growing seasons (2006 and 2007) with different responses regarding plant density (Tokatlidis et al., 2011). Likewise, the results of Tokatlidis (2013) reported a variation of the agronomic optimum density from 27,600 plants ha^{-1} to 112,000 plants ha^{-1}, when there was an alteration of the production environment.

Yield components analysis indicated that yield increase in the HY environments was mainly due to the increase of the number of ears per hectare, once there

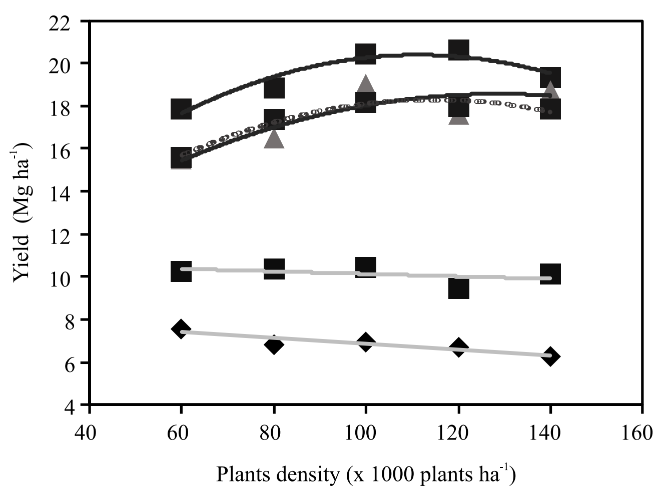

Figure 1. Corn (*Zea mays*) grain yield (at 15.5% moisture) as a function of plant density in the high-yield environment (Júlio de Castilhos) represented by dark grey lines, and the in low-yield environment (Agudo) represented by light grey lines, during the 2018-2019 growing season (dashed line), and in the 2019-2020 growing season (continuous line). Black squares represent the AG9025 hybrid; grey triangles, the P1630 hybrid; and black diamonds, the P30F53 hybrid.

was the availability of environmental resources for contribution of the weight of 1,000 grains (Figure 2 E), compensating for the reduction of the number of grains by row (Figure 2 C) – this relationship has been previously reported in the United States of America (USA) (Assefa et al., 2018). A greater efficiency in the use of available resources by increasing corn yield was also reported by Hou et al. (2020), without the need to increase the fertilization, which also implies a lower GHG intensity in the atmosphere. We observed the same relationship between plant density and grains per row (Figure 2 C) in LY and HY environments. We infer that the limited resources in the LY environment do not allow of gains in yield due to the lack of compensation of the weight of 1000 grains; however, as linear regression was not significant for this yield component, further studies are needed to verify this relationship (Figure 2 E).

The plant density increases in the HY and LY environments reduced the grain rows per ear, grains per row, 1000-grain weight, and stem diameter (Figure 2 A, C, E, and F). Besides, it provided an increase of plant height (Figure 2 B) and ear insertion height (Figure 2 D). The stresses caused by intense competition between plants resulted in greater ova abortion and, consequently, few grains per row, due to the higher asynchronism between the weighing and the exposure of the style-stigmas (Cicchino et al., 2010). The availability of resources in the grain filling phase directly influences the weight of the grains (Novacek et al., 2013), which explains the lower weight of grains at higher densities.

The number of grains per row decreased by the increase of density (Figure 2 C), and it did not vary in the HY and LY (33 grains per row). The density increase from 60,000 plants ha^{-1} to 110,000 plants ha^{-1} caused 9% reduction of the number of grains per row in the LY and HY environments, respectively. A similar decrease of the number of grains per row was also found in three corn hybrids sown in Nebraska and Croatia because of plant density increase from 65,000 to 105,000 plants ha^{-1}, which resulted in 19% decrease in the grains per row, according to reports by Lindsey & Thomison (2016) and Milander et al. (2016). The weight of 1000 grains was 444 g for the HY environment, and 312 g for the LY environment (Figure 2 E). When the density factor was isolated, there was a decrease of the 1000-grain weight of approximately 1 g for each additional 1000 plants ha^{-1} in the LY environment. However, there was a reduction of 1 g in the 1000-grain weight in the HY environment, when density was approximately 1700 plants ha^{-1} higher, starting from 60,000 plants ha^{-1}. Therefore, the 1000-grain weight in an LY environment was 59% higher than a HY environment, when the number of plants increased. Similar results were obtained for three hybrids in Nebraska, USA, where the 1000-grain weight was penalized by 1 g for each increment of 1700 plants ha^{-1}, between 69,000 plants ha^{-1} and 105,000 plants ha^{-1} densities (Novacek et al., 2013; Milander et al., 2016). The greatest loss in the 1000-grain weight can also be explained by the sowing date in the LY environment. In the state of Rio Grande do Sul, when corn sowing is carried out in December, the grain filling phase is

Table 2. Combinations of corn (*Zea mays*) hybrids and yield environments, and the respective equations, determination coefficient (R^2), p-value (95%) and 95% confidence interval (95% CI) for lower and higher densities of agronomic optimum plant density (AOPD), as well as for grain yield potential corrected at 15.5% moisture on the AOPD wet basis.

Corn hybrid	Municipality[(1)]	Equation	R^2	p-value	Plant density (X)			Yield (Y)		
					AOPD	95% CI		AOPD	95% CI	
						lower	higher		lower	higher
					-----(x 1,000 plants ha^{-1})-----			-------------(Mg ha^{-1})-------------		
AG9025 ■		$y = -0.001x^2 + 0.2323x + 7.48$	0.91	0.23	116.2	111.1	122.0	20.97	20.94	20.94
AG9025 ■		$y = -0.0009x^2 + 0.1985x + 6.9$	0.97	0.13	110.3	106.0	116.0	17.84	17.82	17.81
AG9025 ■		$y = -0.0059x + 10.72$	0.22	0.42	60.0	60.0	60.0	10.26	10.26	10.26
P1630 ▲		$y = -0.0007x^2 + 0.1705x + 7.61$	0.77	0.09	121.8	116.0	129.0	17.99	17.96	17.95
P30F53 ◆		$y = -0.014x + 8.27$	0.86	0.02	60.0	60.0	60.0	7.59	7.59	7.59

[(1)]The high-yield environment (Júlio de Castilhos) is represented by dark grey lines, and the in low-yield environment (Agudo) is represented by light grey lines, during the 2018-2019 growing season (dashed line), and in the 2019-2020 growing season (continuous line).

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exposed to a restricted condition of air temperature and solar radiation, causing a lower photothermal coefficient, in comparison with the earlier sowing date (September), as well as in the HY environment (Zanon et al., 2016).

The correlations showed that plant density affects the production environments (Table 3). Plant height seems to be more important in LY than in HY environment for affecting yield. The density showed a positive correlation with yield for the HY (r = 0.57**)

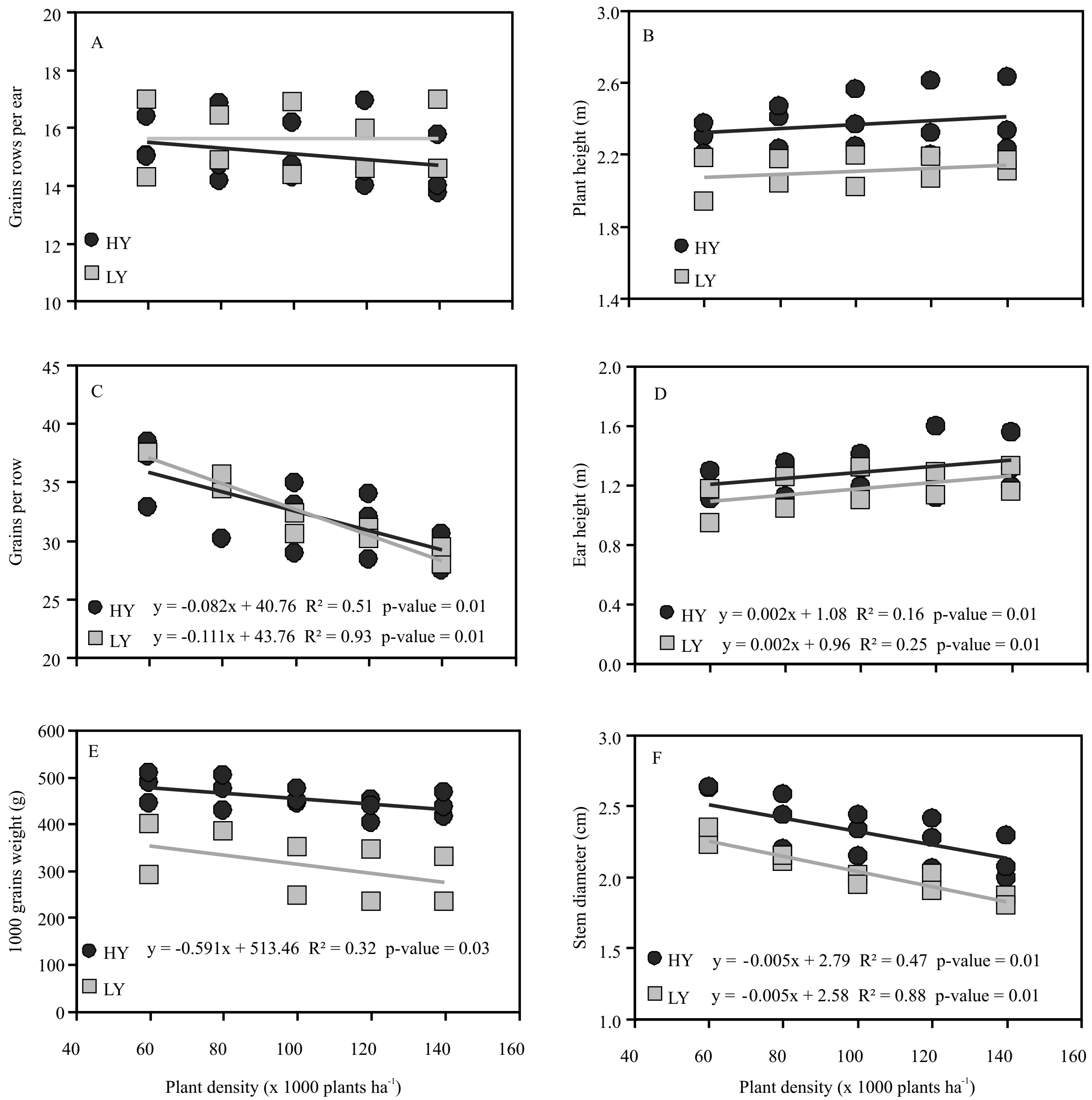

Figure 2. Relationship between corn (*Zea mays*) yield components and plant density, in the high yield (HY) environment (Júlio de Castilhos), represented by dark grey circles, and in the low-yield (LY) environment (Agudo), represented by light grey squares. The panels show the response of the following parameters: A, grain rows per ear; B, plant height; C, number of grains per row; D, ear height; E, 1000-grain weight; and F, stem diameter.

Table 3. Pearson correlations between yield components of corn (*Zea mays*) cultivated in high- and low-yield environments (Júlio de Castilhos e Agudo sites, respectively).

Yield components	SD	PH	EH	EP	RE	GR	GW	PD	YI
					High yield environment - Júlio de Castilhos				
SD	–	0.07	0.27	-0.30	-0.38	0.89***	0.86***	0.69***	-0.26
PH	0.07	–	0.70***	0.39	-0.04	-0.30	0.11	0.22	-0.32
EH	0.27	0.70***	–	-0.10	0.71***	0.04	0.3	0.40	0.19
EP	-0.30	0.39	-0.10	–	0.29	-0.34	-0.45	0.25	0.18
RE	-0.38	-0.04	-0.71***	0.29	–	-0.39	-0.48*	-0.28	-0.52**
GR	0.89***	-0.30	0.04	-0.34	-0.39	–	0.79***	0.72***	-0.10
GW	0.86***	0.11	0.30	-0.45	-0.48*	0.79**	–	-0.57**	-0.22
PD	-0.69***	0.22	0.40	0.25	-0.28	-0.72***	-0.57**	–	0.57**
YI	-0.26	-0.32	0.19	0.18	-0.52**	-0.10	-0.22	0.57**	–
					Low yield environment - Agudo				
SD	–	-0.34	-0.49	0.64**	0.03	0.93***	0.38	-0.94***	0.07
PH	-0.34	–	0.83***	-0.51	0.72**	-0.35	-0.80***	0.30	-0.71**
EH	-0.49	0.83***	–	-0.79***	0.81***	-0.62*	-0.97***	0.50	-0.89***
EP	0.64**	-0.51	-0.79***	–	-0.44	0.75**	0.82***	-0.73**	0.65**
RE	0.03	0.72**	0.81***	-0.44	–	-0.11	-0.85***	-0.01	-0.92***
GR	0.93***	-0.35	-0.62*	0.75**	-0.11	–	0.56	-0.96***	0.28
GW	0.38	-0.80***	-0.97***	0.82***	-0.85***	0.56	–	-0.48	0.95***
PD	-0.94***	0.3	0.5	-0.73**	-0.01	-0.96***	-0.48	–	-0.17
YI	0.07	-0.71**	-0.89***	0.65**	-0.92***	0.28	0.95***	-0.17	–

*, **, *** Significant at 5%, 1%, and 0.1% probability, respectively. Components: SD, stem diameter; PH, plant height; EH, ear height; EP, ears per plant; RE, rows per ear; GR, grains per row; GW, 1000-grain weight; PD, plant density; and YI, grain yield.

environment, and a negative (insignificant) correlation (r = -0.17) for the LY environment. Yield increase caused by the density increment in the HY environment occurs because of the high levels of available resources that support a higher plant density. Contrastingly, the negative correlation in the LY environment indicates that densities higher than 60,000 plants ha^{-1} should not be used. Among the yield components that had a higher correlation with yield, we can mention the grain weight (r = 0.95***). However, for the HY environment, the components showed no significant correlation with yield, remaining more stable in relation to other environments. Therefore, the yield was maximized mainly because of the density increase (r = 0.57**). From a practical point of view, producers who have favorable production environments and have stabilized yield in recent years can increase plant density to achieve higher yields.

Conclusions

1. In a subtropical environment, the average agronomic optimal plant density (AOPD) is 111,000 plants ha^{-1} for yields up to 19 Mg ha^{-1} on farms of corn (*Zea mays*).

2. The AOPD for high yield environments ranges from 110,300 to 116,200 plants ha^{-1}; for medium yield environments, AOPD is 101,000 plants ha^{-1}; and, for low-yield environments, AOPD is 60,000 plants ha^{-1}.

3. The number of grains per row is the yield component most sensitive to variations of plant density, in the three production environments.

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References

ALVARES, C.A.; STAPE, J.L.; SENTELHAS, P.C.; GONÇALVES, J.L. de M.; SPAROVEK, G. Köppen's climate classification map for Brazil. **Meteorologische Zeitschrift**, v.22, p.711-728, 2013. DOI: https://doi.org/10.1127/0941-2948/2013/0507.

ASSEFA, Y.; CARTER, P.; HINDS, M.; BHALLA, G.; SCHON, R.; JESCHKE, M.; PASZKIEWICZ, S.; SMITH, S.; CIAMPITTI, I.A. Analysis of long term study indicates both agronomic optimal plant density and increase maize yield per plant contributed to yield gain. **Scientific Reports**, v.8, art.4937, 2018. DOI: https://doi.org/10.1038/s41598-018-23362-x.

ASSEFA, Y.; PRASAD, P.V.V.; CARTER, P.; HINDS, M.; BHALLA, G.; SCHON, R.; JESCHKE, M.; PASZKIEWICZ, S.; CIAMPITTI, I.A. Yield responses to planting density for US modern corn hybrids : a synthesis-analysis. **Crop Science**, v.56, p.2802-2817, 2016. DOI: https://doi.org/10.2135/cropsci2016.04.0215.

CARCIOCHI, W.D.; SCHWALBERT, R.; ANDRADE, F.H.; CORASSA, G.M.; CARTER, P.; GASPAR, A.P.; SCHMIDT, J.; CIAMPITTI, I.A. Soybean seed yield response to plant density by yield environment in North America. **Agronomy Journal**, v.111, p.1923-1932, 2019. DOI: https://doi.org/10.2134/agronj2018.10.0635.

CICCHINO, M.; RATTALINO EDREIRA, J.I.; URIBELARREA, M.; OTEGUI, M.E. Heat stress in field-grown maize: response of physiological determinants of grain yield. **Crop Science**, v.50, p.1438-1448, 2010. DOI: https://doi.org/10.2135/cropsci2009.10.0574.

FERREIRA, A.S.; ZUCARELI, C.; WERNER, F.; FONSECA, I.C. de B.; BALBINOT JUNIOR, A.A. Minimum optimal seeding rate for indeterminate soybean cultivars grown in the tropics. **Agronomy Journal**, v.112, p.2092-2102, 2020. DOI: https://doi.org/10.1002/agj2.20188.

FISCHER, R.A.; MORENO RAMOS, O.H.; ORTIZ MONASTERIO, I.; SAYRE, K.D. Yield response to plant density, row spacing and raised beds in low latitude spring wheat with ample soil resources: an update. **Field Crops Research**, v.232, p.95-105, 2019. DOI: https://doi.org/10.1016/j.fcr.2018.12.011.

GLOBAL YIELD GAP ATLAS. Available at: <www.yieldgap.org>. Accessed on: July 28 2022.

HOANG, N.T.; KANEMOTO, K. Mapping the deforestation footprint of nations reveals growing threat to tropical forests. **Nature Ecology and Evolution**, v.5, p.845-853, 2021. DOI: https://doi.org/10.1038/s41559-021-01417-z.

HOU, P.; LIU, Y.; LIU, W.; LIU, G.; XIE, R.; WANG, K.; MING, B.; WANG, Y.; ZHAO, R.; ZHANG, W.; WANG, Y.; BIAN, S.; REN, H.; ZHAO, X.; LIU, P.; CHANG, J.; ZHANG, G.; LIU, J.; YUAN, L.; ZHAO, H.; SHI, L.; ZHANG, L.; YU, L.; GAO, J.; YU, X.; SHEN, L.; YANG, S.; ZHANG, Z.; XUE, J.; MA, X.; WANG, X.; LU, T.; DONG, B.; LI, G.; MA, B.; LI, J.; DENG, X.; LIU, Y.; YANG, Q.; FU, H.; LIU, X.; CHEN, X.; HUANG, C.; LI, S. How to increase maize production without extra nitrogen input. **Resources, Conservation and Recycling**, v.160, art.104913, 2020. DOI: https://doi.org/10.1016/j.resconrec.2020.104913.

LINDSEY, A.J.; THOMISON, P.R. Drought-tolerant corn hybrid and relative maturity yield response to plant population and planting date. **Agronomy Journal**, v.108, p.229-242, 2016. DOI: https://doi.org/10.2134/agronj2015.0200.

LIU, G.; HOU, P.; XIE, R.; MING, B.; WANG, K.; XU, W.; LIU, W.; YANG, Y.; LI, S. Canopy characteristics of high-yield maize with yield potential of 22.5 Mg ha^{-1}. **Field Crops Research**, v.213, p.221-230, 2017. DOI: https://doi.org/10.1016/j.fcr.2017.08.011.

LOBELL, D.B.; CASSMAN, K.G.; FIELD, C.B. Crop yield gaps: their importance, magnitudes, and causes. **Annual Review of Environment and Resources**, v.34, p.179-204, 2009. DOI: https://doi.org/10.1146/annurev.environ.041008.093740.

LUO, N.; WANG, X.; HOU, J.; WANG, Y.; WANG, P.; MENG, Q. Agronomic optimal plant density for yield improvement in the major maize regions of China. **Crop Science**, v.60, p.1580-1590, 2020. DOI: https://doi.org/10.1002/csc2.20000.

MILANDER, J.J.; JUKIC, Z.; MASON, S.C.; GLAUSHA, T.; KMAIL, Z. Plant population influence on maize yield components in Croatia and Nebraska. **Crop Science**, v.56, p.2742-2750, 2016. DOI: https://doi.org/10.2135/cropsci2015.09.0565.

NOVACEK, M.J.; MASON, S.C.; GALUSHA, T.D.; YASEEN, M. Twin rows minimally impact irrigated maize yield, morphology, and lodging. **Agronomy Journal**, v.105, p.268-276, 2013. DOI: https://doi.org/10.2134/agronj2012.0301.

RITCHIE, S.W.; JANWAY, J.J.; BENSON, G.O. **How a corn plant develops**. Ames: Iowa State of University of Science and Technology, Cooperative Extension Service, 1993. 21p. (Special Report, n.48).

RIZZO, G.; MONZON, J.P.; TENORIO, F.A.; HOWARD, R.; CASSMAN, K.G.; GRASSINI, P. Climate and agronomy, not genetics, underpin recent maize yield gains in favorable environments. **Proceedings of the National Academy of Sciences of the United States of America**, v.119, e2113629119, 2022. DOI: https://doi.org/10.1073/pnas.2113629119.

SADRAS, V.O.; CASSMAN, K.G.; GRASSINI, P.; HALL, A.J.; BASTIAANSSEN, W.G.M.; LABORTE, A.G.; MILNE, A.E.; SILESHI, G.; STEDUTO, P. **Yield gap analysis of field crops**: methods and case studies. Rome: FAO, 2015. 63p. (FAO Water Reports, 41).

SCHWALBERT, R.; AMADO, T.J.C.; HORBE, T.A.N.; STEFANELLO, L.O.; ASSEFA, Y.; PRASAD, P.V.V.; RICE, C.W.; CIAMPITTI, I.A. Corn yield response to plant density and nitrogen: spatial models and yield distribution. **Agronomy Journal**, v.110, p.970-982, 2018. DOI: https://doi.org/10.2134/agronj2017.07.0425.

THORNTHWAITE, C.W.; MATHER, J.R. **The water balance**. Centerton: Drexel Institute of Technology, Laboratory of Climatology, 1955. 104p.

TOKATLIDIS, I.S. Adapting maize crop to climate change. **Agronomy for Sustainable Development**, v.33, p.63-79, 2013. DOI: https://doi.org/10.1007/s13593-012-0108-7.

TOKATLIDIS, I.S.; HAS, V.; MELIDIS, V.; HAS, I.; MYLONAS, I.; EVGENIDIS, G.; COPANDEAN, A.; NINOU, E.; FASOULA, V.A. Maize hybrids less dependent on high plant densities improve resource-use efficiency in rainfed and irrigated conditions. **Field Crops Research**, v.120, p.345-351, 2011. DOI: https://doi.org/10.1016/j.fcr.2010.11.006.

TSIMBA, R.; EDMEADES, G.O.; MILLNER, J.P.; KEMP, P.D. The effect of planting date on maize: phenology, thermal time durations and growth rates in a cool temperate climate. **Field Crops Research**, v.150, p.145-155, 2013. DOI: https://doi.org/10.1016/j.fcr.2013.05.021.

XU, W.; LIU, C.; WANG, K.; XIE, R.; MING, B.; WANG, Y.; ZHANG, G.; LIU, G.; ZHAO, R.; FAN, P.; LI, S.; HOU, P. Adjusting maize plant density to different climatic conditions across a large longitudinal distance in China. **Field Crops Research**, v.212, p.126-134, 2017. DOI: https://doi.org/10.1016/j.fcr.2017.05.006.

YANG, Y.; XU, W.; HOU, P.; LIU, G.; LIU, W.; WANG, Y.; ZHAO, R.; MING, B.; XIE, R.; WANG, K.; LI, S. Improving maize grain yield by matching maize growth and solar radiation. **Scientific Reports**, v.9, art.3635, 2019. DOI: https://doi.org/10.1038/s41598-019-40081-z.

ZANON, A.J.; STRECK, N.A.; GRASSINI, P. Climate and management factors influence soybean yield potential in a subtropical environment. **Agronomy Journal**, v.108, p.1447-1454, 2016. DOI: https://doi.org/10.2134/agronj2015.0535.