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OPTIMIZATION OF THE MAIZE HYBRID PLANT POPULATION IN A HETEROGENEOUS AGRICULTURAL FIELD

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Resumo

O objetivo deste estudo foi quantificar o impacto da escolha do híbrido de milho e do ajuste da população de plantas em diferentes zonas de produtividade de uma área agrícola. O experimento foi realizado na safra 2015/2016, no município de Boa Vista das Missões-RS, em uma área de 114,91 hectares, sendo 38,2% de baixa produtividade e 61,8% de alta produtividade. Utilizou-se um delineamento experimental de blocos ao acaso em esquema fatorial (2x5), com dois tipos de zona de produtividade, cinco densidades de semeadura (60, 75, 90, 105 e 120 mil plantas por hectare) e quatro repetições. Os híbridos utilizados foram Agroeste 1677 VT PRO3® (AS1677), BioGene 7318 YH (BG7318) e Pioneer 1630H (P1630). Foram avaliadas variáveis como o número de fileiras de grãos, número de grãos por fileira, número de grãos por espiga, diâmetro da espiga e peso de mil grãos. A produtividade de grãos foi determinada por meio de colheita manual das linhas centrais da área. Análises de variância foram realizadas para verificar os efeitos da zona de produtividade e da população de plantas nas características agronômicas, com significância avaliada pelo teste F. A análise de modelos de regressão foi utilizada para calcular o retorno econômico líquido (REL) e a máxima eficiência técnica (MET). A população ideal de plantas variou conforme a zona de produtividade, com o híbrido AS1677 apresentando a melhor resposta à população elevada em ambas as zonas, enquanto o híbrido P1630 teve o pior desempenho. O estudo sugere que o uso de taxas de semeadura variáveis pode aumentar a produtividade em áreas de alta produtividade e otimizar o uso de recursos em zonas de baixa produtividade, necessitando de mais pesquisas para validar a técnica.

Palavras-chave: híbridos de milho; produtividade agrícola; retorno econômico líquido; *Zea mays* L.

Abstract

The aim of this study was to quantify the impact of choosing a corn hybrid and adjusting the plant population in different productivity zones in an agricultural area. The experiment was carried out in the 2015/2016 harvest, in the municipality of Boa Vista das Missões-RS, in an area of 114.91 hectares, 38.2% of which was low productivity and 61.8% high productivity. A randomized block experimental design was used in a factorial scheme (2x5), with two types of productivity zone, five sowing densities (60, 75, 90, 105 and 120 thousand plants per hectare) and four replications. The hybrids used were Agroeste 1677 VT PRO3® (AS1677), BioGene 7318 YH (BG7318) and Pioneer 1630H (P1630). Variables such as the number of grain rows, number of grains per row, number of grains per ear, ear diameter and thousand-grain weight were evaluated. Grain yield was determined by manually harvesting the central rows of the area. Analyses of variance were carried out to verify the effects of yield zone and plant population on agronomic characteristics, with significance assessed by the F test. Regression model analysis was used to calculate net economic return (REL) and maximum technical efficiency (MET). The ideal plant population varied according to the productivity zone, with hybrid AS1677 showing the best response to the high population in both zones, while hybrid P1630 performed the worst. The study suggests that the use of variable seeding rates can increase productivity in high productivity areas and optimize the use of resources in low productivity zones, requiring further research to validate the technique.

Keywords: maize hybrids; agricultural productivity; net economic return; *Zea mays* L.

Introduction

The definition of different productivity zones within the same plot is one of the most important tools for managing spatial variability in agricultural areas, with positive impacts on rationalizing the use of inputs, increasing economic return and reducing environmental impact (Bottega *et al.*, 2022; Liu *et al.*, 2021). However, for practical purposes of genotype selection, nutritional and plant population adjustments, it is extremely important to verify the temporal stability of productivity within each zone (Maestrini; Basso, 2021). The uniform seeding rate traditionally used does not take into account soil heterogeneity and, therefore, recommends a single seeding density for the entire crop, which results in non-optimal plant populations, leading to reduced grain yield and increased seed costs (Munnaf *et al.*, 2022). In this sense, variable rate seeding can be employed to utilize optimal seeding densities for the fertility and yield potential of different management zone zones within the same field (Lajili *et al.*, 2021).

When considering that each zone has a defined and stable productivity potential, it is possible to optimize the use of inputs using technologies such as variable rate, which reflects resource savings and results in greater economic return (Yuan *et al.*, 2022; Ali *et al.*, 2022). Among the variable rate strategies, the adjustment of the plant population by productivity zone stands out, which for maize (*Zea mays* L.) has frequently presented positive results in terms of productivity gains or greater economic return due to resource savings (Du *et al.*, 2024). Therefore, the increase in plant population is a factor that has provided high productivity in environments with high productive potential (Ciampitti; Vyn, 2012; Haarhoff; Swanepoel, 2018). However, when the environment presents factors limiting the development of plants, the increase in the plant population can cause intra-specific competition mainly for water, light and nutrients (Du *et al.*, 2024; Lacasa *et al.*, 2020).

Plant population adjustments are complex, as the response to the environment can vary depending on the chosen hybrid (Stevens *et al.*, 2023; Du *et al.*, 2024) and prevailing climatic conditions. However and Lashkari *et al.* (2011) reported that when seeking high productivity, an ideal plant population must be established for each production environment. This is mainly due to the interaction of genotypes with the production environment, with grain yield and economic return being direct results of this dynamic (Katsenions *et al.*, 2021). For Brazil, Beruski *et al.* (2020), observed that a plant density of 80 thousand plants per hectare is considered an optimal plant density for maize. In the United States, the average plant population increased from 36 thousand plants per hectare in 1950 to 81 thousand plants per hectare in 2010, with an increase of more than 75% over time, going from 2,800 to 11,100 kg ha^{-1} (Mansfield; Mumm, 2014; Luo *et al*., 2020). However, none of the studies stratified the optimal plant population by productivity zone.

It is known that nowadays there are widespread digital platforms that enable the use of variable input application rates. To make the most of this technology, it is necessary not only to define the productivity zones, but also to define the necessary adjustments from the point of view of genetics and management. In Brazil, there are still few studies that address the definition of the best maize genotype and its ideal plant population for each productivity zone (Corassa *et al.*, 2018). Therefore, based on the assumption that it is possible to explore the relationship between these factors, the objective of this work was to quantify the impact of choosing the maize hybrid and adjusting the plant population in different productivity zones at the agricultural plot level.

Material and Methods

The experiment was conducted in an agricultural production area equipped with a central pivot type irrigation system, in the 2015/2016 harvest, in the municipality of Boa Vista das Missões-RS

(27º43'07” S, 53º20'20” W, altitude of 596 m). The region's climate is type Cfa – humid subtropical (Alvares *et al.*, 2014), with gently undulating relief and soil classified as typical dystrophic Red Oxisol (Santos *et al.*, 2018). The experimental area has 114.91 hectares, 38.2% of which is a low productivity zone and 61.8% a high productivity zone (Table 1). It is managed with precision agriculture tools, with emphasis on the variable rate of fertilizers, correctives and generation of harvest maps. The productivity potential of the areas was defined based on the overlay of harvest maps, collected using a CASE® Axial-Flow 2399 harvester (CNH Industrial Group), equipped with a GNSS (Global Navigation Satellite Systems) positioning receiver with correction by internal algorithm, impact plate productivity sensor (Ag Leader Technology, Ames, IA) and humidity sensor, respectively. Productivity zones were delimited as described by Doberman *et al.* (2003), based on relative productivity, being characterized as low or high productivity when lower than 95% and higher than 105% of the general average for the area, respectively. Aiming to eliminate positioning errors and unlikely productivity values, all harvest maps went through the filtering process (Menegatti; Molin, 2004), subsequently relativized with the number of points reduced to the same mesh (30 x 30 m), using a 30 m search radius. The processing of maps and the delimitation of production zones was carried out using the Quantum Gis Information System (QGIS Development Team, 2015). In addition, detailed chemical characterization was performed for each production zone before implementing the experiments (Table 1).

Table 1. Physicochemical characterization of the soil for high and low productivity zones in an area of 114.91 hectares in the municipality of Boa Vista das Missões-RS.

PZ	Area	RP	Depth	Clay	OM*	V%	pH_{H2O}	P	K^+	Al^{+3}	Mg^{+2}	Ca^{+2}	CEC
	(ha)	(%)	(m)	-----------(%)----------			-	-- (mg dm^{-3}) --		------- (cmol$_c$ dm^{-3}) ------			
High Productivity Zone	71.03	61.8	0-10	55	3.8	62.1	5.4	34.0	104.0	0.5	3.0	6.7	16.0
			10-20	71	2.9	57.9	5.4	8.9	18.0	0.8	2.8	5.6	14.5
			20-30	74	2.5	45.1	5.2	3.3	3.6	1.5	2.3	4.0	13.8
Low Productivity Zone	43.88	38.2	0-10	73	3.1	66.1	5.7	16.1	94.0	0.3	3.4	6.5	15.2
			10-20	79	2.4	69.6	5.9	2.9	23.0	0.1	3.4	5.9	13.5
			20-30	81	2.0	62.6	5.8	1.4	5.2	0.3	2.9	4.4	11.6

PZ: productivity zone; RP: relative representation; OM: organic matter; V%: base saturation; PH_{H2O}: pH in water; P: phosphorus; K+: potassium; Al^{+3}: exchangeable aluminum; Mg^{+2}: magnesium; Ca^{+2}: calcium; CEC: cation exchange capacity.

An experimental design of randomized blocks was used in a factorial scheme (2x5), with two productivity zones (high productivity zone and low productivity zone), five sowing densities (60, 75, 90, 105 and 120 thousand plants per hectare) and four replications for each maize hybrid. The hybrids used were: Agroeste 1677 VT PRO3® (AS1677); BioGene 7318 YH (BG7318) and; Pioneer 1630H (P1630). The detailed description of each hybrid investigated is presented in Table 2.

Table 2. Characteristics of the maize hybrids tested in each productivity zone.

Characteristic	Hybrid		
	AS 1677	BG 7318	P 1630
Technology	VT PRO3® (1)	Optimum® Intrasect® (2)	Herculex® (3)
Germplasm	Simple	Simple	Simple
Cycle	Hyperprecocious	Superprecocious	Hyperprecocious
Stature (m)	2.45	2.80	2.33
Cob insertion (m)	1.25	1.30	1.18
Grain texture	Semi-dentate	Semi-dentate	Semi-hard
Grain color	A/AL	A/AL	A/AL
Recommended PP	63.000 to 82.000	75.000 to 90.000	70.000 to 80.000

Recommended PP = plant population recommended by the genetic breeder in one thousand plants ha^{-1}.

(1) VT PRO 3®: Proteins Bt, Cry3Bb1 (control of *Diabrotica speciosa*) and Cry1A.105 and Cry2Ab2 (control *Spodoptera frugiperda*, *Diatraea saccharalis*, *Helicoverpa zea* and *Elasmopalpus lignosellus*) beyond technology RR (*Roundup ready*).

(2) Optimum® Intrasect®: Proteins Bt Cry1F and Cry1Ab for control *S. frugiperda*, *D. saccharalis*, *E.lignosellus*, *H. zea*, *Agrotis ipsilon*, *S. eridania* and *Pseudaletia sequax*.

(3) Herculex®: Proteins Bt Cry1F for control of *S. frugiperda, D. saccharalis* and suppression of *H. zea*.

Sowing was carried out on August 30, 2015, using a row spacing of 0.50 m, which totaled an experimental unit of 960 m^2 within each productivity zone, with 80 m^2 per maize hybrid and 16 m^2 for each plant population level evaluated. 120 kg ha^{-1} of K_2O was applied three days before sowing, complemented by 32.4 kg of N ha^{-1} and 82.8 kg of P_2O_5 ha^{-1} at the time of sowing. Three N top dressing applications were performed at stages V2 (60 kg N ha^{-1}), V4 (70 kg N ha^{-1}) and V6 (70 kg N ha^{-1}) following the phenological scale of Ritchie, Hanway and Benson (1993). Phytosanitary treatments were performed preventively, in order to avoid unwanted biotic effects on the results of the experiment.

The variables number of grain rows (NGR, units), number of grains per row (NGPR, units), number of grains per ear (NGE, units), ear diameter (ED, mm) and thousand grain weight (TGW, g) were measured on five random plants within the 16 m^2 experimental unit. Grain yield was measured by manually harvesting the central rows, avoiding the borders, with grain moisture corrected to 130 g kg^{-1}, with results expressed in Mg ha^{-1}.

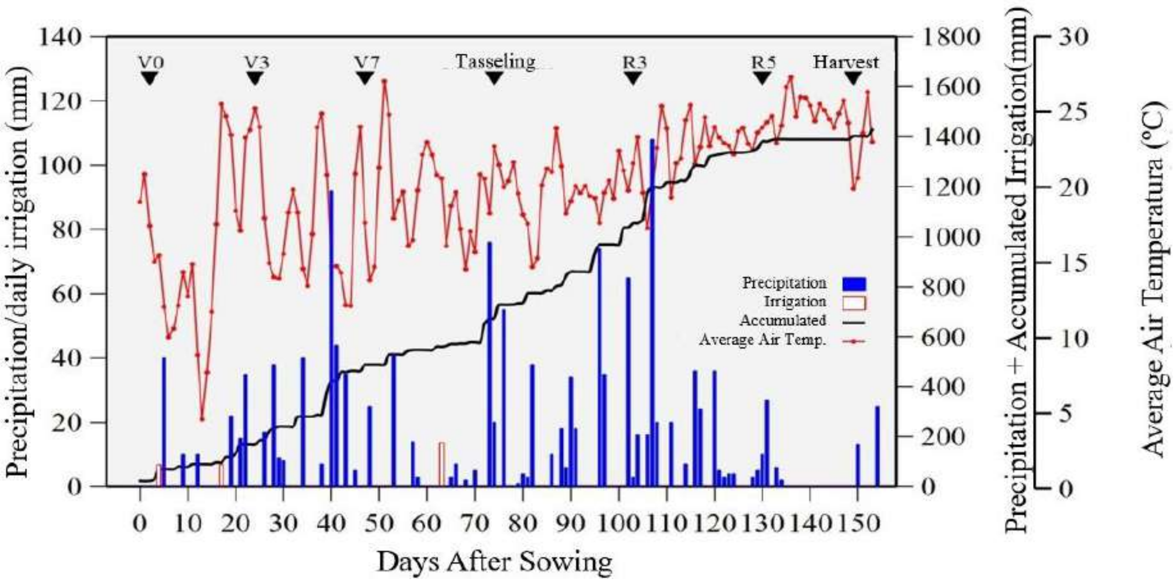
The data set obtained was subjected to the process of identifying and removing outliers, for subsequent verification of the assumptions of the ANOVA model. In this way, the normality of errors, homogeneity of variances and independence of errors were verified using the Shapiro-Wilk, Bartlett and Durbin-Watson tests, respectively. With the assumptions met, individual variance analysis was carried out to determine the effect of the factors productivity zone and plant population, as well as their interaction, on the agronomic traits evaluated. Significance was verified using the F test, the means for the productivity zone factor were compared using the Tukey test, at 5% probability, while the effect of the plant population factor was verified using polynomial regression analysis, at 5% probability using the t test. All analyzes were performed with the R software (R Core Team, 2024), using the functions of the AgroR package (Shimizu; Marubayashi; Gonçalves, 2023).

Using the adjusted regression models, the net economic return (NER) was calculated. For quadratic models, the maximum technical efficiency (MET) for the plant population was determined using the equation: $MET = \frac{-b1}{2b2}$, being $b1$ and $b2$ the angular coefficients of the polynomial regression model. For linear adjustments, NER was estimated by taking the plant population that resulted in the highest grain yield. In the estimates, the value of US$ 8.95 was used for a 60 kg bag of corn grain and seed costs of US$ 179.00 for AS1677; US$ 171.00 for BG7318 and US$ 131.50 for P1630, considering packages of 60 thousand seeds. These costs were added to an average cost for all treatments of US$ 579.00 and a fixed operational cost of US$474.00.

Results and Discussion

The climatic conditions of precipitation, irrigation, accumulated water depth and air temperature during the development of the crop are shown in Figure 1. In general, the conditions were favorable for the growth and development of maize. The accumulated precipitation during the experiment was 1,410 mm, which required few additional irrigations. Köpp *et al.* (2015), reported that water consumption by maize crops during the development cycle varies from 531 to 735 mm. It is observed that the air temperature was also not a limiting factor, remaining between 18 and 24ºC during most of the cycle. The optimum mean temperature for the maize development cycle is 20-22ºC (Hunter *et al.*, 2017). Therefore, the results obtained in this study are valid for agricultural years with low abiotic stress conditions for maize.

Figure 1. Meteorological data on precipitation, daily irrigation depth, precipitation + accumulated irrigation depth and mean air temperature for the maize cultivation cycle for the municipality of Boa Vista das Missões-RS, in the 2015/2016 harvest.



The summary of the analysis of variance (Table 3) shows a significant effect of the productivity zone factor (PZ) for all measured variables, regardless of the hybrid evaluated. When considering the AS1677 hybrid, the different levels of plant population (PP) tested were only significant for the variables ear diameter and grain yield. For the hybrid BG7318, a significant effect of plant population was found for all variables, with the exception of the number of grain rows. In the case of the P1630 hybrid, the effect of this same factor was significant only for the variables NGPR, NGE, ED and TGW. The interaction between PZ and PP was significant for the grain yield of hybrids BG7318 and P1630. This demonstrates the need to explore both simple and main effects of treatments. The coefficient of variation varied between 2.03 and 10.57% among all variables measured for all hybrids, which reflects experimental quality and reliability of information.

Table 3. Summary of variance analysis for the effect of two productivity zones (high productivity zone and low productivity zone), five plant populations (60, 75, 90, 105 and 120 thousand plants per hectare) and interaction between production zone and plant population in the agronomic characters of three maize hybrids grown under irrigation.

SV	DF	Mean Square[(1)]					
		NGR	NGPR	NGE	ED	TGW	GY
PZ	1	26.24*	195.4*	121660.90*	355.8*	18359.0*	4.2*
PP	4	0.33	36.40*	4993.99	4.1*	1145.79	20.2*
Block	3	1.03	3.64	3321.33	0.66	171.26	0.04
PZ x PP	4	0.53	12.73	3051.61	1.98	1186.67	1.70
Residuals	27	0.86	6.90	1915.18	1.22	557.88	0.93
Mean	-	12.63	34.41	435.61	44.04	359.23	14.61
CV (%)	-	7.34	7.63	10.05	2.51	6.58	6.60
SV	DF	Mean Square[(2)]					
		NGR	NGPR	NGE	ED	TGW	GY
PZ	1	50.18*	154.45*	172817.32*	515.52*	8430.64*	26.26*
PP	4	0.22	58.46*	13395.76*	3.03*	1041.38*	3.99*
Block	3	0.08	9.72	1390.98	2.42	122.57	4.40*
PZ x PP	4	0.24	7.98	1703.06	0.57	115.93	4.39*
Residuals	27	0.46	6.97	1560.01	0.86	212.57	1.38
Mean	-	13.48	34.48	465.11	45.56	361.84	14.85
CV (%)	-	5.05	7.66	8.49	2.03	4.03	7.91
SV	DF	Mean Square[(3)]					
		NGR	NGPR	NGE	ED	TGW	GY
PZ	1	94.25*	159.20*	269452.23*	562.50*	11557.93*	26.49*
PP	4	0.66	69.46*	18695.41*	2.85*	716.34*	1.65
Block	3	0.42	14.11	3023.38	0.31	602.92	1.62
PZ x PP	4	0.78	13.41	4147.57	0.58	139.18	6.12*
Residuals	27	1.07	7.46	3122.19	0.97	211.49	0.89
Mean	-	16.01	32.89	528.71	45.74	313.67	13.11
CV (%)	-	6.48	8.30	10.57	2.16	4.64	7.20

[(1)] Hybrid AS1677; [(2)] Hybrid BG7318; [(3)] Hybrid P1630; SV: source of variation; DF: degrees of freedom; PZ: productivity zone; PP: plant population; PZ x PP: interaction between productivity zone and plant population; CV: coefficient of variation; NGR: number of grain rows (units); NGPR: number of grains per row; NGE: number of grains per ear; ED: ear diameter; TGW: thousand grain weight; GY: grain yield (kg ha^{-1}).

The breakdown of the main effects of the interaction (Table 4) demonstrates that, as expected, the high productivity zone reflected statistically higher averages for all variables, regardless of the hybrid. This is directly related to the differences in the physical-chemical characteristics of the soil, due to the greater nutrient supply capacity of the high productivity zone and, as a result, the tendency to support a greater number of plants per unit area. This aspect mainly impacted the number of grains per ear and thousand grain weight for the AS1677 hybrid in the high productivity zone, with values of 490.75 and 380.65, respectively, while in the low productivity zone the results were 380.46 and 337.80. This was decisive for the significant differences observed in grain yield, for which values of 14.94 and 14.29 megagrams per hectare were obtained for the high and low productivity zones, respectively. Furthermore, the high productivity zone also resulted in ears of larger diameter and with a greater number of rows of grains and number of grains per row.

Table 4. Mean comparison test for the effect of two productivity zones (high productivity zone and low productivity zone) on the agronomic characters of three maize hybrids.

AS1677						
PZ	NGR	NGPR	NGE	ED	TGW	GY
High Productivity Zone	13.44 a	36.62 a	490.75 a	47.03 a	380.65 a	14.94 a
Low Productivity Zone	11.82 b	32.20 b	380.46 b	41.06 b	337.80 b	14.29 b
Mean	12.63	34.41	435.61	44.04	359.23	14.61
BG7318						
PZ	NGR	NGPR	NGE	ED	TGW	
High Productivity Zone	14.60 a	36.44 a	530.84 a	49.15 a	376.36 a	
Low Productivity Zone	12.36 b	32.51 b	399.38 b	41.97 b	347.32 b	
Mean	13.48	34.48	465.11	45.56	361.84	
P1630						
PZ	NGR	NGPR	NGE	ED	TGW	
High Productivity Zone	17.54 a	34.88 a	610.78 a	49.49 a	330.67 a	
Low Productivity Zone	14.47 b	30.89 b	446.63 b	41.99 b	296.67 b	
Mean	16.01	32.89	528.71	45.74	313.67	

Means followed by the same lowercase letter in the column do not differ from each other using Tukey's mean comparison test, at 5% probability. PZ: productivity zone; NGR: number of grain rows (units); NGPR: number of grains per row (units); NGE: number of grains per ear (units); ED: ear diameter (mm); TGW: thousand grain weight (g); GY: grain yield (Mg ha^{-1}).

The variable number of grains per ear for the BG7318 hybrid exhibited averages of 530.84 and 399.38 units in the high and low productivity zones, respectively. This is partly due to the greater number of grain rows combined with the greater number of grains per row, with values of 14.6 and 36.44 for the high productivity zone. Furthermore, values of thousand grain weight were found to be 376.36 and 347.32 g for the high and low productivity zones, which confirms that the adjustment of the sowing density must be performed differently. High plant populations can lead to higher yields if the hybrid is tolerant to high competition for light, nutrients and water (Berzsenyi; Tokatlidis, 2012). The differences were even more significant when considering the P1630 hybrid, with 610.78 and 446.63 grains per ear when comparing the different productivity zones, representing a reduction of almost 27%. Du *et al.* (2024) reported that the increase in plant population significantly influenced these same yield components. Furthermore, he also observed that, at the same sowing density, the thousand grain weight increased in areas with greater fertility.

The results confirm the positive response of hybrids to improvements in the production system, mainly due to the greater capacity to support plants through improvements in the soil structure, which directly reflects on the capacity to absorb water and nutrients. This is also directly related to the adjustment of plant populations, as hybrids more affected by low productivity zones tend to have less tolerance to a greater number of plants per unit area. Summarizing the elements of greatest interference in this scenario is an arduous task, a task that requires several studies over several years to identify those causing productivity losses. Pott *et al.* (2021), reported that the presence of compaction and surface acidity, in addition to the low organic matter content, were the main factors that limited root growth and plant access to water and mobile nutrients in the soil profile. Adjusting these factors through feasible management techniques is the best way to reduce productivity losses (Pasuquin *et al.*, 2014).

The adjustments of the regression models for the effect of plant population, as well as the interaction between plant population and production zone for each hybrid evaluated are presented in Table 5. When considering the AS1677 hybrid, a linear adjustment for the number of grains per row, with an intercept of 40,365 and a reduction to 32,445 when using a population of 120 thousand plants per hectare. There was a non-significant angular coefficient for the ear diameter, with an intercept value of 46,345 mm. There was a quadratic adjustment for grain yield, which allows identifying the population of 108 thousand plants per hectare as the maximum technical efficiency (MET) for the AS1677 hybrid. When applying the model obtained, the MET population results in an estimated grain yield of 15.85 Mg ha^{-1}. Munnaf *et al.* (2022), showed that, compared to conventional sowing, variable rate sowing promoted relative gains in grain yield between 1.91 and 7.05% and economic return between 1.91 and 7.09%.

All equations were adjusted to the linear model for the BG7318 hybrid (Table 5), with a non-significant angular coefficient only for ear diameter and grain yield in the low production zone. It is noted that only grain yield in the high productivity zone responded positively to the increase in plant population, starting at 11.36 megagrams per hectare for every 15 thousand plants per hectare. From this, it can be inferred that the low productivity zone did not support the population increase for this hybrid. A similar behavior was observed for the hybrid P1630, where only the angular coefficient for the ear diameter was non-significant, in addition to the increases in the plant population having a positive effect only on the grain yield in the high production zone.

Table 5. Regression models adjusted for the effect of five plant population levels (60, 75, 90, 105 and 120 thousand seeds ha^{-1}) and two productivity zones (high productivity zone and low productivity zone) on the agronomic traits of three maize hybrids.

Hybrid	Variables	PZ	Equation ($\hat{y}=b_0 \pm b_1x \pm b_2x^2$)	R^2
AS1677	NGPR	General	$\hat{y}=40.365-0.0662x^*$	0.54
	ED	General	$\hat{y}=46.345-0.026x$	0.71
	GY	General	$\hat{y}=-2.741+0.344x-0.002x^{2*}$	0.91
BG7318	NGPR	General	$\hat{y}=44.255-0.109x^*$	0.91
	NGE	General	$\hat{y}=617.150-1.689x^*$	0.96
	ED	General	$\hat{y}=47.840-0.025x$	-
	TGW	General	$\hat{y}=403.466-0.462x^*$	0.92
	GY	High Productivity Zone	$\hat{y}=11.360+0.048x^*$	0.71
	GY	Low Productivity Zone	$\hat{y}=14.282-0.003x$	-
P1630	NGPR	General	$\hat{y}=43.835-0.122x^*$	0.96
	NGE	General	$\hat{y}=704.730-1.956x^*$	0.92
	ED	General	$\hat{y}=47.915-0.024x$	-
	TGW	General	$\hat{y}=346.276-0.362x^*$	0.82
	GY	High Productivity Zone	$\hat{y}=9.456+0.050x^*$	0.86
	GY	Low Productivity Zone	$\hat{y}=14.323-0.022x^*$	0.84

PZ: productivity zone; NGR: number of grain rows (units); NGPR: number of grains per row (units); NGE: number of grains per ear (units); ED: ear diameter (mm); TGW: thousand grain weight (g); GY: grain yield (Mg ha^{-1}); ŷ: estimate of the random variable; R^2: coefficient of determination; *significant at 5% probability by t-test.

The estimated net economic return obtained from plant population adjustments (Table 6) shows an ideal population of 108 thousand plants per hectare for the AS1677 hybrid, regardless of the productivity zone. This adjustment results in a productivity of 15.85 Mg ha^{-1}, which totals a net economic return (NER) of US$ 989.09. Due to the linear upward trend for grain yield in the high productivity zone, the population of 120 thousand plants per hectare was defined as optimal for hybrids BG7318 and P1630. Even with a cost 11.69 and 10.03% higher compared to the ideal plant population of these hybrids for the low productivity zone, grain yields were higher at 2.82 and 2.45 Mg ha^{-1} in the high productivity zone, which allows for a NER 22.75 and 23.73% higher ($ 1155.15 – BG7318; USS$ 983.79 – P1630). In this way, the response of the hybrids indicates that the use of variable rate sowing technology within the same field can generate savings in financial resources and an increase in grain yield for low and high productivity areas, respectively.

Table 6. Estimation of grain yield, gross economic return, total cost and net economic return obtained using the plant population adjusted for three maize hybrids, stratified by productivity zone.

Hybrid	High Productivity Zone				
	APP	ŷ/GY (Mg ha^{-1})	GER (US$)	TT (US$)	NER (US$)
AS1677	108	15.85	2364.29	1375.20	989.11
BG7318	120	17.10	2550.15	1395.00	1155.15
P1630	120	15.42	2299.79	1316.00	983.79
Hybrid	Low Productivity Zone				
	APP	ŷ/GY (Mg ha^{-1})	GER (US$)	TT (US$)	NER (US$)
AS1677	108	15.85	2364.29	1375.20	989.11
BG7318	60	14.28	2130.10	1232.00	898.10
P1630	60	12.97	1934.87	1184.50	750.37

APP: adjusted plant population (in thousand plants per hectare); ŷ/GY: estimate of grain yield using the PPR and the adjusted polynomial equation (Table 5); GER: gross economic return; TT: total cost, represented by fixed costs + operational costs + seed costs to use the PPR; NER; net economic return.

Du *et al.* (2024) also evaluated a greater economic return when using a plant population adjusted in relation to the different characteristics of the production environment, with a difference of 0.67 Mg ha^{-1} and 192 USS ha^{-1}. This information corroborates the results of the present study, which made it possible to understand the technical and economic feasibility of adjusting the plant population for different hybrids based on the heterogeneity of the productivity zones of an agricultural plot in southern Brazil. However, there is a need for future studies to determine the viability of these management practices, since the cost of obtaining equipment compatible with the variable seeding rate is high, which justifies caution when making recommendations.

Conclusion

The optimal plant population varied according to the productivity zone, with the magnitude of the adjustment depending on the hybrid investigated.

The AS1677 hybrid supports the increase in plant population in the high and low productivity zones, with an optimal value of 108 thousand plants per hectare, while the BG7318 and P1630 hybrids did not support the increase in the plant population in the low productivity zone.

Greater responsiveness and greater net economic return were observed for hybrids BG7318 and AS1677 through the increase in plant population in the high and low productivity zone, respectively, while hybrid P1630 had the worst performance in both situations.

This study provides relevant information regarding the feasibility of using variable seeding rates to increase grain yield in high productivity areas and optimize the use of resources in low productivity areas, but requires other studies in different agricultural years to validate this management technique.

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