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Seed vigor and adjustment in sowing density: reflections on soybean planting and yield

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Genet. Mol. Res. 23 (4): gmr2315
Received May 14, 2024
Accepted October 28, 2024
Published October 31, 2024
DOI http://dx.doi.org/10.4238/gmr2315

ABSTRACT. The objective of the study was to evaluate different strategies for managing sowing density using batches of seeds with different levels of physiological quality, their impact on the population and spatial arrangement of plants (plantability); and in soybean grain yield potential. Two experiments were conducted corresponding to the 2018/19 and 2019/20 harvests, sown in the first fortnight of September of each agricultural year. The experimental design used was complete randomized blocks arranged in a 2x4 factorial scheme, with two genotypes and four sowing densities, with five replications. Greater productivity and better spatial arrangement of the plant are closely associated and can be attributed to the use of higher vigor seeds at lower densities. Increasing sowing density to compensate for low levels of physiological quality causes a reduction in productivity, in addition to an increase in operational costs with unnecessary expenses with seeds.

Key words: Glycine max; Physiological quality; Productive performance; Plant arrangement.

INTRODUCTION

Several factors can limit the emergence, growth and development of plants and, consequently, limit the grain yield of soybean [Glycine max (L.) Merr.] (Caverzan et al., 2018). According to Winck et al. (2023), the average potential yield of soybean crops in Brazil in the 2017/18 to 2020/21 harvests is 7720 kg ha^{-1}, with a gap of 32.4% of this value being attributed to management. In this context, plant population is a characteristic that is widely studied, mainly because it directly affects crop productivity, where the objective is to define the best population for each genotype available on the market (Bagateli et al., 2020) and, therefore, the quality of the seeds used in sowing directly impacts the soybean grain yield (Bagateli et al., 2019).

Due to the recent increase in seed-related costs, studies have been conducted to analyze the ability of modern cultivars to maintain high productivity under reduced seeding rates (Pereyra et al., 2022), a scenario in which seed quality is of high importance. The physiological quality of seeds is represented by high germination rates, less deterioration of reserves and high vigor (Caverzan et al., 2022), being directly related to obtaining an suitable plant stand, which can be affected by field conditions. In this context, the uniform distribution of seeds, with the use of quality seeds, increases grain productivity while maintaining profitability (Coelho et al., 2023).

Like all products, seeds are also subject to quality standards for their commercialization, with purity and germination being the main standards (Wimalasekera, 2015). However, the values attributed to the germination rate through laboratory tests, which, as they provide ideal conditions, cannot be faithfully extrapolated to field conditions at the time of sowing (Ebone et al., 2020). In this sense, seed vigor is an important and complex characteristic that encompasses aging tolerance, seed dormancy, viability, germination speed and seedling establishment, especially in non-ideal conditions (Reed et al., 2022).

Based on the above, the objective of the study is to evaluate different strategies for managing sowing density using batches of seeds with different levels of physiological quality, and their impact on the population and spatial arrangement of plants (plantability); and soybean grain yield potential.

MATERIAL AND METHODS

The study took place in the municipality of Los Cedrales, Alto Paraná, Paraguay (25°39'07.2"S; 54°43'00.6"W, altitude of 250 m). Two experiments were conducted corresponding to the 2018/19 and 2019/20 harvests, sown in the first fortnight of September of each agricultural year. The climate in this region is classified as mesothermal, where rain occurs more frequently in spring and summer, with no defined dry season. The site's soil has a clayey texture, being classified as Oxisol according to the American soil taxonomy adopted in Paraguay (USDA, 1999). Soil analysis carried out in August/2018 revealed a pH (CaCl2): 5.97; Al content: 0.0; Ca: 9.14; Mg: 2.04; K: 0.37; CTC: 15.99 $cmol_c$ dm^3; P: 37.28; S: 4.63; Fe: 27.56; Mn: 240.6; Cu: 4.16; Zn: 4.42 and B: 0.77 mg dm^{-3}. The experimental design used was complete randomized blocks arranged in a 2x4 factorial scheme, with two genotypes and four sowing densities, with five replications. For the genotype factor, cultivars 63i64 IPRO and 6410 IPRO were used (relative maturity group 6.3 and 6.4, respectively), which have an indeterminate growth type, with physiological maturation estimated between 120 and 130 days after emergence. Before setting up the experiments, the lots of each genotype had their seeds evaluated for germination percentage, according to the methodology indicated by the Rules for Seed Testing (Brazil, 2009); and vigor was determined using the accelerated aging test according to the methodology described by Marcos Filho (2020), at a temperature of 41ºC (± 0.5ºC), for a period of 48 hours. The sowing density (DEN, seeds m^{-1}) took into account the level of physiological quality of the seeds, as described in table 1, adjusting the quantity of seeds to be distributed in order to reach a population of 220 thousand plants ha^{-1}.

Table 1. Determination of physiological quality levels (PQL) and seeding density (DS) based on quality tests carried out on lots of soybean seeds, cultivars BMX 63i64 RSF IPRO and M 6410 IPRO, used in the experiments.

Germination (%)		**Vigor (%) EA 41ºC/48h**		**ClassificationPQL**	**DS (seeds m^{-1})**
63i64 Ipro	6410 Ipro	63i64 Ipro	6410 Ipro		
97	95	93	92	Very High	10
91	90	87	85	High	12
85	87	76	80	Average	15
80	82	68	71	Low	18

Before sowing, two kilograms of seeds from each experimental plot were treated with fungicides based on thiabendazole (150 g L^{-1}), metalaxyl-M (20 g L^{-1}) and fludioxonil (25 g L^{-1}) and insecticide at fipronil base (250 g L^{-1}). In order to reduce abrasiveness and improve fluidity, the seeds received graphite at a dose of 4.0 g kg^{-1} of seeds. Chemical fertilization was carried out fifteen days before sowing, with 10-60-30 kg ha^{-1} of N, P_2O_5 and K_2O, respectively. Sowing was carried out with a seeder with three lines spaced 0.45m apart, and the experimental units were formed by six sowing lines 8.0m long. A mechanical seed distribution system was used with a dosing box, with a horizontal disc with a circular hole of 8.0mm diameter. The displacement speed was 3 km h^{-1}, with a seed deposition depth of 0.03 m. Phytosanitary management was carried out preventively to reduce biotic effects on the results of the experiment. The plant population (plants m^{-1} linear) was determined 21 days after sowing, by counting the number of plants in the two central rows. 25 plants were demarcated within the useful area of each plot, on which the variables related to their spatial arrangement - plantability (normal, grouped and faulty) were determined, considering a reference spacing, as shown in Figure 1. About the data collected on plantability the coefficient of variation of spacing was determined, obtained by the ratio of the standard deviation to the average spacing between plants. The grain weight per plant (GWP, g) was estimated when the demarcated plants reached the harvest maturity stage, which were harvested and threshed and then weighed individually, with grain moisture correction at 13%. To assist in understanding the results obtained, data relating to mean air temperature (Tmean, ºC), maximum air temperature (Tmax, ºC), minimum air temperature (Tmin, ºC) and precipitation (Prec, mm) were estimated for agricultural years using the NASA POWER tool (Sparks, 2018).

The data were subjected to the assumptions of the statistical model, where normality, homogeneity of variances and independence of errors were determined using the Shapiro-Wilk, Bartlett and Durbin-Watson tests. Position and dispersion measurements were calculated for the information. The classification of plant normality in the plots was determined based on the frequency of observation of normal, double and faulty distributions. The effects of the factors genotype and sowing density, in addition to their interaction, on the variables distance between plants (DBP, cm)

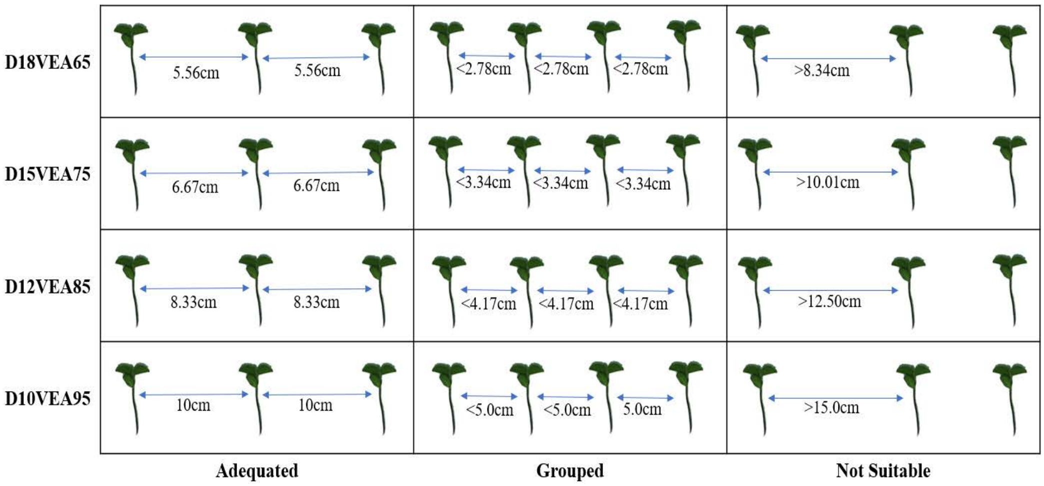

Figure 1. Classification of crop normality (suitable, grouped and not suitable distribution of plants) for different sowing strategies. D10VEA95: density of ten seeds per linear meter, 95% vigor; D12VEA85: density of twelve seeds per linear meter, vigor of 85%; D15VEA75: density of 15 seeds per linear meter, vigor of 75%; D18VEA65: density of 18 seeds per linear meter, vigor of 65%.

and grain weight per plant (GWP, g) were obtained using analysis of variance at 5%. The means were compared with the Tukey test at 5%.

The prediction of the potential productivity of the experiment's extracts was determined using a regression tree, with the grain weight per plant (GWP), seed vigor (V) and seeding density (DEN) as independent variables. In order to verify the existence of a linear relationship between the study variables, correlation was used. All statistical analyzes were performed using the R software (R Core Team, 2023).

RESULTS AND DISCUSSION

The average values for the meteorological variables are shown in Figure 2. In both harvests, average minimum temperatures of 17ºC were observed for the month of September, when soybeans were sown. There was greater thermal amplitude in the 2019/20 harvest for the entire crop cycle, mainly during sowing and plant establishment in the months of September and October. According to Lamichhane et al. (2020), the optimal temperature for the germination process in soybeans is approximately 30ºC, and the germination rate can be reduced by 50% at 17ºC. The optimal temperature for the vegetative development, flowering and grain filling phases is 31, 32 and 25ºC, respectively. Soil moisture conditions for crop establishment were more favorable in the 2018/19 harvest, with an average daily precipitation of 8mm for September and 9mm for October, compared to the 2019/20 harvest, where the average daily precipitation was 1mm for September.

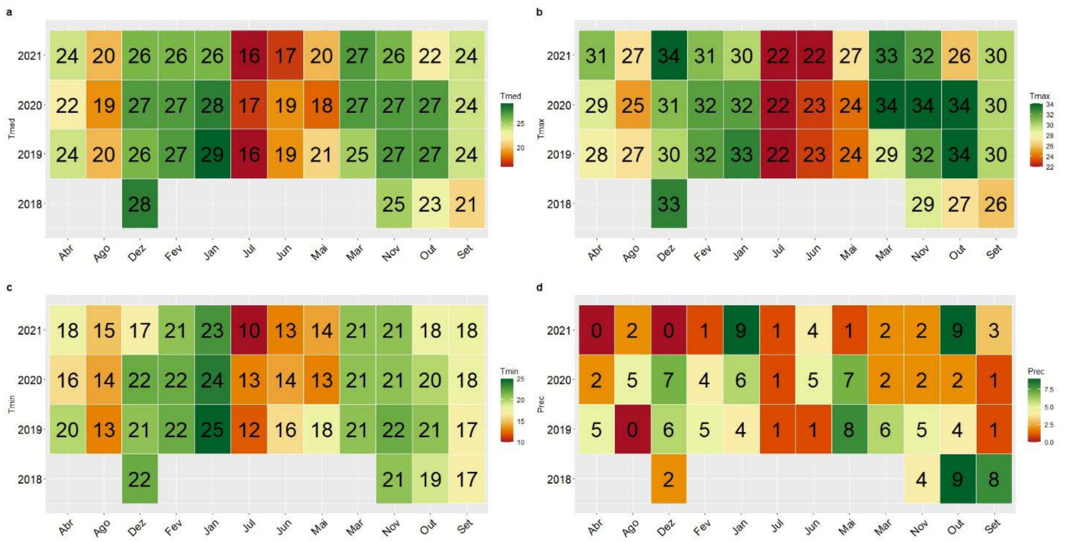

Figure 2. Average values for mean air temperature (Tmean, ºC), maximum air temperature (Tmax, ºC), minimum air temperature (Tmin, ºC) and precipitation (Prec, mm) for the 2018/19 and 2019/20 harvests, in Los Cedrales, Alto Paraná, PY.

Table 2. Analysis of variance for distance between plants. DBP: distance between plants; GWP: grain weight per plant; G: genotype; DVEA: seeding density; G x DVEA: interaction between genotype and sowing density; SV: Source of variation; DF: degrees of freedom; SS: Sum of squares; MS: mean square; F: F value; Pr(F): test probability F; CV: coefficient of variation.

SV	DF	DBP				GWP			
		SS	MS	F	Pr(F)	SS	MS	F	Pr(F)
G	1	0.05184	0.05184	0.102493	7.51E-01	0.275959	0.275959	0.794777	3.80E-01
DVEA	3	19.80216	6.60072	13.0503	1.63E-05	79.46765	26.48922	76.29053	1.37E-13
Block	4	0.9697	0.24243	0.479299	7.51E-01	5.224608	1.306152	3.761796	1.43E-02
G x DVEA	3	0.85896	0.28632	0.566084	6.42E-01	1.382183	0.460728	1.326923	2.85E-01
Residual	28	14.16214	0.50579	-	-	9.72202	0.347215	-	-
Total	39	-	-	-	-	-	-	-	-
CV(%)	-	7.68	-	-	-	5.42	-	-	-
Mean	-	9.26	-	-	-	10.87	-	-	-

The analysis of variance for the distance between plants (Table 2) demonstrates that only the sowing density (DVEA) changed the distance between plants (DBP, cm) and the grain weight per plant (GWP, g) significantly (Pr(F)<0.05). The interaction between genotype and sowing density was not significant.

As for the dispersion parameters (Figure 3), the coefficient of variation (CV) had a range of 5.8 to 8.1% for the distance between plants (DIST), where the smallest variation occurred for the D10VEA95 strategy (ten seeds per linear meter, 95% vigor). For grain weight per plant (GWP), the range of CV was 4.7 to 6.8%, with less variation for the D18VEA65 strategy (eighteen seeds per linear meter, 65% vigor). The sample standard deviation, standard error of the mean and confidence interval showed similar behavior to the coefficient of variation for both variables.

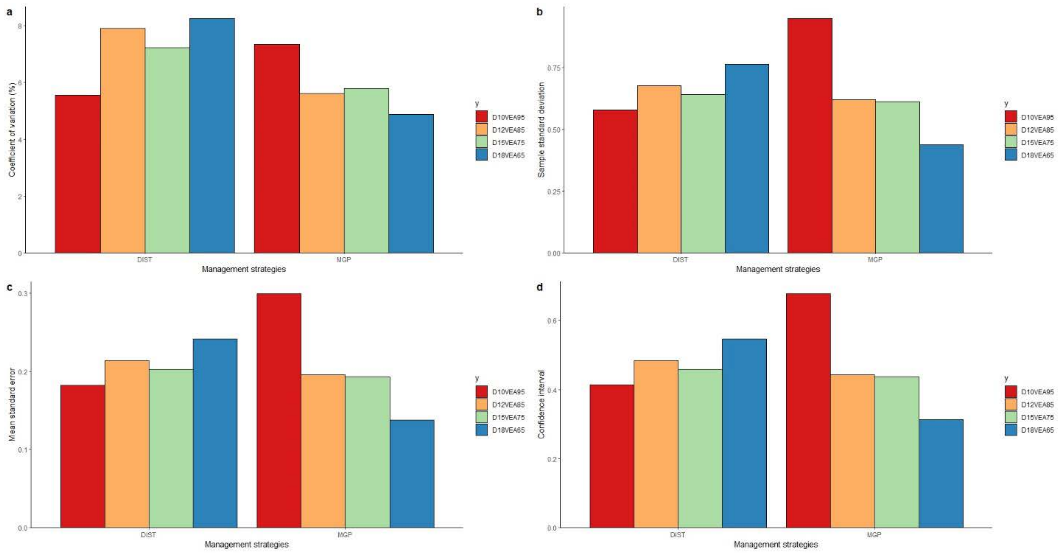

Figure 3. Descriptive graphs of dispersion parameters for management strategies. a) coefficient of variation (%); b) sample standard deviation; c) standard error of the mean; d) confidence interval; D10VEA95: density of ten seeds per linear meter, 95% vigor; D12VEA85: density of twelve seeds per linear meter, vigor of 85%; D15VEA75: density of 15 seeds per linear meter, vigor of 75%; D18VEA65: density of 18 seeds per linear meter, vigor of 65%; CV: coefficient of variation; DIST: distance between plants (cm); GWP: grain weight per plant (g).

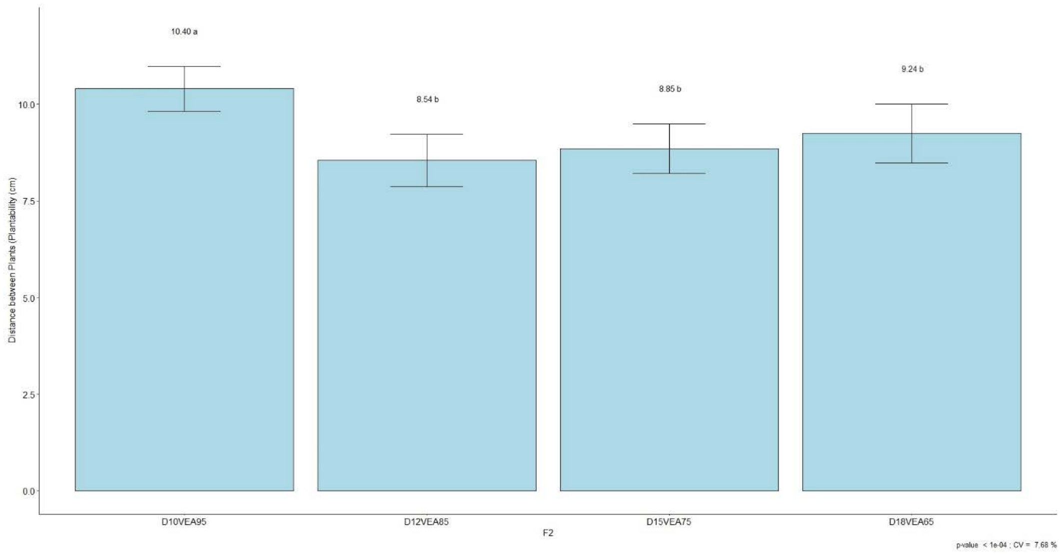

Figure 4. Distance between plants (DBP, cm) for plantability assessments using different sowing strategies. D10VEA95: density of ten seeds per linear meter, 95% vigor; D12VEA85: density of twelve seeds per linear meter, vigor of 85%; D15VEA75: density of 15 seeds per linear meter, vigor of 75%; D18VEA65: density of 18 seeds per linear meter, vigor of 65%; CV: coefficient of variation. Means followed by the same lowercase letter do not differ statistically using the Tukey test at 5%.

Table 3. Dispersal measures for management strategies. D10VEA95: density of ten seeds per linear meter, 95% vigor; D12VEA85: density of twelve seeds per linear meter, vigor of 85%; D15VEA75: density of 15 seeds per linear meter, vigor of 75%; D18VEA65: density of 18 seeds per linear meter, vigor of 65%; DIST: distance between plants (cm); GWP: grain weight per plant (g); CV: coefficient of variation (%); Max: maximum value; Min: minimum value; sd.amo: sample standard deviation; SE: standard error; ci.t: confidence interval.

Strategy	Variable	CV	Max	Mean	Median	Min	sd.amo	SE	ci.t
D10VEA95	DIST	5.554	11.240	10.400	10.410	9.660	0.578	0.183	0.413
	GWP	7.332	14.312	12.930	13.096	11.113	0.948	0.300	0.678
D12VEA85	DIST	7.911	9.800	8.542	8.390	7.480	0.676	0.214	0.483
	GWP	5.611	11.629	11.029	11.154	9.925	0.619	0.196	0.443
D15VEA75	DIST	7.232	10.000	8.854	8.880	8.040	0.640	0.203	0.458
	GWP	5.787	11.562	10.546	10.579	9.430	0.610	0.193	0.437
D18VEA65	DIST	8.255	10.560	9.244	9.010	8.240	0.763	0.241	0.546
	GWP	4.865	9.675	8.980	9.015	8.259	0.437	0.138	0.313

The coefficient of variation values are directly related to the efficiency of seed distribution in the furrow, where both reductions and excessive increases in sowing density compared to the ideal density can contribute to an increase in these values. For the study, the highest CV for the variable distance between plants (DIST, cm) was attributed to the D18VEA65 strategy (Table 3), with a value of 8.26%, while for the D10VEA95 strategy the CV was 5.55%.

For the average plantability assessments (Figure 4), the D10VEA95 strategy resulted in a distance between plants (DIST) of 10.40cm, higher than the others. The use of seeds of low physiological quality (D18VEA65), even at higher densities (18 seeds per linear meter) did not result in an suitable plant stand, with a distance between plants of 9.24cm. The lowest DIST values were evaluated for the strategies D12VEA85 (12 seeds per linear meter, 85% vigor) and D15VEA75 (15 seeds per linear meter, 75% vigor), with distances of 8.54cm and 8.85cm, respectively. High vigor seeds are capable of generating plants with high physiological performance, which tend to present more significant growth, better production of reproductive structures and a deeper root system (Bagateli et al., 2019).

Figure 5, of the crop normality classification, demonstrates the frequency of distribution of plants considered suitable, with doubles and with failures, for the management strategies, on a scale from 0 to 350. Suitable stands were observed more frequently for the D10VEA95 and D12VEA85 strategies (frequencies of 343 and 349, respectively). The increase in density for the seed lot of medium and low physiological quality (D15VEA75 and D18VEA65) reflected in greater quantities of grouped plants (frequencies of 163 and 213, respectively). On the other hand, the lowest failure frequencies were attributed to these strategies. A higher frequency of inappropriate distribution (failures) was evaluated for the D10VEA95 strategy, which may be a reflection of the sowing process itself, and is not related to the physiological quality of the seeds. Very wide distances between plants end up leading to lower productivity, due to wasteful use of soil and solar radiation (Matsuo et al., 2018; Bagateli et al., 2020).

According to figure 6, the grain weight per plant (GWP) was directly proportional to the use of seeds with high physiological quality, where values of 12.93g were obtained when using the D10VEA95 strategy. In a study conducted by Bagateli et al. (2020), plants from high vigor seeds obtained a greater number of productive nodes, in addition to an increase in the number of legumes in different thirds of the plant, in the number of seeds per plant, in the thousand seed weight and

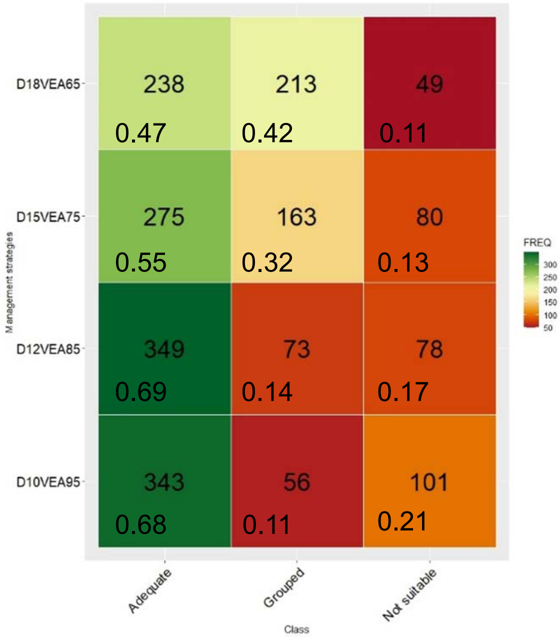

Figure 5. Frequency for classifying normality in the crop (suitable distribution, with doubles and with failures). D10VEA95: density of ten seeds per linear meter, 95% vigor; D12VEA85: density of twelve seeds per linear meter, vigor of 85%; D15VEA75: density of 15 seeds per linear meter, vigor of 75%; D18VEA65: density of 18 seeds per linear meter, vigor of 65%; FREQ: frequency.

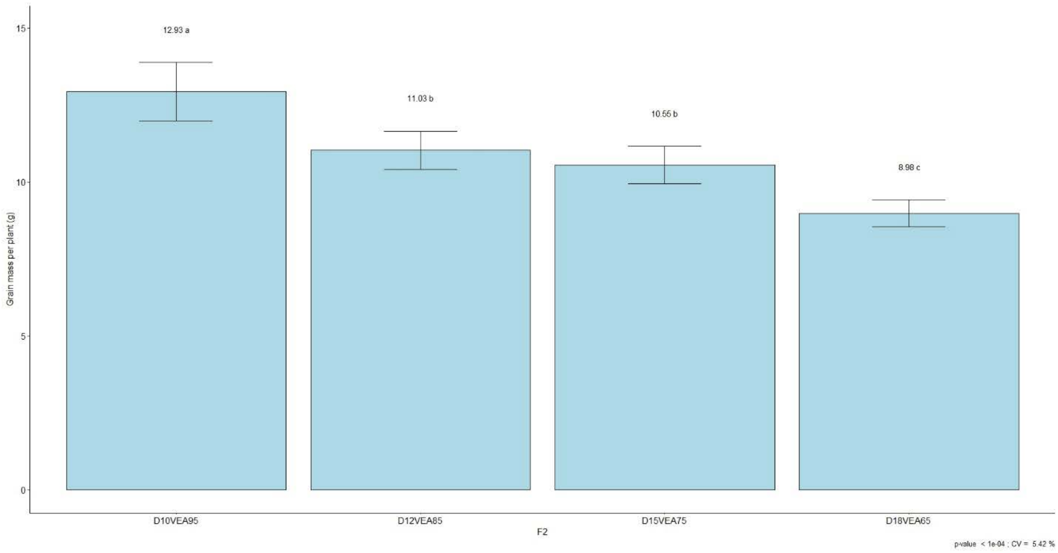

Figure 6. Grain weight per plant (GWP, g) using different sowing strategies. D10VEA95: density of ten seeds per linear meter, 95% vigor; D12VEA85: density of twelve seeds per linear meter, vigor of 85%; D15VEA75: density of 15 seeds per linear meter, vigor of 75%; D18VEA65: density of 18 seeds per linear meter, vigor of 65%; CV: coefficient of variation. Means followed by the same lowercase letter do not differ statistically using the Tukey test at 5%.

in productivity. The D18VEA65 strategy resulted in values of 8.98g for grain weight per plant, totaling a reduction of 31% compared to the batch of seeds with better physiological quality. Crops established using low vigor seeds are less productive due to the high percentage of seedlings with late emergence, which have lower individual productivity (Ebone et al., 2020).

The regression tree (Figure 7) obtained as a function of the variables grain weight per plant (GWP), seeding density (DEN) and vigor (V) allows stratifying the results obtained previously. GWP values greater than 11.6g were obtained using seeds with higher physiological quality and densities with 14 seeds m^{-1}, representing 38.6% of the total. Potential productivity in this scenario is 4.05 t ha^{-1}. With densities below 14 seeds m^{-1} the potential increases to 4.85 t ha^{-1} (13.8%), with the capacity to reach up to 5.32 t ha^{-1} (6.1% of the total). It can be inferred, therefore, that it was possible to obtain more productive extracts from seeds of high physiological quality, even at lower densities, by obtaining stands with a more suitable distribution of plants.

Extracts with GWP lower than 11.6g were attributed to the use of seeds of lower physiological quality, with potential productivity of 2.65 t ha^{-1}, with this fraction representing 61.4% of the total. In this scenario, the strategy of increasing sowing density had a positive effect, showing potential to increase productivity to 3.66 t ha^{-1} with densities greater than 14 seeds m^{-1}, reaching 3.95 t ha^{-1} when using densities greater than 17 seeds m^{-1}. When seed vigor was less than 80%, potential productivity was only 1.79 t ha^{-1} (10.3%). According to a study by Meneguzzo et al. (2021), high vigor seeds generate seedlings with greater physiological potential, greater initial development of the root system and aerial part. This corroborates the study by Bagateli et al., (2020), where the use of high vigor seeds led to an increase of up to 19% in soybean grain productivity.

The linear correlations between the study variables are demonstrated in figure 8. The distribution (DIST) was positively correlated with the potential productivity (PROD), grain weight per plant (GWP), with the coefficient of variation of the distribution for the grain weight per plant (CV_DIST_ GWP) and with vigor (V). Caverzan et al. (2018) also found a positive correlation between grain productivity and seed vigor. Density (DEN) and distribution coefficient of variation (CV_DIST) were strongly negatively influenced by seed vigor and the coefficient of variation for

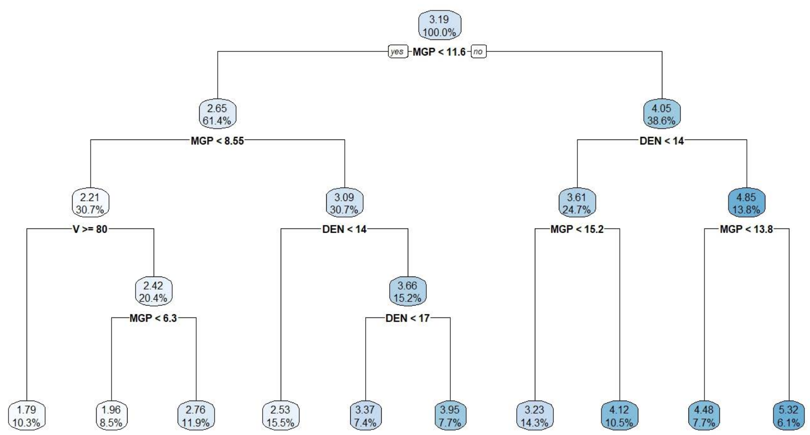

Figure 7. Regression tree for management strategies. GWP: grain weight per plant; DEN: seeding density; V: seed vigor. The values within each extract (terminal node) of the tree demonstrate the potential productivity of the crop (in kg ha^{-1}).

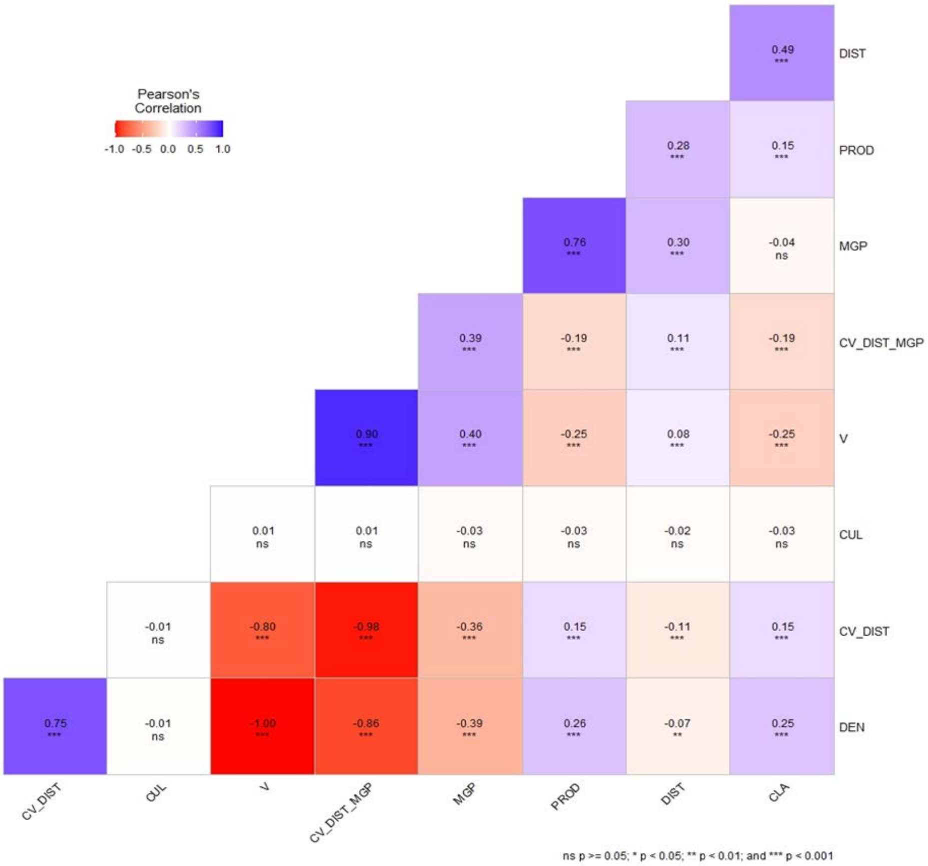

Figure 8. Linear correlations between variables. CV_DIST: distribution coefficient of variation; CUL: cultivars; V: seed vigor; CV_DIST_ GWP: distribution coefficient of variation for grain weight per plant; GWP: grain weight per plant; PROD: potential productivity; DIST: distribution; CLA: normality classification; *: significant at 5%.

grain weight per plant. Potential productivity also showed a positive correlation with grain weight per plant and density and a negative correlation with seed vigor. The opposite is observed for GWP, with a positive correlation with CV_DIST_ GWP and seed vigor and a negative correlation with CV_DIST and density. The normality classification (CLA) did not correlate only with the grain weight per plant and cultivars (CUL). It was not possible to have significant linear correlations between the cultivars and the other study variables.

From an economic point of view, the use of seeds with high germination rates and vigor, associated with more appropriate spatial arrangements, reflects not only an increase in productivity, but also an increase in financial return, through the reduction of costs arising from the use of seeds beyond what is necessary. According to Coelho et al. (2023), when evaluating the economic return of soybeans with different plant arrangements, when seeding density was increased, operational costs also increased due to the high cost of seeds, however, this did not result in an increase in productivity. Therefore, the total expense for implementing the crop can reach high values if the plant arrangement is not managed properly.

In the case of this study, the targeted population of 220 thousand plants ha^{-1} was reached, within certain proportions, for all sowing managements. However, the increase in sowing density, in order to compensate for seeds of lower physiological quality, did not result in productivity gains (Figure 7), a fact that was mainly due to the not suitable distribution of plants (Figure 5). In this sense, from the point of view of operational costs, for an average price of US$ 2.85 kg seed^{-1} of soybeans and considering an average thousand seed weight of 151g, the reference cost with seeds was 95.6; 114.7; 143.4 and 172.1 dollars ha^{-1} for the strategies D10VEA95, D12VEA85, D15VEA75 and D18VEA65, respectively. As a result, the expense to reach the targeted population when using the D12VEA85, D15VEA75 and D18VEA65 sowing methods increased the cost by 19.9; 50.5 and 80.0% in relation to the reference cost, respectively.

CONCLUSION

Greater productivity and better spatial arrangement of the plant community are closely associated and can be attributed to the use of higher vigor seeds at lower densities.

Increasing sowing density to compensate for low levels of physiological quality causes a reduction in productivity, in addition to an increase in operational costs with unnecessary expenses with seeds.

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