Soybean yield components at different densities and planting seasons in Paraguay

Componentes del rendimiento de la soya en diferentes densidades y fechas de siembra en Paraguay

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ABSTRACT

The aim of this research was to evaluate the performance of soybean cultivars using different population densities and planting seasons. The experiments were established using a completely randomized block design with a 14×3×2 factorial arrangement, where factor A consisted of 14 soybean cultivars, factor B were low (177,700 plants ha^{-1}), medium (266,600 plants ha^{-1}), and high (355,500 plants ha^{-1}) population densities, and factor C consisted of early and late planting seasons. We evaluated the number of pods per plant (NPP), number of grains m^{-2} (NG), 1000-grain weight (TGW), and yield (kg ha^{-1}). The interaction between cultivar and planting season affected the NG, TGW, and yield. Cultivars DM-6563-IPRO, TMG-7062-IPRO, 6505-B, NA-5909-RG, M-6410-IPRO, DM-6262-IPRO, SOJAPAR-R19, 6806-IPRO, 6205-B, M-5947-IPRO and SYN-1163-RR showed higher yields in the early planting season and cultivar NS-5959-IPRO in the late planting season. Cultivars 5907-IPRO and DM-5958 showed similar yields for the two planting seasons evaluated. The highest yields were obtained from a density of 266,600 plants ha^{-1}. The cultivar×planting season interaction affected the TGW, with the early planting season showing a greater TGW for most of the cultivars evaluated. The NPP depended on the interaction between cultivar, density, and planting season. The combination of the NG and the TGW showed a more significant influence on the generation of yield in the cultivars. This study highlights the importance of selecting genotypes according to their response to variations in planting date and plant density. This information could help Paraguayan farmers to maximize production in the same area, optimizing the available resources.

Key words: *Glycine max*, genotype-environment interaction, plant density, planting date, soybean cultivars, yield improvement.

RESUMEN

El objetivo de esta investigación fue evaluar el desempeño de cultivares de soya usando distintas densidades y épocas de siembra. Los experimentos se establecieron usando un diseño experimental en bloques completamente al azar con arreglo factorial 14×3×2, donde el factor A consistió en 14 cultivares de soya, el factor B fueron las densidades poblacionales baja (177,700 plantas ha^{-1}), media (266,600 plantas ha^{-1}) y alta (355,500 plantas ha^{-1}), y el factor C consistió en las siembras realizadas en forma temprana y tardía. Se evaluó el número de vainas por planta (NVP), el número de granos por m^2 (NG), el peso de mil granos (PMG), y rendimiento (kg ha^{-1}). La interacción entre el cultivar de soya y la época de siembra afectó el NG, PMG y el rendimiento. Los cultivares DM-6563-IPRO, TMG-7062-IPRO, 6505-B, NA-5909-RG, M-6410-IPRO, DM-6262-IPRO, SOJAPAR-R19, 6806-IPRO, 6205-B, M-5947-IPRO y SYN-1163-RR mostraron rendimientos más altos en las siembras tempranas y el cultivar NS-5959-IPRO en la siembra tardía. Los cultivares 5907-IPRO y DM-5958 mostraron rendimientos similares para las dos temporadas de siembra evaluadas. Los mayores rendimientos se obtuvieron a partir de una densidad de 266,600 plantas ha^{-1}. La interacción cultivar×temporada de siembra afectó el PMG siendo mayor en la siembra temprana que en la siembra tardía para la mayoría de los cultivares evaluados. El NVP fue afectado por la interacción cultivar, densidad y temporada de siembra. La combinación del NG y el PMG influyó significativamente en la generación de rendimiento en los cultivares de soya. Este estudio resalta la importancia de seleccionar genotipos teniendo en cuenta variaciones en la fecha de siembra y en la densidad de plantas. Esta información permitiría a agricultores paraguayos maximizar la producción en la misma área de cultivo optimizando los recursos disponibles.

Palabras clave: *Glycine max,* interacción genotipo-ambiente, densidad de plantas, fecha de siembra, cultivares de soya, aumento del rendimiento.

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Introduction

Soybean [*Glycine max* (L.) Merr.] is one of the most important crops globally due to its high-value grains used as a source of protein and oil for both animal and human consumption (Pagano & Miransari, 2016). Due to the increasing demand for this crop worldwide, the planting area needed is continuously expanding, and alternatives to improve productivity are very active research areas (Masuda & Goldsmith, 2009). According to the Paraguayan chamber of cereal and oilseed exporters (Cámara Paraguaya de Exportadores y Comercializadores de Cereales y Oleaginosas, 2020), Paraguay is the fifth-largest producer and fourth-largest soybean exporter in the world with a production of 10,000,000 t of grains in 3,500,000 ha with a yield of 2,857 kg ha^{-1}. Alto Parana, Canindeyu, Itapua, Caaguazu, and San Pedro are the most productive soybean areas in the country (Cohener & Aguayo, 2009).

The profitability of soybean allows many farmers to invest in improving their production either by increasing the growing area, improving land productivity, or investing in a second planting season (Teixeira *et al.*, 2016). However, the increment of the production area is currently limited due to environmental protection laws restricting the expansion of the crop into new regions (Palau *et al.*, 2012).

Therefore, increasing land productivity is a more practical alternative. This increase in productivity can be achieved with practices that preserve the soil's physical and chemical conditions and allow better pest, weed, and disease control (Gudelj *et al.*, 2018). One of these practices is the use of improved and environmentally specific cultivars (Peluzio *et al.*, 2005; Pires *et al.*, 2005). Additionally, the use of specific cultivars and the adjustment of planting dates and densities can also improve the yield in small areas (Vega & Andrade, 2000).

Alternative planting seasons or a second planting performed in the middle of the summer (also known as "Zafrina") allow farmers to obtain higher income. The downside of this practice is that under these conditions, the photoperiod is lower and, consequently, yields are inferior because days start getting shorter as they approach autumn. Some cultivars may not perform well during the early planting season because average temperatures are lower as this planting coincides with the beginning of spring. The harvest results are conditioned by these phenomena that translate into inferior yields, reduced plant height, lower number of pods, and lower number of grains per plant (Marchiori *et al.*, 1999; Teixeira *et al.*, 2016).

Thanks to the success of soybean breeding programs, a high number of cultivars on the market are highly productive, resistant to pests and diseases, and adapted to various edaphoclimatic conditions (Sediyama, 2009). The growth of these cultivars is influenced by environmental factors like temperature, rain, relative humidity, soil humidity, and photoperiod. Consequently, the planting season has a decisive influence on the production's quantity and quality (Motta *et al.*, 2000). Therefore, evaluating new cultivars must be a constant practice to provide valuable information for extension agents, consultants, and farmers (Vernetti & Vernetti Júnior, 2009).

Plant density is another factor that can be modified to obtain higher land productivity. Optimal plant density is defined as the minimum number of plants that allow the cultivar to achieve its maximum yield (Vega & Andrade, 2000). One of the main concerns among farmers is reducing the amount of seed used per ha to lower the cost of inputs. Thus, understanding the development of different soybean cultivars planted at different planting densities is fundamental for recommendations for the most appropriate guidelines to maximize yields.

Research on adapted cultivars is of fundamental importance to optimize soybean production. In Paraguay, few published works report adapted cultivars that allow optimizing land productivity. So, there is a need for updated information about the eco-physiological behavior and yield of the new varieties offered on the market. Besides, private companies own the existing data, and it is not publicly available. Therefore, the present study aims to establish a benchmark for an appropriate choice of soybean cultivars in Paraguay, evaluating the productive performance of 14 commercial cultivars planted at three plant densities and in two planting seasons in the Yguazu region during 2017-2018.

Materials and methods

Trials were conducted in the experimental field of the Centro Tecnológico Agropecuario del Paraguay (CETAPAR), located in Yguazu, Alto Parana, Paraguay (25°27'41.97" S, 55°02'26.66" W, and 258 m a.s.l.). We obtained data on rainfall and maximum, minimum, and mean daily temperatures during soybean cultivation from September 2017 to April 2018 from the meteorological station of CETAPAR. The water balance graph was constructed using the potential evapotranspiration (ET_c) data of the experimental area from the MOD16A2 MODIS/Terra net evapotranspiration database with a spatial resolution of 500 m (Fig. 1) (Running *et al.*, 2017). Mean temperatures of 24.9°C and total precipitation of 1,925 mm were recorded. The experimental area's soil was characterized as 69.0% clay, 2.2% organic matter, a pH of 5.9, and a base saturation of 70.3%.

The experiment was arranged using a completely randomized block design with a 14×3×2 factorial arrangement and three replicates. Factor A consisted of 14 soybean cultivars (Tab. 1); factor B consisted of three planting densities (177,700, 266,600 and 355,500 plants ha^{-1}), and factor C consisted of early (September 20, 2017) and late (November 20, 2017) planting seasons. Date selection follows soybean planting practices in Paraguay, which generally begin in September. However, when the weather is not appropriate (excessive rains or lack of rain), producers start sowing in mid-October and, exceptionally, in November. In Paraguay, it is common to carry out a second planting no later than February. Our experimental unit consisted of five rows 5 m long and a space between the rows of 0.45 m (a total of 2.25 m wide). The distance between experimental units within each block was 1 m and between blocks was 3 m. In each experimental unit, the useful plot was delimited at 4.05 m^2. To delineate the plots, 1 m was removed from the ends of each experimental plot, and a row from each edge was discarded. Sowing was carried out with a tractor/planter set (model SHP 249, Semeato Plantio Direto, Passo Fundo, RS, Brazil), using a zero-tillage system with a 0.45 cm space between the rows. Other cultural management and treatments followed standard agronomic recommendations for soybean cultivation (Díaz-Zorita & Duarte, 2004). Base fertilization dosage was 150 kg ha^{-1} of a N-P-K fertilizer (04-30-10) at the time of planting on both planting dates (early and late planting), in order to meet the nutritional needs of the crop.

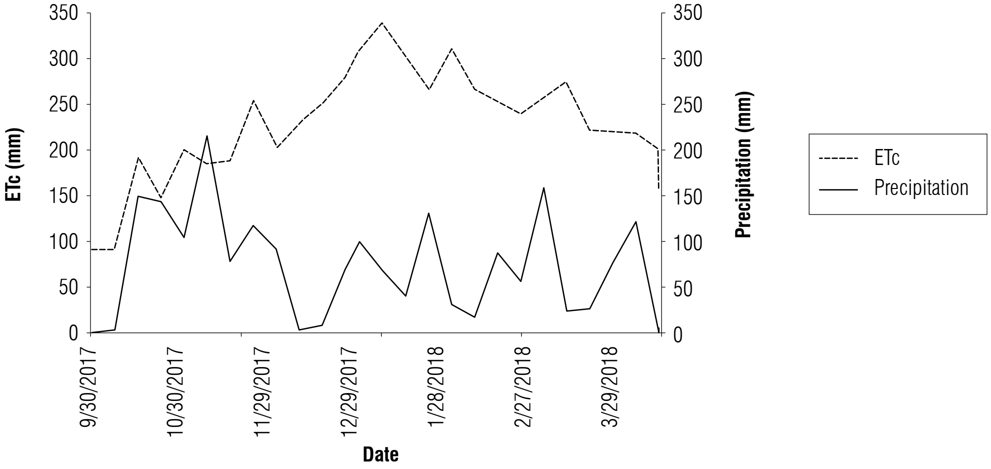

FIGURE 1. Water balance during the experimental period 2017/2018. ET$_{c}$ - potential evapotranspiration.

TABLE 1. Characteristics of the soybean cultivars evaluated.

Cultivar	Maturity group (MG)	Precocity	Breeder
DM-6563-IPRO	VI	Semi-early	Semillas Don Mario
TMG-7062-IPRO	VI	Semi-early	Tropical Melhoramento & Genética
5907-IPRO	Late V	Semi-early	BASF Paraguaya S. A.
6505-B	VI	Semi-early	BASF Paraguaya S. A.
NS-5959-IPRO	Late V	Semi-early	Semillas Nidera
NA-5909-RG	Late V	Semi-early	Semillas Nidera
M-6410-IPRO	VI	Semi-early	Monsanto Paraguay S. A.
DM-6262-IPRO	VI	Semi-early	Semillas Don Mario
SOJAPAR-R19	VI	Semi-early	Instituto Paraguayo de Tecnología Agraria
6806-IPRO	VI	Semi-early	BASF Paraguaya S. A.
6205-B	VI	Semi-early	BASF Paraguaya S. A.
DM-5958	Late V	Semi-early	Semillas Don Mario
M-5947-IPRO	Late V	Semi-early	Monsanto Paraguay S. A.
SYN-1163-RR	VI	Semi-early	Syngenta Paraguay S. A.

When the crop reached the phenological stage of harvest maturity (R8) (Fehr *et al*., 1971), manual harvesting was carried out from the useful plot of each experimental unit. The number of pods per plant (NPP) was quantified by taking 10 plants per experimental unit, and the average NPP was calculated for each experimental unit. To obtain yield and 1000-grain weight (TGW) data, plants of the useful area were threshed. Weight was determined on an electronic balance (AJ150, Mettler Toledo, Columbus, Ohio, USA), and the value was divided by the harvested area and later extrapolated to kg ha^{-1}. Subsequently, the TGW was determined by quantifying four subsamples of 1000-grains for each experimental unit with a seed counter (KC-10, Fujiwara®, Seisakusho, Japan), and the seeds were weighted with a digital precision balance (JA2003, Hongzuan, Shangai, China). The TGW and yield were adjusted to 13% humidity. The number of grains per m^{-2} (NG) was estimated from the ratio of yield to seed weight.

Data analysis

The effect of cultivars, plant densities, planting season and their interaction on the yield, NG, TGW, and NPP were studied. For statistical analysis, the SAS (version 9.4) and Infostat (version 2017) software were used. The variance analysis (ANOVA) was performed following the instructions described in SAS for completely randomized block designs. The Tukey's significance test with a family-wise error rate of 5% was used for the comparison of treatment means. Equation 1 describes the model used:

$$y_{ijkl} = V_i + B_j + D_k + (VD)_{ik} + E_l + (VE)_{il} + (DE)_{kl} + (VDE)_{ikl} + \varepsilon_{ijkl} \quad (1)$$

where y_{ijkl} corresponds to the variable response of the *i*-th cultivar, *k*-th plant density, *l*-th planting season in the *j*-th block. This is the general mean of the response variable. V_i is the effect of the *i*-th cultivar; B_j is the effect of the *j*-th block; D_k is the effect of *k*-th plant density; $(VD)_{ik}$ is the effect of the *ik*-th interaction; E_l is the effect of the *il*-th planting season; $(VE)_{il}$ is the effect of the *ill*-th interaction; $(DE)_{kl}$ is the effect of the *kl*-th interaction; $(VDE)_{ikl}$ is the effect of *ikl*-th interaction; and ε_{ijkl} is the experimental error.

A principal component analysis (PCA) of the agronomic variables of soybean cultivars was performed using data from the variables NG, TGW, NPP and the yield. Results from the PCA are shown as a biplot to illustrate the correlation between the variables.

Results and discussion

The effects of experimental factors on the response variables evaluated are summarized in Table 2. The effect of the blocks was not significant for any of the response variables. There was statistical evidence of second-order interactions only for the effects of the cultivar×planting season interaction on the variables yield, NG, and TGW ($P<0.0001$). A significant third-order interaction was observed for NPP on the effects of the cultivar×density×planting season interaction ($P<0.0001$). The simple result of the density was only effective for the variable yield ($P = 0.0002$).

Yield

No significant interaction was observed between the effects of the factors cultivar, density, and planting season ($P = 0.4286$), not even when considering the interactions between density×planting season ($P = 0.1645$) or cultivar×density ($P = 0.8937$). However, the interaction between cultivar×planting season was highly significant ($P<0.0001$). This interaction implies that the yield of some cultivars is not affected by the planting season, while in others, the yield increases or decreases significantly depending on the planting season. A similar yield was observed during both planting seasons for cultivars 5907-IPRO, NA-5909-RG, and DM-5958. On the other hand, the yields of cultivars DM-6563-IPRO, TMG-7062-IPRO, 6505-B,

TABLE 2. Summary of probability values for all fixed factors related to the agronomic variables yield, number of grains m^{-2} (NG), 1000-grain weight (TGW), and number of pods per plant (NPP).

Factor	Yield	NG	TGW	NPP
Cultivar	<0.0001	<0.0001	<0.0001	<0.0001
Density	0.0002	0.6642	0.9116	<0.0001
Planting season	<0.0001	<0.0001	<0.0001	<0.0001
Cultivar×density	0.8937	0.1078	0.4297	<0.0001
Cultivar×planting season	<0.0001	<0.0001	<0.0001	<0.0001
Density×planting season	0.1645	0.8608	0.2756	0.3274
Cultivar×density×planting season	0.4286	0.3688	0.3535	<0.0001
Coefficient of variation (CV)	21.92%	25.75%	8.541%	11.90%

The factor cultivar consisted of 14 soybean cultivars (Tab. 1), density consisted of three planting densities (177,700; 266,600, and 355,500 plants ha^{-1}), and planting season consisted of early (September 20, 2017) and late (November 20, 2017) planting seasons.

NA-5909, M-6410-IPRO, DM-6262-IPRO, SOJAPAR-R19, 6806-IPRO, 6205-B, M-5947-IPRO, and SYN-1163-RR were significantly higher for the early planting season compared to the late planting season (Fig. 2). Therefore, we can infer that water scarcity affected yields since there was a more significant water deficit in the last season than during the first (Fig. 1). Low yields may be the result of water stress at a critical phenological time. The adverse effects of the lack of water are particularly evident during flowering, seed formation, and seed filling. Lack of available water can reduce yield by reducing the number of pods, the number of seeds, and the mass of seeds that corresponds well with our data (Desclaux *et al.*, 2000).

Because the plant density factor did not interact with any other experimental factor, its simple effect on yield was analyzed ($P = 0.0002$). The plant density that achieved the highest yield was 266,666 plants ha^{-1}. On the other hand, the lower seeding density produced significantly lower yields than the densities of 266,600 and 355,500 plants ha^{-1}. However, the yield for these last two densities was not statistically different (Fig. 3).

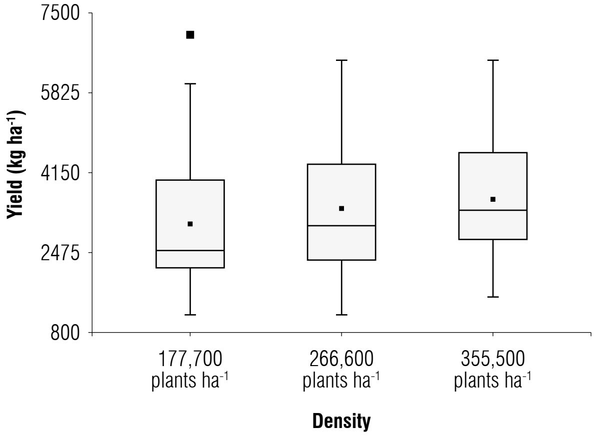

FIGURE 3. Effect of plant density on the yield (kg ha^{-1}) of soybean cultivars. Each box represents the distribution (25th to the 75th percentile) of the yield (kg ha^{-1}) for each treatment. Black dashes inside the boxes represent the medians, and black dots the means. Whiskers represent the maximum and minimum values. Black squares outside the boxes represent extreme values deviating from the expected distribution.

Similarly to the results obtained in this research, the reduction of soybean yield due to late plantings has been reported in previous studies (Girón *et al.*, 2014; Martignone *et al.*, 2016; Teixeira *et al.*, 2016). The planting delay harms yield due to the influence of a smaller number of daily light hours, lower precipitation, and the high temperatures to which the plants are subjected during their initial phase (Martignone *et al.*, 2016). These factors lead to a shorter duration of the vegetative stage, a lower number of nodes per plant and leaf area index, and less dry matter accumulation. Also, the canopy's delayed and inefficient closure causes a more significant loss of water by evaporation (Toledo, 2019).

The soybean response to plant density variations depends on the genotype, soil water conditions, and geographic location (Gaso, 2018). In most soybean cultivars, the response to higher plant density is hindered due to the ability to compensate for gaps between plants, generating longer branches and reducing the energy use for grain filling (Cox & Cherney, 2011). However, different authors mention that soybean yields do not increase significantly when plant

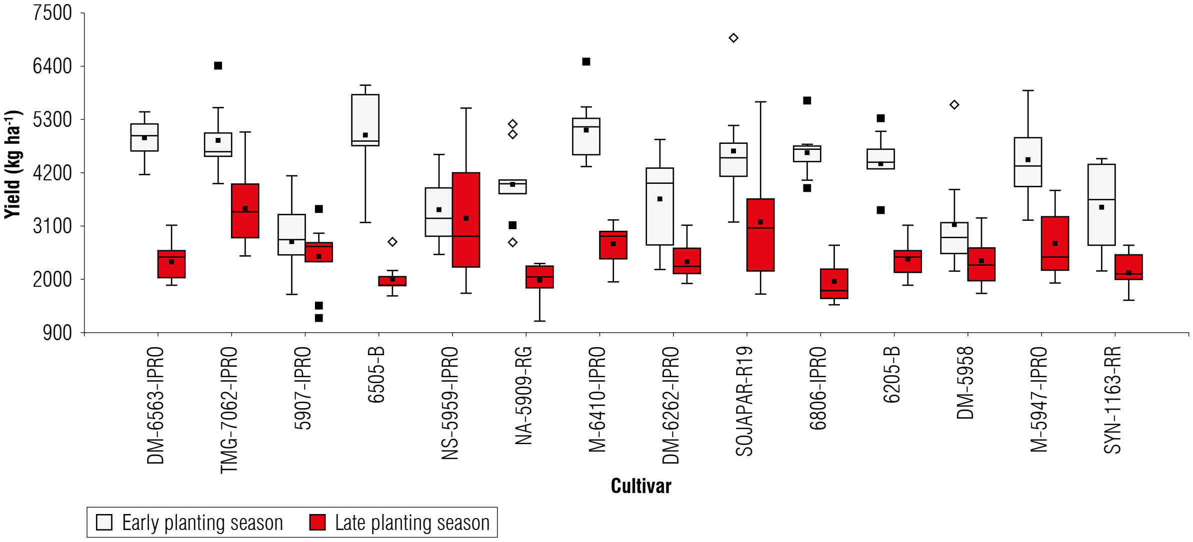

FIGURE 2. Yield (kg ha^{-1}) for different soybean cultivars sown in two different planting seasons. Each box represents the distribution (25th to the 75th percentile) of the yield (kg ha^{-1}) for each treatment. Black dashes inside the boxes represent the medians, and black dots the means. Whiskers represent the maximum and minimum values. Black squares outside the boxes represent extreme values deviating from the expected distribution.

densities range from 100,000 to 600,000 plants ha^{-1} (Lee *et al.*, 2008; Thompson *et al.*, 2015).

According to Rodríguez *et al.* (2015), at densities lower than 200,000 plants ha^{-1}, there is no competition between plants and the number of branches and pods per plant increases; but the tradeoff fails to compensate for the lower number of plants. Therefore, yield is reduced, a situation that was observed at a density of 177,700 plants ha^{-1}. Gaso (2018) found that a significant increase in yield is observed using a density of 300,000 plants ha$^{-1,}$ and, above this density, yields do not increase. In this research, we observed that yields did not increase significantly above 266,600 plants ha^{-1}.

Increasing plant density may be beneficial to mitigate the adverse effects of planting delay that would allow a better use of resources through maximum soil coverage and minimal water loss (Toledo, 2019). Higher plant densities compensate for spaces not covered by the canopy, increasing the number of nodes per m^{-2} (Martignone *et al.*, 2016).

Number of grains

For the number of grains per m^{-2}, no statistical evidence of significant interaction was observed between the cultivar, density, and planting season effects (P = 0.3688) (Tab. 2). No interaction was observed between the density and planting season factors (P = 0.8608) or between the cultivar and density (P = 0.8937). However, the interaction between cultivar and planting season was highly significant (P<0.0001); this implies that the NG that can be produced depends on combining a specific cultivar and the planting season. The cultivars that obtained the same NG in both planting seasons were TMG-7062-IPRO, 5907-IPRO, NS-5959-IPRO, NA-5909-RG, NA-5909, 6262-IPRO, 6205-B, NS-5959-IPRO, M-5947-IPRO, and SYN-1163-RR. On the other hand, the cultivars DM-6563-IPRO, 6505-B, M-6410-IPRO, SOJAPAR-R19, and 6806-IPRO obtained a higher NG in the early planting season compared to the late one (Fig. 4).

The NG was the component that best explains crop productivity variations (Toledo, 2018). The increase of this component is directly proportional to the duration of the period between the emergency and the start of grain filling (R5). The NG is strongly associated with canopy photosynthesis and also the growth rate of the crop during flowering and pod development (growth stage R1–R5) (Egli, 2013). Besides, a particular relationship is implied between the number of nodes per area and the NG. The greater the number of nodes, the greater the NG. This characteristic is related to the cultivar, environment, and management. Thus, to maximize soybean yields, genotypes with a higher number of plant nodes and rapid soil coverage must be selected since they intercept more than 90% of radiation by R5 (Martignone *et al.*, 2016). The decrease in NG observed in most cultivars in the second season may be because the delay in planting shortened the plant cycle, causing a lower rate of photosynthesis, less growth and, therefore, a reduction in the production of nodes and grains per m^{-2}. In this research, the density of plants did not influence the NG.

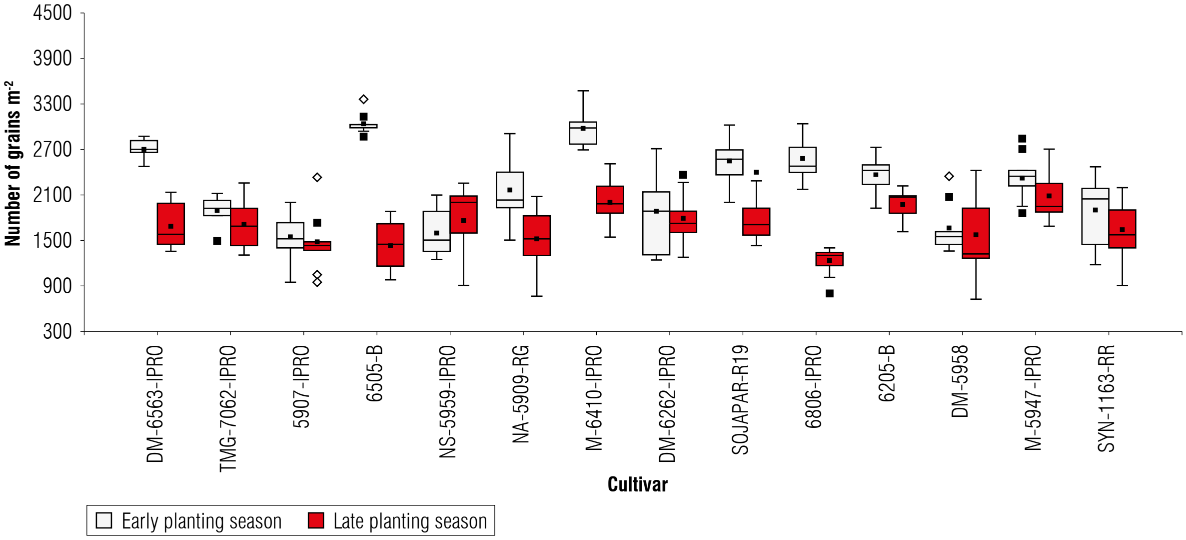

FIGURE 4. Number of grains m^{-2} for different soybean cultivars during two different planting seasons. Each box represents the distribution (25th to the 75th percentile) of the number of grains m^{-2} for each treatment. Black dashes inside the boxes represent the medians, and black dots the means. Whiskers represent the maximum and minimum values. Black squares outside the boxes represent extreme values deviating from the expected distribution.

However, it can be expected that increasing plant density will typically maximize the NG due to the increase in the number of nodes per m^{-2} (Gan *et al.*, 2002).

1000-grain weight

The interaction between the cultivar and planting season was highly significant (*P*<0.0001). The cultivar that obtained a similar weight of 1000 grains in both planting seasons was 6806-IPRO (Fig. 5). The rest of the cultivars had a significantly higher TGW during the early planting season than during the late planting season.

Grain weight is the second component that best explains soybean yield and is an inherent characteristic of the cultivar (Toledo, 2018). The water deficit during November (Fig. 1) could have influenced the decrease in TWG in the second sowing season. Moreover, delayed planting causes a lower daily accumulation of dry matter during the reproductive stage. The TGW tends to be lower as temperature and solar radiation decrease, resulting in the interruption of grain filling as autumn approaches (Martignone *et al.*, 2016; Teixeira *et al.*, 2016).

Number of pods per plant

The interaction between the effects of the factors cultivar, density, and planting time affected the number of pods per plant (*P*<0.0001). This implies that the number of pods that the soybean plant can produce will depend on the cultivar, planting density, and planting season. The cultivars that had a NPP higher than 80 were SOJAPAR-R19, SYN-1163-RR, 6806-IPRO, M-6410-IPRO, DM-6262-IPRO, 6505-B, NA-5909, DM-5958. However, due to the interaction, the effect on the NPP is complex; for example, at a density of 355,500 plants ha^{-1} cultivar 6505-B produced an average of 30 pods per plant during the late planting season, while in the early planting season the average was 40 pods per plant. The same cultivar with a density of 266,600 plants ha^{-1} during the late planting season produced an average of 45 pods per plant, while during the early planting season, the average was 86 pods per plant. Similarly, with a density of 177,700 plants, the average number of pods per plant was 58, but with the same density during the early planting season, the average was 80 pods per plant (Fig. 6). In contrast, other cultivars such as M-5947-PRO did not significantly increase NPP regardless of the density and planting time. In general, low densities during the first planting season allowed obtaining a higher NPP with the SOJAPAR-R19 cultivar at a density of 177,700 plants during the early planting season, showing the highest NPP (121 pods per plant).

The formation of pods begins in the phenological phase R3 and ends in R6. Pod development is delayed at temperatures below 22°C and tend to fall from the plant with long photoperiods and temperatures greater than 32°C (Toledo, 2018). The formation of pods is susceptible to various types of stress, such as water deficit or the presence of pests and diseases (Toledo, 2019). Moreover, the quality and quantity of solar radiation that reaches the lower layers of the canopy stimulate the establishment of reproductive structures in soybeans (Quijano & Morandi, 2011). The delay of planting causes the canopy to take longer to close, explaining the higher NPP in some genotypes in the second planting season.

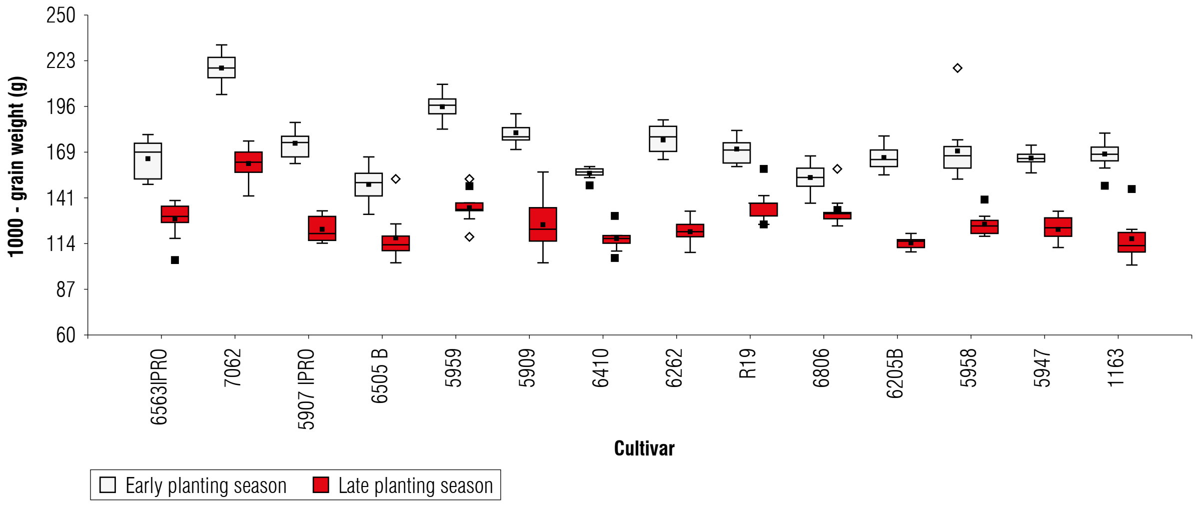

FIGURE 5. 1000-grain weight for different soy cultivars sown in two different planting seasons. Each box represents the distribution (25th to the 75th percentile) of 1000-grain weight for each treatment. Black dashes inside the boxes represent the medians, and black dots the means. Whiskers represent the maximum and minimum values. Black squares outside the boxes represent extreme values deviating from the expected distribution.

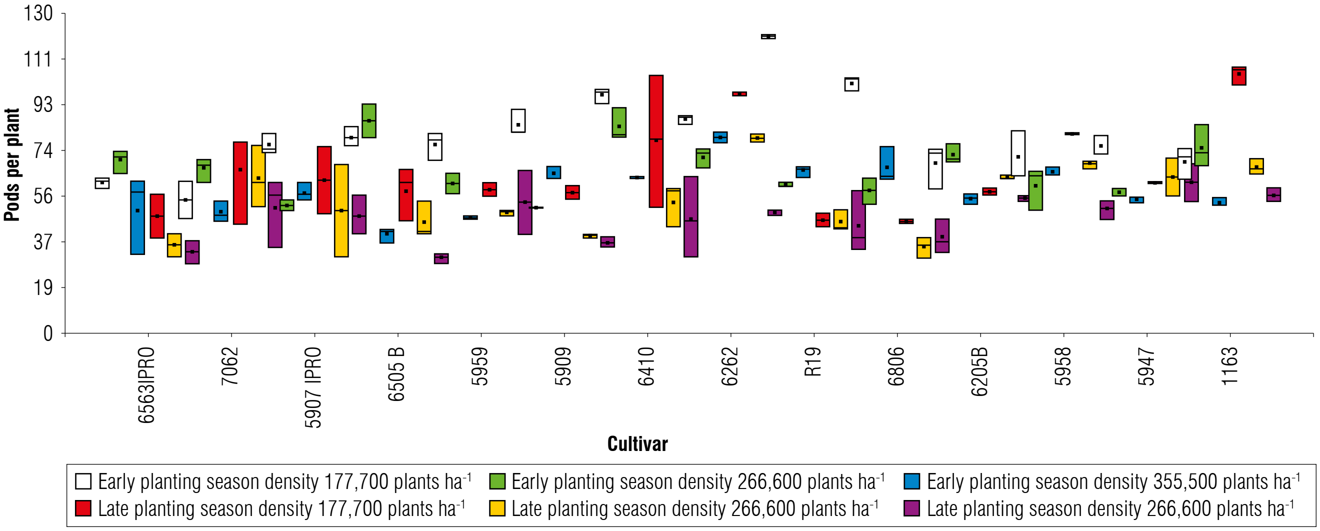

FIGURE 6. Number of pods per plant for different soybean cultivars sown at three densities in two different planting seasons. Each box represents the distribution (25th to the 75th percentile) of pods per plant for each treatment. Black dashes inside the boxes represent the medians and black dots the means. Whiskers represent the maximum and minimum values. Extreme values deviating from the expected distribution are represented by black squares outside the boxes.

The NPP tends to increase with lower plant densities (Toledo, 2019). The number of pods of branches and stems and the number of branches per plant are strongly associated with phenotypic plasticity of indeterminate soybean cultivars. Soybean growth then compensates a lower plant density by showing higher branch emission, higher branch growth and stems, and higher NPP (Balbinot Júnior *et al.*, 2018). Therefore, a higher NPP was observed at a lower plant density.

Principal component analysis

The regions in the biplot contained groups of soybean cultivars with similar characteristics. Cultivars that were closely clustered in one region of the plot represent cultivars that have similar performance patterns. Vectors pointing roughly in the same direction represented yield components that have positive correlations. Yield was slightly correlated with NPP (r = 0.23, $P = 0.0002$), while the response variables NG (r = 0.60, $P<0.0001$) and TGW (r = 0.56, $P<0.0001$) showed a higher correlation with yield. The TGW was not correlated with NG (r = 0.03; $P = 0.598$) and was weakly correlated with NPP (r = 0.17, $P = 0.003$), while NG was weakly correlated with NPP (r = 0.22; $P = 0.0005$). The principal component (PC1) accounted for 43.4% of the variance. The second component (PC2) accounted for 35.7% of the variance. Together, these components accounted for 79.1% of the variance during experiments. In the biplot, the cultivars that obtained the highest average yield are to the graph's right, while cultivars with the lowest yield are to the left (Fig. 7).

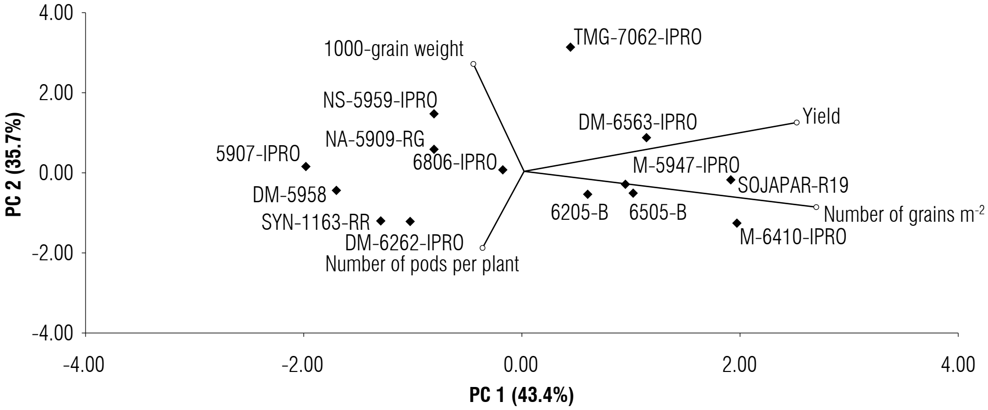

FIGURE 7. Biplot of the principal component analysis of the agronomical variables of soybean cultivars yield (kg ha^{-1}), number of grains m^{-2}, 1000-grain weight, and number pods per plant, during two planting seasons and at three plant densities. The X-axis represents projections of the first principal component (PC1) and the Y-axis the second component (PC2); the two components represent 79.1% of the variance during the field experiments.

This research provided valuable information on the productivity obtained from the interaction between genotype and environment for Paraguayan conditions. It is essential to consider that the meteorological conditions are different each year and that the performance of these genotypes could vary in different locations.

Because of the abundant supply of soybean cultivars in Paraguay, we suggest that subsequent experiments evaluate the impact of climatic factors during the cycle on the yield and its components for cultivars of different maturation groups at different planting dates. Correspondingly, these experiments should include other soybean growth components, such as the leaf area index and the number of nodes per m^{-2}.

Conclusions

This study highlighted the importance of selecting soybean genotypes according to their response to variations in planting date and plant density to increase crop production in the same area. The interaction between the soybean cultivar and planting season affected soybean yield components. Therefore, specific cultivars should be chosen for the early planting season. Cultivars DM-6563-IPRO, TMG-7062-IPRO, 6505-B, NA-5909-RG, M-6410-IPRO, DM-6262-IPRO, SOJAPAR-R19, 6806-IPRO, 6205-B, M-5947-IPRO and SYN-1163-RR can be recommended for early plantings because they show the highest yields, while for late plantings, we recommend cultivating NS-5959-IPRO. Cultivars 5907-IPRO and DM-5958 can be planted in both seasons because they show similar yields for the two planting seasons. Significantly higher yields were obtained starting from a density of 266,600 plants ha^{-1}. The cultivar×planting season interaction affects the weight of 1000-grains that determines the quality of the grain. Therefore, the early planting season provided a greater 1000-grain weight than the late planting season. The number of pods per plant depended on the cultivar, density, and planting season. Still, since it correlated poorly with yield, this characteristic could be less important when selecting a cultivar. The combination of the number of grains and the 1000-grain weight had a more significant influence on the generation of yield in the soybean cultivars evaluated. Therefore, it can work as a proxy of yield to select new cultivars.

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Author's contributions

GEM formulated the overarching research goals and aims, obtained the financial support for the project leading to this publication, designed the methodology, and carried out the manuscript's critical review. ASV carried out activities to annotate scrub data and maintain research data for initial use and later re-use, applied statistical techniques for data analysis, oversaw data presentation, and carried out the critical review of the manuscript. FFR conducted the research process, explicitly performing the experiments, and managed and coordinated the research activity planning and execution. JDN wrote the initial draft and carried out the commentaries of the manuscript. PFS provided the study materials and carried out the critical revision of the manuscript. WLP oversaw and led the research activity planning and execution and carried out the critical review of the manuscript.

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