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PHOTOSYNTHETIC CAPACITY, YIELD COMPONENTS, AND POPULATION DENSITY OF A LOCAL CORN GENOTYPE FROM ECUADORIAN AMAZONIA

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ABSTRACT

Population density is one of the most important agronomic factors in corn (*Zea mays* L.) for achieving high agricultural yields. In the Ecuadorian Amazon, there are no studies that allow us to determine a population density that is suitable for the edaphoclimatic and cultural conditions of the region. This work was carried out at the Experimental Center for Amazonian Research and Production (CEIPA) of the Amazon State University. The effect of population densities of 31 250, 41 666, and 62 500 plants per hectare of the local variety Tusilla on physiological indicators, yield components, and crop agricultural yield was studied. A randomized block experimental design with three treatments and three replicates was used. The data was tested for normality using Shapiro-Wilks, followed by an analysis of variance and a mean comparison test using Tukey ($p \leq 0.05$). Increased population density reduces leaf area and dry matter production per plant while increasing leaf area index and net assimilation rate. Each individual plant showed higher leaf area values at the lowest population density, with averages of 1.18 and 1.56 m^2 at 55 and 75 d, respectively, and higher dry matter production in stems and leaves, with 61.15 g $plant^{-1}$ at 75 d. The highest net assimilation rate was 9.05 g m^2 d^{-1} at the highest population density. At lower population densities, yield components are favored; however, a higher agricultural yield of more than 6405 kg ha^{-1} is obtained at higher densities due to the greater number of plants per unit area.

Keywords: *Zea mays* (L.), sowing distance, agricultural yield.

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INTRODUCTION

Corn (*Zea mays* L.) is one of the most important and widespread staple crops worldwide. It is one of the main sources of food for millions of people, particularly in the Americas and Asia. It is one of the first plants to be domesticated and spread throughout the world (Ruiz *et al.*, 2023). It occupies a prominent position in Latin American agriculture, as a large part of its production is intended for human and animal consumption. In recent years, its use for biofuel production has led to an increase in the price of the product, and it is now one of the most cultivated cereals in the world (Hernández-Córdova and Soto-Carreño, 2012).

Corn is a major economic crop in Ecuador. It is grown on the coast, in the highlands, and in the Amazon under different environmental conditions of temperature, humidity, rainfall, and luminosity. In the Ecuadorian Amazon, two main varieties of corn are grown: Tusilla and Zhubay (Alemán-Pérez *et al*., 2020). According to Saavedra and Gaibor (2018), corn is the most common annual crop in the Amazon region, with a cumulative frequency of 72.5 %, demonstrating the tradition and importance of the crop in Amazonian production systems. Corn production is one of the income-generating activities carried out by the Kichwa communities of Orellana, who do so in a traditional manner throughout the production, harvest, post-harvest, and marketing processes (Arias-Gutiérrez *et al*., 2016).

In this context, the landscapes of the Ecuadorian Amazon region are particularly vulnerable due to the fragility of their ecosystems, which is intensified by extreme climatic conditions that include abundant annual rainfall of high intensity (3000 to 4000 mm per year), high cloud cover, and high temperatures (24 to 30 °C), which, combined with a landscape of irregular topography and soils with very particular characteristics, acquires a high vulnerability (Bravo-Medina *et al*., 2021). The soils in this area have a chemical composition characterized by high acidity, the presence of aluminum, high organic matter content, and low availability of phosphorus and exchangeable bases such as potassium, calcium, and magnesium, which define their physical, chemical, and biological qualities (Bravo-Medina *et al*., 2021). This situation, typical of tropical environments, severely restricts agricultural development, especially for corn cultivation.

Several factors are important in the crop production process because of their significant impact on yield and its components, including fertilization, sanitary control, planting density, and harvesting, among others (Alemán-Pérez *et al*., 2020). Many studies have been conducted to determine the optimum plant density for corn; however, there is no single recommendation for all environmental or controlled factors such as soil fertility, hybrid selection, planting date, and planting frame (Sener *et al*., 2004). According to Rabbani and Safdary (2021), the most important agricultural management methods are hybrid selection, optimum plant density, optimum fertilizer application, appropriate planting date, and irrigation timing; therefore, increasing corn yield requires sufficient information on the simple and interaction effects of these factors on yield, as well as their impact on other plant characteristics.

Population density has a significant impact on corn yield. It is important to consider the number of plants in a given space due to competition for nutrients, minerals, water, and sunlight. However, variations in population density have an impact on the morphological and physiological parameters as well as the productive indicators of the corn crop (Blanco-Valdes and González-Viera, 2021). The reproductive strategy of the corn plant makes it very susceptible when established at high population densities, but it is also very inflexible in terms of translating higher growth into more yield when planted at low density (Quevedo-Amaya *et al*., 2015).

In the Ecuadorian Amazon region, there is no specific corn production system, which means that some producers sow corn “at random,” with no established distances between plants and furrows. Others sow it by hand or with a coa, locating points according to the topography and actual situation in their area, but they do not manage adequate and uniform distances. This situation leads to low yields and production (Alemán-Pérez *et al*., 2020). The lack of agricultural innovations in agronomic management contributes to low productivity, as does the fact that adverse edaphoclimatic conditions in contrasting environments significantly reduce production (Turrent-Fernández *et al*., 2014).

Some studies report that corn responds differently to population density depending on genotype and environmental conditions (Sener *et al*., 2004). Ruiz *et al*. (2023) conclude that fertilization has a significant impact on yields but not population density. In the Amazon, research has primarily focused on the effects of fertilization on yield, while the impact of population density on yield and photosynthesis has been little studied. Therefore, the scientific information available on the subject does not support the crop establishment system under these conditions.

The objective was to analyze the variation of photosynthetic capacity, leaf dry matter, and yield components with population density in a local corn genotype from the Ecuadorian Amazon. It was hypothesized that as population density increases, photosynthetic capacity, yield, and its components can be improved due to the compensation generated by the number of plants per unit area.

MATERIALS AND METHODS

The research was conducted at the Experimental Center for Amazonian Research and Production (CEIPA) in the Arosemena Tola canton of Napo province, Ecuador (Figure 1), which covers an area of 2848 ha.

CEIPA is located in a tropical climate, with its center at coordinates 1° 14′ 13.7″ S and 83˚ 53´ 23.5″ W, at an altitude of 580 m, and topography characterized by slightly undulating relief without steep slopes, distributed in natural plateaus of great

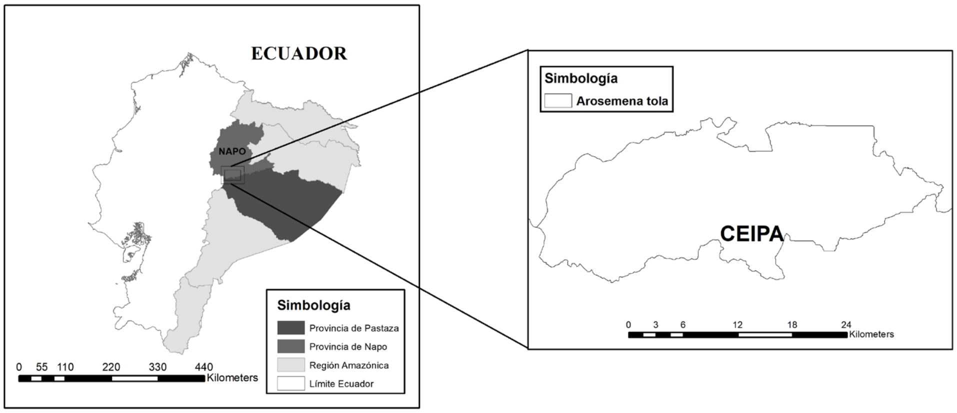

Figure 1. Location of the study area at the Experimental Center for Amazonian Research and Production (CEIPA).

extension. The soil is very heterogeneous in composition; however, the majority of it is formed by fluvial sediments from the Andean region of the country. Annual precipitation reaches 4000 mm, relative humidity is 80 %, and temperatures range from 15 to 25 °C. Some climatic indicators recorded at the CEIPA weather station during the experimental period are considered (Table 1).

Table 1. Climatic conditions during the experiment.

Month	Relative humidity (%)	Temperature (°C)	Wind speed ($m\ s^{-1}$)	Dew point (°C)	Rainfall (mm)
Nov	86.5	24.54	0.25	19.3	400.1
Dec	83.45	26.20	0.21	22.4	390.1
Jan	87.5	23.1	0.2	19.65	370.5
Feb	85.48	23.66	0.18	20.79	300.5
Mar	84.71	22.79	0.28	19.78	414

The experiment was set up on November 5, 2021, using a randomized block experimental design with three treatments corresponding to planting distances: 0.8 x 0.4 m (DP1: 31 250 plants ha^{-1}), 0.8 x 0.3 m (DP2: 41 666 plants ha^{-1}), and 0.8 x 0.2 m (DP3: 62 500 plants ha^{-1}). Three replicates were used in 5 x 5 m plots for an experimental unit of 25 m^2. The local variety Tusilla was planted in seven rows per plot, 0.8 m apart, and plants in perfect intraspecific competition were selected from the five central rows. Foliar fertilizer was applied at 15, 30, 45, 60, and 75 d at a rate of 5 g L^{-1} of water. A hilling was performed at 30 d, followed by a single weeding at 45.

Leaf area (m^2) was measured at 15, 35, 55, and 75 d after germination using the dimensional leaf length and width method, according to Vázquez-Becalli and Torres-García (2007). Previously, the Leaf Area Coefficient (CAF) was determined using a 2.1 cm diameter disc, with which five samples per plant were extracted from different leaves, ensuring that they were representative of the central part of the leaflet. Using the weights of the five disc samples and the total leaf blade weight of the plant, the leaf area of the plant was determined using the following formula:

*CAF = Leaf blade area / leaf length * width*

Dry matter accumulation in stems and leaves was evaluated at 35 and 75 d, with five plants selected at random from all replicates per treatment based on perfect intraspecific competition. The net assimilation rate (g m^{-2} d^{-1}), which represents the amount of dry matter produced per unit leaf area in unit time (Vázquez-Becalli and Torres-García, 2007; García-Castro *et al.*, 2018), was calculated using the following formula:

$$TAN = \frac{2(P2 - P1)}{(A2 + A1)\ (T2 - T1)}$$

where P1 is the initial dry weight per plant (first evaluation), P2 is the final dry weight per plant (second evaluation), A1 is the initial leaf area per plant, A2 is the final leaf area per plant, and T2 - T1 is the time difference between the initial and final evaluations. Yield components were determined: number of ears per plant, number of rows per ear, number of grains per row, weight of 1000 grains, total grain weight per plant (g) at 12 % moisture, and agricultural yield (kg ha^{-1}).

The Shapiro-Wilks test was used to assess data normality, and an analysis of variance (ANOVA) was used to compare variables as a function of population density. A Tukey mean comparison test ($p \leq 0.05$) was then used to examine the effect of population density on the evaluated parameters. All statistical analyses were performed with Origin (Pro) 2020b software (OriginLab Corporation, Northampton, MA, USA).

RESULTS AND DISCUSSION

The leaf area of the plants at 15 d after planting (dds) did not show significant differences in relation to population density (Figure 2A), because the plants are still very small at that age and do not use all the vital area that corresponds to them. At 35 d, the effect of plant spacing begins to be seen with a decrease in leaf area as population density increases, reflecting a statistical difference between densities. This behavior is more evident at 55 and 75 d after planting, with statistical differences between the densities studied for leaf area and lower densities resulting in average values of 1.18 and 1.56 m^2 plant^{-1}, respectively. According to Wu *et al*. (2018), because the leaf is the primary photosynthetic organ, increasing leaf area can boost photosynthetic capacity, which is affected at high densities.

There was statistical variation among treatments in terms of leaf area index, particularly among those with higher density (Figure 2B). This behavior showed a systematic increase pattern in IAF at different times of crop development. The results obtained are consistent with those described by Lashkari *et al.* (2011), who found that using high population densities in corn results in better land use when considering the variety, climate, and edaphic characteristics of the area. Sánchez-Hernández *et al*. (2011), in their experiment, found that the highest leaf area index was 83 333 plants ha^{-1}, while the lowest was 50 000 plants ha^{-1}. In turn, León-Aguilar *et al*. (2018) confirmed that at longer planting distances, the plant has a larger vital area for growth and vice versa, with no competition for nutrients at high densities.

For their part, Rabbani and Safdary (2021) found that increasing the number of plants per unit area reduces the amount of light reaching the canopy floor, thus increasing competition to absorb radiation. According to Morales-Ruiz *et al.* (2014), increasing the amount of intercepted radiation (IR), which depends on cultivar, population density, and stage of development, is critical for increasing grain yield. To achieve high levels of IR, it is necessary for corn to generate a high leaf area index (LAI) in the early stages of development.

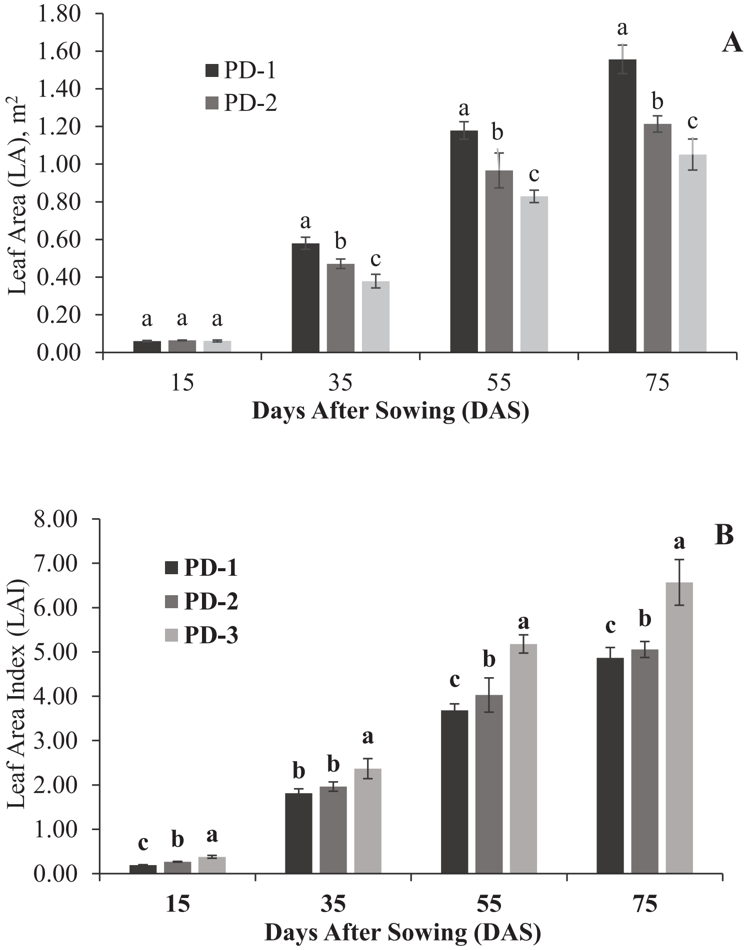

Figure 2. Variation of physiological parameters according to population densities (PD). A: leaf area; B: leaf area index. Mean values of treatments with different letter are statistically different ($p \leq 0.05$).

The increase in population density resulted in lower dry matter production in stems and leaves per plant at 75 dds (Figure 3B). The highest dry matter production per plant was obtained at the lowest population density, with 61.15 g plant^{-1} at 75 dds, with statistical differences among the other densities studied. These results differ from those obtained by other researchers, such as Sánchez-Hernández *et al.* (2011), who obtained the maximum yield with the criollo genotype planted at 83 333 plants ha^{-1}, with 57 Mg ha^{-1} of green and dry matter, outperforming 62 500 and 50 000 plants ha^{-1} in terms of forage yield.

The dry matter production of a crop is directly related to the utilization of incident solar radiation. To achieve maximum yields without significant environmental constraints, crops must take full advantage of the available solar radiation during

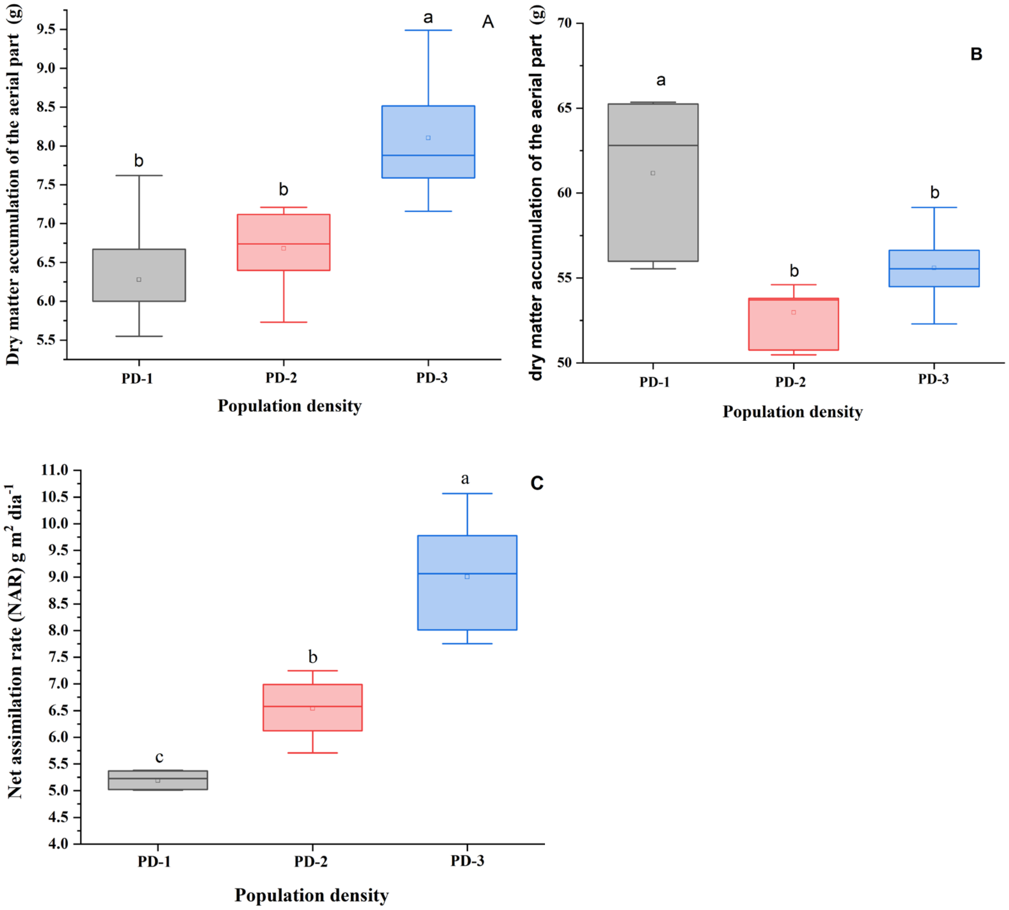

Figure 3. Effect of population density (PD) on dry matter accumulation of the aerial part of the plant. A: value recorded at 35 dds; B: at 75 dds; C: net assimilation rate. Mean values of treatments with different letter are statistically different ($p \leq 0.05$).

critical determination times (Vázquez-Becalli and Torres-García, 2007). In turn, Zhai *et al*. (2022) state that dry matter accumulation after flowering has an impact on yield by affecting the number of grains per ear and grain weight.

According to Yescas *et al*. (2015), there is no increase in dry matter yield when a greater number of plants per hectare are planted. In turn, Sarlangue *et al.* (2007) found that as population density increased, so did biomass production per unit area. The increase in population density allows greater cover earlier in the crop cycle, which promotes higher biomass production. At day 80, Váscones-Montúfar *et al*. (2021) reported biomass values of 1101 g DM m^{-2} at a density of 62 500 plants ha^{-1}.

Corn plants grown at higher population densities showed higher net assimilation rates (NAR), with values of 9.05 g m^{-2} d^{-1} and a statistical difference for the density of 41 666 plants ha^{-1}, which in turn was the lowest population density studied (Figure 3C). Maximum NAR values imply higher dry matter production per unit leaf area and per unit time, which translates into higher photosynthetic efficiency (Morales-Morales *et al*., 2015). Although each individual plant has higher leaf area values at the lowest population density (Figure 2A) and higher dry matter production in stems and leaves at 75 dds (Figure 3B), no better values are obtained for the NAR because this leaf area is not fully utilized to produce dry matter (Figure 3C).

These findings are consistent with those reported by other authors, who state that the corn plant is highly efficient in biomass production at high population densities (Ruiz *et al*., 2023). This high production capacity is due, among other factors, to a high photosynthetic rate, a low energy value of the dry matter produced, and an adequate crop structure. In contrast, Ren *et al*. (2017) and Jia *et al.* (2018) report that high population densities accelerate leaf senescence and reduce net assimilation rates. If this occurs after stigma formation, it also affects the availability of assimilates for grain formation.

According to Assefa *et al.* (2018), in an ideal environment with unlimited resources, the relationship between plant density and yield should be linear, meaning that yield increases as plant density increases. However, factors such as the availability of nutrients, water, and climatic conditions commonly affect production; therefore, obtaining optimal population densities is dependent on the magnitude of the resource constraint.

In the Ecuadorian Amazon, the high density of plants can lead to more intense competition for resources, such as light, water, and nutrients. This may result in a reduction in the amount of available resources per plant and, potentially, a decrease in dry matter production per plant. On the other hand, a lower plant density may provide each individual plant with better access to resources, which could result in higher dry matter production per plant. However, it is important to consider that a very low density can result in suboptimal use of available space and reduced sunlight utilization, which can negatively affect overall crop yield (Alemán-Pérez *et al*., 2020).

The number of grains per row (Figure 4A) is higher in treatment 1 (31 250 plants ha^{-1}), with a statistical difference from treatment number 3 (62 500 plants ha^{-1}). This behavior is expected given the larger cob size and cob length of grains formed at lower population densities. This result coincides with Cervantes-Ortíz *et al.* (2013), who reported that higher population density resulted in fewer grains per row due to smaller cobs and, therefore, a low number of grains per row. The number of grains per row is significantly affected by the distance between rows. This parameter increases as the distance between plant lines increases (Quevedo-Amaya *et al*., 2015).

Other researchers found that the number of grains per row decreased as plant density increased because high levels of plant density can reduce light, reduce the number of seeds per row, and cause seed abortion at the end of the cob (Alam *et al*., 2020), which is consistent with Gurmu *et al*. (2020), who found that the number of grains per row increases significantly as plant density decreases.

The highest values for 1000 grain weight were found at the lowest population density (31 250 plants ha^{-1}), numerically higher than those obtained at the highest population

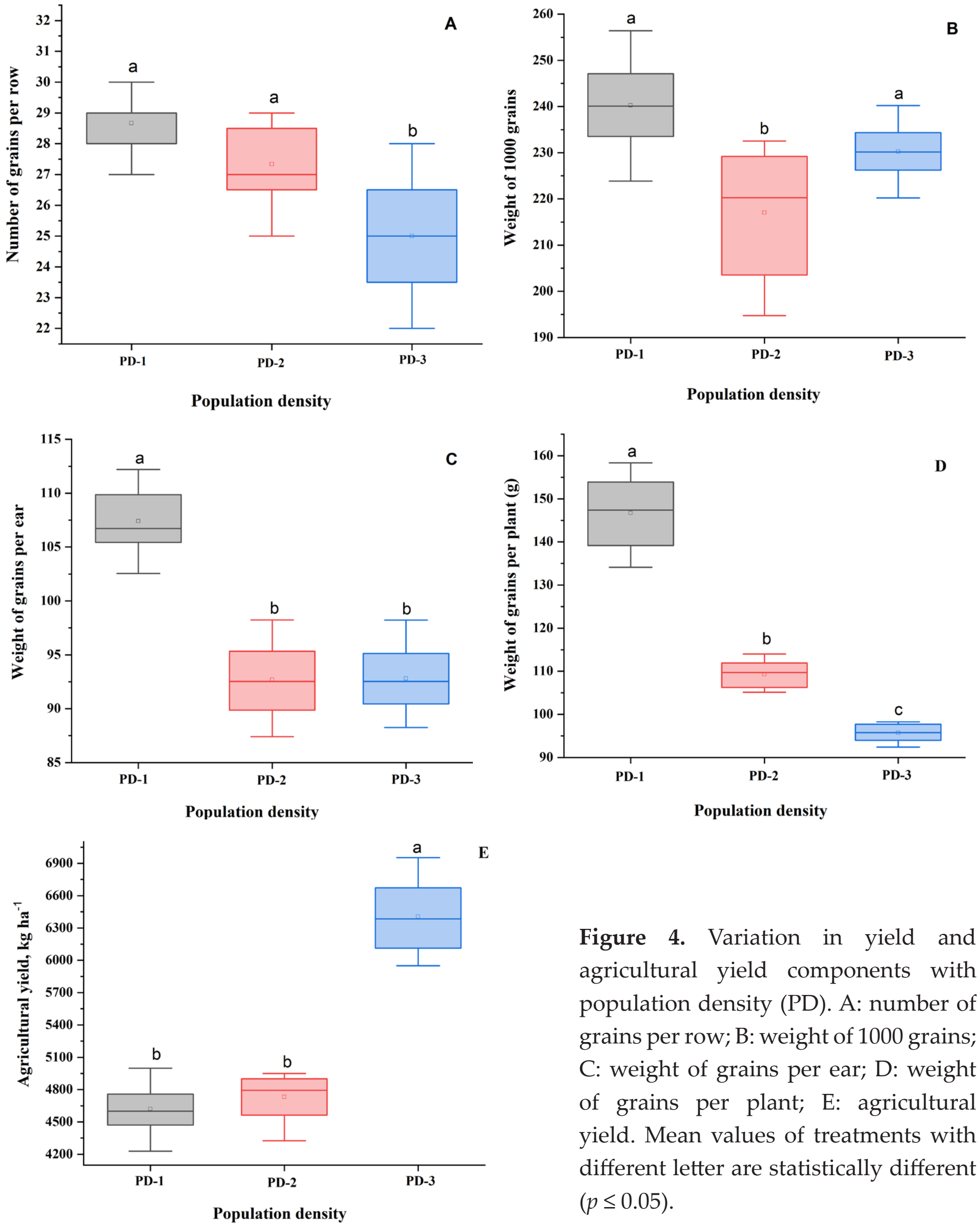

Figure 4. Variation in yield and agricultural yield components with population density (PD). A: number of grains per row; B: weight of 1000 grains; C: weight of grains per ear; D: weight of grains per plant; E: agricultural yield. Mean values of treatments with different letter are statistically different ($p \leq 0.05$).

density (62 500 plants ha^{-1}), with a statistical difference for the density of 41 666 plants ha^{-1}, indicating that there was no linear behavior in this indicator (Figure 4B). According to Rodríguez (2021), the average 100-grain weight achieved at a density of 88 867 plants ha^{-1} (28.55 g) is statistically similar to those obtained at a density of 66 665 plants ha^{-1} (28.33 g). However, Qian *et al*. (2016) found that as population density increased, the weight of 1000 grains decreased, which they attributed to a reduction in nutrient accumulation in the seeds.

The yield component most affected by population density was the number of grains reaching maturity. The number of grains per plant in corn is closely related to plant growth during flowering, which decreases as plant density increases. This relationship between grain yield and population density is complex since the best response in grain yield varies depending on soil characteristics, climate, cultural practices, and genotype (Blanco-Valdes and González-Viera, 2021). In turn, Yang *et al*. (2022) found that increasing corn plant density significantly reduced the number of grains per cob and the 1000-grain weight.

Plants grown at the lowest population density showed higher grain weight per cob, with values exceeding 100 g and statistical differences for the other two densities not differing from each other (Figure 4C). These results are a consequence of the number of grains per ear and 1000-grain weight, which are favored in plants at lower population densities. Conceição dos Santos *et al*. (2019) obtained values higher than 117.7 and 105.8 g cob^{-1} at a population density of 62 500 plants ha^{-1}, which is the maximum density in our study and where a lower grain yield per plant (95 g) was obtained.

Similar behavior was observed in the weight of grains per plant, with values of 147 g at the lowest population density and statistical differences with the other densities (Figure 4D). Likewise, as density increases, the number of cobs per plant decreases, but the number of grains produced per hectare increases. Gurmu *et al*. (2020) found that increasing population density intensifies competition between adjacent plants and leads to lower cob production, thus reducing the length of each seed row in the cob and, consequently, the number of seeds per cob row.

It could be argued that the higher the population density, the lower the weight of grains per plant and smaller the fruit size, but since there are more individuals planted, a higher crop yield per hectare is obtained. In the case of grain production, such as corn, it is appropriate to maximize population density since it is not the size of the cob that is of interest but the quantity of harvested grains. In relation to agricultural yield, the treatment with a density of 62 500 plants ha^{-1} produced around 6405 kg ha^{-1} of grain with 12 % moisture, which was higher than the yields obtained in the other two densities; however, no statistical difference was obtained between the other two densities (Figure 4E).

This result demonstrates that, despite differences in physiological indicators, corn plants adjust their yield components in such a way that, even with smaller cobs, very high grain yields per hectare are achieved, making high densities the worldwide planting scheme for the crop. Research on population densities in corn hybrids showed that increasing density from 4.7 to 8.1 plants m^{-2} resulted in an increase in biomass and grain yield (Ruiz *et al*., 2023). It has also been reported that yield increased by 0.6 Mg ha^{-1} when population density was increased from 60 000 to 70 000 plants ha^{-1} (Guevara-Escobar *et al*., 2005). Several studies report differences in the response of corn to population density as a function of genotype and environmental conditions (Sener *et al*., 2004), which are consistent with the findings of this study.

Similarly, Rabbani and Safdary (2021) reported that the maximum biological yield (13.17 Mg ha^{-1}) was obtained at the highest plant population density (100 000 plants ha^{-1}), contrary to what was reported by Pérez-Somarriba and Hernández-Fernández (2022), who compared densities of 80 000 plants ha^{-1} versus 100 000 and 120 000 plants ha^{-1} and concluded that, at lower population density, better production could be obtained by guaranteeing a greater number of grains per unit area. In this regard, León-Aguilar *et al.* (2018) obtained the best yields when a planting distance of 0.8 m between rows by 0.3 m between plants is established, i.e., 41 666 plants ha^{-1}, which is very different from that reported by Rahmani *et al*. (2016), who posited that the highest grain yield (8.86 Mg ha^{-1}) was obtained at a density of 111 000 plants ha^{-1} and the lowest (7.69 Mg ha^{-1}) at 66 600 plants ha^{-1}.

Consequently, adjusting population density is especially critical for this crop. The density selected is an important factor in growing corn within the farmer's reach. For such reason, it is desirable, agronomists should define the relationships between the number of plants achieved per unit area in a crop and yield for various environmental supply situations (León-Aguilar *et al*., 2018).

CONCLUSIONS

As population density increases, leaf area and dry matter production per plant decrease, while leaf area index and net assimilation rate increase. When the population density increases, the number of grains per row, the weight of 1000 grains, and grain production per cob and per plant decrease. Agricultural yields increase by 38.63 % as population density increases, owing to the increased number of plants per unit area. As a result, it is recommended to use the highest density for the soil and climatic conditions studied.

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