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High population density in arracacha (*Arracacia xanthorrhiza* Bancroft) increase radiation interception, yield, and profitability[1]

Densidad poblacional alta en arracacha (*Arracacia xanthorrhiza* Bancroft) aumenta la intercepción de la radiación, el rendimiento y la rentabilidad

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[1] Reception: August 3rd, 2020. Acceptance: December 14th, 2020. This study is a part of the Project "Integrated crop management focused on soils, water and weed control for the production of arracacha in Colombia" included in the macro project "Generation and use of genetic materials, integrated crop management, postharvest and transformation of arracacha in the Andean region of Colombia."

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Abstract

Introduction. Arracacha (*Arracacia xanthorrhiza* Bancroft) a promising crop due to its nutritional and gastronomic relevance. Population density is an agronomic practice that increases water and radiation use efficiencies, maximizes the yield, and crop profitability. However, the selection of the optimal population density based on physiological, agronomic, and economic criteria for arracacha has not been studied. **Objective.** To describe the effect of different population densities on the physiology, yield, and profitability of arracacha. **Materials and methods.** The experiment was conducted in Cajamarca, Colombia in 2019. There, the soil water potential, relative chlorophyll content, photosynthesis, stomatal conductance, water use efficiency, leaf temperature depression, photosynthetic reflectance index, leaf area index, the fraction of light interception, light extinction coefficient, cracking index, yield, and profitability were evaluated. **Results.** The results showed that high population densities did not generate water deficit because there were no significant differences for the soil water potential, leaf temperature depression, and photosynthetic reflectance index. Furthermore, no nutritional deficiencies were evidenced because the relative chlorophyll content (<32 SPAD) was higher at the critical level. Due to this, no limitations were observed in leaf gas exchange processes. However, the densities of 25,000 and 30,000 plants ha^{-1} showed a higher fraction of light interception due to the increase in the leaf area index; this allowed to obtain a higher yield at these densities. **Conclusion.** The maximum yield (41.96 t ha^{-1}) and profitability (US$ 15,333.06 ha^{-1}) were reached with a population density of 22,222 plants ha^{-1}.

Keywords: plant density, leaf area index, planting systems, intraspecific competition, optimization methods.

Resumen

Introducción. La arracacha (*Arracacia xanthorrhiza* Bancroft) es un cultivo promisorio por su relevancia nutricional y gastronómica. La densidad poblacional es una práctica agronómica que aumenta la eficiencia del uso del agua y la radiación, maximiza el rendimiento y la rentabilidad de los cultivos. Sin embargo, no se ha estudiado para la arracacha la selección de la densidad poblacional óptima basada en criterios fisiológicos, agronómicos y económicos. **Objetivo.** Describir el efecto de diferentes densidades poblacionales sobre la fisiología, el rendimiento y la rentabilidad de la arracacha. **Materiales y métodos.** El experimento se realizó en Cajamarca-Colombia durante el 2019. Allí se evaluó el potencial hídrico del suelo, y en arracacha el contenido relativo de clorofila, la fotosíntesis, la conductancia estomática, la eficiencia en el uso del agua, la depresión de la temperatura de la hoja, el índice de reflectancia fotosintética, el índice de área foliar, la fracción de intercepción de luz, el coeficiente de extinción de luz, el índice de agrietamiento, el rendimiento y la rentabilidad. **Resultados.** Los resultados mostraron que las altas densidades poblacionales no generaron déficit hídrico porque no hubo diferencias significativas en el potencial hídrico del suelo, la depresión de la temperatura foliar y el índice de reflectancia fotosintética. Además, no se evidenciaron deficiencias nutricionales porque el contenido relativo de clorofila (<32 SPAD) fue mayor al nivel crítico. Debido a esto, no se observaron limitaciones en los procesos de intercambio de gases. Sin embargo, las densidades de 25 000 y 30 000 plantas ha^{-1} mostraron una mayor fracción de intercepción de luz debido al aumento del índice de área foliar; esto permitió obtener un mayor rendimiento a estas densidades. **Conclusión.** El máximo rendimiento (41,96 t ha^{-1}) y rentabilidad (US$ 15 333,06 ha^{-1}), se alcanzaron con una densidad poblacional de 22 222 plantas ha^{-1}.

Palabras clave: densidad de plantas, índice de área foliar, sistemas de siembra, competencia intraespecífica, optimización de métodos.

Introduction

Arracacia xanthorrhiza Bancroft is one the most promising crop among Andean roots and tubers (Rosso et al., 2002), due to its gastronomic and nutritional importance for the Andean countries (Zarate et al., 2008). It is widely planting in Brazil, Colombia, Puerto Rico, Peru, Ecuador, and Venezuela, where it is part of the diet of the population (Alvarado & Ochoa, 2010; Morillo et al., 2020). The arracacha genotypes sowing in Colombia have yellow flesh root color (Garnica-Montaña et al., 2020; Pinto-Acero et al., 2019).

With an increasing world population, it is necessary to develop management practices that increase the yield of relevant crops such as arracacha to meet the demand for carbohydrates. Defining an optimal population density is a practice used worldwide to increase crop productivity (Sun et al., 2018), as it determines the number of established plants that are the first crop yield component. An optimal population density allows the radiation use efficiency, water, and nutrients (Hou et al., 2019). To maximize its benefits, intraspecific competition for limiting photosynthesis resources, including nutrients, water, and radiation, should be minimized (Song et al., 2020). Likewise, agronomic management practices must be supported by a higher economic benefit for farmers (Zhang et al., 2018).

For the arracacha crop, the population density has been normally selected from empirical and traditional knowledge, ignoring the physiological behavior of the plant and the relationship with economic indicators of the production system. In Brazil, the population densities used by farmers range between 20,000 and 47,600 plants ha^{-1} (Hermann, 1997; Morillo et al., 2020) while in Colombia, the most common practice is 20,000 plants ha^{-1} (Alvarado & Ochoa, 2010). The behavior of the photosynthetic apparatus of arracacha has been reported only by Jaimez et al. (2008). However, net photosynthesis and photosynthetic reflectance index (PRI) have not been studied under conditions of high population densities. Globally, studies reported the effect of population density on the yield of arracacha with populations higher than 60,000 plants ha^{-1} (Graciano et al., 2007; Torales-Pacito et al., 2015; Zarate et al., 2009); however, the physiological behavior of the plant under intraspecific competition conditions has not been described.

High population densities can limit nitrogen availability and generate deficiencies due to intraspecific competition (Al-Naggar et al., 2015). The lack of nitrogen can reduce the content of chlorophyll and RuBisCO, limiting photosynthesis and the availability of carbohydrates for the part of the plant that is of economic value (Imai et al., 2008), which for arracacha are the commercial roots. The arracacha crop requires between 200-250 kg ha^{-1} of nitrogen for reach an optimal biological yield (Magolbo et al., 2015). The amount of fertilizers is increased depending on the population density to mitigate this effect, but consequently increases the cost of production. Therefore, it is necessary to identify population densities that do not generate nitrogen deficiency (Bänziger et al., 1999; Hou et al., 2019) and that are economically viable.

High population densities increase water uptake attributed to a higher amount of root tissue expressed by a higher number of plants that generate a reduction of soil water potential (Luo et al., 2011; Bermúdez-Florez et al., 2018; Honda et al., 2019). This plant water status alteration produces stomatal and non-stomatal limitations of photosynthesis (Chastain et al., 2016; Drake et al., 2017). For this reason, it is necessary to identify population densities that do not generate water deficit and do not affect crop photosynthesis (Honda et al., 2019).

The leaf area index directly influences the photosynthesis of a crop or its primary productivity since it defines the fraction of light interception (Fang & Liang, 2008), as well as water and nutrient use efficiency (Bréda, 2008). The increase in population densities increases competition for photosynthetically active radiation (PAR) that causes a reduction in crop photosynthesis. Hence, genotypes with tolerance to a high intraspecific competition show morphological adjustments to avoid stress due to a lack of radiation. Changes in the leaf area index and the light extinction coefficient also occur (Quevedo et al., 2018; Sher et al., 2018).

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Variables such as the amount of PAR, the efficiency in the interception and conversion of PAR and CO_2 into biomass, and the efficiency in partitioning biomass to the harvestable organ determine crop yield (Slattery et al., 2017). Therefore, the establishment of the functionality of the photosynthetic apparatus at the leaf and crop levels is a tool for the identification of the optimal population density that maximizes the resources use efficiency. The PRI is related to gross primary productivity (Garbulsky et al., 2008; Kováč et al., 2018); and to non-photochemical quenching related to the xanthophyll cycle as a protection mechanism of photosystem II (PSII) (Kohzuma & Hikosaka, 2018). Leaf temperature depression (LTD) is an indicator of stomatal conductance and is useful for detecting the degree of water deficit (Biju et al., 2018).

Because there is little knowledge of the physiological effect and the technical and economic viability of population densities in arracacha, it is necessary to elucidate the effects of various population densities on the soil water potential, the fraction of light interception, leaf gas exchange, and its relationship with yield and economic indicators. The objective of this study was to describe the effect of different population densities on the physiology, yield, and profitability of arracacha.

Materials and methods

Experimental setup and agronomic management

The study was carried out between January and December of 2019 in the municipality of Cajamarca, province of Tolima, in Colombia, at the geographic coordinates 4°23’44.4” N and 75°28’08.5” W. The soil of the experimental area was an Andisol with a sandy loam dominant texture, granular structure, moderately developed, and good natural drainage (Chaali et al., 2020). Five population densities (PD) were evaluated (Table 1) in a completely randomized block design with three replicates, using a total of fifteen experimental units each with an area of 30 m^2 and six rows with a length of 5 m, using the three central rows as a useful plot. The total test area was 682 m^2. The blocking factors were the slope gradient and soil chemical fertility. The arracacha genotype sown corresponds to the Agrosavia La 22 variety (Rodríguez et al., 2019).

Table 1. Population density treatments evaluated in the variety of arracacha (*Arracacia xanthorrhiza* Bancroft) Agrosavia La 22 variety. Cajamarca, Colombia. 2019.

Cuadro 1. Tratamientos de densidad poblacional evaluados en la variedad de arracacha (*Arracacia xanthorrhiza* Bancroft) Agrosavia La 22. Cajamarca, Colombia. 2019.

Treatment	Furrow distance (m)	Plant spacing (m)	Population density (plants ha^{-1})
1	1.00	1.00	10,000
2	1.00	0.75	15,000
3	1.00	0.50	20,000
4	1.00	0.40	25,000
5	1.00	0.33	30,000

Agronomic management was performed equally in all PD treatments. Mineral nutrition was calculated based on the nutrient content of the soil and crop requirements (Madeira et al., 2017). The control of insect pests and diseases was carried out chemically according to the incidence and level of damage found in plants.

Measurement of variables

Climate

From 50 days after sowing (DAS) were recorded the maximum daytime and minimum night temperatures, average relative humidity, solar radiation, and accumulated daily precipitation using a Vantage Pro2 automated weather station (Davis, San Francisco, CA, USA) located at the experimental field. The vapor-pressure deficit was calculated using Eq. 1, where Ta is the maximum daytime temperature, and HR is the relative humidity in percentage (García & Moreno, 2016).

$$VPD = 0.01078e^{\left(\frac{(17.269*\mathrm{Ta})}{(237.3+\mathrm{Ta})}\right)*\left(1-\frac{\mathrm{HR}}{100}\right)} \qquad (1)$$

Soil water potential

The volumetric soil moisture (θ) was evaluated at 167, 220, 240, and 286 DAS at a depth between 0-10 cm on nine plants per treatment recorded with a GS3 sensor (METER Group. Inc., Pullman, WA, USA) (Son et al., 2017). The soil water potential (Ψs) was calculated using Eq. 2, which was obtained from the soil moisture retention curve of the experimental batch.

$$\Psi s = 0.4514 + \frac{0.009}{\theta} \qquad (2)$$

Relative chlorophyll content

The relative chlorophyll content (RCC) was recorded at 167, 220, 240, and 286 DAS in nine plants per treatment on fully expanded leaves. A SPAD 502 chlorophyll meter (Konica Minolta, Japan) was used (Westerveld et al., 2004).

Leaf gas exchange

The light saturation point of the photosynthesis was estimated in 1,500 μmol m^{-2} s^{-1} (Figure 1) by elaborating a light response curve (0, 100, 300, 600, 900, 1,100, 1,400, 1,700 and 2,000 μmol m^{-2} s^{-1}) on nine plants, according to Vongcharoen et al. (2018). With a photonic flux density of 1,500 μmol m^{-2} s^{-1} and a CO_2 concentration of 400 μmol CO_2 mol^{-1}, were assessed the following leaf gas exchange parameters: net photosynthesis (A), stomatal conductance (gs), and transpiration at 167, 220, 240, and 286 DAS in fully expanded leaves of nine plants per treatment (Jaimez et al., 2008). The instantaneous water use efficiency (WUEi) was calculated as the A and transpiration ratio. An LI-6400 XT open system infrared gas analyzer (Li-Cor, Lincoln, NE. USA) was used.

Leaf temperature depression

Leaf and air temperature were evaluated with a thermocouple adapted to an LI-6400 XT open system infrared gas analyzer (Li-Cor, Lincoln, NE. USA). The LTD was calculated using Eq. 3, where Tf is leaf temperature, and Ta is the air temperature (Biju et al., 2018).

$$\mathrm{LTD} = \mathrm{Tf} - \mathrm{Ta} \qquad (3)$$

Photosynthetic reflectance index

Reflectance at 532 and 570 nm were recorded with an SRS-PRI sensor coupled to an EM-50 datalogger (METER Group. Inc., Pullman, WA, USA) between 11:00 and 12:00 hours at 286 DAS, corresponding to the end of a dry period. The photosynthetic reflectance index (PRI) was calculated employing Eq. 4 (Castro & Sanchez-Azofeifa, 2018).

$$PRI = \frac{\rho 532 - \rho 570}{\rho 532 + \rho 570} \qquad (4)$$

Where ϱ represents the reflectance at a specific wavelength. PRI values were expressed as the scaled PRI (sPRI) in a range of 0-1 using Eq. 5.

$$\mathrm{sPRI} = \frac{(1 + \mathrm{PRI})}{2} \qquad (5)$$

Leaf area index, fraction of light interception and light extinction coefficient

Leaf area index (LAI), fraction of light interception (Fi) and light extinction coefficient were evaluated at 220, 240, and 286 DAS between 11:00 and 12:00 hours with an Accupar LP-80 linear ceptometer (METER Group. Inc., Pullman, WA, USA). The leaf area index (LAI), PAR above (RS) and below the canopy (RD) was evaluated (Vahrmeijer et al., 2018). With this information, the fraction of light interception (Fi) was calculated using Eq. 6 (Shi et al., 2016), and the light extinction coefficient (k) was obtained using Eq. 7 (Flénet et al., 1996).

$$\mathrm{Fi} = 1 - \left(\frac{\mathrm{RS}}{\mathrm{RD}}\right) \tag{6}$$

$$\mathrm{k} = \frac{-\ln\left(\frac{\mathrm{RS}}{\mathrm{RD}}\right)}{\mathrm{LAI}} \tag{7}$$

Yield and cracking index

Yield evaluation was performed at 378 DAS. Thirty plants were harvested per treatment, and the total weight of healthy commercial roots, roots with cracking during harvest, and roots with cracking in the field were recorded. With this information, the cracking index in the field (CIf) and during harvest (CIh) were calculated using Eq. 8 and Eq. 9 adapted from Hartz et al. (2005).

$$CIf = \frac{Weight\ of\ roots\ with\ crackings\ in\ the\ field}{Total\ weight\ of\ roots} \tag{8}$$

$$CIh = \frac{Weight\ of\ roots\ with\ crackings\ during\ harvest}{Total\ weight\ of\ commercial\ roots} \tag{9}$$

Economic analysis

The profitability of the productive system was established using the difference between the gross profit and the production costs for each of the PDs evaluated (Page et al., 2019), using the 2018-2019 average sales prices for Colombia according to the Sistema de Informacion de Precios (SIPSA) of the Departamento Administrativo Nacional de Estadistica (2020).

Statistical analysis

The Michaelis Menten model was used for the identification of the light saturation point of photosynthesis. A third-order sigmoidal regression model was applied between yield, profitability, and PD. Data analysis was performed using generalized linear mixed models with the comparison of DGC means with a p-value of 0.05. The PD treatments and evaluation time were used as fixed effects and the block as a random effect. The best model was selected using the Akaike criterion with Bayesian information and maximum likelihood (Jaramillo-Barrios et al., 2019). The results only interpreted the factors and interaction that showed significant differences and the significant individual effects when the interaction did not show significant differences. The R-studio software version 1.1.463 was used.

Results

Climate behavior

The maximum daytime temperature ranged from 18-28.7 °C and the minimum temperature between 10-15.6 °C. Between 260 and 300 DAS, no precipitation occurred; after 300 DAS, daily rainfall of up to 58.4 mm was recorded. During the life cycle, the accumulated precipitation was 844.6 mm. Further, between 50-300 DAS, the daily radiation was less than 30,000 Cal cm^2 day^{-1}, and after 300 DAS, the solar radiation increased registering values of up to 56,262 Cal cm^2 day^{-1}. The vapor-pressure deficit throughout the plant life cycle was less than 1.0 KPa.

Soil water potential

The soil water potential (Ψs) did not exhibit significant differences because of the PDs, but were observed between the evaluation times (Table 2). During the four evaluation times, the Ψs showed a low variability that ranged between -0.49 and -0.51 MPa (Figure 1).

Table 2. Results of the analysis of the generalized linear mixed models for the evaluated parameters in populations densities in arracacha (*Arracacia xanthorrhiz*a Bancroft) Agrosavia La 22 variety. Cajamarca, Colombia. 2019.

Cuadro 2. Resultados del análisis de los modelos lineales mixtos generalizados para los parámetros evaluados en densidades poblacionales en arracacha (*Arracacia xanthorrhiz*a Bancroft) variedad Agrosavia La 22. Cajamarca, Colombia. 2019.

	Variation source		
Variable	**Population density**	**Assessment time**	**Population density x Time**
Soil water potential	*	ns	ns
Relative chlorophyll content	ns	***	*
Net photosynthesis	ns	***	ns
Stomatal conductance	*	***	**
Water use efficiency	ns	***	ns
Leaf temperature depression	ns	***	**
Photosynthetic reflectance index	***	na	na
Leaf area index	***	***	***
Fraction of light interception	***	***	***
Light extinction coefficient	ns	***	ns
Cracking index in the field	*	na	na
Cracking index during harvest	*	na	na
Number of commercial roots per plant	**	na	na
Average length of commercial roots	**	na	na
Average diameter of commercial roots	*	na	na
Average weight of commercial roots	***	na	na
Commercial yield	***	na	na

Not significant: ns; does not apply: na; p≤0.05: *; p≤0.01: **; p≤0.001: *** / No significativo: ns; no aplica: na; p≤0,05: *; p≤0,01: **; p≤0,001: ***

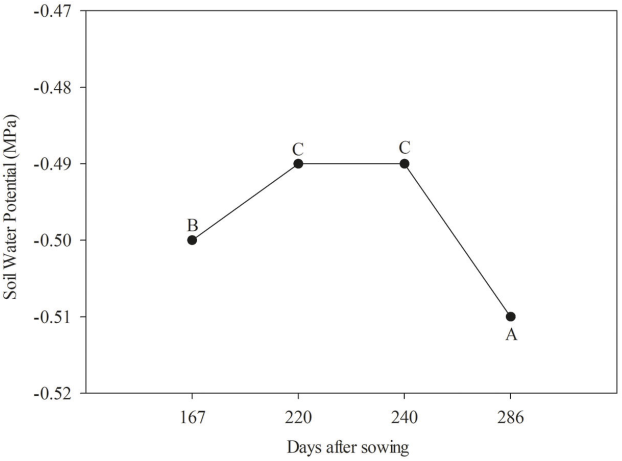

Figure 1. Soil water potential at a depth between 0-10 cm during four evaluation times of populations densities in arracacha (*Arracacia xanthorrhiza* Bancroft) Agrosavia La 22 variety. Cajamarca, Colombia. 2019.

The data shown are the means of three replicates with the standard error indicated by the vertical lines. Different letters indicate significant differences for p≤0.05, according to the DGC test.

Figura 1. Potencial hídrico del suelo a una profundidad de 0-10 cm durante cuatro tiempos de evaluación de densidades poblacionales en arracacha (*Arracacia xanthorrhiza* Bancroft) variedad Agrosavia La 22. Cajamarca, Colombia. 2019.

Los datos mostrados son el promedio de tres repeticiones con el error estándar indicado por las líneas verticales. Diferentes letras indican diferencias significativas para p≤0,05, según la prueba de DGC.

Relative chlorophyll content

The relative chlorophyll content (RCC) showed significant differences for the time-PD interaction (Table 2). A decreasing trend over time was observed for all PDs. With 20,000 plants ha^{-1} at 167 (40.22 SPAD) and 240 DAS (36.41 SPAD), a significantly higher RCC compared to the other PDs was found. The RCC in 220 and 286 DAS was statistically the same in all the PDs (Figure 2). The high difference between 167 and 286 DAS could be attributed to senescence or nitrogen remobilization. The high RCC found with 20,000 plants ha^{-1} it's an indicator of better nutritional status than the others PD.

Leaf gas exchange

The light saturation point was 1,500 μmol m^{-2} s^{-1}, where leaf gas exchange (A) was 14.28 μmol m^{-2} s^{-1}, and the light compensation point was 222.05 μmol m^{-2} s^{-1} of PAR (Figure 3). A showed highly significant differences in the time factor (Table 2). At 220 DAS, a was significantly higher (24.61 μmol m^{-2} s^{-1}) compared to the other evaluation times. Between 240 DAS (19.55 μmol m^{-2} s^{-1}) and 286 DAS (18.25 μmol m^{-2} s^{-1}), no statistical differences were observed (Figure 4A). The gs presented significant differences in the time-PD interaction (Table 2). At 167 and 286 DAS, there were no significant differences between treatments. At 220 DAS, the treatment of 20,000 plants ha^{-1} (0.76 mol m^{-2} s^{-1}) showed the highest gs, being significantly higher compared to the other PDs. At 240 DAS, the treatment of 30,000 plants ha^{-1} (0.79 mol m^{-2} s^{-1}) showed the highest gs with respect to the other PDs (Figure 4B). The WUEi exhibited highly significant differences for the time factor (Table 2) and was statistically different between all the evaluation times (Figure 4C). The lowest WUEi (3.11 μmol mol^{-1}) was found at 240 DAS.

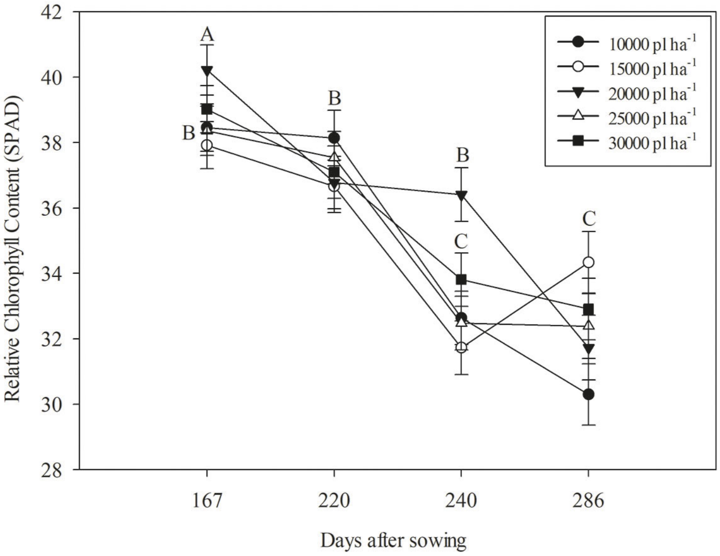

Figure 2. Relative chlorophyll content in four evaluation times for arracacha (*Arracacia xanthorrhiza* Bancroft) plants of the Agrosavia La 22 variety, subjected to five population densities. Cajamarca, Colombia. 2019.

The data shown are the means of three replicates with the standard error indicated by the vertical lines. Different letters indicate significant differences for $p \leq 0.05$, according to the DGC test. pl ha^{-1}: plants per hectare.

Figura 2. Contenido relativo de clorofila en cuatro tiempos de evaluación en plantas de arracacha (*Arracacia xanthorrhiza* Bancroft) variedad Agrosavia La 22, sometidas a cinco densidades poblacionales. Cajamarca, Colombia. 2019.

Los datos mostrados son el promedio de tres repeticiones con el error estándar indicado en las líneas verticales. Diferentes letras indican diferencias significativas para $p \leq 0{,}05$, de acuerdo con la prueba de DGC. pl ha^{-1}: plantas por hectárea.

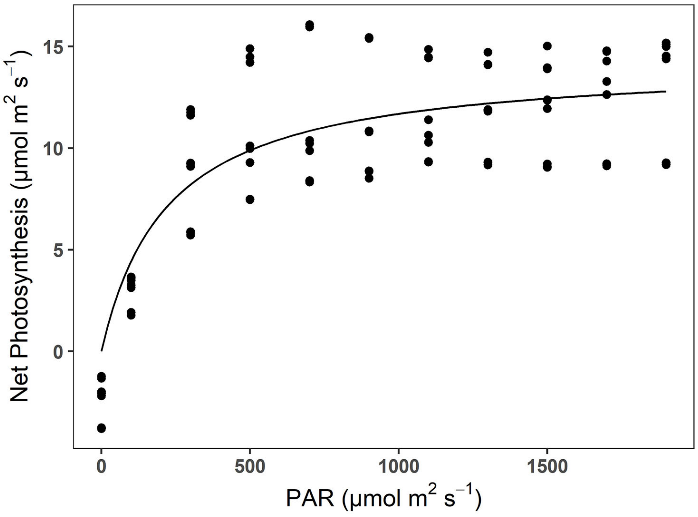

Figure 3. Michaelis Menten model for the response of photosynthesis to the photosynthetically active radiation (PAR) in arracacha (*Arracacia xanthorrhiza* Bancroft) plants of the Agrosavia La 22 variety. Cajamarca, Colombia. 2019.

Figura 3. Modelo Michaelis Menten para la respuesta de la fotosíntesis a la radiación fotosintética activa (PAR) en plantas de arracacha (*Arracacia xanthorrhiza* Bancroft) variedad Agrosavia La 22. Cajamarca, Colombia. 2019.

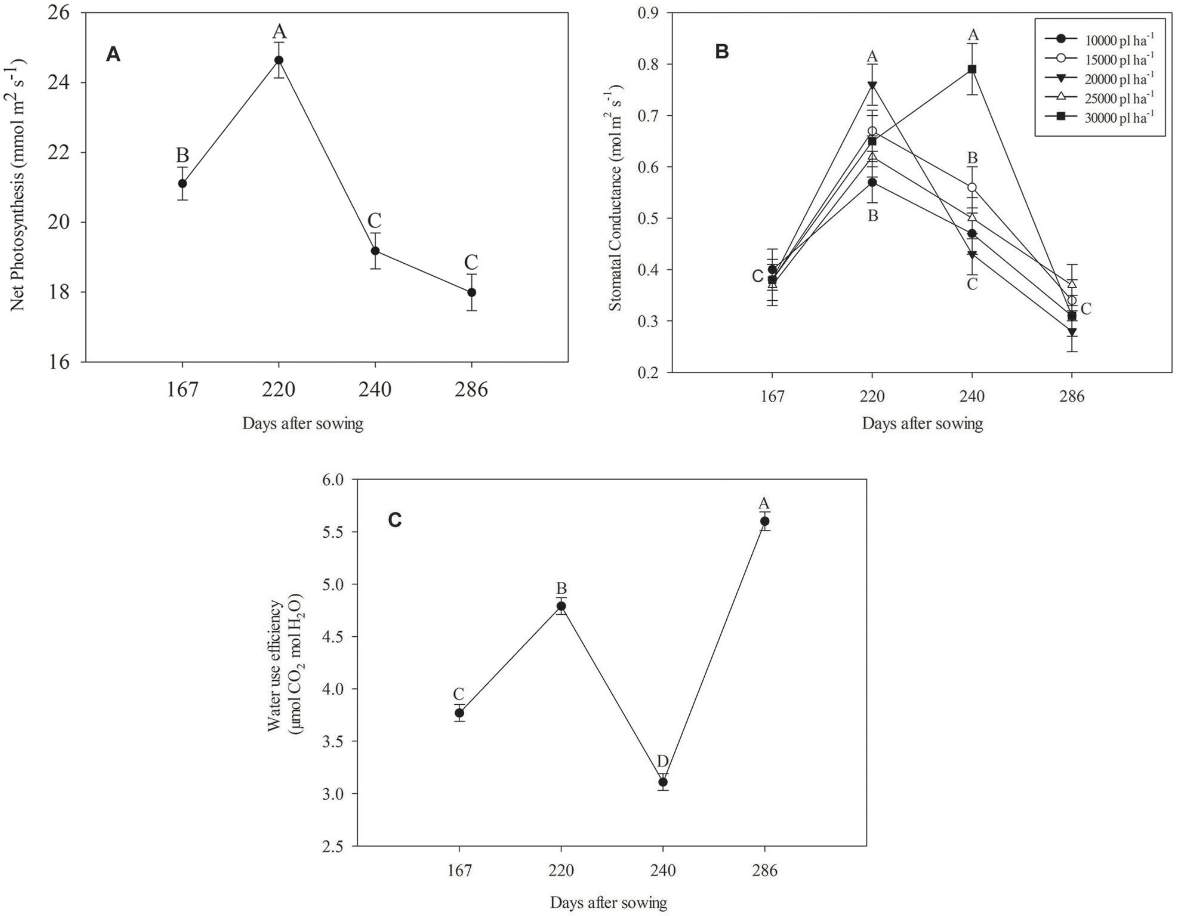

Figure 4. Leaf gas exchange variables for arracacha (*Arracacia xanthorrhiza* Bancroft) plants of the Agrosavia La 22 variety, subjected to five population densities in four evaluation times. Cajamarca, Colombia. 2019. A. Net photosynthesis, B. Stomatal conductance, and C. Instantaneous water use efficiency.

The data shown are the means of three replicates with the standard error indicated by the vertical lines. Different letters indicate significant differences for $p \leq 0.05$, according to the DGC test. pl ha^{-1}: plants per hectare.

Figura 4. Variables de intercambio de gases de la hoja para plantas de arracacha (*Arracacia xanthorrhiza* Bancroft) de la variedad Agrosavia La 22, sometidas a cinco densidades poblacionales en cuatro tiempos de evaluación. Cajamarca, Colombia. 2019. A. Fotosíntesis neta, B. Conductancia estomática, y C. Eficiencia instantánea en el uso del agua.

Los datos mostrados son el promedio de tres repeticiones con el error estándar indicado por las líneas verticales. Diferentes letras indican diferencias significativas para $p \leq 0,05$, según la prueba de la DGC. pl ha^{-1}: plantas por hectárea.

Leaf temperature depression and photosynthetic reflectance index

The leaf temperature depression (LTD) showed significant differences in the time-PD interaction (Table 2). Between 167-240 DAS, the LTD was <0, and no statistical differences were observed between the treatments. The treatment of 30,000 plants ha^{-1} at 240 DAS showed the lowest LTD (-1.3 °C), being statistically different from the other PDs. At 286 DAS, all the treatments showed a LTD>0 (Figure 5A). The photosynthetic reflectante index

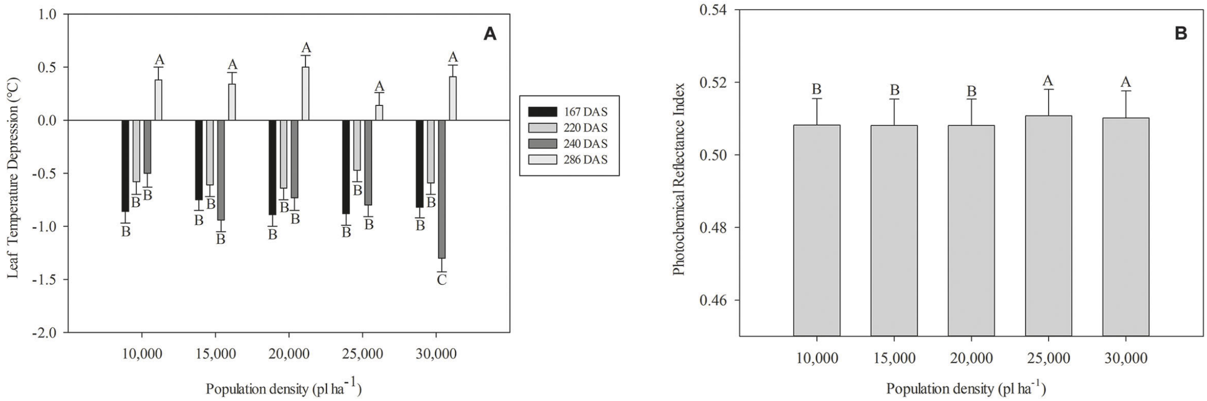

Figure 5. A. Leaf temperature depression in four evaluation times for arracacha (Arracacia xanthorrhiza Bancroft) plants of the Agrosavia La 22 variety, subjected to five population densities. Cajamarca-Colombia. 2019, and B. Photosynthetic reflectance index for arracacha (*Arracacia xanthorrhiza* Bancroft) plants of the Agrosavia La 22 variety, subjected to four population densities. Cajamarca, Colombia. 2019.

The data shown are the means of three replicates with the standard error indicated by the vertical lines. Different letters indicate significant differences for p≤0.05, according to the DGC test. pl ha^{-1}: plants per hectare.

Figura 5. A. Depresión de la temperatura de la hoja en cuatro tiempos de evaluación para plantas de arracacha (Arracacia xanthorrhiza Bancroft) de la variedad Agrosavia La 22, sometidas a cinco densidades poblacionales. Cajamarca, Colombia 2019, y B. Índice de reflectancia fotosintética para las plantas de arracacha (*Arracacia xanthorrhiza* Bancroft) variedad Agrosavia La 22, sometidas a cuatro densidades poblacionales. Cajamarca-Colombia 2019.

Los datos mostrados son el promedio de tres repeticiones con el error estándar indicado por las líneas verticales. Diferentes letras indican diferencias significativas para p≤0,05, según la prueba de la DGC. pl ha^{-1}: plantas por hectárea.

(PRI) showed highly significant differences between PDs (Table 2). The PDs of 10,000, 15,000, and 20,000 plants ha^{-1} were statistically equal (Figure 5B). On the other hand, the PDs of 25,000 and 30,000 plants ha^{-1} did not show statistical differences, and their PRI (0.51) was significantly higher than the PDs of 10,000, 15,000, and 20,000 plants ha^{-1}.

Leaf area index, fraction of light interception, and extinction coefficient

The leaf area index (LAI) showed highly significant differences in the interaction time-PD (Table 2). The LAI at 220 DAS showed an increasing trend as the PD increased, while the PDs of 20,000, 25,000, and 30,000 plants ha^{-1} had statistically equal LAI (2.90-3.02). At 240 DAS, the PDs of 30,000 and 25,000 plants ha^{-1} showed values of 3.69 and 2.9, respectively, for LAI, being statistically higher than the other PDs (Figure 6A). At 286 DAS, the LAI was statistically equal between the PDs, ranging from 1.62 to 1.27. The behavior of fraction of light interception (Fi) (Figure 6B) was similar to the one observed in LAI (Figure 7A). The highest Fi was found at 220 DAS (0.87-0.9) and 240 DAS (0.85-0.89) in the PDs of 25,000 and 30,000 plants ha^{-1}. The light extinction coefficient (k) showed highly significant differences by effect of the evaluation time (Table 2). Further, a decreasing trend was observed over time in the k (Figure 6C); at 220 DAS, the k was 0.78, being significantly higher than the other evaluation times.

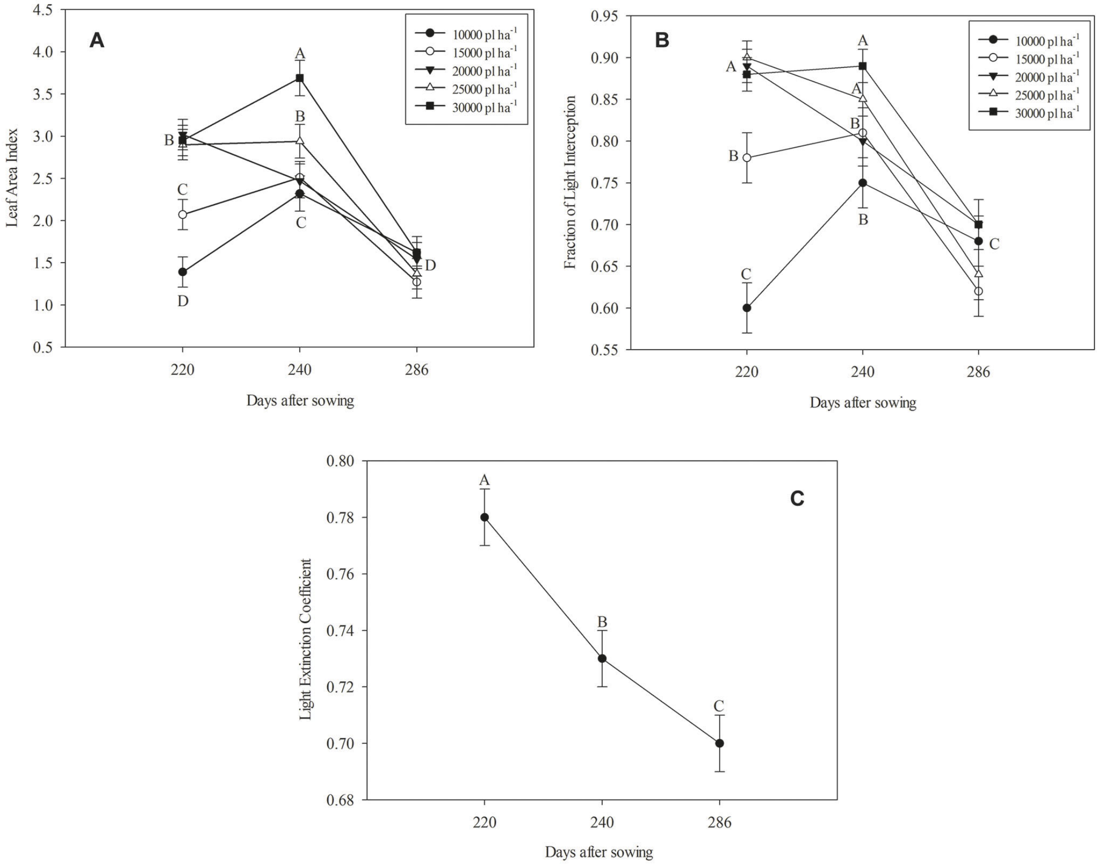

Figure 6. Canopy characteristics for arracacha (*Arracacia xanthorrhiza* Bancroft) plants of the Agrosavia La 22 variety, subjected to five population densities in four evaluation times. Cajamarca, Colombia. 2019. A. Leaf area index, B. Fraction of light interception, and C. Light extinction coefficient.

The data shown are the means of three replicates with the standard error indicated by the vertical lines. Different letters indicate significant differences for $p \leq 0.05$, according to the DGC test. pl ha^{-1}: plants per hectare.

Figura 6. Características del dosel de las plantas de arracacha (*Arracacia xanthorrhiza* Bancroft) de la variedad Agrosavia La 22, sometidas a cinco densidades poblacionales en cuatro tiempos de evaluación. Cajamarca, Colombia. 2019. A. Índice de área foliar, B. Fracción de interceptación de la luz, y C. Coeficiente de extinción de luz.

Los datos mostrados son el promedio de tres repeticiones con el error estándar indicado por las líneas verticales. Diferentes letras indican diferencias significativas para $p \leq 0{,}05$, según la prueba de la DGC. pl ha^{-1}: plantas por hectárea.

Cracking index in the field and cracking index during harvest

The cracking index in the field (CIf) and in harvest (CIh) presented significant differences by effect of the PD (Table 2). The CIf was significantly higher for the PD of 10,000 (0.24), and 15,000 (0.33) plants ha^{-1} compared to the other PDs that were statistically equal and their CIf ranged between 0.18 and 0.15 (Figure 7A). The CIh for the PD of 10,000 plants ha^{-1} (0.32) was significantly higher than the other PDs that showed a CIh between 0.26 and 0.17 (Figure 7B).

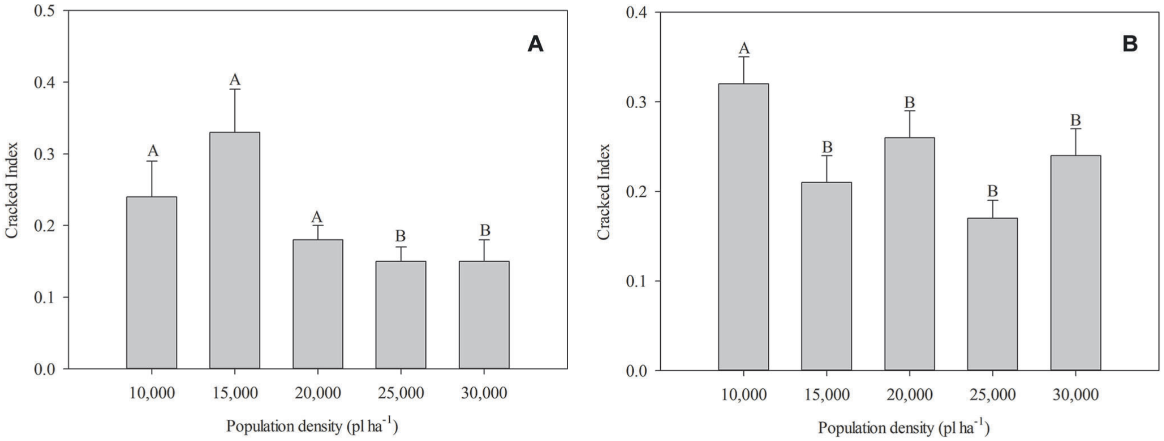

Figure 7. Cracking index for arracacha (*Arracacia xanthorrhiza* Bancroft) plants of the Agrosavia La 22 variety, subjected to five population densities. Cajamarca, Colombia. 2019.

A. Field cracking index, and B. Cracking index during harvest. The data shown are the means of three replicates with the standard error indicated by the vertical lines. Different letters indicate significant differences for p≤0.05, according to the DGC test. pl ha^{-1}: plants per hectare.

Figura 7. Índice de agrietamiento de las plantas de arracacha (*Arracacia xanthorrhiza* Bancroft) de la variedad Agrosavia La 22, sometidas a cinco densidades poblacionales. Cajamarca, Colombia. 2019.

A. Índice de agrietamiento en el campo, y B. Índice de agrietamiento durante la cosecha. Los datos mostrados son el promedio de tres repeticiones con el error estándar indicado por las líneas verticales. Diferentes letras indican diferencias significativas para p≤0,05, según la prueba de la DGC. pl ha^{-1}: plantas por hectárea.

Characteristics of commercial roots

All the characteristics of commercial roots showed significant differences between PDs, except for the average weight of commercial roots, which showed highly significant differences (Table 2). The characteristics of the commercial roots exhibited lower values with low PD (Table 3). The length, diameter, and average weight showed statistically equal values with PDs between 10,000 and 20,000 plants ha^{-1}. With PDs higher than 20,000 plants ha^{-1}, reductions in the length, diameter, and weight of commercial roots were observed (Table 3).

Table 3. Average characteristics of commercial roots of arracacha (*Arracacia xanthorrhiza* Bancroft) plants of the Agrosavia La 22 variety, subjected to five population densities. Cajamarca, Colombia. 2019.

Cuadro 3. Características promedio de raíces comerciales de arracacha (*Arracacia xanthorrhiza* Bancroft) de la variedad Agrosavia La 22, sometidas a cinco densidades poblacionales. Cajamarca, Colombia. 2019.

Population density (plants ha^{-1})	Number of commercial roots per plant	Average commercial root length (cm)	Average diameter of commercial root (mm)	Average commercial root weight (g)
10,000	12.08 ± 0.86 A	18.61 ± 0.66 A	57.49 ± 1.23 A	371.16 ± 17.20 A
15,000	9.50 ± 0.86 B	17.50 ± 0.66 A	58.05 ± 1.23 A	362.40 ± 21.26 A
20,000	8.83 ± 0.86 B	17.46 ± 0.66 A	57.20 ± 1.23 A	340.59 ± 20.23 A
25,000	9.33 ± 0.86 B	15.58 ± 0.66 B	53.35 ± 1.23 B	269.30 ± 14.71 B
30,000	7.25 ± 0.86 B	15.41 ± 0.66 B	54.14 ± 1.23 B	280.87 ± 20.28 B

The data shown correspond to the average of three replicates. Different letters indicate significant statistical differences (p≤0.05) according to the DGC test. Figures after the ± symbol indicate standard error. pl ha^{-1}: plants per hectare. / Los datos mostrados corresponden al promedio de tres repeticiones. Diferentes letras indican diferencias estadísticas significativas (p≤0,05) de acuerdo con la prueba de DGC. Cifras después del símbolo ± indican el error estándar. pl ha^{-1}: plantas por hectárea.

Yield

The commercial yield showed highly significant differences by effect of PD (Table 2). The lowest yield was found with the PD of 10,000 plants ha^{-1} (25.91 t ha^{-1}) and the highest yields with the PDs of 30,000 (43.65 t ha^{-1}) and 25,000 plants ha^{-1} (43.01 t ha^{-1}) (Figure 8A). A sigmoidal relationship (r^2=0.71) between PD and commercial yield was evident (Figure 8A). The yield curve stabilized with an PD of 22,000 plant ha^{-1}, reaching a yield of 41.96 t ha^{-1}. Hence, increasing the PD after 22,000 plants ha^{-1} did not generate a significant change in yield (Figure 8A).

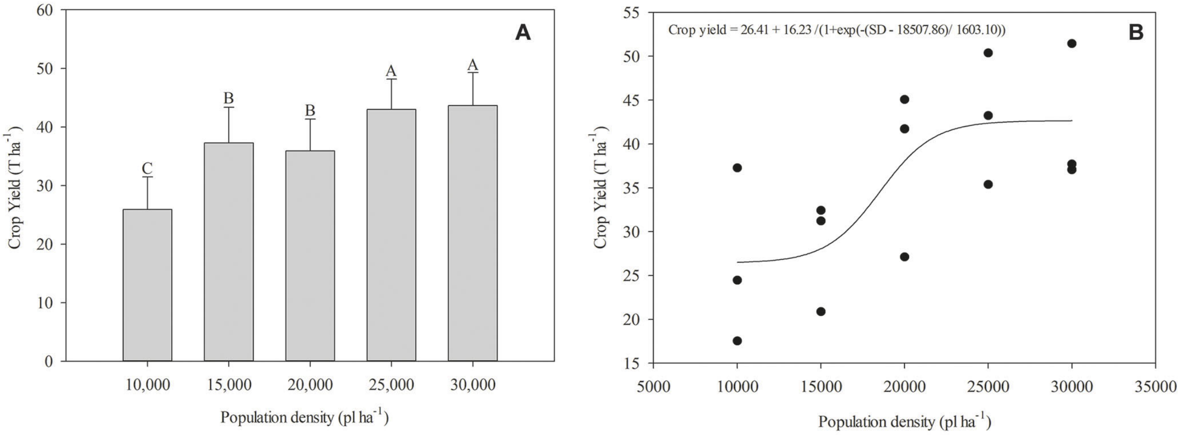

Figure 8. Commercial yield for arracacha (*Arracacia xanthorrhiza* Bancroft) plants of the Agrosavia La 22 variety, subjected to five population densities. Cajamarca, Colombia. 2019. A. Commercial yield, and B. Regression model for arracacha yield under different population densities.

The data shown are the means of three replicates with the standard error indicated by the vertical lines. Different letters indicate significant differences for $p \leq 0.05$, according to the DGC test. pl ha^{-1}: plants per hectare.

Figura 8. Rendimiento comercial de las plantas de arracacha (*Arracacia xanthorrhiza* Bancroft) variedad Agrosavia La 22, sometidas a cinco densidades poblacionales. Cajamarca, Colombia. 2019. A. Rendimiento comercial, y B. Modelo de regresión para rendimiento de arracacha bajo diferentes densidades poblacionales.

Los datos mostrados son el promedio de tres repeticiones con el error estándar indicado por las líneas verticales. Diferentes letras indican diferencias significativas para $p \leq 0,05$, de acuerdo con la prueba de DGC. pl ha^{-1}: plantas por hectárea.

Economic analysis

An increasing trend was observed in total income, production costs, and profitability depending on the PD. The PDs of 25,000 and 30,000 plants ha^{-1} showed profitability of US$ 16,215 and US$ 16,091, respectively, being higher than the other PDs (Table. 4). Using the regression model for profitability based on PD (r^2 = 0.92), the curve stabilized with an PD of 22,222 plants ha^{-1}, where a profitability of US$ 15,333.06 was obtained (Figure 9).

Table 4. Economic analysis of the productive system of arracacha (*Arracacia xanthorrhiza* Bancroft) plants of the Agrosavia La 22 variety, subjected to five population densities. Cajamarca, Colombia. 2019.

Cuadro 4. Análisis económico del sistema productivo de arracacha (*Arracacia xanthorrhiza* Bancroft) de la variedad Agrosavia La 22, sometido a cinco densidades poblacionales. Cajamarca, Colombia. 2019.

Population density (plants ha^{-1})	Total income ($)*	Total costs ($)*	Profitability ($)*	Monthly profitability ($)*
10,000	13,575	4,785	8,789	732
15,000	19,537	5,310	14,227	1,186
20,000	18,824	5,669	13,155	1,096
25,000	22,534	6,319	16,215	1,351
30,000	22,869	6,778	16,091	1,341

* Values in United States dollars (USD) with an average exchange rate for 2018 and 2019. pl ha^{-1}: plants per hectare. / * Valores en dólares estadounidenses (USD) con un promedio de tasa de cambio para el 2018 y 2019. pl ha^{-1}: plantas por hectárea.

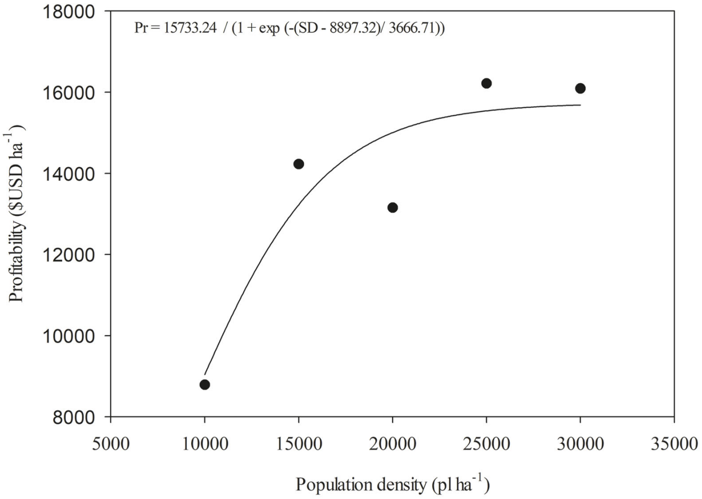

Figure 9. Profitability model for five population densities in arracacha (*Arracacia xanthorrhiza* Bancroft) plants of the Agrosavia La 22 variety. Cajamarca, Colombia. 2019.

The solid dots are the means of three replicates. The line is the trend curve developed using a third-order sigmoidal regression.

Figura 9. Modelo de rentabilidad para cinco densidades poblacionales en arracacha (*Arracacia xanthorrhiza* Bancroft) de la variedad Agrosavia La 22. Cajamarca, Colombia. 2019.

Los puntos sólidos son la media de tres réplicas. La línea es la curva de tendencia desarrollada usando una regresión sigmoidal de tercer orden.

Discussion

The current study showed the effect on the yield and economic indicators of five PDs and their relationship with leaf gas exchange and solar radiation interception processes. The PD is a decisive factor of crop yield (Liu et al., 2017). In arracacha there are few reports of the effect of PD on productivity (Graciano et al., 2007; Torales-

Pacito et al., 2015; Zarate et al., 2009), documenting PDs higher than 60,000 plants ha^{-1}. However, physiological processes such as solar radiation interception, leaf gas exchange, technical and economic viability associated with different PDs have not been studied.

In this research, the soil water potencial (Ψs) varied because of time and not of the PD (Figure 1), and the differences in time were related to changes in precipitation. The results contrast with those reported by Bermúdez-Florez et al. (2018) and Honda et al. (2019), those who found that low PDs were related to high soil moisture due to low water consumption. This behavior can be attributed to the fact that arracacha adjusts the root growth based on intraspecific competition in such a way that root tissue area in the soil does not change according to PD. According to Silva et al. (2014), the observed Ψs values suggest good water availability since the soil was found between 66-70 % of the moisture of field capacity. This result suggests that arracacha plants were not subjected to water deficit. Hence, the variability of commercial yield was not generated by water deficit (Chaali et al., 2020).

In the current research, the relative chlorophyll content (RCC) was higher than 30 SPAD in all the PDs (Figure 2). In a similar plant such as carrot, an RCC higher than 30 SPAD was related to a nitrogen content higher than 1.6 % (Westerveld et al., 2004), being this leaf nitrogen content optimal for carrot (Hanlon & Hochmuth, 2009). Hence, the increase in PD did not generate nitrogen deficiencies. This suggests that the functionality of the photosynthetic apparatus and enzymes involved in photosynthesis were not affected (Padilla et al., 2018). Nevertheless, the 20,000 plants ha^{-1} showed a high RCC, it indicated a better nitrogen status. The huge difference between 167 and 286 DAS could be generated by nitrogen remobilization (Kaur et al., 2015).

The leaf gas exchange (A) was evaluated from the beginning to the end of root filling. Because in arracacha this phenological stage is susceptible to water deficit (Chaali et al., 2020). The results showed that A was twofold (Figure 4A) and the yield was four times (Figure 8A) higher than the local variety of arracacha described by Jaimez et al. (2008). Thus, the Agrosavia La 22 variety has a higher yield potential due to its high photosynthetic capacity compared to genetic materials grown in Venezuela. This behavior observed in Agrosavia La 22 could be attributed to a better nitrogen use efficiency. This hypothesis should be addressed in future investigations.

High PDs can generate stress due to intraspecific competition and A measurement is a tool that can establish the degree of tolerance to these adverse conditions (Olechowicz et al., 2018). In this research, the PD did not affect A, and the observed differences are attributed to plant age (Figure 4A). This behavior was similar to the one reported by Jaimez et al. (2008). These reductions in A can be related to foliar senescence processes and the low demand for carbohydrates of the commercial root at this phenological stage. Because the peak of dry matter accumulation is between 150 and 240 DAS (mid-stage) (Chaali et al., 2020). Hence, the A may be downregulated by the source-sink relationship at late stage (>240 DAS). In Cassava, the competition for water between roots are given by a high PD to reduce leaf gas exchange (Silva et al., 2013). In this investigation, no water deficit was observed because of the PD; this explains the behavior evidenced in the leaf gas exchange process (Figure 4). Hence, the production of carbohydrates at leaf level used in growth processes and yield were not affected (Raines, 2011).

The leaf temperature variability indirectly estimates transpiration and gs, indicating water deficit (Biju et al., 2018) that could be generated by the effect of high PD (Bermúdez-Florez et al., 2018; Honda et al., 2019). The leaf temperature depression (LTD) did not show significant differences between PDs except for 240 DAS in the PD of 30,000 plants ha^{-1} (Figure 5A), and this was related to the water use efficiency (WUEi) (Figure 5C). This behavior was similar to what has been reported by Yang et al. (2014), where they found that the leaf temperature was the same with high or low PDs. The most negative LTD was observed at 240 DAS with 30,000 plants ha^{-1} (-1.4° C), which is a possible indicator of a moderate water deficit (Biju et al., 2018). However, this did not generate an effect in A (Figure 4A) and PRI (Figure 5B), which reflects the light use efficiency that is related to the photochemical efficiency of PSII (Castro & Sanchez-Azofeifa, 2018). In this sense, the high PD in arracacha did not generate a water deficit that affected the functionality and activity of the photosynthetic apparatus similar to what was reported by Olechowicz et al. (2018) in potato.

In the present research, the LAI was influence by PD but the light distribution in the canopy did not change by PD effect. Similar to what was reported by Quevedo et al. (2018), this suggests that it is a feature closely associated with the genotype. The observed k (Figure 6C) was typical of plants with planofile leaves (Wang et al., 2007), where the highest radiation uptake occurs in the upper third of the canopy. Nevertheless, during the maximum root filling (240 DAS), the PDs of 25,000 and 30,000 plants ha^{-1} showed a higher LAI and a Fi higher than 0.85 (Figure 6A-B). Further, it is possible that crop photosynthesis increased (Richards, 2000). What generates a more significant accumulation of carbohydrates destined for root storage that consequently gives a high yield (Jaimez et al., 2008). Hence, the LAI and Fi explain the high yield observed in the PDs of 25,000 and 30,000 plants ha^{-1}. However, these PDs reduce the number and size of the commercial root (Table 3), decreasing the yield per plant, similar to what Torales-Pacito et al. (2015) founds in arracacha and other root crop as Yacon (Doo et al., 2001). These changes in the yield components and the root size are due to intraspecific competition given by a high PD that affects growth so that the distribution of carbohydrates to the root is limited (Silva et al., 2013; Testa et al., 2016). Nonetheless, the yield is compensated by harvesting more plants (Hashemi et al., 2005). The direct relationship found between yield and PD (Figure 9B) has been previously described by Torales-Pacito et al. (2015) and Zarate et al. (2009). However, the performance data obtained with the best PD was 2.5-fold higher than what was reported by Torales-Pacito et al. (2015) and 4-fold higher than what Zarate et al. (2009) founds.

In the current study, the inflection point of yield was a PD of 22,000 plants ha^{-1} This means that the increase in the PD from 22,000 plants ha^{-1} onwards did not generate a significant increase in yield but using PD higher than 30,000 plants ha^{-1} could reduce yield. According to Torales-Pacito et al. (2015), this occurs because the commercial root yield of arracacha was reduced by decreasing the distance between plants less than 0.25 m.

Root cracking generates significant yield losses (Hartz et al., 2005). The CIf was reduced with the use of PD higher than 20,000 plants ha^{-1} (Figure 7A) because, with this PD, the commercial root reaches a small size, which makes it less susceptible to cracking (Table. 3). On the contrary, plants with larger roots such as those observed with low PDs are more susceptible to cracking. In commercial roots such as carrots, the quality is also measured through broken roots at harvest and healed wounds, which should not exceed 7 % for commercial acceptance (Richmond-Zumbado & Méndez-Soto, 2010). In the present research, the cracking index in PD higher than 20,000 plants ha^{-1} was near to 7 %. Nevertheless, the optimum cracking index for arracacha should be estimated in future research.

New agricultural management practices must be technically and economically viable (Zhang et al., 2018). By increasing the PD, an increase in the profitability of the production system was generated (Table 4), obtaining the best profitability (US$ 15,333.06) with 22,222 plants ha^{-1} (Figure 9). This behavior was similar to the one described by Torales-Pacito et al. (2015), who affirm that using a high PD, the profitability reaches US$ 19,227.37. The average profitability of arracacha for Colombia between the years 2006-2010 was US$ 3,184.25 (Gutiérrez-Malaxechebarría, 2011) in contrast to what this study obtained. Therefore, an increase of US$ 12,148.81 in production system profitability was generated using the optimal PD (22,222 plant ha^{-1}). The production cost increase with population density. Due to seed and harvest costs (Table 4). With optimal PD (22,222 plant ha^{-1}), the yield and production cost increase by 61.94 % and 17.56 %, respectively, compared to 10,000 plant ha^{-1}. It generates this high benefit-cost ratio. In annual crops such as corn and rice-wheat cropping system, high population densities have shown the best yields, profit margin, and optimal benefit-cost ratio for the farmer (Quevedo et al., 2018; Singh et al., 2020).

Conclusions

High population densities in *A. xanthorrhiza* plants did not generate water or nutritional limitations that affect the photosynthetic process. However, with high population densities increases the photosynthetically active radiation (PAR) interception and possibly increases crop photosynthesis allowing a greater accumulation and breakdown of carbohydrates towards the tuberous root. Therefore, yield increased as a function of population density.

In the population density of 22,222 plants ha^{-1} (1 m x 0.45 m), the Agrosavia La 22 variety reaches a yield of 41.96 t ha^{-1}. This PD shows the lowest cracking index at field and harvest due to having roots with less length, diameter, and weight. The profitability with this PD for the productive chain of $ 15333.06 USD. Nevertheless, the process validation of this practice to a commercial scale is necessary.

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