Plant spacing assessment in cocoa (*Theobroma cacao* L.) agroforestry systems in the Colombian Pacific region

Evaluación de densidades de siembra en sistemas agroforestales con cacao (*Theobroma cacao* L.) en la región Pacífica colombiana

José Ives Pérez-Zuñiga[1], Jairo Rojas-Molina[2*], and Andrés Felipe Zabala-Perilla[3]

ABSTRACT

Cocoa beans produced in the municipality of Tumaco (Colombia) are very attractive for chocolate producers and consumers because of their fine and aromatic characteristics. However, optimal plant spacing that could improve income for cocoa farmers is uncertain. To address the problem, this study was carried out from 2016 to 2017 taking into account two phases. In the first phase, a characterization of the cocoa production system in the Colombian Pacific region was conducted. This characterization included plant spacing, cocoa-associated species, production costs, financial sources, and system yields. In the second phase, an analysis of optimal plant spacing was conducted using the results from the characterization phase. Thus, a linear programming model was developed that utilizes the three plant densities most used by producers (3x3 m, 3.5x3.5 m, and 4x4 m). Labor force, monthly bank fees, and minimum farmer income were considered as constraints of the model. Profitability was established as the objective function. This model was optimized with GAMS software, using the CPlex solver. Plant spacing of 4x4 m (625 plants ha^{-1}) was found to be the optimal solution that maximized profitability. The minimum cocoa bean price required for this solution was 5,000 Colombian pesos kg^{-1} and the rural capitalization incentive (RCI) needed to be greater than or equal to 40%.

Key words: linear programming, profitability, incentives, plant density.

RESUMEN

Los granos de cacao producidos en el municipio de Tumaco (Colombia) son muy atractivos para los productores y consumidores de chocolate por sus características finas y aromáticas. Sin embargo, la distancia de siembra óptima que podría mejorar los ingresos de los cacaoteros es incierta. Para abordar este problema, este estudio se realizó entre 2016 y 2017 en dos fases. En la primera fase se realizó una caracterización del sistema de producción de cacao en el Pacífico colombiano que incluyó distancias de siembra, especies asociadas al cacao, costos de producción, fuentes de financiación, y rendimientos del sistema. En la segunda fase se realizó un análisis del espaciamiento óptimo de siembra con los resultados de la fase de caracterización. Así, se desarrolló un modelo de programación lineal que utiliza las tres densidades más usadas por los productores (3x3 m, 3.5x3.5 m y 4x4 m). La mano de obra, las cuotas bancarias mensuales y un ingreso mínimo del agricultor se consideraron como las restricciones del modelo. La rentabilidad se estableció como la función objetivo. Este modelo se optimizó con el software GAMS, utilizando el solucionador CPlex. Se identificó que el espaciamiento de 4x4 m (625 plantas ha^{-1}) era la solución óptima que maximizaba la rentabilidad. El precio mínimo del cacao requerido para esta solución era de 5000 pesos colombianos kg^{-1} y el incentivo a la capitalización rural (ICR) debía ser mayor o igual al 40%.

Palabras clave: programación lineal, rentabilidad, incentivos, densidad de plantación.

Introduction

In Colombia, cocoa production has high socio-economic relevance. Twenty-five thousand families depend on this crop, and more than 7.5 million labor days are generated annually. The reported planted area during 2017 reached 175,000 ha with a dry bean yield of 65,535 t (Baquero López, 2018). According to official data, cocoa is planted in 29 of the 32 departments of Colombia (Zambrano & Chávez, 2018). Because of weather and soil variability in these areas, cocoa beans produced in Colombia have favorable organoleptic characteristics for the national and international markets. Thus, 95% of Colombian cocoa beans are classified as "fine aroma cocoa", a valuable distinction given to only 5% of the grains in the world (Ballesteros *et al.*, 2015; FEDECACAO, 2019).

[1]   Corporación Colombiana de Investigación Agropecuaria (AGROSAVIA), Centro de Investigación El Mira, Tumaco, Nariño (Colombia).
[2]   Corporación Colombiana de Investigación Agropecuaria (AGROSAVIA), Centro de Investigación La Suiza, Rionegro, Santander (Colombia).
[3]   Purdue University, West Lafayette, Indiana (USA).
*   Corresponding author: jrojas@agrosavia.co

As a result of external market conditions, the global cocoa bean market is expected to grow, and both demand and prices are expected to increase. Based on these market circumstances, the Colombian government defined cocoa as "the peace crop", in a strategy that seeks the expansion of crops in the post-conflict areas of the country, as an option for economic development (USDA, 2018). The department of Nariño in the Colombian Pacific region stands out within the post-conflict areas as the sixth largest dry bean producer nationwide with 2871 t per year (FEDECACAO, 2019).

The municipality of Tumaco is responsible for 70% of the total cocoa production in the department. Several cocoa samples from Tumaco were internationally awarded the "Foreign Excellence" at the "Salon du Chocolat" in Paris (Ballesteros et al., 2015; Montoya-Restrepo et al., 2015).

Plant density is an important variable for crop productivity. Some previous reports have shown the variability in plant density (200 to 1,000 trees ha^{-1}) and cocoa production is frequently seen as a low-tech production system (Montoya-Restrepo et al., 2015). At the technical and production levels, variability in cocoa plant densities faces two main criteria. On the one hand, the government and chocolate factories (e.g., Casa Luker and Compañía Nacional de Chocolates) recommend cultivating 1,000 cocoa trees ha^{-1}, used as a reference density for granting agricultural loans and subsidies (e.g., rural capitalization incentive - RCI). The government only grants incentives to plantations with densities of 1,000 trees ha^{-1}. The percentage of government incentives can be as high as 40% (DNP, CVC, & UNICEF, 1983; Pinzón Useche et al., 2012). The criteria of some farmers in the Pacific coast of Colombia for planting cocoa are based on environmental conditions, such as high levels of relative humidity, high rainfall, and low luminosity that lead to planting at densities from 625 to 800 trees ha^{-1}. Since the densities differ from those recommended by the government, the RCI on agricultural loans is generally not granted to these producers.

Access to financial services, especially loans, enhances the development of the agricultural sector, mainly for small producers who do not have enough capital (Echavarría Soto et al., 2018). Perfetti et al. (2013) suggested that this practice has a negative impact on the aggregate consumption and, consequently, on the generation of new investment opportunities.

Formal loans are regularly offered to rural producers in Colombia through the Fund for the financing of the agricultural sector (FINAGRO), mainly by the Banco Agrario (Agricultural Bank of Colombia). These programs usually involve incentives, such as the RCI, that are granted as an additional resource that relieves the net cash flow of producers (FINAGRO, 2017).

Currently, there are no studies about the post-conflict of the Colombian Pacific zone that show that farmer incomes decrease when the planting density is reduced to less than 1,000 trees ha^{-1}. In this regard, some authors suggest that the plantations are easier to manage at slightly greater distances (Pinzón Useche et al., 2012). When cocoa is produced under agroforestry systems, shading plays an important role in the correct management of the crop and, consequently, in the generation of income for producers (Álvarez-Carrillo et al., 2013).

The main purpose of the algebraic linear modelling applied to agriculture is to identify the optimal outcome (maximum or minimum) from a mathematical model, including parameters, equations, and restrictions (Aliev et al., 2015). This method of optimization has been followed by Colombian and Latin American research institutions. For example, the Agricultural Research Corporation of Colombia (AGROSAVIA) and CIAT performed algebraic linear modelling in the models of adaptation and agroclimatic prevention (MAPA) initiative. By doing this, they identified technologies that maximize farmer's incomes in the country. Several regions and 18 crops, including cocoa, were evaluated. The results of the MAPA initiative allowed researchers and farmers to define the optimal method of introducing irrigation systems and fertilization plans to the crops (Ministerio de Agricultura, Fondo Adaptación, & CORPOICA, 2017).

This study aimed to assess the optimal plant spacing that would maximize the monetary income of cocoa producers in the Colombian Pacific, allowing the repayment of bank loans and the improvement of living standards.

Materials and methods

Study area

This research was carried out in the municipality of Tumaco (Fig. 1) located in the southeast of Colombia (2°48'24" N, 78°45'53" W) on the Pacific coast of the department of Nariño. It has a warm humid climate, with an average temperature of 28°C, average annual relative humidity of 83.86%, and annual precipitation of 2,531 mm. The municipality has an area of 3,760 km^2 and most of its territory is flat or slightly slopped (Angulo Guevara, 2016).

FIGURE 1. Location of the municipality of Tumaco in Colombia.

The municipality of Tumaco, with 134,992 ha suitable for agriculture (UPRA, 2020), has a vocation and productive commitment mainly based on traditional agriculture, fishing, forestry and, to a lesser extent, tourism. The agricultural sector is historically based on production systems such as cocoa, coconut, oil palm, and rice, and some specialty crops such as tabasco pepper (Bitácora & Territorio, 2017). However, illegal crops have affected traditional agricultural activities (UNODC, 2019). Cocoa crops are a productive alternative that is being promoted by the government for the substitution of illicit crops in the region (Barbosa, 2019).

Selection of cocoa farms and data collection in the municipality of Tumaco

Before visiting and/or selecting the farms to collect data, we carried out a review of reports and research studies focused on cocoa in the Pacific area of Nariño. By doing this, we were able to analyze the biophysical and socio-economic aspects of cocoa farmers in this region. To select the farms, we consulted cocoa corporations, community councils, producer associations, and agricultural technical assistance service providers (EPSAGROS). We then classified the study farms considering the variables crop age, planting

distance, and type of clone. Villages were selected using the criteria of five or more cocoa producers in the area, accessibility, and a planted area greater than 1 ha. The number of farms selected for each density was defined by stratified probability sampling, in which 10 farms were required for each density for sampling (Barrantes *et al.,* 2018).

Characterization of the farms and identification of cocoa tree spacing

Cocoa corporations and organizations provided a database of 926 producers, of which 95% had plant densities below 1,000 trees ha^{-1} (Compañía Nacional de Chocolates, 2012; Pinzón Useche *et al*., 2012). A total of 483 producers were surveyed in the townships of the municipality of Tumaco: Alto Mira (n = 45), Las Varas (n = 71), Medio Mira (n = 110), Rio Chagui (n = 87), Rio Tablon Dulce (n = 29), veredas adicionales (n = 8), zona carretera (n = 86), Rio Rosario (n = 47). Based on this data, 358 producers were not included, 335 because they were in areas affected by a social conflict (*e.g.,* presence of illegal armed groups), 15 because they were located in distal regions where there were no more than five cocoa farmers, and 8 because they had less than 1 ha of cocoa crop.

The information collected through the surveys and the structure (Pássaro, 2014) and function of traditional cocoa production systems were systematized using Excel software. A descriptive statistical analysis was performed to characterize the cocoa farms in the municipality of Tumaco. As a result, three planting densities were defined for the region, and these were used to model the optimal planting density.

Determining the optimum plant spacing

To determine tree spacing that allows cocoa farmers to maximize their profits, the linear programming method was used.

An algebraic model was developed based on costs and yields of each tree spacing (1,111, 816, or 625 trees ha^{-1}) along with parameters of typical prices and financial costs of the cocoa market in the municipality of Tumaco. The model was optimized with the Cplex solver, using the general algebraic modelling system (GAMS). Following linear programming, the model was used to identify the planting density that maximizes the gross margin (income minus costs) and allows local farmers to pay their annual obligations of a bank loan (offered by the Banco Agrario). Land and capital restrictions were included, stating that the start-up budget required was 15 million Colombian pesos (COP) ha^{-1}, adding the loan value and the farmer's own contribution. Given the purpose of the model, cash flow and optimal planting area outputs were used to determine the optimal condition for maximizing the producer's profit. Once the optimal planting density was obtained, simulations of price scenarios (3,500, 4,000, 4,500, 5,000, and 5,500 COP kg^{-1} of dry cocoa beans) and loan subvention levels (RCI = 20%, 40%, and no incentive = 0%) were carried out.

These simulations helped to determine the levels of prices and subventions that generate feasible and non-feasible outputs at a given density. In addition, a financial analysis was carried out using the net present value (NPV) approach. The NPV is an absolute metric for measuring economic profitability. This parameter expresses rates of return that allow investors to identify the financial efficiency of a project (*e.g.*, a cocoa crop) (Magni & Marchioni, 2020). Although other financial parameters could be used (*e.g.*, internal rate of return), because of the purpose of the study, only the NPV was calculated. This parameter allowed us to identify the cocoa plant spacing that maximizes financial income.

The NPV is calculated as follows:

$$NPV = \frac{Rt}{(1+i)^t} \qquad (1)$$

where NPV is the net present value (COP), Rt is the net cash flow at time t (COP), i is the discount rate (percentage), and t is the time of the cash flow (years).

Description of the model used

Sets:

    D: Densities (*ha*); (*d* = {1,.....m})

    T: Time periods (*year*); (*t*={1,....p})

Objective function:

$$\sum_{(d\in D)} \sum_{t\in T} \left((Y_t\, N_t\, P) - (C_t\, N_t)\right)$$

Parameters:

    A: Farm size (*ha*)

    P: Price (*COP kg^{-1}*)

    Y_t: *Yield per planting density per period* (*kg ha^{-1}*)

    C_t: *Costs per planting density per period* (*COP ha^{-1}*)

    I_t: *Minimum family income* (*COP*)

    K_t: *start-up budget* (*COP*)

Variables:

    N_t: *planted area per density per period* (*ha per year*)

    CF_t: *cashflow* (*COP per year*)

Constraints:

Land:

$$\sum_{(d\in D)} N_t \leq A \quad \forall\, t \in T, \quad \forall\, d \in D$$

Cash flow:

$$\sum_{(d\in D)} \left((Y_t\, N_t\, P) - (C_t\, N_t)\right) + CF_t\,(t-1) + K_t - I_t = CF_t, \forall\, t \in T$$

Results

Characterization of farms and identification of local planting densities

Among the 483 producers interviewed, 95% were currently using densities lower than 1,000 plants ha^{-1}. The most used densities by producers were: 816 trees ha^{-1} (87%), 943 trees ha^{-1} (7%), 1,100 trees ha^{-1} (5%), and 625 trees ha^{-1} (1%).

Regarding land ownership, 97% of the farmers owned the land they used for the cocoa crop and most of crops were on lands situated within the territories of community councils (ethnic entities that manage a territory collectively). Therefore, these lands were assigned as work areas for the families that were members of the community council, according to decree 1745 of 1995 (Ministerio de Agricultura, Fondo Adaptación, & CORPOICA, 2017), where 2% was leased, and 1% was under another form of land ownership.

Moreover, 72% of the producers had less than 3.3 ha planted with cocoa (Fig. 2) that showed that cocoa cultivation was a small-scale activity in this region. In many cases, producers complemented their labors in cocoa with other activities.
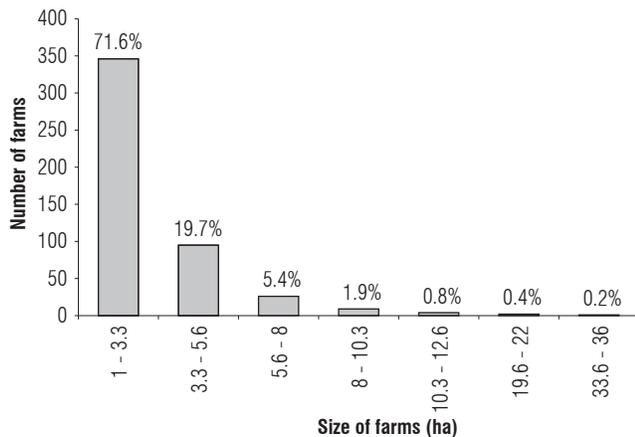
FIGURE 2. Size of areas established with cocoa crop in the municipality of Tumaco.

Cocoa accompanying species

On the Pacific coast of Nariño, cocoa is planted in agroforestry systems that were not included in the monoculture study. Although cocoa crops were already in the production stage, different species were still present in the crop (Fig. 3), predominantly timber, fruit, and plantain. These species are important for food security and generate income in the short, medium, and long terms.
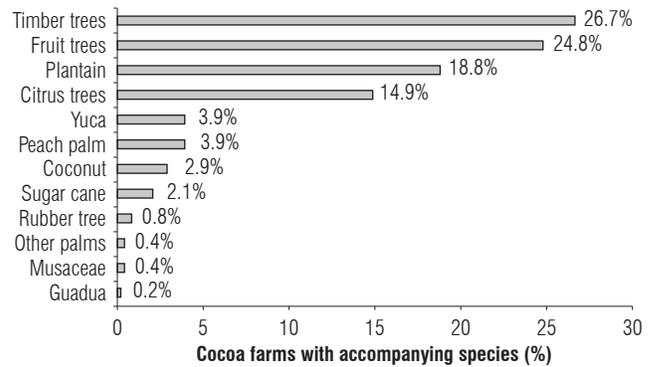
FIGURE 3. Cocoa farms with accompanying species in the municipality of Tumaco.

Financing the establishment and management of cocoa farming

Among the producers surveyed, 76.3% stated that the area they currently own and maintain was established with their own resources, and only 19.6% did so with the help of a loan (Fig. 4). However, when producers were asked why they did not expand their cocoa growing area, 63% of them indicated that the lack of resources through loan lines was one of the major causes for not planting new areas of cocoa (Fig. 5). Because of a lack of guarantees, cocoa farmers have difficulties for accessing bank loans. Most producers have not defined the legal situation of their land, so they do not have deeds to support the loan credit application since these are collective territories. Moreover, they cannot obtain the loan scores needed because they were not able to meet their obligations when loans were granted to them. This situation is sometimes due to a lack of banking assistance (CORDEAGROPAZ, 2011).
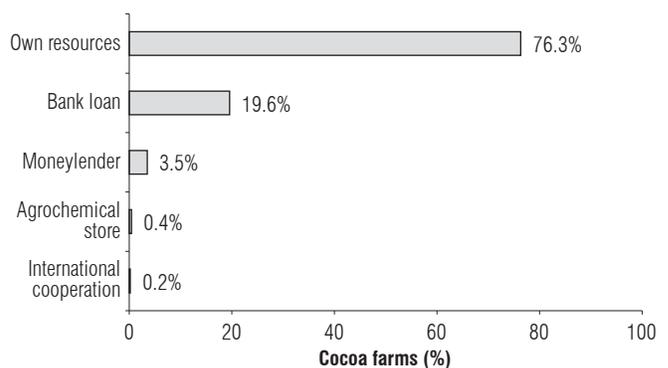
FIGURE 4. Percentage of farms with the financing sources used for the establishment and maintenance of cocoa cultivation in the municipality of Tumaco.
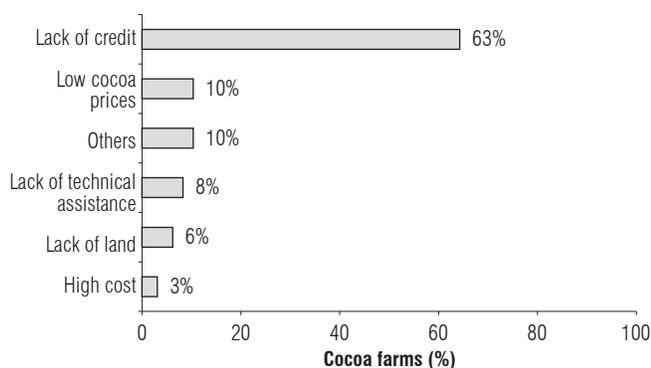
FIGURE 5. Percentage of farms with causes for not planting cocoa in new areas in the municipality of Tumaco.

Cocoa marketing

According to the results obtained in the diagnostics, there is a high level of intermediation; 65% of cocoa beans was sold to middlemen, suggesting that the price paid to the producer does not generate a surplus, making production non-profitable, 17% was sold to producer organizations, 17% was sold to the industry, and 1% was sold to cooperatives. Although cocoa farmers could sell the beans at higher prices at the market center without intermediation, the costs associated with the transportation from the farm to the market center are higher than the benefit of selling without intermediation. Therefore, they prefer to sell their products to an intermediate buyer. This situation was specially aggravated during seasons in which cocoa trees do not produce enough quantities of pods (April to October).

Determination of the optimal plant density in the municipality of Tumaco

Sixty-five farms were pre-selected using the data from the survey and the criteria areas planted with cocoa (greater than 1 ha) and sowing density. These farms were then visited by the research team to verify the information provided by the producer at field level. Among these farms, 16 did not meet the above-mentioned criteria and, therefore, were discarded. Also, several farms were not selected because they showed the same density of cocoa planting. This allowed, in some cases, selecting up to 10 farms per planting density. Finally, the data revealed that the most common densities used by cocoa farmers with technified crops in

Tumaco are 625, 816, and 1,111 trees ha^{-1}. However, for the last density it was not possible to obtain the number of representative farms. This left a total of 22 farms in different parts of the municipality of Tumaco to be analyzed by the model.

A specific economic survey was applied to the producers of the 22 selected farms. In addition, an area of 40 x 40 m was delineated in the farms, and, within this area, 20 cocoa trees were selected to monitor production and incidence of diseases. This process allowed the consolidation of information for quantifying the costs and income generated by the activity of cocoa producers in the region of Tumaco. With the organized information, it was possible to determine the activities and infer the costs (considering prices in 2016) incurred in the cocoa activity in the region of Tumaco (Tab. 1).

The analysis of start-up and production costs (Tab. 1) allowed inferring that the farmers did not invest in drainage construction during any year, despite the high levels of rainfall and constant crop flooding. The number of daily labors used in the first year of cultivation was 194, 182, and 84 for planting densities of 816, 1,111, and 625 trees ha^{-1}, respectively. Moreover, the greatest demand for labor was observed in the planting density of 816 trees ha^{-1} (1072 labor days). This was mainly because this density requires more crop management tasks than other densities. Indeed, under a density of 1,111 trees ha^{-1} 668 labor days are required, and under a density of 625 trees ha^{-1} 493 labor days are required (Fig. 6).

Regarding start-up and general management activities, more than 20% of labor days corresponded to weed control. This proportion is higher in the 625 trees ha^{-1} scheme, probably because of more free space in which weeds can grow.

The yield ha^{-1} in the main components of the agroforestry system with cocoa also varied (Tab. 2). For this specific analysis, the harvest of other crops (different from cocoa and plantain) was not included (*i.e.*, some other crops were harvested to be consumed within the farm). Likewise, within the evaluation period, the yield of timber products

TABLE 1. Estimated annual costs ha^{-1} for the cocoa plant densities in the municipality of Tumaco.

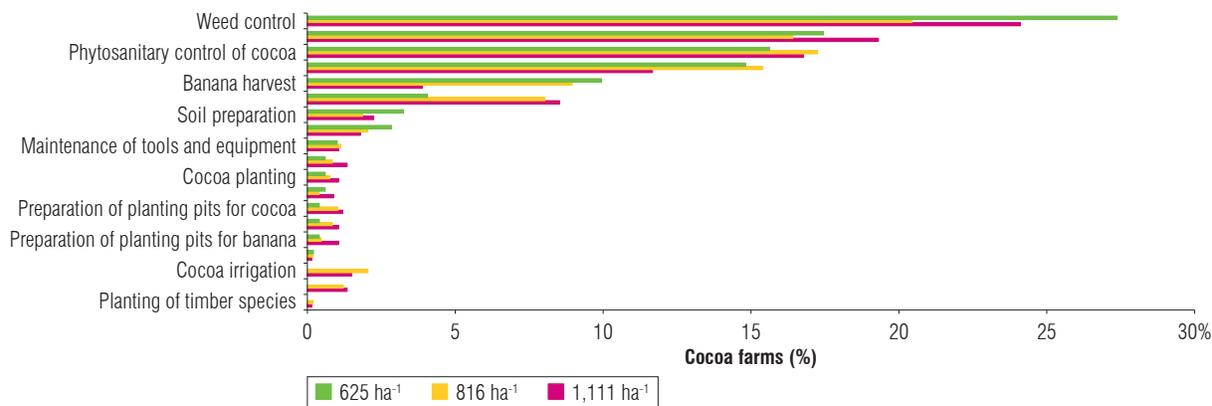| Plant density (trees ha^{-1})	Years of establishment of the plantation				
	1	2	3	4	5-10
1,111	8,928,400	6,406,000	3,905,800	2,789,500	3,327,000
816	9,683,600	12,552,800	8,430,400	4,162,600	4,392,600
625	4,553,300	4,386,600	3,394,000	2,288,00	2,533,000

FIGURE 6. Percentage of farms with activities reporting the greatest use of wages by cocoa crop in the first 5 years of cultivation in the municipality of Tumaco.

TABLE 2. Yield (ha⁻¹) of the components of the cocoa agroforestry system by planting density.

Planting density (plants ha⁻¹)	Yield (ha⁻¹)	Year				
		1	2	3	4	5-11
1,111	Cocoa dry beans (kg)	0	561	514	510	455
	Plantain (hundred)	44	46	29	0	0
816	Cocoa dry beans (kg)	0	620	944	711	733
	Plantain (hundred)	107	88	64	x	x
625	Cocoa dry beans (kg)	0	630	772	701	864
	Plantain (hundred)	73	90	43	20	x

Hundred: 100 fingers of bananas, which is the way bananas are marketed in the municipality of Tumaco.

was not included because the harvesting period was longer than 12 years. In the short term (years 2 to 4), the best yield was obtained at a density of 816 trees ha⁻¹ and in the medium term (years 6 to 11) the highest yield was recorded with a density of 625 trees ha⁻¹. This is probably related to cocoa tree growth since as the crop matures, the rows become more closed and, if there is no adequate pruning and disease control, this affects the production of the crop (Tab. 2).

Optimal planting area

The data shown in Table 3 (sets, scalars, and parameters) was used as an input for the model studied here. After compiling these data, iterations under linear programming assumptions rendered financial viability results only in the 4x4 m plant density. For this density, the model compilation found an optimal solution, in which the profit variable (revenues minus costs) was maximized, and land and cash flow constraints were met.

According to the results obtained, the solution that maximizes the profit and complies with all the restrictions was the planting of the 4x4 m density, in the totality of the

available area (1 ha) (Fig. 7), during the deadline for the payment of the loan (11 years).

This result indicated that, for the area studied, the 4x4 m density maximized the income of the cocoa producers and allowed farmers to cover the obligations of the agricultural loan offered by the Banco Agrario.
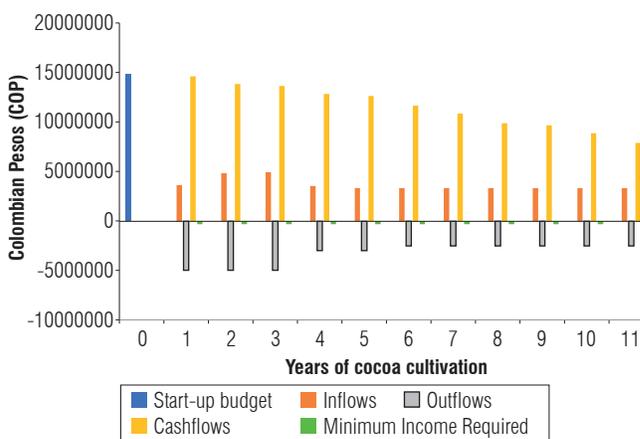

FIGURE 7. Cocoa system cash flow under a 4x4 m plant density in the municipality of Tumaco.

TABLE 3. Input from the microeconomic optimization model for three densities of cocoa planting in the municipality of Tumaco.

Type of data (input)	Data description	Data
Set	Year	1-11
Set	Densities (m)	3x3 3.5x3.5 4x4
Scalar	Crop area (ha)	1
Scalar	Price (COP kg⁻¹)	5,500
Parameter	Minimum family income (COP) per year	500,000
Parameter	Start-up budget (COP)	15,000,000
Parameter	RCI (%)	40
Parameter	Annual loan payment (COP)	Years 1-3 = 1,552,000 Year 4 = 2,882,000 Year 5 = 2,688,000 Year 6 = 2,494,000 Year 7 = 2,300,000 Year 8 = 2,106,000 Year 9 = 1,912,000 Year 10 = 1,718,000 Year 11 = 1,524,000
Parameter	Gross margin (COP)	= incomes – total costs

RCI - Rural capitalization incentive.

Cash flow

The output of this component (Fig. 7) was made up of total income, expenses, and initial capital, corresponding to the value of the loan granted by the Banco Agrario and the amount contributed by the farmer. It should be noted that the annual income included the minimum income value for the family, in this case $500,000 COP per year ha⁻¹ (above this value, the model does not find an optimal solution).

The cashflow values for all periods were positive, which guarantees that the farmer had the necessary financial resources to carry out the cultivation labors. Given the value of the initial capital, the farmer could cover the expenses from year 1 to year 4, the time range in which cocoa maintains low production and relatively low income. From year 4 onwards, expenses are stabilized and income increases, generating a considerable increment in capital flow. This increase can be considered as the surplus between total income and the established minimum family income.

Behavior of the net present value (NPV)

Given the planting system cash flow for the 4x4 m density in the municipality of Tumaco, NPV behavior was evaluated with a 10% discount rate to determine, under this parameter, the financial viability of the investment. This discount
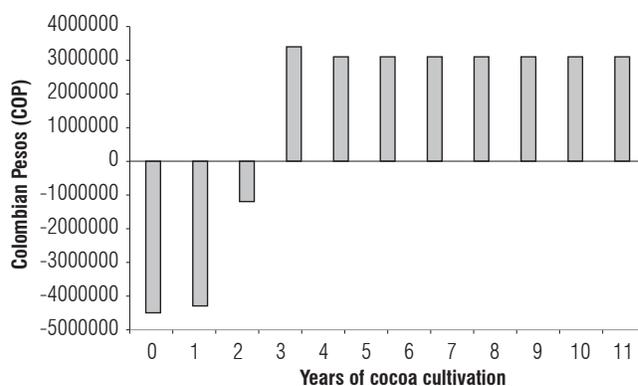

FIGURE 8. Discounted cash flow of the cocoa production system under a plant density of 4x4 m.

rate is between the values mentioned by Piraquive Galeano *et al.* (2018). The exception is that this cash flow does not include the leverage that the farmer carries out with the bank loan; therefore, neither the initial capital nor the annual loan obligations shown in Figure 8 were considered.

The cash flow behavior (income and expenses) of the density that maximized the profit for the municipality (4x4 m) showed a positive NPV (4,390,003 COP) during the evaluated period (11 years) (Fig. 8). Under this modeling scenario, based on this parameter, the planting system

showed financial viability and the data are consistent with the results of the previously proposed model.

RCI and price scenarios

To determine the effect of the variation on both the RCI and the cocoa bean price in Tumaco, modeling was carried out and the viability of the cocoa production system was observed at a density of 4x4 m in nine combined scenarios (three price scenarios and three RCI scenarios) (Tab. 4). The modeling "base" was selected subjectively, assuming a cocoa price at the lowest level in the current period (4,500 COP kg^{-1}) and a bank loan without subsidy or incentive (RCI = 0%). The other values, 20% and 40% for the RCI, were set assuming the actual rate for the area (40%) and its average value (20%). The price values of the remaining scenarios were set considering the average of historical cocoa prices over the last 7 years (5,500 COP kg^{-1}) and the price at the time of modelling (4,700 COP kg^{-1}).

TABLE 4. Feasibility of rural capitalization incentive (RCI) scenarios and prices for a 4x4 m plant density in the cocoa system in the municipality of Tumaco.

Price (COP)	RCI (%)		
	40	20	0
5,500	Feasible	Not feasible	Not feasible
5,000	Feasible	Not feasible	Not feasible
4,500	Not feasible	Not feasible	Not feasible

According to the RCI scenarios and prices proposed in the model, only under conditions of RCI 40% with prices above 5,000 COP kg^{-1}, the model showed viable results (Tab. 3).

Discussion

The information from the survey of 483 producers revealed that most of them planted cocoa with a density of less than 1,000 trees ha^{-1}, disagreeing with the recommendations for cocoa cultivation in the country (Compañía Nacional de Chocolates, 2012; Pinzón Useche *et al.*, 2012). These recommendations have not been implemented due to several factors such as low support from governmental and/or private institutions, absence of bank loan programs focused on cocoa crop establishment and development, proliferation of illicit crops and/or crop switching (*e.g.*, establishment of oil palm), and insufficient knowledge about the technical management of the crop (CORDEAGROPAZ, 2011).

Regarding the area planted with cocoa, 72% of the producers have less than 3.3 ha planted with this species (Fig. 2) that is the minimum recommended economic area for

the crop (Moreno Rozo & López Villalobos, 2013). This result is consistent with a characterization performed in a community council in Tumaco where the size of the production unit of 55.4% of the producers included areas between 2 and 3 ha. Preciado *et al.* (2011), in a study of the traditional system of cocoa in the region, concluded that 53% of producers have areas of 1 to 5 ha. These assessments state that the size and low yields of areas cultivated with cocoa do not generate capital accumulation because income and expenditure are equivalent, making producers engage in other productive activities. In Tumaco and other frontier regions of Colombia, the infrastructure for transporting the product is less developed and there are difficulties for moving the cocoa beans to purchasing centers. Therefore, marketing costs are higher, and the prices and income received by the producer are low (Abbott *et al.*, 2018).

Espinosa-Álzate and Ríos-Osorio (2016) classified the cocoa production systems in Tumaco into two groups: complex local systems with greater biodiversity and commercial exploitation systems with less biodiversity and a greater number of cocoa trees (plant density greater than 1,000 trees ha^{-1}). In this study, there was no evidence for the presence of crops with commercial exploitation systems, also identified by several authors. In these crops the predominance of timber and fruit species and banana stands out, with the latter being important for food security and, in the case of timber, for generating income in the short, medium and long terms (Aguiño, 2010; Laing, 2011; Preciado *et al.*, 2011).

Other studies have shown that cocoa production profitability depends on four factors: 1) the plant material used, 2) the plant densities, 3) the type of system adopted (*e.g.*, agroforestry), and 4) the crop technological management. Moreover, agroforestry systems with yields above 1,000 kg ha^{-1} and cocoa prices above 4,800 COP kg^{-1} of bean dry weight are economically viable options for farmers (Pinzón Useche *et al.*, 2012; Yambure *et al.*, 2014). For profitability indicators to be positive, annual production should be between 1,500 and 2,000 kg of dry beans ha^{-1}, with the minimum production unit being 3 ha (ERS - ABC USAID/MIDAS Crops, 2009). In this way, it is possible to obtain the internal rate of return (IRR that is an interest rate that equates the current worth of a cash flow stream to zero) values of 46.7% and 55.5%, respectively.

In Mexico, cocoa cultivation is profitable for the humid tropics when it produces more than 770 kg dry beans ha^{-1} even with variations in price and increased costs of fertilizers (Espinosa-García *et al.*, 2015). A net profit for cocoa

cultivation is obtained when the crop is properly managed with 1,000 trees ha^{-1} under the conditions of Colombia, with a yield of 2,000 kg ha^{-1} and a price of 7,000 COP kg^{-1} of dry cocoa in 2016 (Barón Urquijo, 2016). For the Caquetá region, a feasibility study of cocoa cultivation in agroforestry arrangement results in positive financial indicators with an IRR of 5.23%, a benefit-cost ratio of 6.45, and a planting density for cocoa of 1,000 trees ha^{-1} (Yañez Agudelo, 2009).

In Tumaco, cocoa is traditionally cultivated with low planting densities from 200 to 250 trees ha^{-1}. However, new crops are being planted at densities such as 800 trees ha^{-1}, especially by using loans to finance them. This is the determining factor for access to financial services used to boost economic growth because of its positive impact on aggregate consumption and the generation of investment opportunities (Perfetti *et al.,* 2013). However, due to the difficulties for accessing loans in the region, this factor was not identified as a strategy for improving or increasing cocoa areas according to Montoya-Restrepo *et al.* (2015). Espinosa-Álzate and Ríos-Osorio (2016) identified the reduction of product sales to intermediaries in the chain as a priority action for strengthening organizational processes to achieve economies of scale. However, this is a complex action since the producers only harvest small volumes in very heterogeneous conditions of presentation and quality, making it very difficult for farmers to meet the market demands (DNP, 2014).

FEDECACAO currently recommends planting approximately 1,000 trees ha^{-1}, which is a reference for FINAGRO to apply for 40% RCI. This is a complex issue for the Pacific region, that has high cloudiness, rainfall, and temperature. These conditions favor a rapid development of plants with exuberant foliage, but they also allow the occurrence of diseases as well as increased production costs due to a higher demand for labor such as pruning and phytosanitary management. In this study, the number of labor days used in the first year of cultivation was 194, 182, and 84 for planting densities of 816, 1,111, and 625 trees ha^{-1}, respectively. For the planting density of 1,111 trees ha^{-1}, this value is lower than that reported by Pinzón Useche *et al.* (2012) for the same density.

The economic analysis carried out in this study showed that RCI is required for the producer to maintain a positive cash flow. Therefore, the cocoa farmers might ask FINAGRO and the Banco Agrario to recognize the incentive for new crops with planting densities used in the municipality of around 625 to 800 trees ha^{-1}.

The linear programming method used helps to improve resource allocation and optimize profit. For example, Adewumi *et al.* (2020) used linear programming to allocate the best land use efficiency in farms in Nigeria and found that the best solution for increasing yield was to employ mixed cropping instead of monocropping. Indeed, these data showed that the mixed cropping strategy increased the net income return to farmers and optimized the land use efficiency. Shirshahi *et al.* (2020) also used linear programming to optimize crop areas and water allocation in Iran, with profit maximization as the objective function. In that study, higher revenue was obtained using less area and water, by selecting species that are well acclimated to those environmental conditions.

Conclusions

Cocoa farmers in Tumaco have, on average, less than 1,000 trees ha^{-1} planted and a total yield of 400 kg of dry cocoa ha^{-1}. Consequently, to make cocoa crops viable in the Colombian Pacific zone, a rural capitalization incentive (RCI) of 40% is required. Additionally, we recommend to cocoa farmers to use the 4x4 m planting density when establishing their crops. These conditions, with prices above 5,500 COP kg^{-1}, allow cocoa farmers not only to pay the bank loan fees but also to obtain an income from the cocoa production.

Conflict of interest statement
The authors declare that there is no conflict of interest regarding the publication of this article.

Author's contributions
JIPZ and JRM designed the experiments; JIPZ conducted the experiments; JIPZ, JRM and AFZP wrote the article; JIPZ, JRM and AFZP contributed to the data analysis. All authors improved and approved the article.

Literature cited

Abbott, P. C., Benjamin, T. J., Burniske, G. R., Croft, M. M., Fenton, M. C., Kelly, C. R., Lundy, M. M., Rodriguez Camayo, F., & Wilcox Jr., M. D. (2018). *An analysis of the supply chain of cacao in Colombia.* Purdue University, International Center for Tropical Agriculture (CIAT). https://cgspace.cgiar.org/bitstream/handle/10568/96636/Cacao_Final_Report.pdf?sequence=5&isAllowed=y

Adewumi, A., Tanko, L., Ibrahim, F. D., & Yisa, E. S. (2020). Net returns maximizing combination of arable crops among smallholder farmers in Kaiama agricultural zone of Kwara State, Nigeria. *Asian Journal of Economics, Business and Accounting, 15*(4), 66–74.

Aguiño, J. E. (2010). *La perspectiva de desarrollo agroindustrial y empresarial de los productores de cacao del municipio de Tumaco departamento de Nariño.* [Unpublished master's thesis]. Universidad de Nariño.

Aliev, R. A., Alizadeh, A. V., Huseynov, O. H., & Jabbarova, K. I. (2015). Z-number-based linear programming. *International Journal of Intelligent Systems, 30*(5), 563–589. https://doi.org/10.1002/int.21709

Álvarez-Carrillo, F., Rojas-Molina, J., & Suarez-Salazar, J. C. (2013). Simulation arrangements cocoa agroforestry as a diagnosis and planning strategy for producers. *Ciencia y Tecnología Agropecuaria, 13*(2), 145–150. https://doi.org/10.21930/rcta.vol13_num2_art:249

Angulo Guevara, M. E. (2016). *Plan de desarrollo municipal 2016 - 2019: Tumaco nuestra PAZión.* Alcaldía municipal de Tumaco. https://cpd.blob.core.windows.net/test1/52835planDesarrollo.pdf

Ballesteros, W., Lagos, T. C., & Ferney, H. (2015). Morphological characterization of elite cacao trees (*Theobroma cacao* L.) in Tumaco, Nariño, Colombia. *Revista Colombiana de Ciencias Hortícolas, 9*(2), 313–328.

Baquero López, E. (2018, November 23–24). *Federación Nacional de Cacaoteros, Fondo Nacional del cacao* [Conference presentation]. Quinto seminario internacional de saberes y sabores de cacao: aromas de paz, Bogotá, Colombia. https://drive.google.com/file/d/1s5molI7fsrauRD8AAYX1-fvy4XwvcWNr/view

Barbosa, F. (2019, July 21). Plátano, coco y cacao remplazan la coca en Tumaco. *Semana.* https://www.semana.com/medio-ambiente/articulo/cultivos-tradicionales-reemplazan-la-coca-en-tumaco/45085/.

Barón Urquijo, J. D. (2016). *El cultivo del cacao; un negocio rentable, competitivo y ambientalmente sostenible en Colombia.* Fondo Nacional del Cacao.

Barrantes, C., Siura, S., Castillo, E., Huayarca, M., & Rado, J. (2018). *Manual para el análisis de la sostenibilidad de sistemas de producción de la agricultura familiar.* Instituto Interamericano de Cooperación para la Agricultura. http://repositorio.iica.int/bitstream/handle/11324/7035/BVE18040193e.pdf?sequence=1

Bitácora & Territorio. (2017). *Lectura territorial de San Andrés de Tumaco.* Fondo Internacional de Desarrollo Agrícola, Centro Latinoamericano para el Desarrollo Rural. https://www.rimisp.org/wp-content/files_mf/1514388162Producto2_LecturaterritorialTumaco_GRANTFIDA1.pdf

Compañía Nacional de Chocolates. (2012, January 24). *El cultivo de cacao: paquete tecnológico.* http://infocafes.com/portal/wp-content/uploads/2016/12/paquete_tecnologico_cacao_cnch_enero_2012.pdf

CORDEAGROPAZ. (2011). *Acuerdo regional de competitividad de cacao de Nariño.* CORDEAGROPAZ, PNUD, Gobernación de Nariño, Agencia de Desarrollo Local Nariño.

DNP. (2014). *Documento insumo para la Misión para la Transformación del Campo - propuesta para desarrollar un modelo eficiente de comercialización y distribución de productos.* Centro Regional de Estudios Regionales Cafeteros y Empresariales. https://colaboracion.dnp.gov.co/CDT/Agriculturapecuarioforestal%20y%20pesca/Comercializaci%C3%B3n.pdf

DNP, CVC, & UNICEF. (1983). *Plan de desarrollo integral para la Costa Pacífica colombiana.* Corporación Autónoma Regional del Cauca, Departamento Nacional de Planeación, UNICEF. https://ecopedia.cvc.gov.co/mas/costa-pacifica/plan-de-desarrollo-integral-para-la-costa-pacifica-colombiana-pladeicop-sector

Echavarría Soto, J. J., Villamizar-Villegas, M., Restrepo-Tamayo, S., & Hernández-Leal, J. D. (2018). Impacto del crédito sobre el agro en Colombia: evidencia del nuevo Censo Nacional Agropecuario. In J. J. Echavarría Soto, M. Villamizar Villegas, & S. Restrepo Tamayo (Eds.), *Superando barreras: el impacto del crédito en el sector agrario en Colombia* (pp. 41–72). Banco Interamericano de Desarrollo (BID). https://babel.banrepcultural.org/digital/collection/p17054coll18/id/452

Espinosa-Álzate, J. A., & Ríos-Osorio, L. A. (2016). Caracterización de sistemas agroecológicos para el establecimiento de cacao (*Theobroma cacao* L.), en comunidades afrodescendientes del Pacífico Colombiano (Tumaco - Nariño, Colombia). *Acta Agronómica, 65*(3), 211–217. https://doi.org/10.15446/acag.v65n3.50714

Espinosa-García, J. A., Uresti-Gil, J., Vélez-Izquierdo, A., Moctezuma-López, G., Inurreta-Aguirre, H. D., & Góngora-González, S. F. (2015). Productividad y rentabilidad potencial del cacao (*Theobroma cacao* L.) en el trópico mexicano. *Revista Mexicana de Ciencias Agrícolas, 6*(5), 1051–1063. https://doi.org/10.29312/remexca.v6i5.598

ERS - ABC USAID/MIDAS Crops. (2009). Situación actual y perspectivas del mercado de cacao en grano colombiano. In C. F. Espinal, L. Narváez, J. Naranjo, O. Pantoja, & M. A. Urueña (Eds.), *La producción nacional frente a las tendencias de los mercados nacional e internacional de cacao en grano* (pp. 79–96). USAID.

FEDECACAO. (2019). *Economía nacional.* Federación Nacional de cacaoteros, Fondo Nacional del Cacao.

FINAGRO. (2017). *ICR programa general.* Ministerio de Agricultura y Desarrollo Rural. https://www.finagro.com.co/productos-y-servicios/icr-programa-general

Laing, D. R. (2011). Análisis de actividades agrícolas potenciales para incrementar los ingresos de los afrocolombianos, con énfasis en la región pacífica. *Revista Agricultura Tropical, 34*(3–4), 18–50.

MADR. (2017). *Decreto 1745 de 1995.* Ministerio de Agricultura y Desarrollo Rural. https://www.minagricultura.gov.co/Normatividad/Decretos/Decreto%20No.%201745%20de1995.pdf

Magni, C. A., & Marchioni, A. (2020). Average rates of return, working capital, and NPV-consistency in project appraisal: a sensitivity analysis approach. *International Journal of Production*

Economics, *229*, Article 107769. https://doi.org/10.1016/j.ijpe.2020.107769

Ministerio de Agricultura, Fondo Adaptación, & CORPOICA. (2017). *Modelos de prevención y adaptación agroclimática - MAPA. Boletín 19.* http://hdl.handle.net/20.500.12324/34920

Montoya-Restrepo, I. A., Montoya-Restrepo, L. A., & Lowy-Ceron, P. D. (2015). Oportunidades para la actividad cacaotera en el municipio de Tumaco, Nariño, Colombia. *Entramado, 11*(1), 48–59. https://doi.org/10.18041/entramado.2015v11n1.21107

Moreno Rozo, F., & López Villalobos, A. (2013). Nuevos proyectos de cacao en 2013. *Colombia Cacaotera, 6*(15), 4–5.

Pássaro, C. (2014). *Informe final de producto. Oferta tecnológica para el proceso de beneficio de cacao en Colombia: caracterización, análisis crítico y selección de sistemas a evaluar.* CORPOICA.

Perfetti, J. J., Balcázar, Á., Hernández, A., & Leibovich, J. (2013). *Políticas para el desarrollo de la agricultura en Colombia.* FEDESARROLLO, Sociedad de Agricultores de Colombia, INCODER, FINAGRO, Banco Agrario. https://www.repository.fedesarrollo.org.co/bitstream/handle/11445/61/LIB_2013_Pol%c3%adticas%20para%20el%20desarrollo%20de%20la%20agricultura_Completo.pdf?sequence=1&isAllowed=y

Pinzón Useche, J. O., Rojas Ardila, J., Rojas, F., Ramírez, O. D., Moreno, F., & Castro, G. A. (2012). *Guía técnica para el cultivo del cacao* (5th ed.). FEDECACAO.

Piraquive Galeano, G., Matamoros Cárdenas, M., Céspedes Rangel, E., & Rodríguez Chacón, J. (2018). *Actualización de la tasa de rendimiento del capital en Colombia bajo la metodología de Harberger.* Dirección de Estudios Económicos, Departamento Nacional de Planeación. https://colaboracion.dnp.gov.co/CDT/Estudios%20Econmicos/487.pdf

Preciado, O., Ocampo, C. I., & Ballesteros Possú, W. (2011). Caracterización del sistema tradicional de producción de cacao (*Theobroma cacao* L.), en seis núcleos productivos del municipio de Tumaco, Nariño. *Revista de Ciencias Agrícolas, 18*(2), 58–69.

Shirshahi, F., Babazadeh, H., Ebrahimi Pak, N. A., & Khaledian, M. R. (2020). Determining optimum major crops cultivation areas in different levels of deficit irrigation in Qazvin irrigation and drainage district. *Water and Soil Science*, *30*(1), 83–95.

UNODC. (2019, August). *Colombia, monitoreo de territorios afectados por cultivos ilícitos 2018.* Oficina de las Naciones Unidas contra la Droga y el Delito. https://www.unodc.org/documents/colombia/2019/Agosto/Informe_de_Monitoreo_de_Territorios_Afectador_por_Cultivos_Ilicitos_en_Colombia_2018_.pdf

UPRA. (2020). *Planificación nacional.* Unidad de Planificación Rural Agropecuaria. https://sipra.upra.gov.co/

USDA. (2018). *Colombia: cacao for peace update: firing on all cylinders.* United States Department of Agriculture. https://www.fas.usda.gov/data/colombia-cacao-peace-update-firing-all-cylinders

Yambure, O., Fernández, A. C., & Maldonado, R. (2014). *Proyecto de emprendimiento de cultivo de cacao bajo sombreado permanente* [Undergraduate thesis, Colegio de Estudios Superiores de Administración]. Repositorio Institucional CESA. https://repository.cesa.edu.co/handle/10726/1294

Yañez Agudelo, M. G. (2009). *La estrategia del cacao para la recuperación económica de familias campesinas desplazadas por la violencia del departamento de Caquetá* [Undergraduate thesis, Universidad de La Salle]. Ciencia Unisalle repositorio institucional. https://ciencia.lasalle.edu.co/cgi/viewcontent.cgi?article=1059&context=administracion_agronegocios

Zambrano, J. L., & Chávez, E. F. (2018). *Diagnóstico del estado del arte de la cadena de valor del cacao en América Latina y el Caribe.* Instituto Nacional Autónomo de Investigaciones Agropecuarias de Ecuador, FONTAGRO, Banco Interamericano de Desarrollo. https://www.fontagro.org/wp-content/uploads/2019/03/2018-CacaoDocFinal.pdf