



Agronomic conditions of cacao cultivation: its relationship with the capitals endowment of Colombian rural households

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Abstract Cacao cultivation has great socio-economic importance for the development of rural areas of Colombia, especially for the approximately 52,000 rural households that depend on it. Therefore, is important to analyze the relationship that the capitals endowment of cacao-growing rural households has with the agronomic status of the crop. To establish this relationship, we determined the endowment of community capitals in 22 rural households and the agronomic status of their cacao crops, grown in 83

plots. In each of these plots, these components were characterized: (1) floristic composition and crop structure; (2) soil quality; (3) pest attack status and diseases in the crop; (4) sensory quality of cacao beans, and (5) production. We found a positive correlation between the tree structure and physico-chemical indices of the soils ($p < 0.05$). Crops with greater shade showed a greater impact of pests and diseases (shade range 2.2–85.7%). Estimated cacao bean yield ($\text{kg ha}^{-1} \text{yr}^{-1}$) were higher where cacao cultivation was the main livelihood ($961 \text{ kg ha}^{-1} \text{yr}^{-1}$ in Cacao Farmers and $774 \text{ kg ha}^{-1} \text{yr}^{-1}$ in Diversified Farmers with Cacao). Crops demonstrating less damage caused by pests and diseases and less

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diverse tree structures obtained a higher cacao bean yield ($\text{kg ha}^{-1} \text{ yr}^{-1}$). Households with greater knowledge, experience and interaction with institutions that offer training, had more diverse tree structures and better soils physicochemical conditions. Households with greater capitals endowment had better agronomic conditions in cacao cultivation and had crops that generated additional products.

Keywords Cacao production · Agroforestry · Livelihoods · Tropical crops

Introduction

Cacao (*Theobroma cacao* L.) is a tropical crop of great economic, social, and environmental importance in Colombia (Jaimes et al. 2011). Approximately 80% of its production around the world is carried out by small rural households (Vaast and Somarriba 2014). Commercially, it is the third most exported agricultural product worldwide (Díaz et al. 2018) and its consumption is significant and of great interest to the food and beverage industry (Braga et al. 2019).

Colombia's increasing cacao production is carried out by approximately 52,000 rural households (Gutiérrez et al. 2020), with production of 59,740 tons of dry beans in 2019. The department of Meta, where approximately 2000 rural families depend on cacao as part of their livelihoods (Espinosa 2016), contributed 4.4% of total production (AGRONET 2019). About 90% of Colombian cacao is grown in agroforestry systems (Espinosa 2016; Suárez et al. 2018) that contribute to ecosystem services (Asigbaase et al. 2019), biodiversity conservation (Abada et al. 2016; Wartenberg et al. 2017), production of food that diversifies the farmers' diets and economic incomes (Vaast and Somarriba 2014) and adaptation to climate change (Asigbaase et al. 2019). These significant contributions strengthen the livelihoods of rural households (Vaast and Somarriba 2014) by allowing them to reach better markets and strengthen the cohesion between rural households and the community (Sánchez et al. 2015), reduce uncertainty and the risks and vulnerability associated with the contingencies of agriculture (Valencia et al. 2018), and improve economic incomes (Abdulai et al. 2018).

Problems in cacao production include incorrect planting schemes, volatility in prices (Espinosa 2016), low technical assistance and dependence on high inputs (Correa et al. 2014). These problems, added to low capital investment capacity and poor technological innovation of rural households (Vaast and Somarriba 2014), generate negative impacts at the agronomic conditions. For example, poor fertilization and a high degree of attack by pests and diseases may cause low yield (Correa et al. 2014; Jaimes et al. 2011; Ortíz et al. 2015; Sterling et al. 2015). These conditions threaten the sustainability of the crop, affecting the well-being of the rural households.

The objective of this study was to determine the relationship between the agronomic conditions of cacao crops and the capitals endowment of the rural household communities. To accomplish this, the sustainable livelihoods approach and the community capitals framework (Emery and Flora 2006; Gutierrez-Montes et al. 2009), together with the agronomic condition of cacao cultivation, were used. This enabled an analysis of elements that could generate actions to improve the agronomic condition of Colombian farmers' cacao crops. According to Musinguzi et al. (2018), these actions must be framed in a local context and be worked from particularities involving local assets (Díaz et al. 2018; Zhang et al. 2019).

Materials and methods

Study area and types of rural households with cacao activities

The study was conducted between 2017 and 2019 in rural areas of the municipalities of Vista Hermosa and Mesetas in the department of Meta (Fig. 1) (Espinosa 2016). These areas lie within the Inter Tropical Convergence Zone, influenced by the trade winds. The average temperature varies between 22.2 °C and 26.8 °C, with the relative humidity averaging 82%. Average rainfall is 2950 mm yr^{-1} ; the hottest and driest months are from December to March. The soils are mostly Humic Ferralsols and Acric Ferralsols (IDEAM 2017).

Households were selected according to the types defined by Hernández et al. (2020): 12 Cacao Farmers and 10 Diversified Farmers with Cacao. For

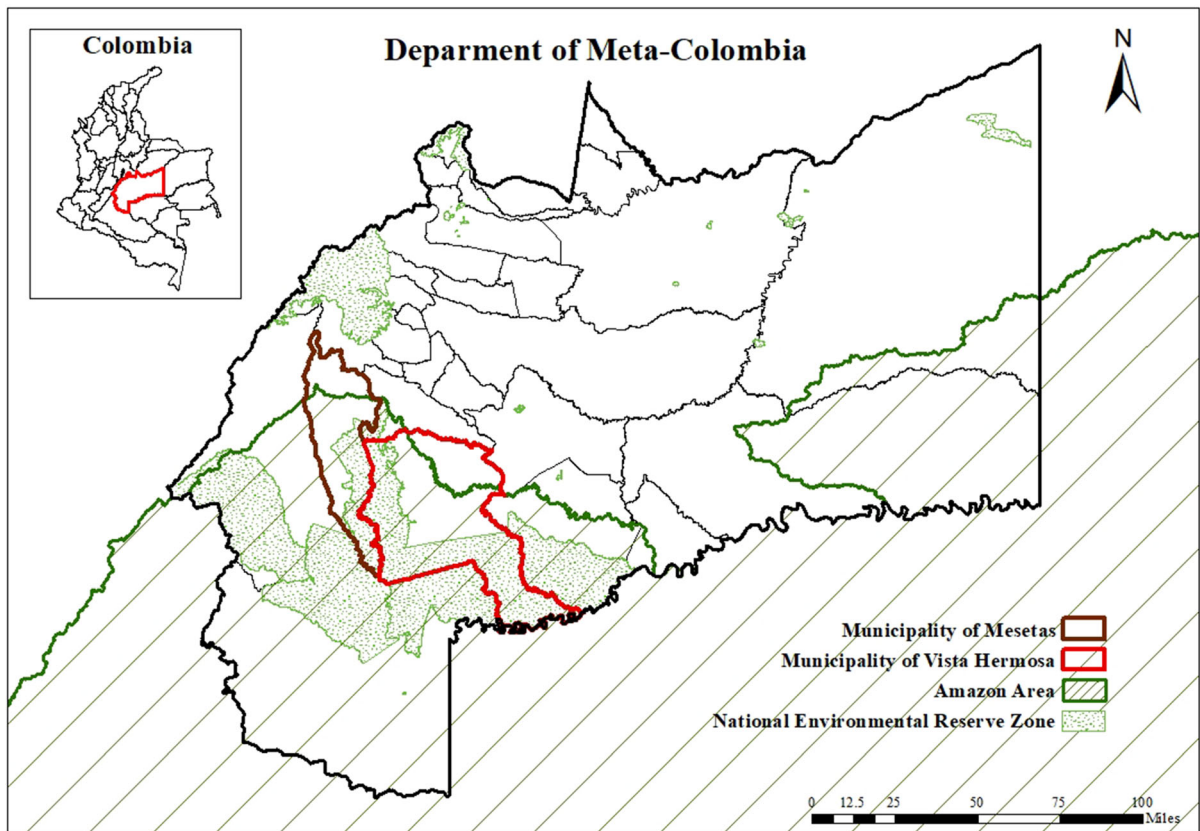


Fig. 1 Study area

households of Cacao Farmers, cacao cultivation was one of their most important productive activities; their experience with the crop averaged 9.88 years. The average cacao income per year was USD 3056, corresponding to 65.7% of total household income, and the area of cacao under cultivation was 58% of the total productive area of the farm (on average 4.33 ha). Because Cacao Farmers have established new lots of cacao, 26.5% of the established area had not yet reached the productive stage (Hernández et al. 2020).

Households of Diversified Farmers with Cacao averaged 7.7 years of experience in cultivating cacao. The income from cacao sales represented 33.6% of total household income. The area established in cacao was 41.2% of the total productive area, their average yield 40% lesser than Cacao Farmers. The area in cacao averaged 1.64 ha, and only 9% of newly established areas had not yet reached the productive stage (Hernández et al. 2020).

Agronomic condition of cacao cultivation

In lots producing cacao, we established plots ($n = 83$) of 1000 m² (50 × 20 m) (Jagoret et al. 2017), selecting 49 plots for Cacao Farmers households and 34 plots for Diversified Farmers with Cacao households. In each plot, we characterized the agronomic condition of different components: (1) floristic composition and crop structure; (2) soil quality; (3) attack status of pests and diseases in the crop; (4) cacao bean quality; and (5) bean production. The characterization was carried out between November and December of 2017.

Floristic composition and crop structure

In each plot, we determined the floristic composition and crop structure (Jagoret et al. 2017; Suárez et al. 2018). We counted the number of cacao trees and associated plants and extrapolated these to trees per hectare; the associated plants were identified at the species level (Suárez et al. 2018). We made

dasometric measurements in all associated plants with $DBH \geq 10$ cm (Ngo Bieng et al. 2013). Based on these variables, we determined the percentage of total shade and percentage of shadow without Musaceae, and we calculated the Shannon–Weaver and Simpson biodiversity indices and species richness (Suárez et al. 2018).

Soil quality

The sampling to determine soil chemical and physical characteristics was performed at a 0–10 cm depth. Four subsamples were used to form a composite sample for each plot. We determined the parameters: real density, total porosity, pH (relation soil: solution 1:1), exchangeable acidity (extraction with KCL 1 N and titration with sodium hydroxide), organic material (Walkley–Black titulation), cation interchange capacity (CIC) (ammonium acetate) and Ca, Na, Mg, K (atomic absorption) (IGAC 2006). Likewise, we determined the penetration resistance and bulk density. The macrofauna was quantified in a monolith (25×25 cm and 30 cm deep) per plot: specimens were taxonomically identified at the order level (Rodríguez et al. 2018). Subsequently, we determined the richness and the indices of Shannon–Weaver and Simpson.

Condition of pest incidence and diseases in the crop

In each plot, we determined the infestation status and severity of damage caused by *Monalonium dissimulatum*, *Moniliophthora roreri* and *Phytophthora* spp. We identified the degree of external severity damage of *Moniliophthora roreri* in 50 pods per plot, utilizing the scale used by Sterling et al. (2015): 0, healthy pod; 1, oily points; 2, swelling and/or premature maturation; 3, spot (necrosis); 4, mycelium up to 25% of the necrotic spot; and 5, mycelium that covers more than 25% of the necrotic spot. To determine internal severity, a longitudinal cut was made in 50 pods. The percentage of internal necrosis caused by *Moniliophthora roreri* was measured and classified in a range of 0 to 5: 0, without necrosis; 1, 1–20%; 2, 21–40%; 3, 41–60%; 4, 61–80%; and 5, more than 80% of with necrosis (Sterling et al. 2015). The incidence of *Phytophthora* spp. and *Monalonium dissimulatum* was determined by counting all pods on trees in the plot and identifying those affected

(Ramírez 2016; Vargas et al. 2005). We identified the percentage of incidence with the formula: (number of pods affected/number of pods evaluated) \times 100.

For *Phytophthora* spp. severity, we identified the degree of involvement in 50 pods. This we categorized into a grade of 1 to 5: 1, free of symptoms; 2, involvement less than 2 mm; 3, involvement between 2 mm and 2 cm; 4, affection of up to 25%; and 5, spots on more than 25% of the pod (Ramírez 2016). For *Monalonium dissimulatum* severity, we counted the number of bites caused by *Monalonium dissimulatum* in all pods of all cacao trees per plot. We classified severity from 0 to 4, as follows: (0) zero bites; (1) 1–10 bites; (2) 11–25 bites; (3) 26–50 bites; (4) more than 50 bites (Vargas et al. 2005).

Cacao bean quality

From each plot we collected 50 systematic sample mature pods ($n = 50$). Twelve clones (CCN-51, FAR-5, FEAR-5, FSA-11, FSA-12, FSA-13, FTA-2, ICS-1, ICS-51, ICS-95, MON- 1, TSH- 565) and three hybrids (yellow, red and green) were present in the 83 plot. Fermentation and drying processes were carried out uniformly with all samples to avoid variation in sensory characteristics. Fermentation lasted seven days. Later, beans were dried to 6% to 8% humidity and were roasted and transformed into cacao liquor to identify sensory characteristics (Machado et al. 2018). We described the organoleptic qualities as three flavors according to the *Guía Técnica Colombiana 165 GTC 165* and the *Norma Técnica Colombiana 3929* of ICONTEC: basic, specific and acquired. To determine the intensity of flavor, we used the international scale of cacao sensory profile evaluation, which establishes a range of 0 to 10: 0, absent; 1–2, low intensity; 3–5, medium intensity; 6–8, high intensity; and 9–10, very high or strong intensity (Machado et al. 2018).

Bean production

We collected 50 pods in each plot, counted and weighed the number of beans per pod. We estimated the cacao bean yield according to the methodology proposed by Jagoret et al. (2017), using the formula: cacao bean yield ($\text{kg ha}^{-1} \text{ yr}^{-1}$) = (average number of pods/cacao tree) \times (average weight of fresh beans (kg/pod) \times (weight of fresh beans/dry

weight) \times (number of cacao trees/hectare) \times 10. The sample was taken during the highest production period (November–December of 2017).

Data analysis

We generated an additive index for each agronomic component based on their variables transformed to the interval [0; 1] before adding them up for the construction of the respective index; for the crop pests and diseases variables, we multiplied them by (-1) to inverse the value ($>$ higher index: lower attack and incidence). A biplot constructed by principal component analysis (PCA) was generated using the agronomic indices. Due to the relationship between the structure of the cacao crop and the incidence of pests and diseases, a coinercia analysis was performed, allowing us to establish the correlation between the variables of the two components. We performed an analysis of variance to determine the status of agronomic variables between the two types of rural households. We analyzed continuous variables through mixed linear models (Di Rienzo et al. 2011), discrete variables through generalized mixed linear models using the Poisson distribution (Di Rienzo et al. 2017), and ordinal variables with tables of contingency. We carried out mean comparisons with the Fisher LSD test ($p < 0.05$). In order to determine the relationship between community capitals endowment and agronomic conditions, we used the average of each index at the farmers level. We performed a partial least squares (PLS) analysis using the community capitals indices as predictive variables and agronomic indices as dependent variables, identifying the two types of rural households. In addition, we used a coinercia analysis that enabled analysis of the correlation between variables that constitute the capital of the communities and the agronomic indices of cacao cultivation. We performed all statistical analyses using the statistical software InfoStat (Di Rienzo et al. 2019) and R Studio (RStudio Team 2016).

Results

Agronomic condition of cacao cultivation

According to results obtained through the PCA, 56.4% of the original variability represented using the

agronomic indices (Supplement 1) was explained for the first two components. Type of rural household (Cacao Farmers and Diversified Farmers with Cacao) had no effect on the indices of the five agronomic components (Fig. 2).

A positive correlation was found between tree structure and physicochemical indices of soils and the quality of bean and macrofauna of the soil; however, the index of tree structure and soil physicochemistry showed a negative correlation with the index of pests and diseases and the production index—the latter two had a positive correlation (Fig. 2). The relationship between variables of abundance and diversity of the tree structure of the crop and the variables of incidence and severity of pests and diseases had a significant correlation coefficient ($RV = 0.10, p < 0.05$) (Fig. 3). Crops with more shade, a higher number of Musaceae, and greater diversity of accompanying species were more strongly affected by *Phytophthora* spp. Crops with a greater abundance of leguminous trees had a higher incidence of *Monalonium dissimulatum*. Crops with a greater abundance of fruit trees showed greater damage caused by *Monalonium dissimulatum*, *Moniliophthora roreri* and *Phytophthora* spp. (Fig. 3).

Number of fruit trees (NoFru), number of legumes (NoLeg), number of timber trees (NoTim), diversity of species (DiEsp), number of Musaceae (NoMus), number of individuals accompanying cacao (NoInd), total shade (TotSha), accompanying shadow (AcoSha), incidence of *Monalonium dissimulatum* (InMd), incidence of *Phytophthora* spp. (IncPh), percentage of severity of *Monalonium dissimulatum* (PSMd), percentage of external severity of *Moniliophthora roreri* (PSEMr), percentage of internal severity of *Moniliophthora roreri* (PSIMr), percentage of external severity of *Phytophthora* spp. (ESEPh).

Floristic composition and crop structure

The density of cacao trees per hectare differed between household types ($p < 0.0001$): Cacao Farmers had an average of 10.3% more cacao trees per hectare than Diversified Farmers with Cacao. The composition and structure of species in the cacao plot differed between types of rural households ($p < 0.05$). Cacao Farmers had 22.9% more Shannon–Weaver diversity, 3.4% more abundance, and 9% more wealth than did Diversified Farmers with Cacao (Tables 1, 2). The abundance of timber and legumes trees averaged

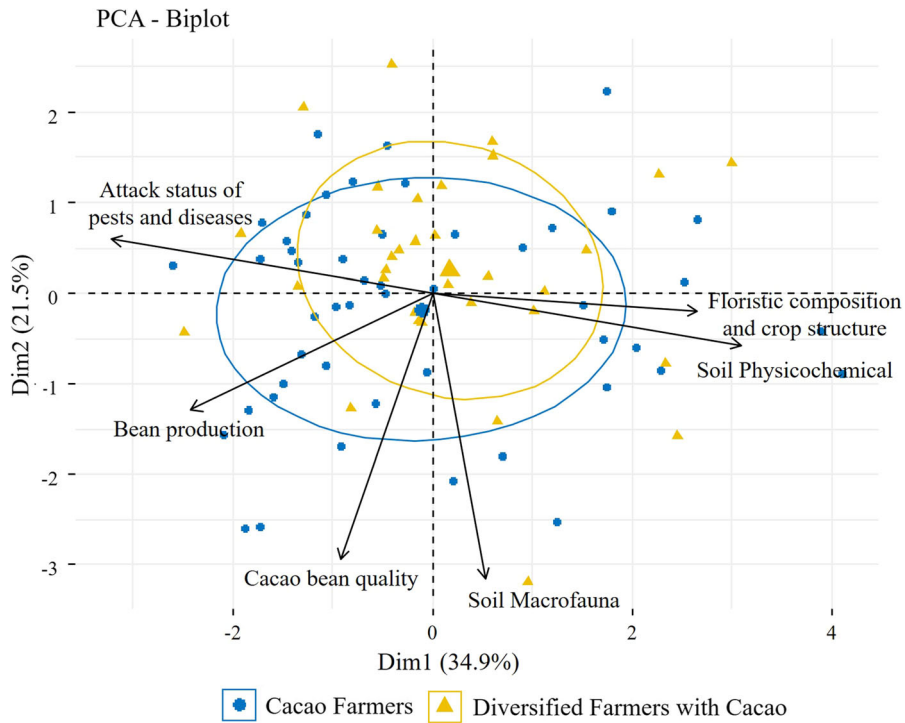


Fig. 2 Biplot constructed by principal component analysis using all agronomic indices of cacao cultivation and identifying the type of rural household

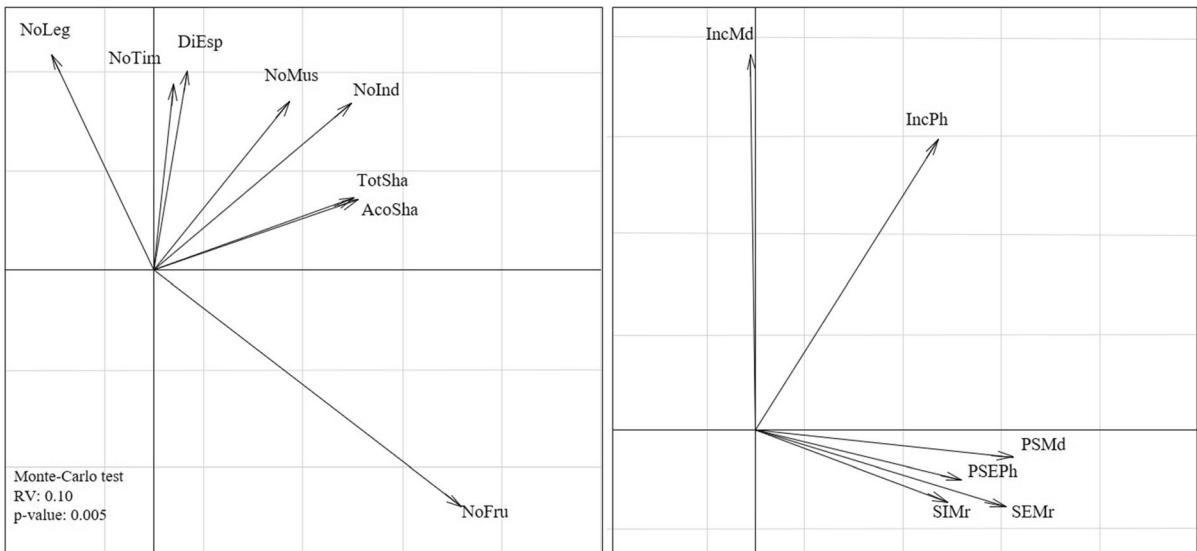


Fig. 3 Projection in the F1/F2 factorial plane of a coinertia analysis of tree structure variables and variables of pests and diseases

33.8% and 18.4% more in crops of Cacao Farmers compared with Diversified Farmers with Cacao. In contrast, the abundance of fruit trees was 29% higher

in Diversified Farmers with Cacao, though 92.8% of them were *Persea americana* Mill (Table 2).

Table 1 Agronomic variables of cacao cultivation in the types of rural households: values represent the mean \pm standard error

Agronomic component	Variable	Unit	Cacao Carvers	Diversified Farmers with Cacao	<i>p</i> -value
Soils	Resistance to penetration	MPa	1.3 \pm 0.04a	1.27 \pm 0.04a	0.6115
	Apparent density	gr cm ⁻³	1.48 \pm 0.03a	1.4 \pm 0.04a	0.1098
	Total porosity	%	39.56 \pm 1.33a	42.65 \pm 1.6a	0.1407
	pH		5.43 \pm 0.06a	5.24 \pm 0.07b	0.0316
	Organic material	%	2.18 \pm 0.11b	2.98 \pm 0.14a	< 0.0001
	Interchangeable acidity		0.36 \pm 0.10b	0.79 \pm 0.12a	0.0077
	Cation interchange capacity		14.83 \pm 0.67b	18.45 \pm 0.8a	0.0008
	Ca	meq 100gr soil ⁻¹	1.91 \pm 0.18a	1.97 \pm 0.22a	0.8268
	Na		0.34 \pm 0.03a	0.37 \pm 0.03a	0.3771
	Mg		0.55 \pm 0.04a	0.54 \pm 0.05a	0.7994
	K		0.14 \pm 0.01a	0.18 \pm 0.02a	0.0558
	Richness of macrofauna		5.88 \pm 0.27a	5.21 \pm 0.32a	0.1087
	Shannon–weaver macrofauna		1.37 \pm 0.05a	1.11 \pm 0.06b	0.0027
	Simpson macrofauna		0.37 \pm 0.03a	0.44 \pm 0.04a	0.1122
	Floristic composition and structure of the crop	Shannon–weaver		1.26 \pm 0.07a	0.79 \pm 0.09b
Simpson			0.24 \pm 0.03b	0.54 \pm 0.04a	< 0.0001
Total shade		%	43.89 \pm 3.09a	40.78 \pm 3.71a	0.5212
Shade without musaceae			41.14 \pm 3.13a	37.39 \pm 3.76a	0.4453
Cacao trees		Number	867.76 \pm 4.21a	704.41 \pm 4.55b	< 0.0001
Accompanying individuals			168.57 \pm 1.85a	157.35 \pm 2.15b	0.0002
Timber abundance			35.10 \pm 0.85a	17.35 \pm 0.71b	< 0.0001
Abundance musaceae			56.12 \pm 1.07a	51.18 \pm 1.23b	0.0035
Abundance fruits			31.84 \pm 0.81b	57.94 \pm 1.31a	< 0.0001
Abundance leguminosae		40.61 \pm 0.91a	27.94 \pm 0.91b	< 0.0001	
Blights and diseases	Incidence of <i>monalonium dissimulatum</i>	%	18.79 \pm 0.78a	19.21 \pm 0.93a	0.7315
	Incidence of <i>phytophthora</i>		0.36 \pm 0.09a	0.47 \pm 0.11a	0.4279
Sensory quality of cacao beans	Cacao	[1; 10]	3.90 \pm 0.28a	3.65 \pm 0.33a	0.5656
	Bitter		4.08 \pm 0.29a	3.79 \pm 0.33a	0.5196
	Astringent		3.73 \pm 0.28a	3.41 \pm 0.32a	0.4483
	Acid		3.16 \pm 0.25a	3.21 \pm 0.31a	0.915
	Fresh fruit		3.18 \pm 0.25a	3.21 \pm 0.31a	0.9557
	Sweet		3.35 \pm 0.26a	3.76 \pm 0.33a	0.3216
	Nutty		2.96 \pm 0.25a	3.03 \pm 0.30a	0.856
	Dry fruit		3.02 \pm 0.25a	3.09 \pm 0.30a	0.8623
	Floral		3.35 \pm 0.26a	3.47 \pm 0.32a	0.7645
Bean production	Bean	Number	40.54 \pm 0.72a	40.13 \pm 0.87a	0.7177
	Weight of wet cacao bean	gr	158.03 \pm 5.08a	153.94 \pm 6.1a	0.6075
	Index of pod		19.67 \pm 0.57a	19.89 \pm 0.68a	0.811
	Yield	kg ha ⁻¹ yr ⁻¹	961.43 \pm 0.08a	774.23 \pm 0.09b	0.0393

Table 2 Species abundance accompanying (trees ha⁻¹) the cultivation of cacao in types of rural households

Use	Scientific name	Cacao Farmers	Diversified Farmers with Cacao
Fruit	<i>Persea americana</i> Mill.	91	183
	<i>Citrus reticulata</i> Blanco	22	0
	<i>Coffea arabica</i> L.	12	1
	<i>Psidium guajava</i> L.	11	5
	<i>Carica papaya</i> L.	8	3
	<i>Mangifera indica</i> L.	4	0
	<i>Manihot esculenta</i> Crantz	3	0
	<i>Annona muricata</i> L.	1	0
	<i>Passiflora quadrangularis</i> L.	1	0
	<i>Eugenia stipitata</i> McVaugh	1	0
	<i>Annona cherimola</i> Mill.	0	2
	<i>Solanum</i> sp.	0	2
Tree legumes	<i>Gliricidia sepium</i> (Jacq.) Kunth ex Walp.	111	67
	<i>Stryphnodendron pulcherrimum</i> (Willd.) Hochr.	78	23
	<i>Hymenolobium heterocarpum</i> Ducke	2	0
	<i>Inga spectabilis</i> (Vahl) Willd.	1	0
	<i>Hymenolobium petraeum</i> Ducke	1	0
	<i>Cassia grandis</i> L.f.	0	1
Tree for wood	<i>Tabebuia rosea</i> (Bertol.) DC.	21	1
	<i>Cordia alliodora</i> (Ruiz & Pav.) Oken	20	4
	<i>Trema micrantha</i> (L.) Blume	18	0
	<i>Cedrela odorata</i> L.	12	2
	<i>Acacia mangium</i> Willd.	5	6
	<i>Guarea</i> sp.	4	0
	<i>Guazuma ulmifolia</i> Lam.	2	3
	<i>Sapium allenii</i> Huft.	2	0
	<i>Andira multistipula</i> Ducke	1	0
	<i>Ceiba pentandra</i> (L.) Gaertn.	1	0
	<i>Cecropia peltata</i> L.	1	0
	<i>Ficus americana</i> Aubl.	1	0
	<i>Andira inermis</i> (W. Wright) Kunth ex DC.	0	11
	<i>Astronium graveolens</i> Jacq.	0	6

Soil quality

The physical conditions of soils in the two types of rural households did not show significant differences. Organic matter, exchangeable acidity, and cation exchange capacity were 15.5, 37.3, and 10.8%, respectively, and were higher in cacao crops of Diversified Farmers with Cacao than Cacao Farmers. The level of Ca, Na, Mg and K does not differ

significantly between the two types of households (Table 1).

State of attack of pests and diseases

The presence and damage caused by pests and diseases is greater in the crops of Diversified Farmers with Cacao. The incidence of *Monalonium dissimulatum* was 18.7% and 19.2% in Cacao Farmer and Diversified Farmers with Cacao households, respectively

(Table 1). Diversified Farmers with Cacao households showed greater severity of damage at grade three and four caused by *Monalonion dissimulatum* bites. Only 29.9% and 22.5% of pods in Cacao Farmers and Diversified Farmers with Cacao, respectively, were not affected by the pest (Table 3). The percentage of *Phytophthora* Spp. did not show significant differences between the two types of rural households ($p > 0.05$), where 94.4% and 91.1% of fruits were symptom free.

The external severity caused by *Moniliophthora roreri* was statistically higher for Diversified Farmers with Cacao (16.24%) than for Cacao Farmers (11.73%). About 6.41% of the external severity in crops of Diversified Farmers with Cacao had grade 5 involvement, where the mycelium covers more than a quarter of the necrosis on the pod (Table 3). In crops of Cacao Farmers and Diversified Farmers with Cacao, 89.7% and 87.4% of pods, respectively, did not show internal necrosis caused by *Moniliophthora roreri*; however, of the total pods affected, 7.3% and 6.4% of crops of Diversified Farmers with Cacao and Cacao Farmers, respectively, had an area of internal necrosis greater than 80% (Table 3).

Production

The cacao bean yield ($\text{kg ha}^{-1} \text{ yr}^{-1}$) was significantly different between types of rural households ($p = 0.0393$). Yields of Cacao Farmer households peaked at $1425.04 \text{ kg ha}^{-1} \text{ yr}^{-1}$, with an average

yield of $961 \text{ kg ha}^{-1} \text{ yr}^{-1}$, 10.79% more than Diversified Farmers with Cacao (Table 1).

Enabling variables of the agronomic condition of the cacao crop

The interaction between agronomic indices and capitals endowment indices (Supplement 1) explains 54.1% of the original variability represented in the first two principal components (Fig. 4). Crops with a high rate of pests and diseases and production were found in households with a high endowment of cultural capital. Better conditions of soil macrofauna and greater index of composition and tree structure can be explained by the better endowment of the human, physical, and political capital of the rural households (Fig. 4).

The relationship between agronomic indices and variables of the community capitals framework showed a significant correlation coefficient ($RV = 0.31$, $p = 0.0440$) (Fig. 5). Households where the main agricultural activity was cacao cultivation spent more time on the crop, such as in management of pests and diseases (ManPlaEn) (harvesting pods every 15 days, control of pits, and annual maintenance pruning), which can explain the best conditions in the indices of pests and diseases. As one producer said, “If one manages the crop well, it gives a good product, and the idea is then every day to get stronger, to know the crop well” (Supplement 1). Production, soil macrofauna, and bean quality showed a correlation with the area established in cacao (Fig. 5). Households

Table 3 Percentage of pods by grade of severity of damage caused by *Monalonion dissimulatum*, *Moniliophthora roreri*, and *Phytophthora* in cultivation of cacao in types of rural households

Grade	Cacao Farmers				Diversified Farmers with Cacao			
	PSMd	PSEMr	PSIMr	ESEPh	PSMd	PSEMr	PSIMr	ESEPh
0	29.92	88.29	89.71	–	22.59	83.76	87.41	–
1	15.31	0.98	0.12	94.49	13.35	1.71	1.12	91.18
2	23.06	2.33	1.1	0.37	22.88	3.18	0.76	1.06
3	16.12	1.35	1.31	0.82	20.18	2.59	1.53	1
4	15.59	2.29	1.27	1.02	20.94	2.35	1.82	1.71
5	0	4.78	6.49	3.31	0.06	6.41	7.35	5.06
Damage	70.08	11.73	10.29	5.52	77.41	16.24	12.58	8.83

PSMd Percentage of severity of *Monalonion dissimulatum*, PSEMr Percentage of external severity of *Moniliophthora roreri*, PSIMr Percentage of internal severity of *Moniliophthora roreri*, ESEPh Percentage of external severity of *Phytophthora*

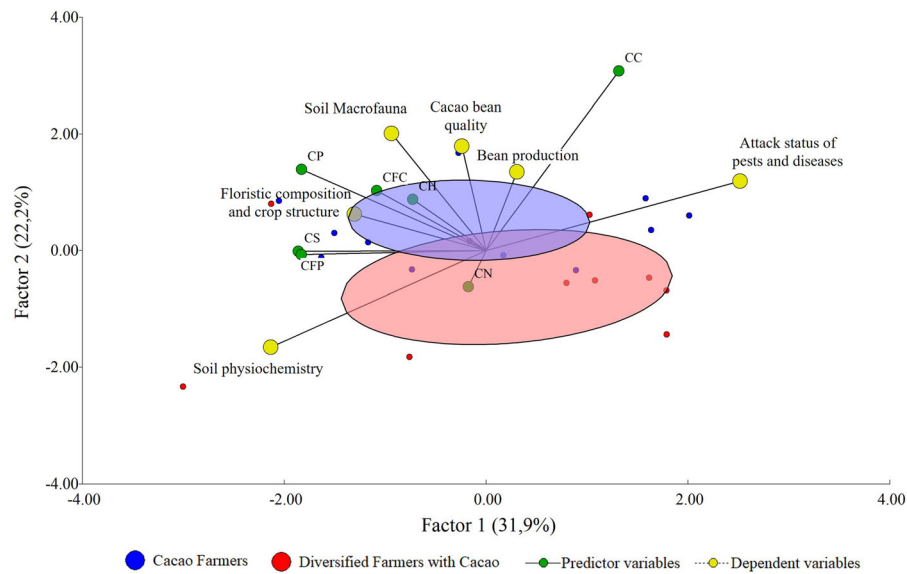


Fig. 4 Tri-plot constructed by PLS using community capital indices as predictors, agronomic indices as dependent variables and identifying the two types of rural households

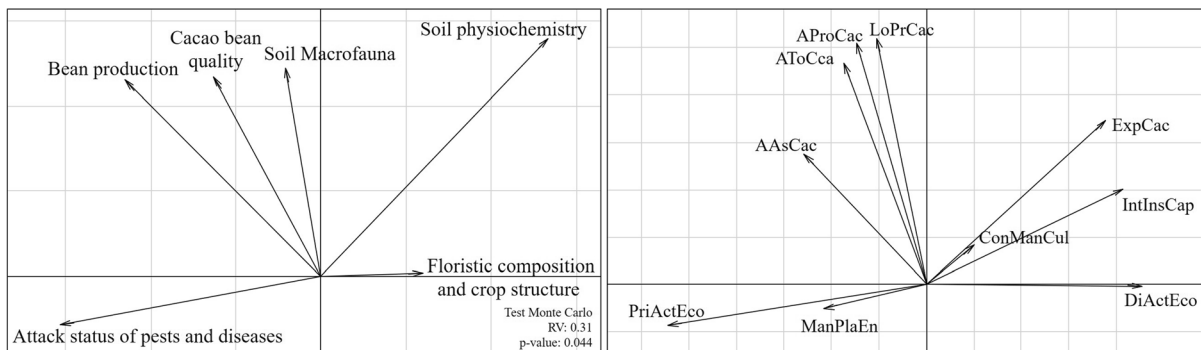


Fig. 5 Projection in the F1/F2 factorial plan of a coinercia analysis of agronomic indices and variables of the community capitals framework

with greater knowledge, greater experience in cacao, and greater interaction with institutions that offer training correlated with households having better soil physicochemical conditions and more diverse tree structures (Fig. 4).

Main economic activity (PriActEco), pest and disease management (ManPlaEn), area in associated cacao (AAsCac), total area in cacao (AToCca), cacao production area (AProCac), lots of cacao in production (LoPrCa), experience in cacao (ExpCac), knowledge in cacao cultivation management (ConManCul), number of institutions that have trained in cacao (IntInsCap), diversity of household economic activities (DiActEco).

Discussion

We found a direct relationship between all agronomic components, influenced by the type of rural household. Specifically, for those plots with more trees providing canopy shade for cacao, the soil fertility was positive. However, this increase in shade canopy could particularly affect cacao bean yield and impact of pests and diseases (Fig. 3). If the producer managed the crop adequately, the cacao bean yield ($\text{kg ha}^{-1} \text{yr}^{-1}$) was not affected even with high diversity and abundance of species accompanying cacao (Fig. 5); This reaffirms that an improvement in agricultural practices

positively affects yield (Vaast and Somarriba 2014), which increases economic income (Viteri et al. 2018).

In Colombia the planting density for cacao is around 600–700 trees ha⁻¹ (FEDECACAO 2015). Low densities are mainly tied to cacao's being established within agroforestry systems (Suárez et al. 2018), with shade species providing foods and extra incomes to the householders. It is important to analyze not only the cacao bean yield but also other products derived from the accompanying species, which can contribute substantially to household livelihoods (Cerdeña et al. 2014). For example, in the cacao crops of the households studied, the 62 other species (fruit trees, legumes, wood and Musaceae) identified, provided additional financial and food security to households (Asigbaase et al. 2019; Hosseini et al. 2017; Viteri et al. 2018; Wartenberg et al. 2017). The diversity and abundance of these other species is tied to the producer's degree of local knowledge (Valencia et al. 2018). Rural households with more knowledge, more experience in cacao cultivation and greater interaction with institutional institutions, had crops with more diverse and complex structures; selecting appropriate tree species for intercropping with cacao is critical for minimizing negative effects on cacao bean yields (Hosseini et al. 2017). Cacao planted under agroforestry systems provides a balance between the conservation of natural resources, particularly biodiversity and human well-being (Asigbaase et al. 2019; Musinguzi et al. 2018; Vaast and Somarriba 2014).

Cacao crops with structures of greater diversity and abundance of accompanying species (mainly Musaceae and fruit trees) demonstrated better physical and chemical soil characteristics—especially greater availability of Na, K and Ca. This is in line with studies conducted by Hosseini et al. (2017) and Asigbaase et al. (2019) that indicated factors such as density and shade of the accompanying species improve nutrient cycling and minimize losses of soil minerals through leaching and erosion. This improves the availability of nutrients for the crop (Vaast and Somarriba 2014; Wartenberg et al. 2017), a factor important in cacao bean yield (Santos et al. 2017). Soil chemical conditions (pH, organic material, cation interchange capacity; Table 1) of the cacao crops in the households studied are among the optimal ranges for cacao production (Van Vliet and Giller 2017). Moreover, the physical characteristics (Table 1) indicate that the soil is compacted (León et al. 2019).

Soil conditions, however, were not the determining factor for the cacao bean yield for these rural households, but the damage caused by pests and diseases. Several authors (Jaimes et al. 2011; Ortíz et al. 2015; Sterling et al. 2015; Vaast and Somarriba 2014) claim that phytosanitary problems in cultivation are among the main causes of decreased cacao production. For the rural households studied, cacao bean yield was higher when damage caused by pests and diseases was lower. Sonwa et al. (2018) and others point out that higher levels of shade and diversity of species intensify pest and disease attacks (Sonwa et al. 2018). However, more important than the reduction of species is an appropriate selection of species. For example, in the crops with high abundance of the species *Persea americana* Mill, we found the highest attacks of pests and diseases. Likewise, the producer's knowledge of pest and disease management practices in cacao affects outcomes. Daniel et al. (2011) found that improving the knowledge of practices of cultural management of pests and diseases in cacao by producers led to a decrease in the incidence of these problems and allowed an average increase of 30% in yields. Time dedicated to control is also important (ManPlaEn): Jaimes et al. (2011) and Sterling et al. (2015) reported a reduction in the incidence of *M. rozeri* with the increase in cultural management practices. In addition, Ortíz et al. (2015) found that integrated crop management accomplished an efficiency of 79.9% in decreased incidence of cacao moniliasis, thus increasing productive capacity.

This study showed that agronomic conditions of cacao cultivation depend on the capitals endowment of the community. Households with greater endowment of human (i.e., knowledge), cultural (i.e., identity and management practices), and physical (i.e., availability of land) capitals had better agronomic conditions of cacao cultivation (fewer pest and disease effects, crop with greater diversity of accompanying species, better soil conditions) (Fig. 4; Supplement 1) and additional products were produced. It is essential to understand not only the agroecosystem or biophysical characteristics of the farms but all the cultural (symbolic, organizational, and technological) scaffolding on which production is based. This is because the livelihood strategies of rural households change over time (Walelign et al. 2016), depending on the endowment of capital assets held by households (Zhang et al. 2019), the use to which they were put (Díaz et al.

2018), and the technology used (Cárdenas et al. 2013). Therefore, agricultural productivity is an important livelihood within the strategy of rural households and all the decisions that affect cultivation are influenced by social and personal variables, such as motivation and personal values (Šūmane et al. 2018).

Conclusions

The agronomic conditions of the cacao crop have both positive and negative correlations. It is important to have a balance in the condition of agronomic components, otherwise, cacao bean yield is affected. For example, although the soil may have the fertility suitable for the development of cacao, if the incidence levels of pests and diseases are high, cacao bean yields will be negatively affected. This usually occurs in crops with high diversity where the accompanying species have an important economic and food security function in the household strategy. To improve the balance between cacao bean yield and other products, it is essential to make a careful selection of these species and maintain good control of pests and diseases.

A high endowment of human, cultural, and physical capitals enables rural households to improve the agronomic conditions of cacao cultivation, thereby affecting its contribution to household livelihoods, specifically production of beans and other products generated within the agroforestry system. The synchrony of factors such as knowledge about the crop, time devoted to its management, careful selection of other species cultivated with the cacao, and planting density positively affect the agronomic condition, increasing cacao production and generation of other products. Knowing the realities of the types of rural households and their similarities and differences, enables generation of specific and differentiated actions that strengthen the agronomic condition of the cacao crop and the endowment of capital and well-being. Moreover, future studies involving livelihoods and production should consider the cost–benefit relationship between cacao and companion trees, taking into account not only the additional income and other benefits but also increased likelihood of problems with pests and diseases.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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