



A typological characterization of cocoa farmers in the Amazon region of Colombia based on biophysical and cultural variables

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Abstract In the Colombian Amazon, cacao (*Theobroma cacao* L.) is often cultivated with limited productive, environmental, and cultural scopes, largely due to an insufficient understanding of the different types of cacao farmer. A multiple factor analysis of 200 cacao farms in the Putumayo region identified five producer typologies based on qualitative and quantitative variables. Among them, Typology 3 consists mainly of Indigenous farmers (*Indigenous with diversified agricultural productions*), while Typology 1 includes both farmers and Indigenous people (*Predominantly agriculture-oriented farmers*). Typologies 2, 4, and 5 comprise peasants, Indigenous people, Afro-descendants, and mestizos. Typology 2 corresponds to *Moderately agriculture-oriented peasants* with a lower level of education than those in Typology 4, which represents *Mixed moderately*

agriculture-oriented. Typology 5 includes *Conservation-oriented farmers*. These findings suggest that varying land-use orientations may play a key role in shaping cocoa farmer typologies. Understanding these farming typologies enables the development of policies and strategies tailored to each type of farmer. Moreover, this approach can be applied to other cacao-producing regions worldwide, offering a valuable framework for analysis in contexts with high cultural and ecological diversity. This study offers valuable insights that will help balance agricultural productivity with environmental sustainability, and contribute to an inclusive, resilient rural development.

Keywords Agroforestry systems · Cacao · Farm typology · Landscapes units · Conservation · Amazon

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Introduction

The analysis of household farming systems requires an approach that accounts for their inherent complexity (Viteri Salazar et al. 2018). This heterogeneity, which is reflected in both biophysical and cultural differences, presents a challenge for decision-makers in determining the most effective intervention strategies for agricultural systems (Huber et al. 2024). Historically, decision-makers have often attempted to optimize resource use in a uniform manner, based on the incorrect assumption that all farmers in a given region share similar characteristics

(Manga Essouma et al. 2021). This fails to consider that agricultural structures are dynamic and changing globally (Graskemper et al. 2021). It has resulted in the unintended oversight of key factors that distinguish farmers and could enhance the positive impacts of interventions (Viteri Salazar et al. 2018).

Consequently, tailored actions by decision-makers should underpin the formulation of development strategies (Gaitan and Ríos 2020; Huber et al. 2024; Nainggolan et al. 2013a). This approach is grounded in a thorough analysis of data that enables identifying farmer groups or typologies with shared characteristics, yet distinct from other groups (Weltin et al. 2017), even when they engage in the same productive activity or venture (McElwee 2008; Díaz-Gaona et al. 2019). These differences are based on the characteristics of each production system (Ibidhi et al. 2018), including geographic and climatic factors (Fanchone et al. 2020), but also on the social characteristics of the farmers, who are the key actors in this context (Graskemper et al. 2021). Typologies are typically constructed at the local or regional level (LaFevor 2022) to reflect the coherence of agricultural management among groups that share similar values, while also pursuing distinct productive objectives (Perazzo et al. 2023). In terms of perceptions, attitudes, or motivations, these typologies are also dynamic (Manga Essouma et al. 2021; Hamidou et al. 2023). Just as agricultural systems are constantly subject to disturbances, the reorganization of production factors can lead to shifts, causing farmers to transition from one typology to another (Tonet et al. 2023). Therefore, it is essential to analyze and manage the differences in the social, economic, productive, and environmental characteristics of each farm (García-Arias et al. 2015; Methorst et al. 2017; Kilwinger et al. 2021a). Thus, it is important to design actions based on the differences in attitudes, motivations, and behaviors among farmers (Foguesatto et al. 2019; Upadhya et al. 2021; Graskemper et al. 2021). This enables targeting long-term technical messages (Nainggolan et al. 2013a) that address agricultural value-chain stakeholders' needs, with particular focus on farmers' livelihood needs (Jagoret et al. 2008; Viteri Salazar et al. 2018; Fanchone et al. 2020).

Today, farmers face the twin challenges of agricultural production and social and environmental sustainability (Darnhofer et al. 2005; Morris et al.

2017; Bánkuti et al. 2020). In addition to their productive efforts, they must manage and adapt to the impacts of various land-use practices on biodiversity and ecosystem services (Brauman et al. 2020; Perazzo et al. 2023). Farmer characteristics and land distribution play a critical role in land-use decisions and projections which in turn shape agroecosystem landscapes (García-Arias et al. 2015). This is particularly evident in agroforestry systems, where agriculture and forestry are interconnected along a functional continuum, making land-use decisions more complex and context-dependent (van Noordwijk 2019). Manga Essouma et al. (2021) have highlighted the relationship between cacao agroforestry systems and pressure on forest cover, emphasizing the need to explore the underlying causes of this relationship through a farmer classification informed by an objective typification process. In the case of cacao, it is essential to recognize that this production system is often associated with other forest-related plant species (Saj et al. 2023; Silue et al. 2024). Therefore, one potential approach to classifying cacao production systems could involve using wealth and diversity indicators (Notaro et al. 2020).

Moreover, different types of farmers follow distinct pathways in response to incentives (Foguesatto et al. 2019), regulations, market opportunities (Nainggolan et al. 2013b; Manga Essouma et al. 2021), and subsidized development programs (Kilwinger et al. 2021b). They also consider strategies for family economy diversification (García-Arias et al. 2015), or on-farm labor dynamics (Weltin et al. 2017) and gender-related social factors (Mzoughi 2011; Franzén et al. 2016; Barnes et al. 2022). All of the above-mentioned issues highlight multiple factors influencing farmers' technical behavior (Martin-Collado et al. 2014a) and their adoption of potential innovations in production systems (Mc Fadden and Gorman 2016). This analysis underscores the need to redesign actions in alignment with the diverse livelihoods and social contexts of farmers (Righi et al. 2011; Martin-Collado et al. 2014b; LaFevor 2022).

The farmer typologies methodology has been criticized due to its reliance on structural variables, its arbitrary classification methods, and its perceived political irrelevance (LaFevor 2022). However, typification aims to maximize the heterogeneity between groups and the homogeneity within them (Foguesatto et al. 2019). This approach enables the

generation of hypotheses about farmers' behavior, thereby facilitating the design or adjustment of incentives for production practices, diversification, and the adoption and adaptation of technologies (Weltin et al. 2017; Kilwinger et al. 2021b; Awoke Eshetae et al. 2024). It also facilitates the management of natural resource conservation, environmental emergency actions (Barnes et al. 2022; Antwi-Agyei and Amanor 2023; Jan et al. 2024), and transformations in the context of the climate crisis (Graskemper et al. 2021). This includes agroecological transition processes (Fanchone et al. 2020; Barnes et al. 2022), access to voluntary conservation payment programs (Upadhaya et al. 2021), and even genetic resources conservation (Hamidou et al. 2023).

Cacao agroforestry system typification primarily aims to understand the systems' technical characteristics and their relationship with productivity levels (Jagoret et al. 2008), as well as to differentiate between smallholder farms, state-owned plantations, and private plantations (Fahmid 2013). Additionally, typification assesses the growth of cacao agroforestry systems in environmentally fragile areas, making it a valuable tool for local, national, and cooperation institutions (Viteri Salazar et al. 2018). Cacao farmers can also be classified according to their level of knowledge of the production system which, in the case of cacao, has been measured through tools such as the Cacao Knowledge Index (CKI) (Gutiérrez García et al. 2020) or sustainability indicators (Heredia-R et al. 2024). In cacao agroforestry systems, an aging farmer population has been observed, coupled with a decreasing interest in agricultural activities among younger generations. Consequently, it is essential to examine the relationship between farmer typologies and age demographics (Amon-Armah et al. 2022).

In Colombia, the cacao value chain has emerged as a key alternative for agricultural and rural development. Its significance has grown within the context of the peace-building process and the transition from illegal to legal economies, with crops such as cacao, *chontaduro* (peach palm, *Bactris gasipaes*) or *açaí* (*Euterpe spp.*). One of the regions where this value chain has gained significant interest is the Amazon, particularly in the department of Putumayo. Since the late 2000s, cacao development programs have been introduced in the Colombian Amazon, based on technological models borrowed

from agro-climatically different areas, but without considering the farms' biophysical and cultural differences (Cardona et al. 2022). According to the *Prefeasibility Study of the Integrated Project for Socioeconomic Transformation and Territorial Peace Building for the Municipalities of the Putumayo PDET Subregion, around the Cacao value Chain* (Gutiérrez and Olarte 2024), cacao producers in this department were characterized and classified based on farm size, cacao clones, crop age, and yields. However, other biophysical and cultural variables, which could enhance the design of planning and intervention tools, were not considered.

To address these gaps, this study seeks to answer the following research questions: (1) What typologies of cacao farmers can be identified in the Colombian Amazon piedmont? (2) How do these typologies relate to land-use patterns and the distribution of agroforestry landscape units?. Using a robust statistical approach, combining multivariate analysis techniques, multiple factor analysis and hierarchical cluster analysis, this study integrates productive, cultural, socioeconomic, and landscape variables to construct a typology of cacao farmers. In doing so, it deepens the understanding of cacao agroforestry systems in a region marked by both ecological and cultural heterogeneity. Ultimately, the study provides a valuable framework to support context-sensitive planning and decision-making, offering insights to balance productivity with sustainability, promote sustainable land use, and foster inclusive, resilient rural development.

Materials and methods

Figure 1 presents a summary of the workflow followed in this study. The methodology draws on established frameworks for the construction of agricultural typologies, as described by Hassall et al. (2023) and Alvarez et al. (2018).

First, the study area was defined in the Colombian Amazon piedmont. Second, data were collected and 27 quantitative and qualitative variables were selected. Then, the data were processed and analyzed using statistical techniques. Multivariable analysis (PCA and MCA) was applied for were applied to reduce dimensionality, followed by a multiple factor analysis (MFA) to identify the most

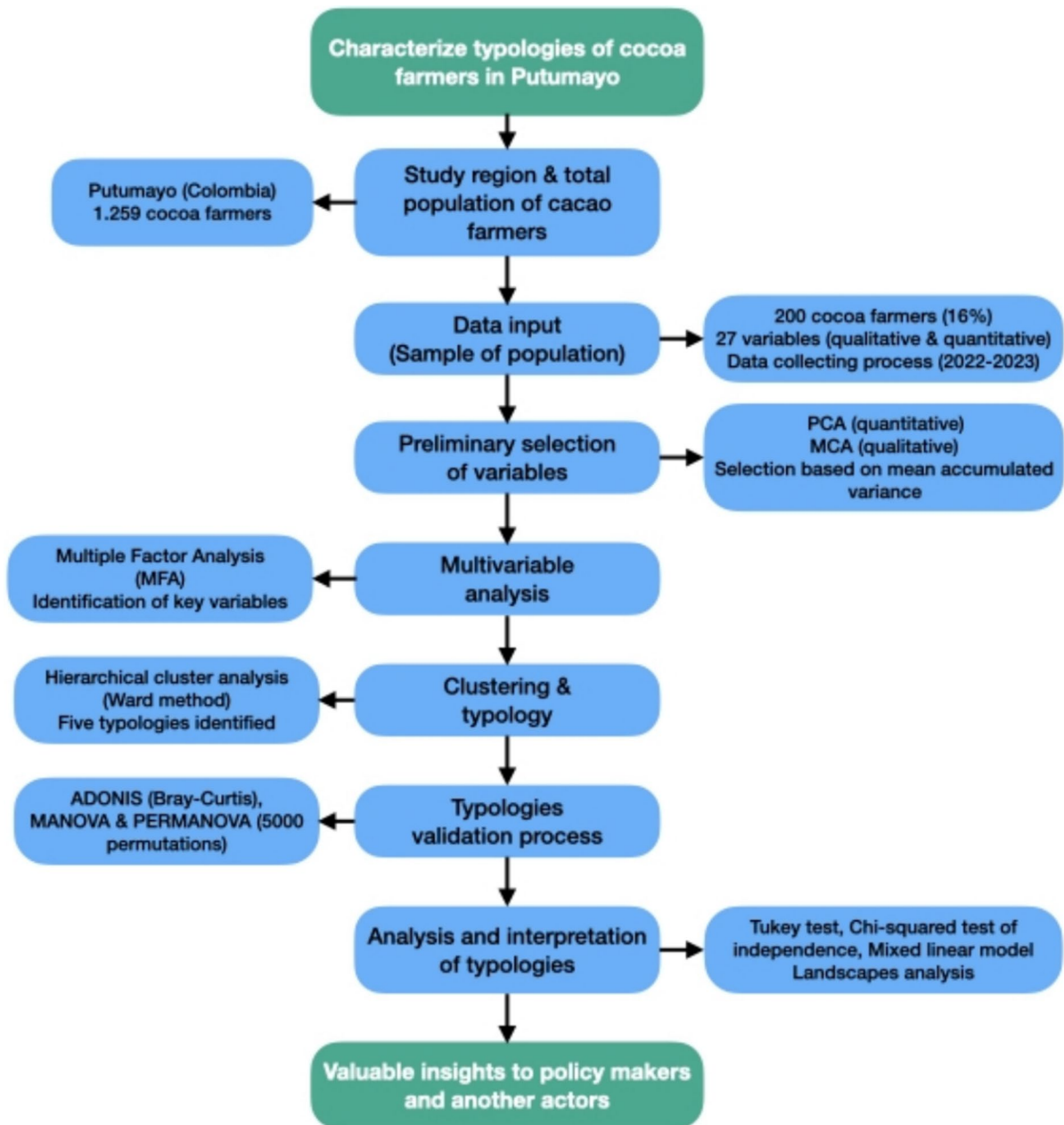


Fig. 1 Analysis process work-flow

influential variables. A hierarchical cluster analysis (Ward's method) was then performed to identify farmer typologies. These typologies were validated through ADONIS, MANOVA, PERMANOVA, and Chi-squared tests, and refined using Tukey post-hoc comparisons. Finally, landscape composition and

typology distribution across municipalities were analyzed, along with a supplementary interpretation of culturally relevant variables, to enhance the policy relevance of the findings.

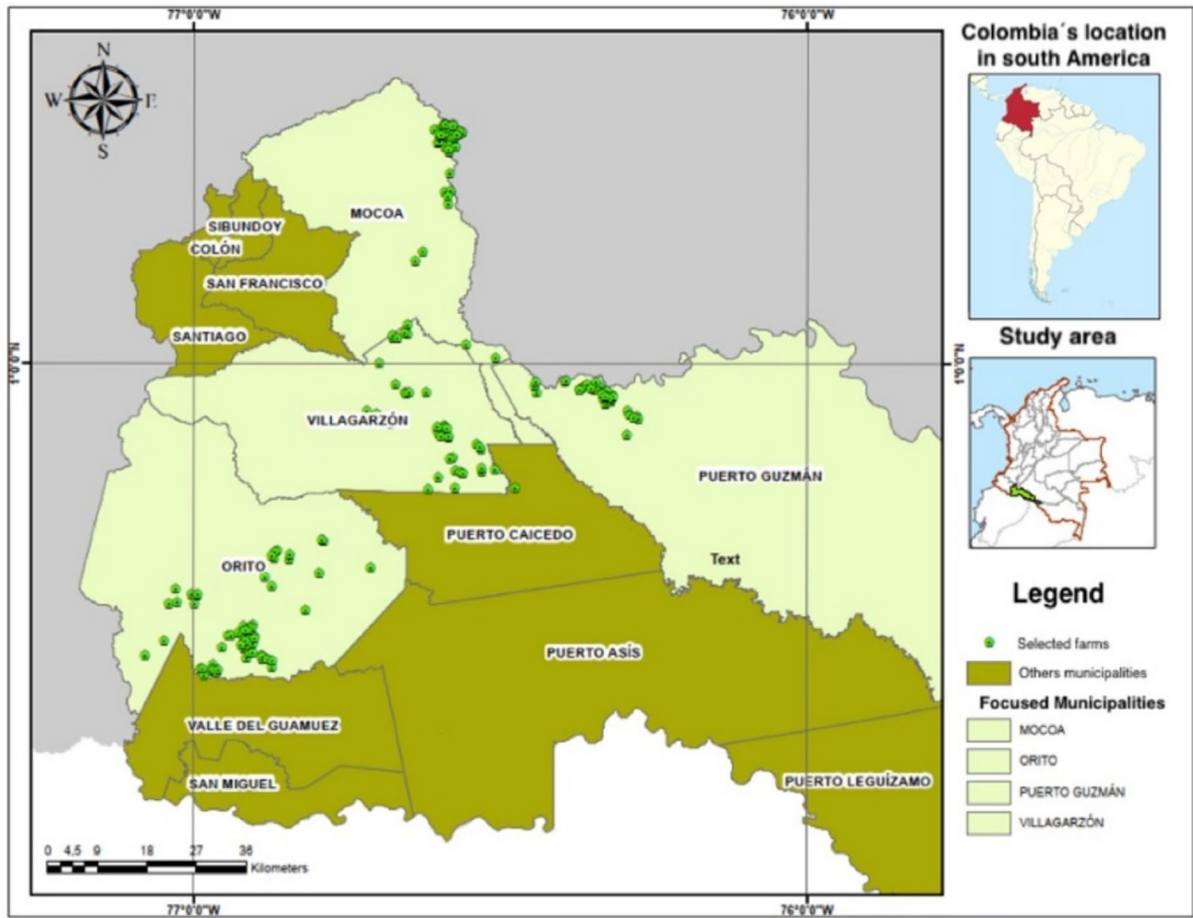


Fig. 2 Study location

Study area

The department of Putumayo is located in the southwest of Colombia, within the Colombian Amazon piedmont region (Fig. 2). In this area, 1,259 households are engaged in cacao production, with an average production area of 2 ha per household, totaling approximately 3,000 ha. Although not historically known for cacao cultivation, production expanded in the early 2000s as part of peace-building and rural development strategies that promoted legal alternatives to illicit crops. Early plantations consisted predominantly of monoculture and monoclonal systems characterized by family labor use, exhibiting low agroclimatic adaptation, limited use

of technology, low productivity and quality. Currently, cacao is planted in agroforestry systems in association with palms, timber and fruit trees, supported by development cooperation and institutional programs aimed at fostering sustainable livelihoods (Cardona et al. 2022).

Data collection

Personal and farm data were collected digitally offline using forms administered through KOBO Collect between 2022 and 2023. Information was collected, previously written informed consent included within individual inclusion agreement. This includes personal data from the farmers, which were coded

and anonymized for this study. The data collection was approved by Institutional Review Board (IRB) of the Alliance of Bioversity International and CIAT (2021-IRB12).

Based on a productivity and environmental diagnosis of 245 cacao farms participating in the European Union's European Fund for Peace program, the PDET Routes Program, and a literature review on cacao typologies (Viteri Salazar et al. 2018; Gutiérrez García et al. 2020; Notaro et al. 2020; Manga Essouma et al. 2021; Amon-Armah et al. 2022; Heredia-R et al. 2024), 27 variables were selected to use in this study (Table 1). After performing quality control on the data, a final sample of 200 farmers (16% of the

total of 1,259 households existing within the department) was selected. These farmers are located in the municipalities of Mocoa (58), Orito (63), Puerto Guzmán (42), and Villagarzón (37), where cocoa production is most prevalent (Fig. 1).

Additionally, as a verification mechanism for increased accuracy, the farms were mapped at the farm scale using eTrex 30 GPS units, ensuring that the data related to the areas of the landscape units corresponded to actual measurements rather than those self-reported by the farmers. Some data were transformed for clarity. For instance, the sum of cacao, pasture, and both transitory and permanent crop areas was used to represent the total productive

Table 1 Biophysical and cultural variables applied in the study

Variable	Abbreviation	Type of variable	Unit of measurement
Access to external labor	External Labor	Qualitative	Yes/No
Area dedicated to cacao	Cacao area	Quantitative	Ha
Area of environmental conservation	Conservation area	Quantitative	Ha
Area of forest transitions	Forest transition	Quantitative	Ha
Area of pastures	Pastures	Quantitative	Ha
Area of permanent crops	Permanent	Quantitative	Ha
Area of transitory crops	Temporary	Quantitative	Ha
Cacao yield	Yield	Quantitative	Kg/ha/year
Conservation agreement	Conservation agreement	Qualitative	Yes or No
Ethnic group	Ethnicity	Qualitative	Indigenous, peasants, mestizo, afro-descendant
Farm area	Farm Area	Quantitative	Ha
Farm specialization in agriculture	Spec Agri	Quantitative	%
Farm specialization in cacao	Spec Cacao	Quantitative	%
Farm specialization in conservation	Spec Conservation	Quantitative	%
Farm specialization in forest transition	Spec forest transition	Quantitative	%
Gender of the head of household	Gender	Qualitative	Female, male
Head of family age	Farmer Age	Quantitative	#
Highest educational level	Highest Edu Level	Qualitative	None, elementary, secondary, Technical, Technology professional,
Income from non-agricultural activities	Income Non Agri	Qualitative	Yes or No
Labor availability	Workers/ha	Quantitative	# people/ha
Landscape type	Landscape	Qualitative	Flat, undulating, mountainous
Management practices for pests & disease control	Mgmt Pest Control	Qualitative	Conventional, organic
Number of people of working age (> 14 years old)	Family workers	Quantitative	#
Number of people over 65 years old	over65	Quantitative	#
Number of people under 14 years old	under14	Quantitative	#
Number of plots dedicated to cacao	Cacao plots	Quantitative	#
Postharvest infrastructure	Postharvest	Qualitative	Yes or No

area. Similarly, the ratio of productive area to total farm area was employed to calculate the variable '*farm specialization in agriculture*.'

Statistical analysis

Two multivariate analysis techniques were applied to explore the relationships between the variables and reduce the dimensionality of the dataset. The first analysis was a principal component analysis (PCA) for quantitative variables, performed in two dimensions. The second was a multiple correspondence analysis (MCA) for qualitative variables, also in two dimensions. The variables were selected based on accumulated variance, which indicates the proportion of variance explained by each dimension, with the accumulated variance mean serving as the selection threshold.

Subsequently, the selected variables from both PCA and MCA were included in a multiple factor analysis (MFA). This analysis allowed for the identification of the most influential variables that explain the majority of the variability among the typologies. Finally, a hierarchical cluster analysis was performed using the Ward method to group the observations based on the selected key variables. This methodology allows for the grouping of typologies (observations) based on their interactions, differences, and similarities with each other, while distinguishing them from other types of farms belonging to other typologies (Alvarez et al. 2018).

Additionally, to validate the identified typologies and the interaction between the variables and the typologies, a non-parametric analysis of variance (ADONIS) was conducted using a Bray–Curtis distance matrix. Additionally, a parametric multivariate analysis of variance (MANOVA) was conducted to validate the results obtained from the ADONIS. Pillai value was calculated to analyze the influence of typologies on the quantitative variables. Subsequently, the results were segmented univariately by performing a one-way permutational analysis (PERMANOVA) with 5,000 permutations, allowing for the verification that the results are applicable to a larger number of potential observations.

Once the range of typologies was obtained and validated, a Tukey test was performed using $P < 0.05$ to identify significant differences for the quantitative

variables. To compare qualitative data among typologies, a Chi-squared test of independence was used, aimed at determining whether significant associations exist between two categorical variables. Finally, a mixed linear regression model (Eq. 1) was applied to deductively assess the influence of the qualitative variables on the quantitative variables, and simultaneously, how the different typologies also affect the quantitative variables.

$$\begin{aligned} \{Ql(a)\} \sim Typology \\ + (1|Ql(a)) + (1|Ql(b)) + (1|Ql(c)) \dots + (1|Ql(n)) \end{aligned} \quad (1)$$

Where Ql corresponds to the quantitative variable analyzed as a function ($\sim$) of the typology and random effects, that is, the qualitative variables (Ql) prioritized by the MFA.

Additionally, a geographical distribution analysis of the different farm typologies within the municipalities involved in the study was conducted in order to understand the co-existence of different typologies at the regional scale. A landscape analysis of the identified typologies was also performed. For this, data on the areas measured on each farm (*cacao area, conservation area, forest transition, transitory crops, permanent crops, pastures*) were used. A Tukey test ($P < 0.05$) was applied to identify differences among the mean values of the typologies. Finally, an analysis is conducted on the qualitative variables initially selected through MCA but later excluded from the MFA used for typology construction. This analysis aims to shed light on culturally relevant aspects of the study area, providing a more grounded basis for the policy recommendations presented in the manuscript.

Results

Determination of main variables

Results of the multivariate analysis (PCA and MCA)

Through the PCA, two principal components were identified, explaining 65% of the total variance. The first component, which explains 24.1% of the variance, is strongly associated with variables such as *cacao area, specialization in agriculture, and farm specialization in cacao*. The second component,

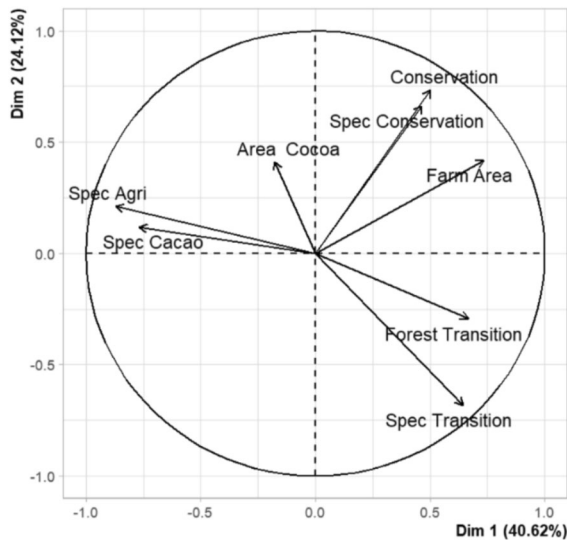
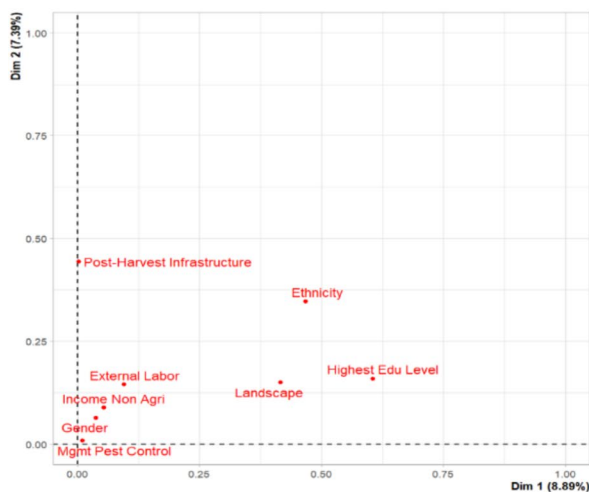
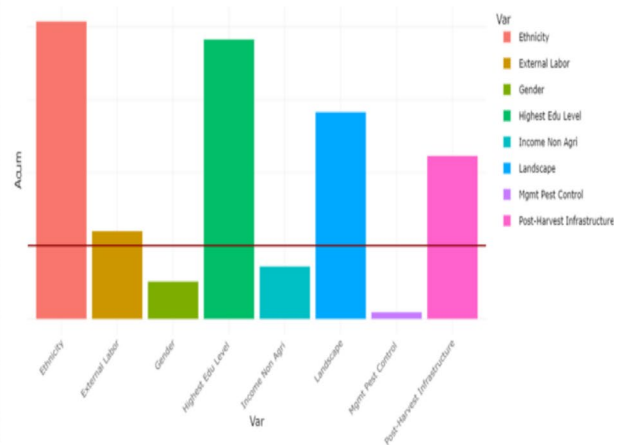


Fig. 3 PCA biplot illustrating the relationship between quantitative variables in cacao farms *Note:* Arrows indicate the contribution of each variable to the principal components. Correlation circles represent the principal components (PCs)

explaining an additional 40.6%, is related to variables such as *farm area*, *conservation area*, *forest transition area (stubble)*, and *conservation specialization* (Fig. 3).



a



b

Fig. 4 MCA analysis for selecting qualitative variables. **a** biplot illustrating the relationship between qualitative variables and **b** variable selection threshold based on the mean value of variance

Table 2 Variance of each MFA variable. Variables showing variance values higher than the overall mean

Variable	Variance
Highest educational level	38.62
Ethnicity	34.74
Forest transition specialization	33.05
Conservation area	29.61
Landscape type	26.96
Specialization in agriculture	26.53
Farm Area	25.85
Specialization in conservation	23.67
Cacao specialization	18.81
Forest transition	17.44
Cacao area	13.46
External labor	10.34
Post-harvest infrastructure	0.89

be explained within a range of 30% to 40% (designed to capture variability within each group of variables without allowing any single variable to dominate) (Pagès 2004).

The first three dimensions, which explain 30.9% of the variance, are primarily influenced by eight key variables: *farm area*; *forest transition specialization* (*stubble*); *conservation area*; *specialization in*

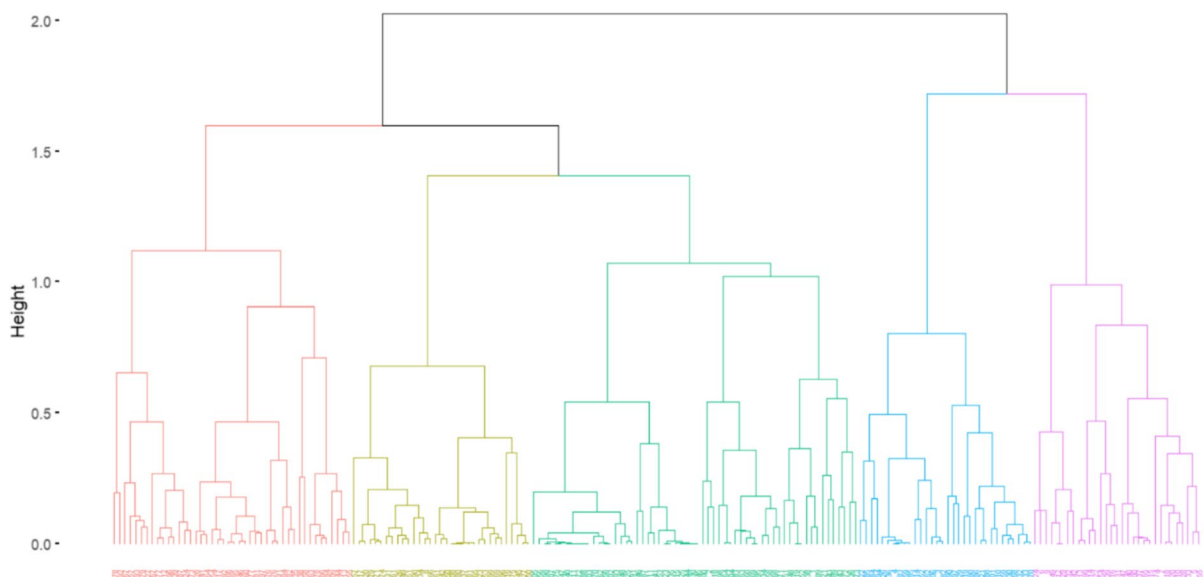
agriculture; *specialization in conservation*; *highest educational level*; *ethnicity*, and *landscape type*. These variables show individual variance values higher than the overall mean (23.07) from the global analysis, which served as the selection threshold, based on the canonical analysis of the variables (Legendre and Legendre 2012) (Table 2).

Hierarchical Cluster Analysis Based on the eight variables selected in the MFA, a hierarchical cluster analysis was conducted, and a dendrogram was created to determine the optimal cutoff and define five distinct typologies (Fig. 5).

Based on the analysis, five farm systems (typologies) were identified. The descriptors for each typology are presented below and will be further described and analyzed in “[Description and comparative analysis of farmer typologies](#)” section.

Interaction between variables and typologies

The ADONIS model showed that the typologies explained a significant proportion (20%) of the total variance in the quantitative variables ($R^2=0.23283$, $p=0.001$). A more complex model, which included the qualitative variables (*ethnicity*, *landscape*, and *highest educational level*), demonstrated higher

**Fig. 5** Dendrogram illustrating the five identified typologies. Typology 1 (green), Typology 2 (blue), Typology 3 (golden), Typology 4 (purple) and Typology 5 (red)

statistical significance ($R^2=0.39723$, $p=0.001$), explaining 40% of the total variance in the quantitative variables.

The results from the MANOVA, conducted to validate the findings from the ADONIS, indicated that the quantitative variables collectively contributed significantly to explaining the variance between the typologies ($F_{(20, 776)}=4.7082$, $p<0.001$). Furthermore, the Pillai value obtained (0.43286) suggests a moderate effect of the typologies on the quantitative variables. The PERMANOVA results confirmed the previous findings, showing consistent p values (<0.001) for all the quantitatively analyzed variables in the univariate analysis. The post hoc analysis for the variables is presented in Table 3.

Tests of independence for the qualitative variables (*highest educational level, ethnicity, and landscape*) revealed a significant association with typology ($p<0.001$), indicating that these variables also contribute to the differentiation among typologies, reinforcing the findings from the ADONIS test.

Finally, a mixed linear regression analysis was conducted to assess the individual effects of typologies on each quantitative variable, while accounting for variability through random effects with the other quantitative variables. The fixed effects coefficients reflect the influence of each typology on all quantitative variables. For instance, the negative estimator values for Typologies 2, 3, 4, and 5 suggest a decreasing effect on farm specialization in agriculture compared to the reference category (Typology 1).

These results highlight the complex interplay between quantitative and qualitative variables in shaping each typology while also indicating that typologies, as a fixed factor, can influence the response of quantitative variables.

Description and comparative analysis of farmer typologies

Table 3 presents the data for the eight key variables defining the identified typologies.

The characteristics of each typology are detailed below:

- *Typology 1 (n=60) – Predominantly agriculture-oriented farmers.* They have diverse ethnic self-perceptions, but the majority are peasants and Indigenous farmers. The average farm size is 5.52 ha, with a high proportion dedicated to agriculture (84.2%) and a small area dedicated to conservation (4.07%). While the terrain varies, flat and mountainous landscapes predominate. The highest education level is mostly elementary school.
- *Typology 2 (n=32) – Moderately agriculture-oriented peasant.* Overall, they are farmers with an average farm size of 7.68 ha, a moderate-to-high farm-specialization level in agriculture (61.7%), and a low proportion of areas dedicated to conservation (8.07%). The farms have predominantly flat and undulating terrain. This group is characterized by a high percentage of farmers with secondary education.
- *Typology 3 (n=31) – Indigenous with diversified agricultural production.* This group consists entirely of Indigenous individuals, with an average farm size of 12.8 ha and moderate agricultural specialization (53.5%). The predominant terrain is flat and undulating. A significant proportion of farmers in this group has technical or secondary education.
- *Typology 4 (n=33) – Mixed moderately agriculture-oriented.* Most of the group are peasant farmers with a significant presence of Indigenous and Afro-descendant individuals. Their farms exhibit moderate to high agricultural specialization (61.7%), with a notable proportion dedicated to conservation (11.2%). All farms are located in undulating terrains, and nearly all farmers have completed only elementary education.
- *Typology 5 (n=44) – Conservation-oriented farmers.* They are predominantly peasants, and the group also includes individuals of Afro-descendant. They have the lowest degree of agricultural specialization (29.6%) and the highest proportion of land dedicated to conservation (25.5%) compared to other types of farmers. Most farms are located on flat terrain, though a significant proportion is distributed across undulating and mountainous areas. This group has the highest percentage of individuals with lower educational levels compared to the other typologies.

Table 3 Characteristics of the identified typologies

	Typology 1 (N = 60)	Typology 2 (N = 32)	Typology 3 (N = 31)	Typology 4 (N = 33)	Typology 5 (N = 44)	Overall (N = 200)
<i>Farm area (ha)</i>						
Mean (SD)	5.52 (6.01) b	7.68 (9.09) ab	12.8 (18.1) ab	5.62 (5.49) b	16.1 (20.7) a	9.32 (13.8)
Median [Min, Max]	2.98 [0.210, 26.2]	4.42 [1.45, 49.9]	3.35 [0.160, 63.0]	4.46 [0.510, 24.2]	8.75 [1.16, 102]	4.67 [0.160, 102]
<i>Agriculture specialization (%)</i>						
Mean (SD)	84.2 (24.0) a	61.7 (30.6) b	53.5 (32.0) b	61.7 (29.7) b	29.6 (19.6) c	60.1 (32.9)
Median [Min, Max]	100 [8.51, 100]	61.9 [0, 100]	43.5 [10.6, 100]	60.4 [6.78, 100]	26.0 [1.64, 71.7]	60.3 [0, 100]
<i>Specialization in conservation (%)</i>						
Mean (SD)	4.07 (9.99) b	8.07 (17.5) b	7.92 (15.1) b	11.2 (16.3) b	25.5 (29.9) a	11.2 (20.3)
Median [Min, Max]	0 [0, 52.3]	0 [0, 75.6]	0 [0, 49.9]	0 [0, 56.4]	9.94 [0, 98.4]	0 [0, 98.4]
<i>Conservation area (ha)</i>						
Mean (SD)	0.418 (1.25) b	0.746 (1.98) b	1.80 (5.43) ab	0.668 (1.56) b	6.36 (16.8) a	2.03 (8.52)
Median [Min, Max]	0 [0, 6.67]	0 [0, 8.52]	0 [0, 29.0]	0 [0, 8.05]	1.28 [0, 101]	0 [0, 101]
<i>Forest transition specialization (%)</i>						
Mean (SD)	11.7 (20.1) c	30.2 (28.4) ab	38.6 (29.6) ab	26.5 (25.4) bc	44.8 (33.9) a	28.6 (29.8)
Median [Min, Max]	0 [0, 82.4]	25.3 [0, 100]	37.0 [0, 89.4]	26.1 [0, 77.5]	47.8 [0, 93.2]	22.6 [0, 100]
<i>Ethnicity</i>						
Afro-descendant	1 (1.7%)	0 (0%)	0 (0%)	1 (3.0%)	2 (4.5%)	4 (2.0%)
Indigenous	20 (33.3%)	0 (0%)	31 (100%)	4 (12.1%)	0 (0%)	55 (27.5%)
Mestizo	3 (5.0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	3 (1.5%)
Peasant	36 (60.0%)	32 (100%)	0 (0%)	28 (84.8%)	42 (95.5%)	138 (69.0%)
<i>Highest educational level</i>						
None	4 (6.7%)	0 (0%)	3 (9.7%)	0 (0%)	9 (20.5%)	16 (8.0%)
Elementary	53 (88.3%)	0 (0%)	9 (29.0%)	32 (97.0%)	34 (77.3%)	128 (64.0%)
Professional	1 (1.7%)	0 (0%)	0 (0%)	0 (0%)	1 (2.3%)	2 (1.0%)
Secondary	2 (3.3%)	28 (87.5%)	14 (45.2%)	0 (0%)	0 (0%)	44 (22.0%)
Technical	0 (0%)	2 (6.3%)	4 (12.9%)	1 (3.0%)	0 (0%)	7 (3.5%)
Technology	0 (0%)	2 (6.3%)	1 (3.2%)	0 (0%)	0 (0%)	3 (1.5%)
<i>Landscape</i>						
Flat	36 (60.0%)	16 (50.0%)	17 (54.8%)	0	29 (65.9%)	98 (49.0%)
Undulating	8 (13.3%)	14 (43.8%)	13 (41.9%)	33 (100.0%)	11 (25.0%)	79 (39.5%)
Mountainous	16 (26.7%)	2 (6.3%)	1 (3.2%)	0	4. (9.1%)	23 (11.5%)

Significant differences in quantitative variables were assessed using Tukey's test ($P < 0.05$). Typologies sharing the same letter do not differ significantly, while different letters indicate significant differences. Shared letters show similarities between certain typologies but differences with others.

Significant differences are observed between Typologies 1 (*Predominantly agriculture-oriented farmers*) and 5 (*Conservation-oriented farmers*) in the variables of *farm area*, *agricultural specialization*, *conservation area*, and *forest transition specialization*—locally referred to as *stubble*. For Typologies 2, 3, and 4, differences are identified only in *farm area* and *forest transition specialization*, whereas in *agriculture specialization*, *conservation area*, and *conservation specialization*, these typologies can be considered similar to each other.

Most farmers received a primary education (64%), followed by secondary education (22%), while only 6% hold a high-school diploma (professional). Typologies 2 and 3 show the highest levels of education, whereas Typologies 1 and 5 show the lowest. Although farms with flat, undulating, and mountainous terrain are present across all typologies, 100% of the farms in Typology 4 are on undulating land. Typology 1 has the highest proportion

of mountainous farms, though a considerable share also has flat terrain, similar to Typologies 4 and 5.

Geographic distribution of typologies

Table 4 shows the distribution of the five typologies across the different municipalities included in the study.

With the exception of Typology 3 (*Indigenous with diversified agricultural production*), which is primarily concentrated in Mocoa, the other typologies are geographically spread across all municipalities. This suggests that different cacao farmer typologies can be found throughout the municipalities of the department.

Landscape unit analysis

Based on the results presented above, the analysis of the characterized landscape units was further explored (Table 5). The Tukey test ($P < 0.05$) revealed no statistically significant differences between the five typologies in terms of *transitory crops*, *permanent crops*, and *pasture areas*. In addition to the differences outlined in Table 3, significant variations in cacao areas were observed among the different typologies, although this was not one of the variables

Table 4 Distribution of farmer typologies across the four analyzed municipalities

Municipality	1 (N = 60)	2 (N = 32)	3 (N = 31)	4 (N = 33)	5 (N = 44)	Overall (N = 200)
Mocoa	23 (38.3%)	2 (6.3%)	28 (90.3%)	4 (12.1%)	1 (2.3%)	58 (29.0%)
Orito	25 (41.7%)	12 (37.5%)	2 (6.5%)	10 (30.3%)	14 (31.8%)	63 (31.5%)
Puerto Guzmán	6 (10.0%)	11 (34.4%)	0 (0%)	11 (33.3%)	14 (31.8%)	42 (21.0%)
Villagarzón	6 (10.0%)	7 (21.9%)	1 (3.2%)	8 (24.2%)	15 (34.1%)	37 (18.5%)

Table 5 Size (in hectares) and distribution (in %) of landscape units across the analyzed farms

	Cacao area			Conservation area			Forest transitions			Transitory crops			Permanent crops			Pastures			Total area
Typology 1	1.64	ab	30%	0.42	b	8%	0.59	b	11%	0.26	a	5%	0.29	a	5%	2.33	a	42%	5.53
Typology 2	2.17	a	28%	0.75	b	10%	1.86	ab	24%	0.18	a	2%	0.41	a	5%	2.33	a	30%	7.7
Typology 3	0.91	b	7%	1.80	ab	14%	6.84	a	54%	0.62	a	5%	0.27	a	2%	2.34	a	18%	12.78
Typology 4	1.49	ab	27%	0.67	b	12%	1.98	ab	35%	0.20	a	4%	0.27	a	5%	0.97	a	17%	5.58
Typology 5	1.83	ab	11%	6.36	a	40%	6.49	a	40%	0.34	a	2%	0.07	a	0%	0.96	a	6%	16.05
Average	1.63		18%	2.03		22%	3.29		35%	0.31		3%	0.25		3%	1.8		19%	9.31

highlighted in the PCA analysis. On average, 18% of farm area is dedicated to cacao cultivation, with Typology 1 having the highest proportion (30%), although its average cacao area is only 1.64 ha.

Typologies 4 and 5 have average cacao areas of 1.49 ha and 1.83 ha, respectively, and are statistically similar to Typology 1. The typology with the largest average cacao area is Typology 2, with 2.17 ha, which represents 28% of the total farm area. The farms with the smallest cacao area are those of Typology 3, with only 0.91 ha on average, accounting for 7% of the total farm area. In these same farms, the largest areas were identified as being dedicated to transitory crops (0.62 ha) and pastures (2.34 ha). This indicates that the agriculture orientation nature of these farms is not solely a result of cacao cultivation, but also reflects their engagement in other agricultural activities.

Significant differences in quantitative variables were assessed using Tukey's test ($P < 0.05$). Typologies sharing the same letter do not differ significantly, while different letters indicate significant differences. Shared letters show similarities between certain typologies but differences with others.

Table 5 also illustrates the relative importance of *forest transition areas* and *conservation areas*, which are landscape units where significant differences between typologies were identified. Additional to typology 5, Typology 3 may also show

conservationist characteristics. This interpretation can be extended to Typologies 2 and 4, particularly when considering forest transition areas that are not actively used for production, but are in natural fallow and ecological recovery (synonymous with stubble). This land use reflects a level of environmental management that extends beyond agricultural production, and it differs in the land-sharing or land-sparing strategies for each typology.

Analysis of qualitative variables

Although the MFA model retained only three qualitative variables (Ethnicity, Highest Educational Level, and Landscape, see Table 3), Table 6 presents the remaining qualitative variables initially selected through the MCA.

External labor use is present across all typologies, though it is less frequent in Typology 1, which also has the smallest average farm size. Male-headed households predominates in all typologies, except Typology 3. *Income from non-agricultural activities* represents a significant share of total income, possibly linked to subsidies, although this aspect was not assessed in the present study.

Conventional *Management practices* prevail across typologies, especially in Typology 1 (*Predominantly agriculture-oriented farmers*). Interestingly,

Table 6 Qualitative variables selected by MCA that do not influence the typologies

Variables	Typology 1 (N=60)	Typology 2 (N=32)	Typology 3 (N=31)	Typology 4 (N=33)	Typology 5 (N=44)	Overall (N=200)
<i>External labor</i>						
No	41 (68.3%)	20 (62.5%)	17 (54.8%)	19 (57.6%)	20 (45.5%)	117 (58.5%)
Yes	19 (31.7%)	12 (37.5%)	14 (45.2%)	14 (42.4%)	24 (54.5%)	83 (41.5%)
<i>Gender</i>						
Female	23 (38.3%)	13 (40.6%)	17 (54.8%)	9 (27.3%)	10 (22.7%)	72 (36.0%)
Male	37 (61.7%)	19 (59.4%)	14 (45.2%)	24 (72.7%)	34 (77.3%)	128 (64.0%)
<i>Income from non-agricultural activities</i>						
Yes	45 (75.0%)	19 (59.4%)	22 (71.0%)	26 (78.8%)	33 (75.0%)	145 (72.5%)
No	15 (25.0%)	13 (40.6%)	9 (29.0%)	7 (21.2%)	11 (25.0%)	55 (27.5%)
<i>Management practices for pests & disease control</i>						
Organic	18 (30%)	10 (31.3%)	15 (48.4%)	17 (51.5%)	17 (38.6%)	77 (38.5%)
Conventional	42 (70.0%)	22 (68.8%)	16 (51.6%)	16 (48.5%)	27 (61.4%)	123 (61.5%)
<i>Postharvest infrastructure</i>						
No	24 (40.0%)	16 (50.0%)	8 (25.8%)	14 (42.4%)	20 (45.5%)	82 (41.0%)
Yes	36 (60.0%)	16 (50.0%)	23 (74.2%)	19 (57.6%)	24 (54.5%)	118 (59.0%)

Typology 5 (*Conservation-oriented farmers*) also relies on conventional management techniques, suggesting that a conservation orientation may be more closely associated with farm size than with management practices. *Postharvest infrastructure* is present in all typologies, with no clear association with the other variables analyzed.

Discussion

Overall discussion

The combination of PCA, MCA, and MFA facilitated the objective identification of five distinct cacao farmer typologies. This approach integrates earlier methodologies, such as that of García-Arias et al. (2015) who applied MCA to classify different typology of farmers in northwestern Spain, or Manga Essouma et al. (2021) who used PCA for classifying cacao farmers in Cameroon. As an adaptation of the method proposed by Hassall et al. (2023), this study did not apply weighting, thereby enhancing the understanding of the cultural and ecological diversity among farmers. This approach offers a robust, adaptable framework for analyzing cacao-producing regions with diverse socio-ecological contexts.

The five farming systems (typologies) we identified were: *Predominantly agriculture-oriented farmers* (Typology 1), *Moderately agriculture-oriented peasant* (Typology 2), *Indigenous with diversified agricultural production* (Typology 3), *Mixed moderately agriculture-oriented* (Typology 4), and *Conservation-oriented farmers* (Typology 5). Similar typologies, which range from productivist to conservationist with varying degrees, have been identified by Upadhaya et al. (2021) in the case of large-scale farmers in the U.S. and, in the case of cacao producers, by Manga Essouma et al. (2021) in Cameroon. However, in the present study, typologies are not based on productivist logic or land-use intensification gradient. Instead, they are shaped by how agricultural and forestry elements interact within a functional continuum (van Noordwijk 2019), where cultural characteristics also play a decisive role in configuring the landscape, particularly within the Amazonian context (Viteri Salazar et al. 2018).

Five of the key variables that define the identified typologies are quantitative (*farm area*; *forest*

transition specialization (stubble); *conservation area*; *specialization in agriculture*; *specialization in conservation*), while three are qualitative (*highest educational level*; *ethnicity*, and *landscape type*). Other studies, such as Tonet et al. (2023), have observed similar trends, emphasizing quantitative factors such as productivity and household income used to classify livestock systems, often without considering social factors. In contrast, Awoke Eshetae et al. (2024) highlight food and nutritional security as crucial elements in classifying farmers based on their levels of technological adoption.

Ethnic differences are evident, as seen in Typology 3 (*Indigenous with diversified agricultural production*), which consists entirely of Indigenous people. This pattern, where typologies are composed exclusively of Indigenous people, has been previously identified, such as in LaFevor's (2022) study of Mexican farmers, where he classified them into 12 typologies. Interestingly, he found that the typologies with the least agricultural diversification were those in Indigenous communities in which are specialized in corn, bean and coffee crops. On the other hand, Bucheli and Bokelmann (2017) in their study on silvipastoral, agrosilvipastoral and agrisilvicultural systems in Sibundoy Valley (Putuyamo, Colombia) reported a high diversity of plant species contributing to ecosystem and cultural services in indigenous farm systems. Particularly those related to food, medicine fuel and fibers. The maintenance of such diversity within agricultural landscapes appears to be closely linked to the needs and practices to local communities. This may help explain why, in the present study, Typology 3 allocated greatest proportion of land cover use to forest transition areas where plants provide various medicinal and cultural uses.

Differences in educational levels are observed across typologies with typologies 1, 2 and 3 showing the highest levels of education and allocating larger areas to agricultural activities, highlighting the influence of qualitative variables on the typologies identified. Studies, including those by Graskemper et al. (2021); Martin-Collado et al. (2014), and Nainggolan et al. (2013b), show that farmers with higher levels of education tend to allocate more land to productive activities, adopt sustainable practices, distribute land use and respond more effectively to institutional incentives. Moreover,

these characteristics also influence climate-change adaptation strategies and the diversification of on-farm activities. Bánkuti et al. (2020) support this by highlighting that the educational level and age of farmers are the two most significant factors in adopting more sustainable practices.

No significant differences were identified based on household-head gender. Studies confirm that factors such as educational level, associativity, and area cultivated have a greater influence on farmers' rankings than gender or age. For example, see the studies by Gutiérrez García et al. (2020) in a cacao-growing region of Colombia and Amon-Armah et al. (2022) with young farmers in Ghana. However, Kilwinger et al. (2021) found that in Rwandan cassava production systems, gender, along with income and educational level, did indeed influence farmers' classification.

No differences were found in the identified typologies regarding age or labor availability. However, studies such as García-Arias et al. (2015) and Weltin et al. (2017) in various European production systems indicate that younger farmers tend to operate farms with higher levels of agricultural activity and income. Moreover, younger households with more members tend to diversify their operations, taking advantage of available labor. Research by Jagoret et al. (2008) in cacao farming in Cameroon shows that labor intensification is a key determinant in the formation of typologies. Similarly, Righi et al. (2011) found that labor, along with mechanization and irrigation, plays a crucial role in classifying horticultural farms in Uruguay.

Farm area and specialization in agriculture were key determinant variables in the construction of typologies, as supported by several studies. Daloğlu et al. (2014) emphasize structural factors, such as farm size and specialization, in classifying farmers in the U.S. Corn Belt. Similarly, Fanchone et al. (2020), in his study on agroecological transitions in the French Caribbean islands of Guadeloupe and Martinique, identified farm size and orientation (household vs. commercial) as determining factors. Gaitan and Ríos (2020) found that in Antioquia (Colombia) farm size influences the classification of avocado-producing farms, with larger farms facing labor shortages. Oliva Oller et al. (2022) also noted that larger farms require more external labor, aligning with the findings of this study, where larger farms

rely on hired labor. However, other studies, such as Bánkuti et al. (2020) on dairy farmers in Brazil, suggest that productivity, rather than size, may be the key factor in classifying farms from a sustainability perspective.

The presence of different production system typologies across municipalities highlights their geographic relevance. This aligns with Jagoret et al. (2008) who identified variations in technological models at the department, province, and village levels in a study of 1,428 cacao production units in Cameroon. Similarly, Graskemper et al. (2021) noted that *typologies can coexist* within the same geographic area.

The largest proportion of farm area is dedicated to conservation and transition, which plays a key role in classifying farmers in this study as either agriculture-oriented or conservation-oriented farmers. Previous studies support this distinction. Righi et al. (2011) found that small farmers maintain natural areas to meet self-consumption needs, while Fanchone et al. (2020) noted that fallow areas, though reducing production, facilitate agroecological transition. Additionally, Viteri Salazar et al. (2018) emphasized the importance of economic incentives in adopting environmental practices, which can influence conservationist tendencies. However, Jan et al. (2024) argued that ecosystem-friendly practices can also be implemented without financial incentives.

Upon examining conservation areas, only typology 5 clearly reflects a land-sparing strategy, while typologies 1, 2, 3 and 4 align more closely with varying degrees of land-sharing approaches. This pattern is consistent with findings from contexts, such as Saj et al. (2017) in Sub-Saharan Africa, where cacao-based agroforestry systems (land-sharing) coexist with intensive monoculture cacao plantations (land-sparing). Nevertheless, when examining the forest transition area (stubble) in the present study, it becomes evident that, except for typology 1, all typologies allocate land within the functional continuum between agriculture and forestry. This observation aligns with the work of Oliveira-Xavier et al. (2025), who documented similar dynamics in southern Mexico, where cacao agroforestry systems coexist with intensive banana (*Musa x paradisiaca*) plantations. In this context, and consistent with our results, a land-blending

strategy, one that integrates elements of both land-sparing and land-sharing to enhance agricultural productivity while supporting biodiversity conservation, emerges as an approach within the agricultural matrix of the Colombian Amazon.

Although *cacao area* was not a decisive variable in defining typologies, differences were observed among them. Fahmid (2013) found that in Indonesia, farm classification is influenced by the area dedicated to cacao cultivation. Similarly, Manga Essouma et al. (2021) highlighted that in Cameroonian cacao systems, farm specialization is determined by the extent of land allocated to cacao cultivation. Charry et al. (2025) also identified cacao as the primary source of income in the department of Putumayo, Colombia, with its cultivated area directly linked to productivity. They reported an average cacao area of 1 to 3 ha, which aligns with our findings, where the average ranges from 0.9 to 2.2 ha.

Study limitations and future research

This study did not assess tree biodiversity within cacao production systems. However, studies like Notaro et al. (2020) suggest that biodiversity indicators could be crucial for classifying production systems. This underscores the need for a more detailed analysis of the ecosystem structure within the agroecosystems analyzed in this study.

A limitation of this research is its focus on the interactions between cultural and biophysical variables to classify farmers, without exploring the implications of these variables on production-system performance. This suggests that further research is necessary to better understand the Main Agroecological Structure (MAS) (León-Sicard et al. 2018) and multifunctionality of farms classified within the typologies identified in this study. The next steps of the research process are focused on it.

Given the dynamic nature of household farming systems, farmers may transition between different typologies over time, particularly regarding land distribution (Benitez-Altuna et al. 2023). This highlights the need to interpret the results as a dynamic framework of typologies, rather than as a fixed classification of individual farmers. Finally, to ensure the most effective development practices at the local level, it is recommended to regularly

validate these typologies in collaboration with extensionist workers and researchers (Manners et al. 2025).

While the construction of typologies helps identify more context-appropriate interventions for heterogeneous groups of farmers, moving beyond one-size-fits-all approaches (Sinha et al. 2022), it remains an exploratory methodology that does not, in itself, define specific actions for farmers to improve their socioeconomic conditions (LaFevor 2022). For instance, it does not provide solutions to market risks, access to subsidies, agricultural extension services, or basic subsistence needs like food security (Giller et al. 2021; Ongachi and Belinder 2025). Further studies should explore how farmer typologies can be operationalized to inform targeted policies and support mechanisms that enhance both livelihoods and sustainability.

Conclusions

By combining PCA, MCA, and MFA, five distinct typologies of cacao farmers were identified in the Colombian Amazon piedmont. Typology 1 represents a *Predominantly agriculture-oriented farmers* group, while Typologies 2, 3, and 4 are *moderately agriculture-oriented*, with ethnicity being a key distinguishing factor. On the other hand, Typology 5 is characterized by a *Conservation-oriented* approach. Rather than fitting neatly within a conventional productivist–conservationist spectrum, these typologies reflect the socio-ecological diversity of the Colombian Amazon and invite broader reflection on land-use complexity.

The typologies were defined by key variables, such as *educational level*, *ethnicity*, *landscape*, *farm area*, *specialization in agriculture*, *conservation area*, and *specialization in conservation*. By integrating both qualitative and quantitative variables, this study aligns with global research that underscores the complexity and diversity of cacao farming systems, challenging the view that farming communities are homogeneous.

The study highlights that educational level, ethnicity and cultivated area influence farmer classification more than gender or age. This finding is key to designing effective policies that prioritize access to

training, institutional incentives for sustainable land uses, over less decisive demographic factors.

The typologies displayed variations in average farm sizes and levels of cacao specialization. However, the most notable differences were found in the conservation and forest transition areas, reflecting varying degrees of land-sparing and land-sharing strategies. In this context, a land-blending approach, integrating elements of both strategies, could represent a promising direction to balance agricultural productivity with biodiversity conservation in the agricultural matrix of the Colombian Amazon.

The widespread presence of all typologies (except Typology 3) across municipalities reflects the region's rich cultural and ecological diversity. This spatial distribution highlights the importance of localized interventions tailored to the unique socio-cultural and environmental contexts of each area.

Overall, this study offers valuable insights for policymakers, technicians, researchers, and other stakeholders, offering a foundation for inclusive and resilient agricultural policies. In predominantly agriculture-oriented farms (typology 1), targeted support could facilitate a gradual transition toward greater conservation, particularly in pasture areas. For conservation-oriented farms (typology 5) and, to some extent, typology 3, a partial use of forest transition (stubble) zones for cacao-based agroforestry, might help optimize agricultural production without compromising core conservation areas. In both cases, a higher reliance on external labor may be anticipated. Moderately agriculture-oriented farms may benefit from maintaining current landscape configurations while gradually adopting more diversified production systems. Across all typologies, there appears to be an opportunity to strengthen the promotion of sustainable practices, such as organic agriculture, through improved access to tailored incentives and differentiated market opportunities.

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Declarations

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