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MODERNIZAÇÃO AGRÍCOLA NA PRODUÇÃO DE CACAU: UMA PERSPECTIVA SOCIOECONÔMICA EM MUNICÍPIOS DA AMAZÔNIA ORIENTAL

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ABSTRACT

This article aims to investigate the level of agricultural modernization in cocoa production in municipalities of the Eastern Amazon and to analyze its relationship with socioeconomic variables of rural producers, such as education, gender, income, and access to social benefits. The research was conducted in the municipalities of Medicilândia, Tucumã, and Ourilândia do Norte, in the state of Pará, based on primary data collected between 2021 and 2023 from 874 rural properties. Through Multiple Correspondence Analysis (MCA), indicators of technological modernization were constructed, and cluster analysis was used to identify distinct production patterns. The results reveal the existence of groups with higher technological levels associated with better socioeconomic indicators, such as lower illiteracy rates, greater female participation in property management, and a higher presence of retirees. The empirical evidence indicates that modernization occurs unevenly across municipalities, reflecting territorial and structural specificities. The study contributes to the debate on sustainable regional development in the Amazon by showing that agricultural modernization, when accompanied by appropriate public policies, can promote productive inclusion, improved living conditions, and environmental conservation.

Keywords: Regional development. Sustainability. Agricultural modernization. Cocoa production. Eastern Amazon.

RESUMO

Este artigo tem por objetivo investigar o nível de modernização agrícola na produção de cacau em municípios da Amazônia Oriental e analisar sua relação com variáveis socioeconômicas dos produtores rurais, como escolaridade, gênero, renda e acesso a benefícios sociais. A pesquisa foi conduzida nos municípios de Medicilândia, Tucumã e Ourilândia do Norte, no estado do Pará, com base em dados primários coletados entre 2021 e 2023 em 874 imóveis rurais. Por meio da Análise de Correspondência Múltipla (MCA), foram construídos indicadores de modernização tecnológica e a análise de cluster permitiu identificar padrões produtivos distintos. Os resultados revelam a existência de grupos com maior nível tecnológico associados a melhores indicadores socioeconômicos, como menor taxa de analfabetismo, maior participação feminina na gestão das propriedades e maior presença de aposentados. As evidências empíricas apontam que a modernização ocorre de forma desigual entre os municípios, o que vem a refletir as especificidades territoriais e estruturais. O estudo contribui para o debate sobre o desenvolvimento regional sustentável na Amazônia, ao indicar que a modernização agrícola, quando acompanhada de políticas públicas adequadas, pode promover inclusão produtiva, melhoria das condições de vida e conservação ambiental.

Palavras-chave: Desenvolvimento regional. Sustentabilidade. Modernização agrícola. Cacauicultura. Amazônia Oriental.

INTRODUCTION

Cocoa production is predominantly found in countries with tropical forests and an equatorial climate. Brazil stands out as one of the main cocoa producers in South America, occupying the second position, just behind Ecuador (Aremu-Dele et al., 2022). Data from the Municipal Agricultural Production (PAM) indicate that in 2022, the state of Pará (located in the eastern Brazilian Amazon) concentrated 25.8% of the harvest areas in the country (IBGE, 2022). Production in the state peaked in 2021, registering 146,375 tons of cocoa (in beans) and representing 48.4% of the total produced in Brazil.

In 2022, this percentage increased to 53.3%, reflecting reduced production in other states (IBGE, 2022). The Amazon, through the state of Pará, holds the position of the largest cocoa producer in the country. The average production in the state reaches 955 kg/ha of cocoa, which exceeds the national average of approximately 464 kg/ha (IBGE, 2023).

The Amazon region plays a crucial role not only in the national context but also in the international context. In addition to serving as an important carbon sink and climate regulator, the Amazon stands out in the production of agricultural commodities such as soy, corn, rice,

sugarcane, cocoa and beef (Simon; Garagorry, 2005; Arvor et al., 2017; Koch et al., 2019). In addition, the region is recognized for hosting a substantial portion of global biodiversity and for being inhabited by traditional communities, including indigenous peoples and quilombolas (Fearnside, 2021). These aspects give the Amazon region multifaceted relevance in both environmental and socioeconomic terms and highlight its importance on a global scale.

However, the production model adopted in the Transamazonian and Xingu territories, as in the entire Amazon, has historically generated problems in cocoa cultivation. During the colonization period, there was no focus on promoting the sustainable use of land and natural resources. The common practice for cultivation involved felling and burning the forest (Rebello; Homma, 2005; Schroth et al., 2016; Igawa, 2022).

The lack of technical monitoring and the indiscriminate use of chemical products to combat major pests and diseases represented a second problem. This not only affected crop quality but also had negative impacts on the health of producers and the environment (Schroth et al., 2006; Igawa; Toledo; Anjos, 2022). In summary, cocoa cultivation in the region faced challenges arising from unsustainable practices, such as deforestation, the excessive use of chemicals and the lack of adequate technical guidance (Homma; Menezes; Moraes, 2014; Braga et al., 2023).

Although many studies approach cocoa production from an economic perspective, few examine the social dynamics of cocoa producers in the Amazon region, especially in relation to the challenges regarding access to technology and rural credit, combating poverty and the promotion of sustainability. This study fills this gap by providing primary data obtained through a field survey conducted in two production centres in the Eastern Amazon—Medilândia (Transamazonian) and Tucumã and Ourilândia do Norte (Southeast Pará)—during the years 2021 to 2023, with interviews conducted on 874 rural properties.

From this perspective, the objective of this study is to investigate the degree of modernization of cocoa production in municipalities in the eastern Amazon and relate it to socioeconomic indicators. The findings will contribute to the planning of strategies aimed at sustainable regional development and the identification of inequalities within the region.

This study contributes to the field of regional development by investigating agricultural modernization using improved indicators in a region marked by historical inequalities. Focusing on the Eastern Amazon, a region with high environmental relevance but low social development, this study highlights how technological advances in cocoa production can drive local economic and social transformations.

Multiple correspondence analysis (MCA), a multivariate statistical technique derived from principal component analysis (PCA), was used to investigate the relationships among nine categorical variables related to agricultural management, which include tilling characteristics (manual and mechanized), the use of analytical instruments, the correction of acidity, irrigation, buoyancy, demarcation of holes and fertilization (mineral and organic). The results supported the analysis of clusters with consideration of sociodemographic variables, such as age, gender, education and income.

These variables were chosen to investigate different aspects related to land preparation and agricultural cultivation. MCA was used to identify patterns and relationships among these variables via cluster analysis, which supported a deeper understanding of the processes involved in the agricultural activities studied and their relationships with the socioeconomic development of rural producers.

This article is structured in five sections. After the introduction, we present the theoretical framework designed to address agricultural modernization in the Amazon and its relationship with sustainable development. The third section presents the methodology, including the characterization of the study area, the variables analysed and the statistical methods applied, such as MCA and clustering. The fourth section presents the results and discussion, with a focus on the socioeconomic profile of producers and the levels of agricultural modernization. Finally, the fifth section presents the final considerations.

THEORETICAL FRAMEWORK

EVOLUTION OF AGRICULTURAL MODERNIZATION AND THE DYNAMICS OF COCOA PRODUCTION IN THE STATE OF PARÁ, AMAZON

From the mid-20th century, during the era of industrialization, Brazilian economic policy began prioritizing the modernization of agriculture through intense state intervention. This strategy aimed to integrate the different economic sectors, stimulate capital accumulation and expand agricultural production aimed at both the domestic and foreign markets, as well as promote the occupation of the Amazon by migrants from other regions of the country (Silva; Botelho, 2014; Júnior; Garvão, 2015). To achieve these goals, the State created various instruments, such as subsidized rural credit, policies to guarantee minimum prices, rural insurance and agricultural research and extension programs (Bacha, 2004).

In the Amazon, agricultural modernization was driven by the Integrated Colonization Project of Altamira (PIC), which aimed to promote colonization and agricultural development in the region through the opening of roads (especially the trans-Amazonian highway). This process, however, was controversial and faced several challenges, especially because it disregarded the specificities of the Amazon ecosystem, which resulted in the intensive exploitation of natural resources (Guimarães et al., 2011).

The technological standards were not completely absorbed by small producers because of factors such as the requirements of a minimum production scale, a lack of own resources and difficulties in accessing sources of finance (Silva et al., 1983; Bacha, 2004; Homma, 2022). In addition, at the end of the 20th century, issues such as high land concentration, income inequality and the diversity of productive capacities in the agricultural sector in the Amazon began to receive attention (Helfand; De Rezende, 2001; Marques; Marques, 2013).

Historically, the development of the Amazon region has been closely related to its agricultural development. Homma (2000) noted that agricultural modernization intensifies the relationship with agriculture in the region and enables greater productivity in areas that have already been deforested. However, technology can play two roles: it can contribute to more sustainable practices or intensify the exploitation of natural resources.

In this context, the National Program for the Strengthening of Family Agriculture (Pronaf), which aims to provide financial resources for the development of small producers (84.4% of the sector in 2006 (IBGE, 2009)), was established. The main interest of Pronaf is to provide technical assistance to smallholders by generating income and improving socioeconomic conditions and the environment (Mattei, 2001).

According to Souza (2021), Pronaf generated R$ 7.5 billion in Pará, dedicated to livestock (with 71.89% of resources) and agriculture (with 28.11% of resources), between 2000 and 2019. Pronaf supported the strengthening of the cocoa production chain by allowing producers to acquire inputs and machinery and improve their properties.

One of the main initiatives aimed at cocoa production was the Brazilian Cocoa Program, created in 1976, which was formalized through the Guidelines for the Expansion of National Cocoa Farming and known as PROCACAU. The program aimed to significantly expand cocoa cultivation in the country over the next decade, with the objective of reaching 300,000 planted hectares, of which 160,000 hectares would be located in the Amazon region, and the remainder would be distributed between southern Bahia and Espírito Santo (Tafani, 1980; Silva Neto et al., 2017).

To strengthen the cocoa production chain in the state of Pará, public policies aimed at stimulating cocoa production in the Amazon region gained prominence. In particular, the "Inova Cacau 2030" project was conceived as a strategy to support Brazilian producers through mechanisms combining sustainability and competitiveness. The plan's main objective was to develop integrated actions for the cocoa production chain, with the goal of increasing production efficiency, increasing farmers' income and promoting the sustainable use of natural resources (Vidal, 2024).

In addition, technical assistance and rural extension (ATER) combined with rural credit played an essential role in the promotion of sustainable agriculture and the strengthening of cocoa production in Pará. According to Oliveira, De Araújo and De Queiroz (2017), ATER is a strategic instrument for integrating family farmers into public policies and markets and promoting productive and social inclusion. When linked to rural credit, this assistance becomes even more effective, as it guides the use of financed resources in a technical, rational and sustainability-oriented manner. In the case of cocoa farming in Pará, it is essential to expand production according to the principles of sustainability, efficiency and equity (Alves et al., 2024).

COCOA PRODUCTION AND AGRICULTURAL MODERNIZATION AS TOOLS FOR SUSTAINABLE DEVELOPMENT

The sustainability of cocoa production is related to the diversity of production models, in addition to the adaptation of the crop to local conditions and the ability to generate income through the commercialization of its derivatives. According to Guimarães (2011), the modernization of this productive activity involves a set of structural and technological transformations aimed at increasing productivity and efficiency in agricultural practices, with emphasis on the use of chemical inputs and agricultural mechanization as central elements of this process.

Gontijo (2020) argues that cocoa cultivation can be considered an activity compatible with sustainable management practices because, in addition to being economically viable, production systems based on this crop can be structured to respect environmental limits and meet the productive demands of the communities involved. In addition, Guimarães (2011) highlights the socioeconomic relevance of cocoa production for local development, especially in the Transamazonian region. In a survey of 851 cocoa farmers in the state of Pará in 2009, 98.6% of the respondents indicated that cocoa was an important source of family income.

Almeida et al. (2012) indicated that agricultural modernization can positively impact the social development of rural producers by increasing income and enhancing quality of life. However, the authors clarify the challenges of modernizing the primary sector, such as the concentration of technology in large producers, the unsustainable exploitation of natural resources and the lack of economic resilience, which leave producers vulnerable to economic shocks (Homma, 2020).

However, authors such as Aguiar et al. (2021) argue that modernization refers to a process of meeting legal and market requirements and that the modernization of producers on the basis of agroforestry systems and crop diversification can offer a balance between financial security and sustainability. In this sense, the cocoa production chain is identified as an opportunity for sustainable rural development. It is seen as an opportunity to generate income for local populations while promoting environmental preservation.

Dos Santos et al. (2023) noted that the technological demands of cocoa farming are aimed at strengthening the local economy, the viability of business and economic sustainability in rural areas. Modernization is considered to facilitate access to new markets and financial resources, promote the independence of producers in cultural matters and encourage the adoption of improved cultivation practices. The authors noted that the technological demands are concentrated in the development of automated irrigation systems; the adoption of agroforestry systems with the cultivation of cocoa in deforested areas; fertigation tests; efficiency in the production of seedlings; technologies for the fermentation and drying of almonds and the reduction in related economic losses; the valuation of soil carbon and nitrogen stocks; and agroeconomic evaluations of the entire production process.

Authors such as Cancino et al. (2022) indicate that modernization accompanies the social development of cocoa producers. For the authors, education is associated with the adoption of sustainable agricultural practices, such as the use of organic fertilizers and appropriate management techniques. In addition, the characteristics of improved education and youth can lead to a greater willingness to try new techniques and improve the quality of production, such as through the use of organic compounds and sustainable waste management.

Governance is also identified as a factor impacted by agricultural modernization. Ansong et al. (2024) reported that as the willingness of producers to adopt modern agricultural practices increases, educated farmers present increased willingness to understand tax regulations, participate in social organizations and create initiatives against corruption in the market. Furthermore, Dos Santos et al. (2023) indicated that the implementation of cooperatives and access to rural credit facilitates collaboration between producers, promotes the economic and social development of the region, and ensures the sustainability of the production chain.

Agricultural modernization is also believed to reduce gender inequality among cocoa farmers. Torres et al. (2021) reported that the participation of women is significant but invisible. The authors noted that in Pará, despite the female contribution, women do not participate in decision-making. In addition, the education and income of women working in agriculture are often limited. Lina and Lazzarini (2022) noted that socioeconomic factors contribute to gender inequality, with women having greater difficulty accessing productive land and rural credit.

METHODOLOGY

DESCRIPTION OF THE STUDY AREA

The investigation of the technological level covered two production centres: the municipality of Medicilândia and the municipalities of Tucumã and Ourilândia do Norte, located in the state of Pará, in the eastern Amazon. The territory accounts for 42% of cocoa production in the state of Pará and 35% of that in the entire Amazon region, in addition to having an average production yield (1,014 kg/ha) higher than the state average (976 kg/ha) and national average (503 kg/ha) (IBGE, 2021; 2022).

To determine the study sample, the number of properties estimated by the Executive Committee of the Cocoa Crop Plan (CEPLAC) linked to the Ministry of Agriculture and Livestock of the Brazilian government was considered, with 1,046 rural properties in Tucumã, 563 in Ourilândia do Norte and 3,457 in Medicilândia. The sample size calculation, with a confidence level of 95% and a margin of error of 5%, was obtained according to the following formula:

$$amostra = \frac{z^2 * p * q * população}{e^2 * (população - 1) + z^2 * p * q}$$

In which:

z^2: chosen confidence level, expressed as the number of standard deviations;

p: percentage with which the phenomenon occurs;

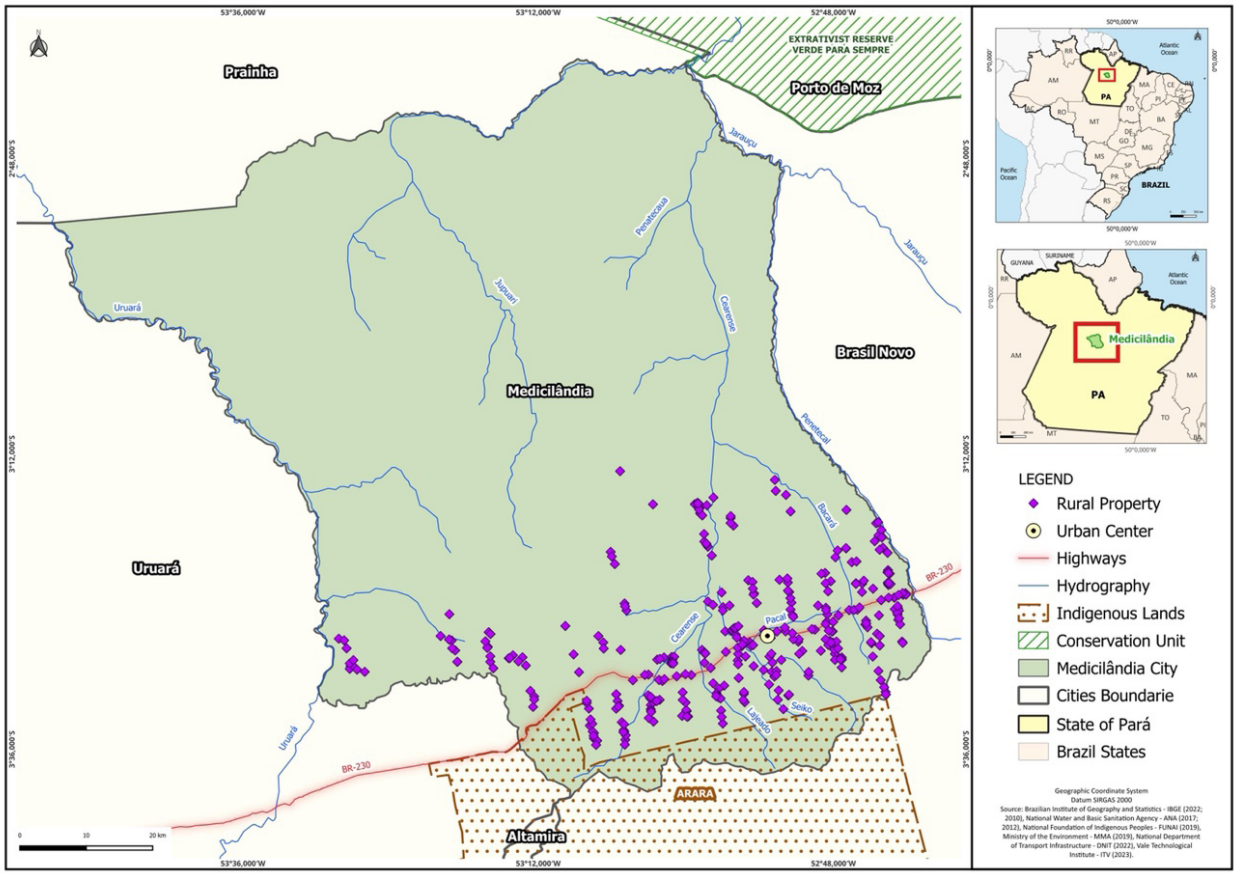
q: complementary percentage;

and ^{2}: maximum error allowed.

In this study, 360 rural properties were visited in Medicilândia, and the household heads were interviewed using questionnaires administered between 2021 and 2022. The study also included 230 rural properties in Ourilândia do Norte and 284 in Tucumã, and questionnaires were administered to the household heads in 2023.

Figure 1 shows that the municipality of Medicilândia stands out as the fifth largest cocoa producer in Brazil (in terms of production yield, in R$) and is the main producer in the state of Pará and in the Amazon region (IBGE, 2021).

Figure 1 | Locations of rural properties in the municipality of Medicilândia, Pará State

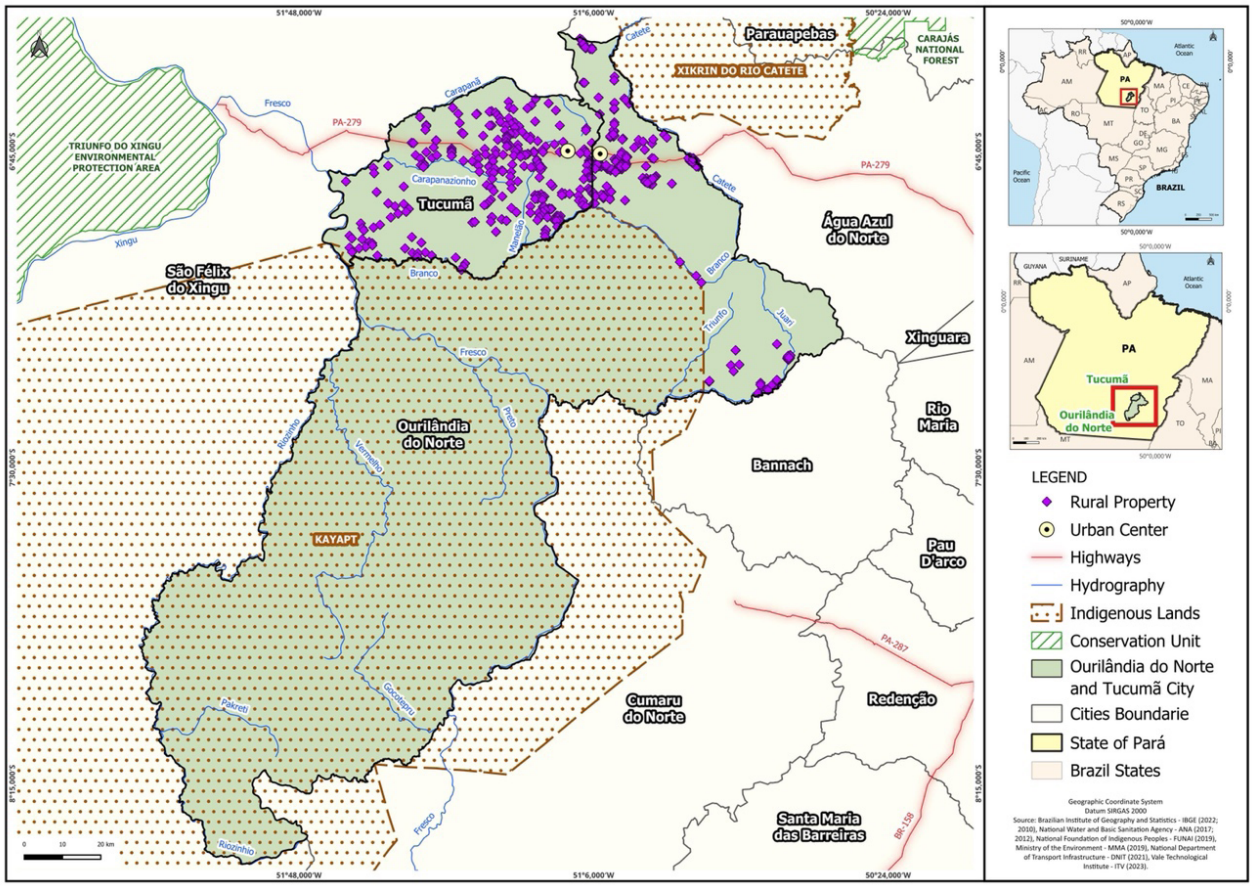


Source: Prepared based on the survey data.

In 2022, the municipality had the highest yield of cocoa production among the 772 municipalities in the Amazon (R$ 693.21 million). With an average altitude of 51 metres, the municipality covers a territory of 8,309 km². In 2020, its estimated population was 31,975 inhabitants. The municipal seat is located near the region's main highway, the trans-Amazonian highway (IBGE, 2022).

The study also addresses the technological level of the municipalities of Tucumã and Ourilândia do Norte, located in southeastern Pará. Tucumã, with a territorial area of 2,535 km², had an estimated population of 39,550 inhabitants in 2022 (IBGE, 2022). In turn, Ourilândia do Norte covers a territory of 13,826 km², with a population of 32,467 people in 2022 (IBGE, 2022). The municipal seats of both municipalities are located on the PA-279 highway (Figure 2).

Figure 2 | Location of the municipalities of Tucumã and Ourilândia do Norte, state of Pará



Source: Prepared based on the survey data.

The two municipalities are important because their inclusion helps characterize the region as a cocoa producer. The municipalities are located farther southeast in the region, where there is a more intense presence of other activities, such as soy and beef production (Fearnside et al., 1987).

The municipality of Tucumã produced the 9th highest yield in the Amazon region (IBGE, 2022), with R$ 53.45 million. The municipality stands out because its territory is 70% smaller than that of the main producer in the region, yet it has a high cocoa crop yield.

In addition, the economy of the municipality is based on the production of soybeans (in grains) and corn (in grains), both of which are main crops that are exported for international trade. These production sites are located in the part of the region that is undergoing the most active deforestation to yield land for grazing (Morton et al., 2006; Nepstad et al., 2006; Zu Ermgassen et al., 2020).

Finally, the study focused on the municipality of Ourilândia do Norte, which neighbours the municipality of Tucumã. Despite having similar production levels, 74% of its territory has been preserved, classified as indigenous land of the Kayapó people. Additionally, mining is present in the municipality and represents less than 1% of its area.

SOCIOECONOMIC QUESTIONNAIRE REGARDING COCOA PRODUCING RURAL PROPERTIES

In this study, questionnaires were administered to gather information about socioeconomic and productive characteristics of cocoa farmers. The main objective was to investigate the socioeconomic profile of rural producers, with a focus on the scale of the cocoa production on their properties. Exploratory analysis techniques were used to characterize the rural properties because such models do not require prior assumptions.

The questionnaire solicited information on the gender, age and sex of the main owner of the property from the cocoa farmers. In addition, data were collected on the producer's level of education (including the last grade completed and the ability to read and write), income from all economic activities (classified by intervals of R$1,212.00) and the productivity of the farm in terms of the cocoa crop (measured by production volume in tons of cocoa beans per hectare). These variables were selected to provide a comprehensive understanding of the socioeconomic and productive characteristics of cocoa farmers and supported a detailed analysis of the characteristics and dynamics of this agricultural context.

ANALYTICAL STRATEGY FOR THE EVALUATION OF THE TECHNOLOGIES USED IN COCOA PRODUCTION

Multiple correspondence analysis (MCA) was used to develop indicators according to the characteristics of the production systems managed by cocoa farmers in the study area. This technical approach enabled us to quantify the technological levels of these systems and offered an in-depth and comprehensive understanding of the practices and innovations used in cocoa production.

MCA is an advanced multivariate statistical technique designed to address categorical variables. The method consists of binary columns represented by binomial values, which explain a

significant part of the data without depending on the original dataset (Nascimento et al., 2013). MCA is an extension of principal component analysis (PCA), a common technique used in multivariate statistics, and is noteworthy for its effective application in contexts with nondescriptive variables (Abdi; Williams, 2010).

R software, through the commands FactoMineR and factoextra, was applied for data analysis and visualization (Kassambara; Mundt, 2017). MCA is a multivariate statistical technique for addressing categorical variables, and the method consists of binary columns represented by binomial values, which explain a portion of the data without using the original set (Nascimento et al., 2013).

We apply MCA with the aim to understand the intricate interactions among the categorical variables related to the cocoa production system. The variables are represented in a two-dimensional format via binary codes, where "1" denotes the presence of the variable and "0" denotes its absence. Table 1 lists the nine variables used to assess the technological level of cocoa production using the MCA model.

Table 1 | Questionnaire applied in the cocoa production centre of the eastern Amazon.

Indicator	Question	Answer	Sample size
X1	Is the land prepared for cultivation manually (slashing, felling, burning)?	Yes or No	
X2	Is the land prepared for cultivation mechanically (ploughing, harrowing, furrowing or subsoiling)?	Yes or No	
X3	Is soil collection and analysis performed to assess soil quality?	Yes or No	
X4	Are inputs used to correct soil acidity (liming and/or gypsum)?	Yes or No	
X5	Does the owner mark out the area for production?	Yes or No	874
X6	Does the property have an irrigation system (micro sprinklers or drip)?	Yes or No	
X7	Are holes marked manually?	Yes or No	
X8	Are holes marked mechanically?	Yes or No	
X9	Is mineral (chemical) adduction performed for planting and management?	Yes or No	

Source: Prepared based on the survey data.

MULTIPLE CORRESPONDENCE ANALYSIS (MCA) AS A TOOL FOR ASSESSING REGIONAL DEVELOPMENT

MCA is commonly applied to identify patterns of socioeconomic factors. Strzeleckaa et al. (2020) noted that this method allows exploration of the relationships among multiple variables, such as income, education and access to financial services. The method reduces the complexity of the data by condensing information to facilitate interpretation. This allows the analysis of variables with many levels or categories and supports the identification of trends and patterns.

Ferrari et al. (2023) emphasized that MCA is useful for simplifying and grouping categorical variables, reducing complexity and increasing the efficiency of the analysis. Shigaki et al. (2023) applied this approach to investigate sleep quality on the basis of health variables and characteristics such as sex, age, race, marital status, education and income. The study revealed that sleep disorders tend to be associated with specific demographic and socioeconomic profiles.

Rodrigues and Simões (2004) used MCA to investigate the relationship between industrial concentration and indicators such as poverty, the literacy rate and access to basic services, such as water and sanitation. On the basis of the estimation, the authors observed that municipalities with greater industrial concentration tend to have better quality of life indicators, with a lower incidence of poverty and greater access to education. By associating the variables analysed with the results of the MCA, the study highlighted the relevance of public policies that encourage industrial concentration as a strategy to improve the socioeconomic conditions of the population in different regions.

Bessa et al. (2019) used MCA to compare the motivations that lead family farmers to participate in forest recovery initiatives. The method supported the examination of relationships among multiple variables, such as the connection of farmers with the forest, knowledge about environmental laws and individual characteristics, such as age and education. The results indicated that forest recovery was not among the main interests of rural producers. In addition, the MCA revealed that knowledge of environmental legislation was not necessarily associated with greater adherence to standards among farmers.

Mohammed et al. (2024) applied MCA to assess the relationships between socioeconomic and demographic variables in the context of the COVID-19 pandemic and demonstrated that these factors together influenced the spread of the disease in the state of Gezira, Sudan. Education, awareness of the pandemic and adoption of preventive measures were affected by anxiety about possible job loss. The results highlighted the robustness of MCA for understanding the complex interrelationships among the different factors impacted by the pandemic and suggested the potential of other advanced analytical approaches, such as predictive models, to deepen this understanding.

METHOD FOR THE INTERPRETATION OF RESULTS

Exploratory data analysis (EDA) was used to process the dataset and the most relevant variables, transform the data into usable information and compare it with other results to evaluate the suitability for the construction of plausible models. This approach aims to consolidate, analyse and interpret the results (Bussab; Morettin, 2010). Additionally, cluster analysis was applied to identify similar characteristics among the observed cocoa producers in the municipalities under study. Homogeneous groups that present different technological levels in production were thereby identified.

Cluster analysis is facilitated by the hierarchical clustering on principal components (HCPC) method. This technique is used to explore similar behaviours among the observations regarding certain variables with the aim to create groups (clusters) with homogeneous internal characteristics (Fávero; Belfiore, 2017). In this study, the HCPC method makes it possible to identify heterogeneous groups of cocoa farmers. The process involves choosing the number of clusters on the basis of hierarchical clustering and Ward's criterion to determine the optimal number of clusters. In addition, the K-means method is used to consolidate the producer grouping based on the optimal number of groups indicated in the previous step (Kassambara, 2017).

This methodological approach allowed us to understand not only the technological landscape but also the socioeconomic and environmental aspects that shape agricultural practices and sustainability in these locations.

RESULTS AND DISCUSSION

PROFILE OF COCOA-PRODUCING RURAL PROPERTIES IN THE EASTERN AMAZON

In this study, we sought to understand the characteristics of the owners of rural properties that produce cocoa. The age group ranged between 20 and 94 years, with a mean of 53.3 years, and 58.2% of the owners were over 50 years of age. Among all the rural property owners in the survey, 22.7% were women. The highest percentage of female owners was observed in the municipality of Ourilândia do Norte, with 29.1% of the properties managed by female owners.

Regarding the receipt of social benefits (derived from federal public policies), 30.5% of the owners of cocoa farming properties were retired. In addition, 16.3% were registered in the program to combat extreme poverty in the country (Bolsa Família).

Regarding the level of education, 5.4% of the owners were illiterate (could not read and write), 18.1% had completed elementary school, and only 1.7% had completed higher education. Among those who had completed higher education, half were women, and the smallest portion was found in the municipality of Ourilândia do Norte, where only one owner had completed education.

When asked about wages received (including income from cocoa production and other activities), 20.7% of the owners received less than R$1,212.00, and 56.6% received between R$1,212.00 and R$2,424.00 (between the minimum wage and twice the minimum wage). Among those with earnings exceeding five times the minimum wage, 1.3% earned more than R$6,060.00 (in Ourilândia do Norte, no producer received more than this amount). Finally, we investigated the productivity of cocoa production, measured by the tons produced in 1 hectare. Among the samples, 88.9% of the rural properties produced less than 1 ton (1000 kg) per hectare, 8.5% produced between 1 and 2 tons, and 3% produced more than 2 tons.

EXPLORATORY ANALYSIS OF AGRICULTURAL MODERNIZATION DATA

The information collected during the field research provides a detailed and accurate analysis of the degree of technology adoption in cocoa production. Through the direct observation and collection of data on the agricultural practices used, we gained a comprehensive understanding of the strategies producers employed to optimize cocoa production and the existing socioeconomic vulnerabilities.

Among the sampled farmers, only 26% of the owners had equipment for land preparation. When asked whether the owners investigated soil quality, 46.4% responded affirmatively. The data show that most landowners did not perform soil acidity correction; among all landowners, 57.5% did not add inputs for pH correction.

Among those who demarcated holes, only 4% did so using equipment. The owners preferred to dig the holes for planting using hoes, not drills or furrowers. Finally, when asked about their use of fertilizer, 55.2% said they used fertilizer from mineral sources, whereas only 26.4% of the owners used organic sources.

AGRICULTURAL MODERNIZATION AND SOCIOECONOMIC IMPACTS ON COCOA PRODUCTION

In accordance with the methodology, MCA was applied using only qualitative variables. The MCA results present the explained variance values for each component. The first four components (CPs) explain more than 57.9% of the total accumulated variance of the dataset. Table 2 presents the contributions of the variables that formed the main components of the study.

Table 2 | Contribution of the variables to the formation of the components.

	Dim 1 (%)	Dim 2 (%)	Dim 3 (%)	Dim 4 (%)
Manual_Prep_No	2,45	18,33	10,56	0,79
Manual_Prep_Yes	0,67	5,05	2,91	0,21
Mechanized_Prep_ No	3,15	1,10	1,65	1,45
Mechanized_Prep_ Yes	8,94	3,11	4,67	4,11
Collec_Analy_ No	9,14	1,22	2,87	3,45
Collection_Analy_ Yes	10,54	1,40	3,31	3,98
Acidity_Correction_ No	8,70	0,33	2,72	2,45
Acidity_Correction_ Yes	11,80	0,44	3,69	3,32
Marking_ No	4,61	16,42	10,69	4,49
Marking_ Yes	0,68	2,43	1,58	0,66
Irrigation_ No	0,29	0,16	0,00	0,02
Irrigation_ Yes	7,23	4,04	0,07	0,68
Manual_Demarc_ No	0,65	27,30	13,29	0,14
Manual_Demarc_ Yes	0,05	2,34	1,13	0,01
Mechan_Demarc_ No	0,11	0,44	0,11	0,07
Mechan_Demarc_ Yes	2,74	10,64	2,70	1,80
Mineral_Adub_ No	10,95	0,83	1,56	0,54
Mineral_Adub_ Yes	8,86	0,67	1,26	0,44

Source: Prepared based on the survey data.

The analysis revealed that the main component of the study was strongly influenced by the variables related to the use of inputs to correct for soil acidity, soil collection and analysis, mechanized preparation, mineral fertilization and irrigation. Additionally, variables that did not include mineral fertilization, soil collection and analysis, and acidity correction played a significant role in the composition of this component. Together, these variables contributed more than 65.2% of the variability observed in the first component of the model.

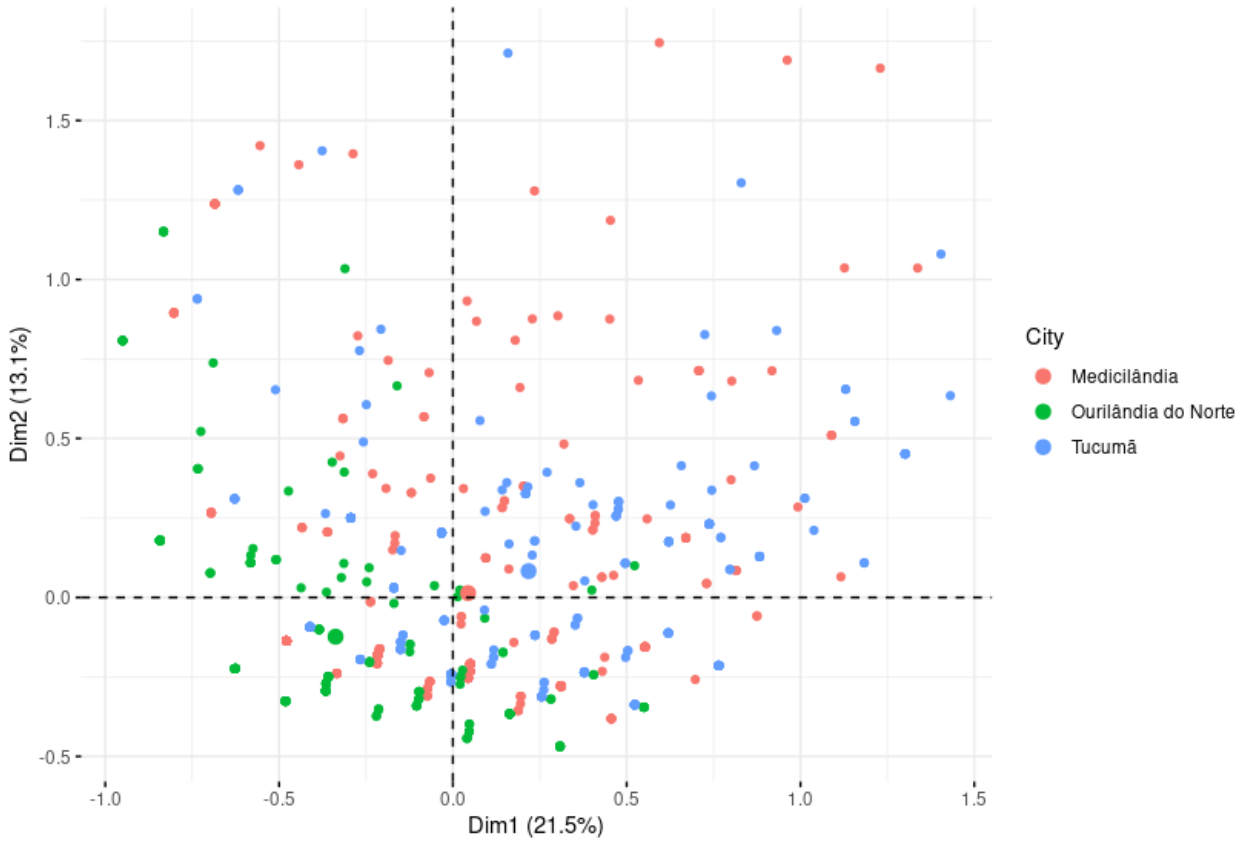
The second component found was characterized by the contribution of variables other than mechanized soil demarcation, manual land preparation and area demarcation. Additionally, the presence of variables related to mechanized demarcation was notable in this component. In total, the aforementioned variables composed 72.6% of the variability of the second component of the model.

The third component was predominantly influenced by the contribution of variables that did not involve the marking, preparation and manual demarcation of the land. These variables represented 34.54% of the composition of the third component of the model.

The fourth component of the model was influenced mainly by the contributions of the variables related to the mechanization of land preparation and soil collection and analysis. The variables other than data collection and analysis and marking also contributed to the formation of this component. In total, these variables comprised 16.03% of the fourth component of the study.

In Figure 3, the cocoa farmers in Medicilândia and Tucumã are presented in the quadrants of the two-dimensional graph.

Figure 3 | Multiple correspondence analysis for dimensions 1 and 2 for all municipalities.



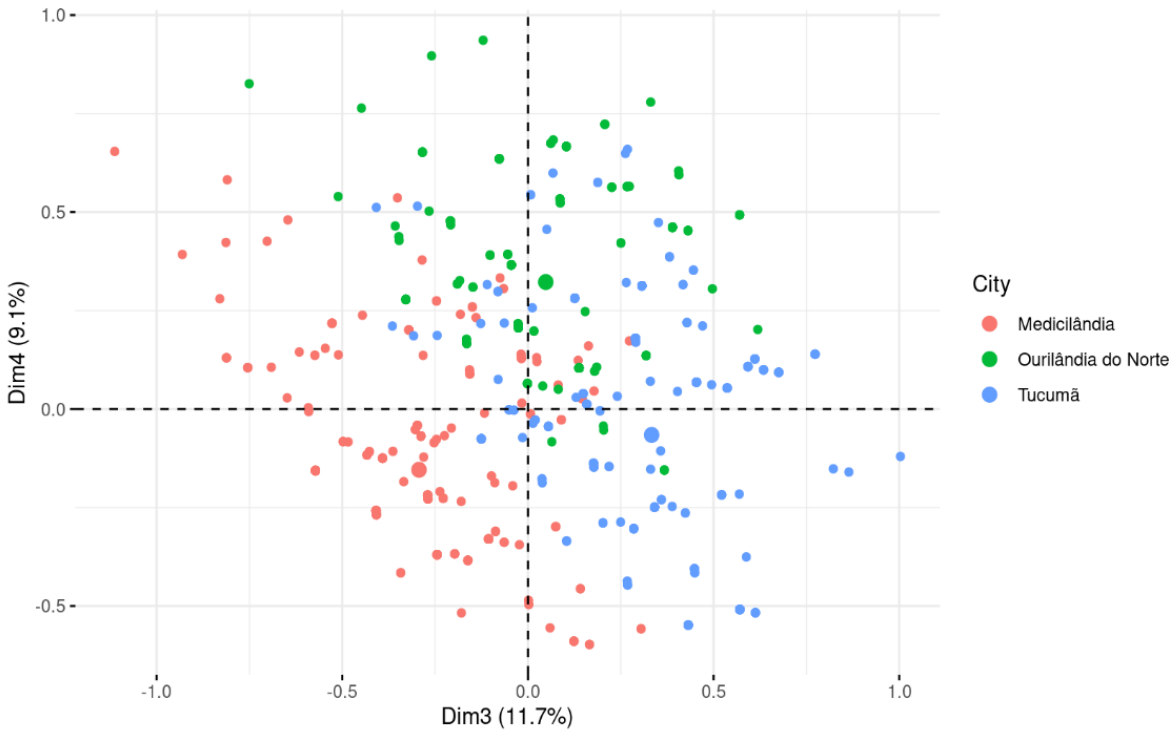
Source: Prepared based on the survey data.

In the region of quadrant A, which comprises mainly producers of Medicilândia and Tucumã, the municipalities present a positive relationship with the two dimensions, being characterized by the use of acidity correction instruments, the use of soil collection and analysis, mechanized crop preparation, mineral fertilization, mechanized demarcation and irrigation. The producers located in quadrant B (which includes producers from all three municipalities in the study) present characteristics similar to the variables mentioned above, except they do not mechanically demarcate the holes for planting.

Quadrant C includes the rural producers who are not associated with the two above dimensions. Quadrant D includes cocoa farmers from all three municipalities who do not use manual soil demarcation and do not carry out marking and manual preparation of the cocoa cultivation area. The producers in quadrant B present a similar characteristic of mechanically demarcating holes.

The positions of the observations in the other components of the model are shown in Figure 4.

Figure 4 | Multiple correspondence analysis for dimensions 3 and 4 for all municipalities.



Source: Prepared based on the survey data.

The farmers in quadrant A, who are mainly from Ourilândia do Norte and Tucumã, are identified by their use of mechanized land preparation and soil collection and analysis. The quadrant also includes farmers who do not perform marking, manual preparation or manual demarcation.

The producers in quadrant B, who are mainly from Tucumã, are grouped by the variables other than manual preparation, marking and manual demarcation. Those in quadrant C, formed mostly of farmers from Medicilândia, do not show any similarity highlighted by dimensions 3 and 4.

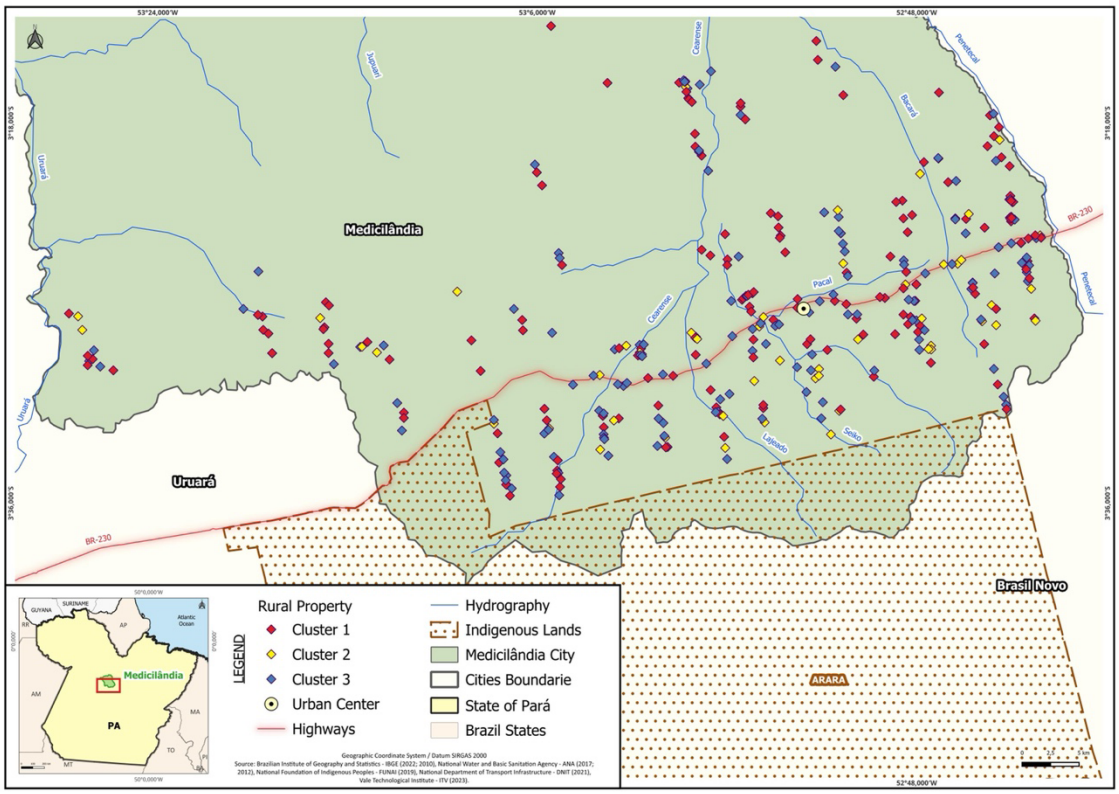
The rural producers located in quadrant D, which includes farmers from all three municipalities, engage in mechanized preparation and soil collection and analysis. In addition, the results showed that this cluster does not resemble the others in terms of demarcation.

TECHNOLOGICAL LEVEL OF COCOA PRODUCTION IN THE EASTERN AMAZON

After application of the MCA method, the solution composed of three groups (clusters) presented the best arrangement to assess the technological level in the municipalities investigated. In Medicilândia, the selected clusters represented 64.2% of the total variance of the selected data. In Tucumã, the variance of the groups represented 57.5%, and in Ourilândia do Norte, it represented 56.9%.

The spatialization of properties by cluster in the municipality of Medicilândia is shown in Figure 5.

Figure 5 | Map of clusters at the technological level in Medicilândia.



Source: Prepared based on the survey data.

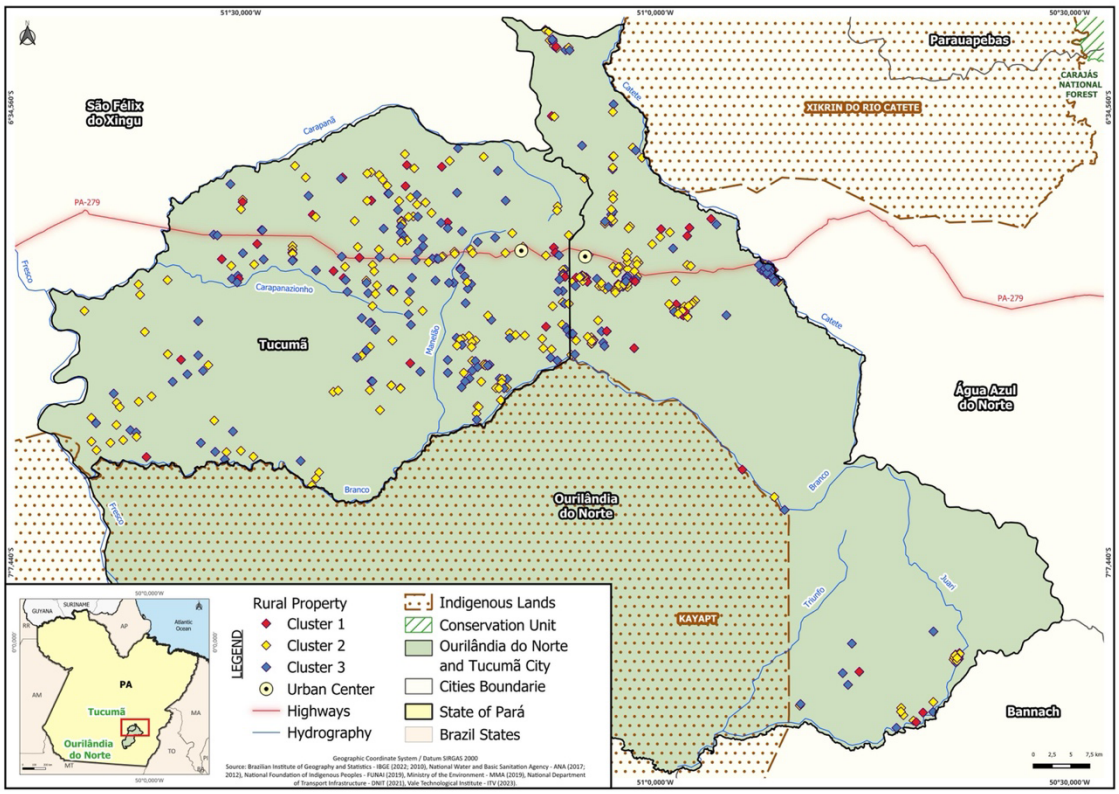
In Medicilândia, the first cluster comprised 170 rural properties. The cluster included the producers that performed soil preparation manually (96.4%), with a minority that performed soil collection and analysis (27%). Additionally, all of them manually demarcated the holes (100%).

Mineral fertilization was adopted in only one plot (43.5%). In this cluster, the farmers' lack of specialization resulted in a low level of modernization in agricultural practices.

The second cluster included 50 rural properties. Within this cluster, 64% of the properties prepared the crop manually; 74% did not perform soil acidity correction; and 84% did not perform soil collection and analysis. The second cluster did not include farmers who used mechanized demarcation or irrigation. All the properties in the cluster marked out the cultivation area. On the basis of these measures, the level of modernization within this cluster is considered low.

The third cluster comprised 140 rural properties. Only 42.8% of the farmers engaged in mechanized preparation; 93.5% performed soil collection and analysis; 90.7% used technology to correct soil acidity; 78.8% engaged in demarcation; and 95.7% used mineral-based fertilizer. The producers included in this group were highly concerned with soil quality and the adoption of best practices, tools and technologies. Figure 6 shows the results of the grouping of the municipalities of Tucumã and Ourilândia do Norte.

Figure 6 | Map of the technological level clusters in Tucumã and Ourilândia do Norte.



Source: Prepared based on the survey data.

In the municipality of Tucumã, the first cluster was composed of 16 rural properties. None of these properties had irrigation capacity, and 93.7% did not perform soil collection and analysis or correct for soil acidity. In addition, within this cluster, no farm engaged in the mechanized demarcation of holes or used organic fertilizer. The rural producers in this cluster present low specialization in agricultural modernization techniques.

The second cluster included 124 rural properties; 58.8% of these farmers performed soil preparation manually, 92.7% did not perform soil collection and analysis, and 97.5% did not engage in efforts to reduce soil acidity. Only one property delimited the area of cultivation. These farmers had no irrigation systems or mechanized hole demarcation. The second cluster comprises farmers with a low level of modernization. Despite the demarcation of the cultivation area (99.1%), the adoption of mechanization in cultivation and tools to promote better production performance was not observed.

The third cluster included 144 rural properties. In this cluster, 96.5% of the farmers carried out the demarcation of the area, whereas 91.6% carried out soil evaluation. In addition, 85.4% of these farmers adjusted the soil pH, 86.8% practiced mineral fertilization, and 57.6% had the ability to mechanize land preparation. These indicators point to a high level of agricultural modernization within this group.

In Ourilândia do Norte, the first group comprised 50 rural properties, with 90% of the properties marking the cultivation area and 64% manually demarcating the holes. In addition, the cluster includes farmers that did not have irrigation systems and that did not mechanically demarcate holes or prepare the land. The first cluster in this municipality does not include rural properties with a high technological level of production.

The second cluster included 118 rural properties. Within this cluster, 94.9% of the farmers prepared the land manually, and 88.1% did not perform soil collection and analysis. Only 11.8% of the farmers corrected soil acidity. All landowners carried out demarcation, but none had the technology for the mechanized demarcation of holes or irrigation. The second cluster in the municipality of Ourilândia do Norte thus also presents a low level of modernization. These rural farmers showed

little use of mechanization, low concern for soil quality and low adoption of technologies to increase production mechanization.

For the third cluster, which included 62 rural properties, 88.7% of the farmers used mineral fertilizers, 79% performed soil acidity reduction treatment, 87% evaluated the soil quality, and 96.7% evaluated the cultivation area. However, only 25.8% engaged in the mechanized preparation of the cultivation area, and no farmer engaged in the mechanized demarcation of holes.

Technological level and socioeconomic development of cocoa farmers in the Eastern Amazon

The groups with high technological levels were compared with consideration of the socioeconomic variables of the study, such as education, social benefit receipt, gender, age and income.

In the municipality of Medicilândia, the group with the highest technological level (Cluster 3) stood out for having a mean age of 54.4 years, with 78.5% of the individuals being men. This cluster also showed the highest participation of women as owners, with 21.5%. This cluster with the highest use of technology included the highest proportion of retirees (43.5%). In addition, this group had the lowest proportion of illiterate people (2.1%) and the lowest number of people with low income (less than twice the minimum wage) (75.4%).

For the other clusters in the same municipality, Cluster 1 included the largest number of people who had not completed elementary school (46.4%) and the largest percentage of people who received the Bolsa Familia (21.1%). The second cluster included individuals of older age (54.5 years) and the highest percentage of male owners (86%). In addition, Cluster 2 included the highest percentage of literate individuals (54%) and the lowest percentage of those who had not finished elementary school (14%).

In Tucumã, the cluster with the highest level of modernization recorded an average age of 52.5 years. The cluster also had the highest percentage of female owners, with 26.3%; the lowest percentage of illiterate people (2.7%); and the highest percentage of retirees among all the clusters (22.9%). For the other clusters in the same municipality, Cluster 1 included those with older age (53.1 years) and presented a large proportion of male property owners (93.7%). The cluster also included the largest percentage of retirees (37.5%) and those with earnings in the lowest ranges (less than twice the minimum wage) (81.2%). Nothing noteworthy was observed in Cluster 2 of the municipality of Tucumã.

We compared the results of Cluster 3 in Ourilândia do Norte, characterized by greater agricultural modernization in the municipality, with the same variables analysed in Medicilândia. This group had the highest proportion of male farmers (79%) and the lowest proportion of illiterate people (1.6%) and those receiving the Bolsa Familia (19.3%). In addition, the third cluster had the highest proportion of people who had not completed primary education (50%).

The receipt of social benefits showed no clear relationship with the use of modern technologies in Tucumã. Retirees represented 43.5% of Cluster 3, whereas in Clusters 1 and 2, they represented 44% and 24.5%, respectively. With respect to income, the cluster with high modernization showed no evidence of an impact on the salary range of farmers: in Cluster 3, 69.3% of owners received less than twice the minimum wage, whereas in Clusters 1 and 2, the percentages were 92% and 88.1%, respectively.

The application of MCA yields significant results that are useful for characterizing the cocoa production in two production centres in the state of Pará and evaluating the degree of technological specialization of the producers. The findings of this study are supported by data from the national literature that highlight a proportion of rural cocoa farmers who present little effort to use technologies/equipment and adopt sustainable production practices (Rebello; Homma, 2005; Schroth et al., 2016; Igawa, 2022). While some farmers use little technology, others adopt measures to improve soil use, with measures and inputs based on best practices, contrary to the findings reported in the literature (Homma; Menezes; Moraes, 2004; Braga et al., 2023).

The method applied could consistently highlight the technological mechanisms used in the region and reveal the social aspects and economic productivity of rural properties. The estimation of the indicator and the use of the methodology proved to be consistent, according to the methodological procedures. The results obtained support the use of the methodology by previous scholars (Mota, Vasconcelos and Assis, 2007; Abdi and Valentin, 2007; Nascimento et al., 2013; Kamalja and Khangar, 2017).

Related to our key results, previous studies have found that the participation of individuals with diverse characteristics, especially with respect to gender, and the increased participation of women in decision-making improve the opportunities for socioeconomic development (Qanti; Peralta; Zeng, 2022). In addition, our results concur with those of the study by Qanti, Peralta and Zeng (2022), who reported that groups presenting more technology use tend to include more women managing the properties.

The results corroborate studies that emphasize that formal education (or high educational levels) is related to the adoption of modern practices in production (Beuchelt, 2016). Compared with less educated individuals, rural producers with better education are more likely to add technological practices, with the objective of improving production and income (Furst, 2019). The relationships among more education, less illiteracy and greater participation of women in technologically advanced groups reinforce the findings of Rubi and Vargas (2022) and Beuchelt (2016).

The identification of clusters of farmers who use technologies, marked by practices such as soil acidity correction, mineral fertilization and soil quality analysis, corroborates the results of Guimarães (2011) and Gontijo (2020). The data show that agricultural modernization is uneven among municipalities, which confirms the observations of Homma (2000) and Almeida, Silva and Angelo (2012) regarding the heterogeneity of the modernization process in Brazil and its structural challenges. This finding reinforces the need for specialized policies to promote regional development in the territory, especially in areas where the use of manual practices and low access to technology predominate, as is the case for Clusters 1 and 2 in the municipalities analysed.

The results obtained through MCA and clustering provide a detailed overview of the relationship between agricultural technology and socioeconomic conditions and support the theoretical proposal that agricultural modernization can improve productivity, sustainability and social inclusion, as discussed by Aguiar et al. (2021) and Santos et al. (2023). The empirical confirmation of these relationships in the Amazon context reinforces the strategic role of cocoa production as an axis of regional development, especially when supported by credit policies, technical assistance and incentives for the transition to agroforestry systems.

The relationship between a greater number of retirees and the adoption of more technological practices is highlighted by Beuchelt (2016). The fact that retirees tend to have higher technological levels is related to their available time and experience, which enhance their awareness of agricultural challenges.

This study represents a unique contribution to the literature and provides a broader understanding of the interaction between cocoa production and socioeconomic and productive development. In the context of cocoa production in the Amazon, this study offers a more sophisticated approach for the evaluation of cocoa farming municipalities in the region.

CONCLUSION

The results show that there is a group of cocoa producers with a relatively high level of technological modernization in the three municipalities of interest. In Medicilândia, the model results highlighted the farmers with the greatest application of production technologies through component 1 in Cluster 3. The properties with the highest level of modernization were classified based on their use of tools for soil collection and evaluation, inputs for soil acidity, demarcation of the cultivation area and fertilization.

For the municipality of Medicilândia, agricultural modernization was found in the group with the highest participation of women, a greater presence of retirees, better education and the highest wages. The data support the finding of international studies that an increase in women's participation in decision-making in the countryside is linked to an increase in agricultural productivity and economic development.

In addition, the adoption of improved technologies and equipment is related to socioeconomic development, including greater democratization of the countryside and better living conditions.

In the municipality of Medicilândia, two distinct clusters with different levels of technological specialization were found. Cluster 2 had a medium degree of technological specialization; the farmers did not perform manual land preparation but rather performed soil collection and analysis, demarcation of the crop area and organic fertilization. On the other hand, the farmers in Cluster 1, characterized by low modernization, engaged predominantly in manual practices and did not engage in mechanization, soil collection and evaluation, soil pH correction or mineral fertilization.

However, despite Cluster 2 showing better indicators for some variables, socioeconomic development remained low in both clusters. Most farmers did not have formal studies, and there were many who benefitted from supplementary income policies. It is necessary to investigate whether there is a correlation between these data and distinguish the effect of welfare policies on the education of the farmer's spouse and children.

In Tucumã, the greatest specialization of cocoa production was found in Cluster 3. Many farmers in this municipality demarcated the area for cultivation, performed soil analysis, reduced

soil acidity, conducted mineral fertilization and engaged in mechanized land preparation. As in Medicilândia, the group with the highest technological level presented the highest participation of women and retirees and the lowest participation of illiterate people.

The results of this article highlight the low modernization of rural landowners in Clusters 1 and 2 of the studied municipality. In Cluster 2, although some landowners carried out demarcation of the cultivation area, the demarcation of the holes and the preparation of the land were still performed manually, they did not evaluate soil quality. This suggests a dependence on traditional methods and a lack of adoption of more advanced technologies. In Cluster 1, the situation was even more critical, with cocoa producers showing low specialization in agricultural modernization. They rarely used irrigation and did not engage in mechanized land preparation, demarcation of the cultivation area, soil quality evaluation or organic fertilization. This absence of modern and sustainable practices may significantly limit the productivity and sustainability of these properties.

Finally, the municipality of Ourilândia do Norte presented modernization in Cluster 3, which included farmers who performed mineral fertilization, evaluated and addressed soil acidity and demarcated the crop area. However, in the same cluster, few farmers engaged in mechanized land preparation, and none used mechanical methods to mark holes. In Ourilândia do Norte, the group with modernization presented different socioeconomic indicators than the groups in the other municipalities. This group presented the highest participation of men in rural areas, the lowest participation of illiterate individuals and the lowest representation of those receiving Bolsa Família.

In the municipality of Ourilândia do Norte, farmers in Cluster 3 showed a relatively high level of agricultural modernization. This group included farmers who performed mineral fertilization, evaluated and addressed soil acidity, and demarcated crop areas. However, few landowners mechanized the preparation of the land, and none had enough technology to mechanize the hole demarcation. The socioeconomic indicators of this group significantly differed from those of the other municipalities analysed. The cluster with the highest technological level recorded the highest participation of men in the countryside, the lowest proportion of illiterate individuals and the lowest representation of beneficiaries of the Bolsa Família program. These results suggest that agricultural modernization is correlated with improved socioeconomic conditions, as evidenced by the higher

education and lower dependence on assistance programs of the farmers in this group.

These observations indicate the importance of continuing to promote agricultural modernization in Ourilândia do Norte and other municipalities, with a focus on improving access to technologies that can mechanize land preparation and other stages of cultivation. This can potentially increase productivity and further improve farmers' socioeconomic conditions.

In addition, we highlight the importance of investigating the level of technological development in municipalities in the Amazon, especially given the environmental importance of the region in the face of the challenges posed by climate change. Agricultural modernization can not only increase the productivity and sustainability of rural activities but also play a vital role in the preservation of the Amazon ecosystem. The implementation of sustainable agricultural practices and the use of advanced technologies can mitigate negative environmental impacts, such as deforestation and soil degradation, and significantly contribute to the conservation of biodiversity and natural resources.

Finally, this study highlights the modernization of cocoa production as an important instrument for sustainable regional development by demonstrating that the adoption of agricultural technologies is associated with improved socioeconomic indicators, such as higher education levels, a lower incidence of illiteracy and greater participation of women in property management. The results indicate that this modernization process occurs unevenly among municipalities, which reflects territorial specificities and different degrees of access to resources and public policies.

By incorporating the territorial dimension into the analysis, the study contributes to the debate on the formulation of more effective public policies, especially with respect to rural credit, technical assistance and access to technology, which are essential elements for promoting productive inclusion and overcoming regional inequalities.

In this sense, the research reinforces the importance of agriculture as a strategic axis of development, especially when farmers adopt sustainable practices, such as rational soil use, agroforestry systems and organic fertilization. By considering sustainability, productivity and social inclusion, this study contributes to the construction of a more equitable regional development model adapted to the local realities of the Amazon.

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