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A new geographical distribution of coffee production? Analysis of the concentration and specialization of coffee production (*Coffea arabica*) in Colombian municipalities between 2007 and 2021

¿Una nueva distribución geográfica de la producción de café? Análisis de la concentración y especialización de la producción de café (Coffea arabica) en los municipios colombianos entre 2007 y 2021

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ABSTRACT

Colombian coffee is produced in 629 out of 1,121 municipalities and accounted for 0.6% of the national Gross Domestic Product (GDP) in 2021, equivalent to 8.9% of the agricultural GDP. This study analyzes the concentration and specialization of coffee production in Colombian municipalities between 2007-2021 to identify coffee's agricultural clusters (AC). The methodology includes the analysis of four statistical databases applying the Gini coefficient, Location Quotient (LQ), Herfindahl-Hirschman Index (HHI), and Moran's Index to identify the AC in the Colombian coffee sector, complemented by bivariate thematic cartography. Additionally, we link coffee production, LQ, and HHI with the Multidimensional Poverty Index (MPI) for 2018, and average annual temperature (AAT) and average annual precipitation (AAP) with a small sample of municipalities. The results reveal that in 2021, the regional Gini was 0.71, and the municipal Gini was 0.80. A total of 416 municipalities were identified with an LQ greater than 1.0, of which 78 are among the top 20% with the highest values. The average HHI was 0.151, ranging from 0 to 0.879. Additionally, MPI shows higher levels in rural areas and a low correlation with LQ and HHI. Average annual temperature and precipitation have a low correlation with HHI and LQ. A significant concentration of coffee production is observed in the municipalities of Huila, Antioquia, Cauca, Tolima, Caldas, and Santander accounting for 70.4% of total production. Likewise, we found that multidimensional poverty is high in rural areas of coffee-growing municipalities (average 48.0%, maximum 93.2%, minimum 9.2%). We established that the variables with the highest incidence were low educational achievement, informal work, and lack of access to improved water sources. These results should be of interest to regional and municipal governments, guild institutions, and public policymakers in agriculture, especially concerning climate change, production costs, associativity programs, agro-industrial promotion, and quality-based commercialization strategies.

Keywords: coffee production, agricultural clusters, productive concentration, productive specialization, Colombia.

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RESUMEN

El café colombiano se produce en 629 de los 1.121 municipios y representó el 0,6% del Producto Interno Bruto (PIB) nacional en 2021, equivalente al 8,9% del PIB agrícola. Este estudio analiza la concentración y especialización de la producción de café en los municipios colombianos entre 2007-2021 con el fin de identificar los clústeres agrícolas (CA) del café. La metodología incluye el análisis de cuatro bases de datos estadísticas aplicando el coeficiente de Gini, el Cociente de Localización (LQ), el Índice de Herfindahl-Hirschman (HHI) y el Índice de Moran para identificar Clústers Agrícolas (CA) en el sector cafetero colombiano, complementado con cartografía temática bivariada. Adicionalmente, correlacionamos la producción de café, LQ y HHI con el Índice de Pobreza Multidimensional (IPM) para 2018, y la temperatura media anual (TMA) y la precipitación media anual (PMA) con una pequeña muestra de municipios. Los resultados revelan que en 2021, el Gini regional fue de 0,71, y el Gini municipal fue de 0,80. Se identificaron un total de 416 municipios con LQ superior a 1,0, de los cuales 78 se encuentran entre el 20% con los valores más altos. El HHI promedio fue de 0,151, con un rango de 0 a 0,879. Además, el IPM muestra niveles más altos en las zonas rurales y una baja correlación con LQ y HHI. La temperatura media anual y la precipitación tienen baja correlación con HHI y LQ. Se observa una importante concentración regional y municipal de la producción de café en los municipios de Huila, Antioquia, Cauca, Tolima, Caldas y Santander (70,4% de la producción total). Además, la pobreza multidimensional es alta en las zonas rurales de los municipios cafeteros (promedio 48,0%, máximo 93,2%, mínimo 9,2%). Se estableció que las variables con mayor incidencia fueron el bajo logro educativo, el trabajo informal y la falta de acceso a fuentes mejoradas de agua. Estos resultados deben ser de interés para los gobiernos regionales y municipales, instituciones gremiales y formuladores de políticas públicas en agricultura, especialmente en lo relacionado con cambio climático, costos de producción, programas de asociatividad, fomento a la agroindustria y estrategias de comercialización basadas en calidad.

Palabras clave: producción de café, clústers agrícolas, concentración productiva, especialización productiva, Colombia.

Introduction

Coffee is a plant native to Ethiopia, specifically from a region called Kaffa in East Africa, and is currently one of the most commercialized agricultural *commodities* (FNC, 2015; Guhl, 2008). Colombian coffee accounted for 0.6% of the national Gross Domestic Product (GDP) in 2021, equivalent to 8.9% of the agricultural GDP. This study examines the concentration and specialization of coffee production in Colombian municipalities between 2007 and 2021, aiming to identify agricultural clusters (AC) within the coffee sector. The methodology involves analyzing four statistical databases using the Gini coefficient, Location Quotient (LQ), Herfindahl-Hirschman Index (HHI), and Moran's Index to identify Agricultural Clusters (AC) in the Colombian coffee sector, complemented by bivariate thematic cartography. The AC were proposed by FAO (2010) where the agriculture in the 21st century must reach higher levels of productivity. Also, the *agro-based clusters* (ABCs) are a sectoral organization tool for government institutions and public policies. The ABCs are "geographic concentrations of interconnected producers, agribusinesses and institutions that participate in the same agricultural or agro-industrial subsector and create value networks to address common challenges and seek joint opportunities" (FAO, 2017). Additionally, Otsuka & Ali (2020), categorize ABCs into two types: *agricultural clusters* (AC), which market fresh produce without rigorous grading or processing, and *agro-industrial clusters* (AIC), which focus on value addition and transformation processes. The main challenge for developing countries is to boost ABCs and transform their ACs into AICs (Otsuka & Ali, 2020). The ABCs contribute to the articulation of the actors in the *value chain*, promote innovation, competitiveness, and relations with support organizations (FAO, 2010). ABC analysis is a necessity for the contemporary agricultural economy (Tapia et al., 2015).

Since 56.1% of Colombian municipalities reported coffee production, and that 90% of the coffee production was concentrated in 283 municipalities (25.2% of the total), we propose addressing the following three research questions:1) which municipalities constitute the agricultural clusters in Colombian coffee production?; 2) Is specialization in coffee production associated with rural multidimensional poverty?; and 3) do variations in mean annual temperature and precipitation have any association with coffee production and specialization? Our primary hypotheses suggest an inverse relationship between the concentration and specialization of coffee production measured by the LQ and HHI, and the incidence of multidimensional poverty in the *populated rural centers and dispersed rural areas* (PRCDRA) of coffee production municipalities, indicating that municipalities with a higher level of specialization in coffee production have lower rates of multidimensional poverty in PRCDRA. In this sense, the objective of this article is to analyze the concentration and specialization of coffee production (*Coffea arabica*) in Colombian municipalities between 2007-2021, through the application of the Gini coefficient, the location coefficient (LQ), the Herfindahl-Hirschman Index (HHI) and autocorrelation by Moran's index, to identify the agricultural clusters (AC) of Colombian coffee. LQ measures specialization through the volume of annual municipal coffee production in tons, while HHI measures specialization according to the annual amount of land cultivated with coffee by municipality. The measurements were carried out mainly for 2007, 2014, and 2021 (start- middle-end). The period 2007 to 2021 was selected due to the availability of statistical information in institutional sources. The "start-middle -end" periods are discretionally selected to perform inter-temporal analysis in three-time periods with an equal number of years between each segment.

Additionally, the document provides thematic cartography at the municipal scale to visualize the spatial distribution of production, agronomic yield (t/ha), LQ, HHI, Moran index and the Multidimensional Poverty Index (MPI) in PRCDRA (the latter only for 2018). For concentration measurements, the Gini coefficient and the Lorenz curve have traditionally been implemented (Castro & Fuentes, 2017), while for the measurement of productive specialization, the location coefficient (LQ) is used (Schouten & Heijman, 2012; Schouten, 2011). According to Castro & Fuentes (2017), there is valuable evidence on economic concentration and specialization in industrial activities, however, information for the agricultural sector is limited. This work provides evidence on the concentration and specialization of coffee production for the main municipalities of Colombia.

The coffee markets

The world coffee market for season 2020/21 recorded a total production of 178.9 million 60 kg bags and a total demand of 167.9 million bags. Coffee production comes mainly from five countries: Brazil (40.2%), Vietnam (16.2%), Colombia (7.5%), Indonesia (6.5%), and Honduras (3.5%) (FNC, 2021c). Two main species satisfy the worldwide demand: arabica coffee (*Coffea arabica*) and robusta coffee (*Coffea canephora*) (BID, 2020). *Coffea canephora* is grown at altitudes between 700 and 1,000 masl and temperatures ranging from 24°C to 30°C. Brazil, Vietnam, and Indonesia are the leading producers, reaching a 30% share (approximately) of the world market (FNC, 2015; Guhl, 2008). Robusta coffee tolerates temperature variations, reduces susceptibility to pests and diseases, and achieves higher yields (tons/hectare). However, it is less favored for consumption due to its sensory characteristics perceived in the cup (BID, 2020). In contrast, Arabica coffee, known as mild coffee due to its quality attributes fragrance, aroma, flavor, acidity, and sweetness represents approximately 70% of the world market. Arabica coffee is cultivated in Colombia, Costa Rica, Mexico, Ecuador, Peru, and other tropical countries at altitudes between 1,200 and 1,800 meters above sea level (masl) and temperatures between 15°C and 24°C. However, it is susceptible to pests and diseases, highly sensitive to temperature changes, and has lower yields (tons/hectare) than Robusta coffee varieties (FNC, 2015; Guhl, 2008; BID, 2020; ICO, 2022).

In Colombia, until 2021 the records indicate the exclusive cultivation of Arabica coffee varieties. However, some studies underscore the comparative advantages associated with the introduction of Robusta coffee (*Coffea canephora)*. Campuzano-Duque et al., (2021) show positive adaptation and eco-regional productivity indicators in areas that are not traditional producers of Arabica coffee. Likewise, the studies of Campuzano-Duque & Blair (2022) and Harvey et al., (2021), assert that climate change creates favorable conditions for the introduction of Robusta coffee. Also, Collazos et al., (2020) reveal the economic viability for the production of Robusta coffee in Sabana de Torres (Santander) and Martínez et al., (2022) identify field experiments to implement Robusta. Complementarily, González-Orozco et al., (2024) recognized the areas with the greatest biophysical and socioeconomic potential to grow Robusta coffee in Colombia. These studies foresee that Colombia will produce Arabica and Robusta coffee crops in different regions, with different production systems and marketing strategies, which justifies studying the coffee agricultural clusters, and the opportunities that this represents for Colombian agriculture in the world coffee market.

In 2021, Colombian coffee generated 960,000 direct jobs and was the main source of income for 540,000 coffee producers and their families, affiliated to the *National Federation of Coffee Growers* (FNC). Regarding farm size, 96% of coffee producers are small (less than 5 ha), 3% medium (between 5 and 10 ha), and 1% large (more than 10 ha) (FNC, 2021c; Criollo Escobar et al., 2019; Jacobi et al., 2024). Additionally, in 2021, coffee production in Colombia was 754,656.5 tons equivalent to 12.5 million 60 kg bags, representing a percentage variation of -9.5% compared to the previous year (FNC, 2022). Of the total production, 85.1% came from nine departments: Huila (18.6%), Antioquia (14.3%), Cauca (12.8%), Tolima (11.9%), Caldas (6.4%), Santander (6.4%), Valle del Cauca (5.7%), Risaralda (4.8%), and Nariño (4.3%). Of the 1,121 municipalities in the country, 629 reported production, the most representative being Pitalito (2.1%), Acevedo (2.1%), Planadas (1.9%), La Plata (1.4%), El Tambo (Cauca) (1.4%), and Garzón (1.2%) (Minagricultura-UPRA, 2022).

According to the *Social Household Registry* in 2020, 54.4% of coffee producers were in poverty FNC (2021a). Likewise, FNC (2017) identifies the vulnerability of coffee-growing households through the analysis of *multidimensional poverty* based on information from the *National Agricultural Census-2014*. The study highlights that 46.5% of people who live in coffee-growing households are poor, and the results contrast with those of non-coffee-growing areas where poverty was 48.5%. These results justify the need to analyze the incidence of poverty in rural areas of coffee-growing regions using information from the *National Population and Housing Census*-2018. In Colombia, two types of poverty measurements are carried out: according to income (monetary poverty) and according to the *Multidimensional Poverty Index* (MPI). The MPI is a measure that captures the shortage faced by individuals in poverty related to fifteen variables grouped into five dimensions: 1) educational status, 2) living conditions of children and youth, 3) health, 4) employment, and 5) access to public services and housing conditions. Households are considered multidimensionally poor when they are deprived in at least 33.3% of the indicators (DANE, 2019). Since 2010, the MPI has been a reference in measuring deprivation and poverty because it *reflects the incidence of multidimensional poverty* (the proportion of the population who is multidimensionally poor), as well as its *intensity* (the average number of deprivations experienced by a poor person).

According to the Inter-American Development Bank (BID, 2020), the global increase in temperature will be a decisive factor in the regional changes in coffee production in Latin America. It is estimated that by 2050 there will be a reduction of up to 50% in the area suitable for growing coffee, especially Arabica varieties (BID, 2020). In this regard, Ovalle-Rivera et al., (2015) confirm that temperature increases and changes in precipitation patterns will decrease yield, reduce quality, and increase pest and disease pressure. In the Colombian case, productive areas located in the departments of Huila, Antioquia, Tolima, Cundinamarca, Santander and Bolívar would be affected. From this perspective, it is pertinent to study the agglomeration and specialization of coffee production in Colombian municipalities, seeking to find key information for guilds institutions and public policy makers.

The results of this work aim to contribute to the study of the Colombian and regional economy, where coffee stands as a representative icon of the country's culture and agricultural vocation. Coffee has historically been, and remains, a product of strategic importance for rural development and peasant family agriculture (Jacobi et al., 2024; Echavarría et al., 2015). To the best of our knowledge, this article provides the first analysis of the Gini coefficient, LQ, HHI, and Multidimensional Poverty Index (MPI) in coffee production areas in Colombia, utilizing bivariate cartography. The remainder of the paper is organized as follows: Section two describes the databases used, variables, and analysis techniques implemented. Section three presents the results, section four discusses the findings, and section five concludes the study.

Materials and methods

Description of the study area

According to The *National Administrative Department of Statistics* (DANE), Colombia has 32 Departments (regions) and 1,121 municipalities (1,102 municipalities, San Andres Island, and 18 non-municipalized areas-ANM) (DANE-Divipola, 2022). In 2021, 629 municipalities (56.1% of the total) registered coffee production in mountainous regions at altitudes above 1,000 meters above sea level and temperatures above 15°C.

Data and variables

Four statistical databases were used:

1. Report of the Municipal Agricultural Evaluations (EVA) [Agricultural Base EVA from 2019 to 2021 - Publication date 22042022], from the Agriculture Rural Planning Unit and the Ministry of Agriculture and Rural Development (Minagricultura-UPRA, 2022);

2. Report of the Municipal Agricultural Evaluations (EVA) [Agricultural Base EVA from 2007 to 2018 (P)_12_02_2020], from the Agricultural Rural Planning Unit and the Ministry of Agriculture and Rural Development (Minagricultura-UPRA, 2020). These first two bases contain statistics for the 1,121 Colombian municipalities, related to *planted area* (measured in hectares), *harvested area*, and *production* (measured in tons), for a diverse range of 150 crops. These crops are classified into eight typologies: cereals, fruits, vegetables, legumes, oilseeds, roots and tubers, traditional tropical crops, and crops for condiments and medicinal and aromatic beverages. The period 2007 to 2021 was selected due to the availability of statistical information in institutional sources.
3. Database of the "Municipal multidimensional poverty measure from census source 2018", from the National Administrative Department of Statistics (DANE, 2018). This database contains information from the *Multidimensional Poverty Index* (MPI) for the 1,121 municipalities of Colombia, disaggregated into three categories: *total poverty by municipality*, in *municipal urban areas and in populated rural centers and dispersed rural areas* (PRCDRA). The IPM data corresponds to the information recorded in the *National Population and Housing Census*-2018.
4. Database of the *Institute of Hydrology, Meteorology and Environmental Studies* - IDEAM (2022), containing temperature and precipitation measurements between 2007 and 2021. We selected the meteorological stations located in the coffee production municipalities between 1,000 and 2,000 masl, that is the ideal altitude for growing Arabica coffee. The *temperature database* contained information from 42 stations with daily data recorded three times a day (at 07:00, 13:00, and 18:00), located in 34 municipalities. The *precipitation database* contained information from 197 stations with daily data, located in 104 municipalities. Subsequently, we formed a data panel with the *average annual temperature* and *average annual precipitation* between 01/January/2007 and 31/December/2021.

Data analysis techniques

The statistical information is analyzed in five stages:

1. *Concentration of coffee production*: the *Gini coefficient* is applied at the departmental and municipal levels for the years 2007, 2014, and 2021. The *Gini coefficient* quantifies the concentration of a variable taking values between 0 and 1, where 1 represents concentration or absolute inequality and 0 represents equal distribution. Complementarily, the *Lorenz curve* is added, which is a graphical representation that shows the distribution of the variable (Garavito et al., 2022). The concentration occurs with respect to the *agglomeration of volume production per municipal unit*. The measurements were made for the years 2007, 2014, and 2021 (start- middle-end). The "start-middle-end" periods are discretionally selected to perform inter-temporal analysis in three periods with an equal number of years between each segment. It is necessary to note that agricultural production is strongly determined by environmental and geographic conditions. Consequently, while the Gini coefficient measures the concentration of coffee production, it does not account for the impact of these environmental and geographic factors.
2. *Specialization of coffee production in municipalities*: The *Location Quotient* (LQ) is applied at the municipal level for 2007 and 2021. The LQ quantifies the concentration of a variable or economic activity in a specific region with respect to the national total, revealing

the productive activities with comparative advantage (EMSI, 2020, Schouten & Heijman, 2012). Specifically, LQ is a comparative relationship between a locality and a more extensive reference region with respect to a specific variable, being the most commonly used methodology to identify clusters (EMSI, 2020). The LQ can take three values: greater than, less than, or equal to 1. An LQ of 1 indicates that the variable's share in regional production is proportional to its contribution to national production; while an LQ greater than 1.0 indicates a high level of relative specialization of the region in the variable under study with respect to national production, and vice versa (ONA-UK, 2018). The following equation is used to measure the LQ:

$$LQ = \frac{E_i^j / E_i}{E^j / E} \quad [1]$$

Where $\boldsymbol{E_i^j}$ is the production of coffee (***i***) in municipality ***j***; $\boldsymbol{E_i}$ is the production of coffee (***i***) in Colombia; $\boldsymbol{E^j}$ is the total agricultural production in municipality ***j***; ***E*** corresponds to the total agricultural production in Colombia (Schouten & Heijman, 2012; ONA-UK, 2018).
In addition, this article analyzes agricultural productive specialization through the application of the Herfindahl-Hirschman Index (HHI):

$$\mathrm{HHI}_j = \sum_{h=1}^{H} \left(\frac{L_{jh}}{L_j}\right)^2 = \sum \left(\frac{L_{jh1}}{L_j}\right)^2 + \left(\frac{L_{jh2}}{L_j}\right)^2 + \left(\frac{L_{jh3}}{L_j}\right)^2 + \cdots + \left(\frac{L_{jH}}{L_j}\right)^2 \quad [2]$$

where $\boldsymbol{L_{jh}}$ is the amount of cultivated land (planted area) dedicated to *crop h* in municipality *j*, $\boldsymbol{L_j}$ is the total amount of cultivated land (planted area) in municipality *j*, and *H* is the total number of crops present in the municipality *j*. Note that if all the land in a municipality is dedicated to a single crop, the specialization index HHI_j equals to one ($\mathrm{HHI}_j = 1$), therefore, as the number of crops cultivated in a municipality increases, the value of HHI_j decreases (Emran & Shilpi, 2012). Specialization occurs with respect to the sum of the squares of the percentage shares of participation of the number of hectares dedicated to each of the crops present in the municipality. This study focused on coffee cultivation; therefore, specialization should be understood as the preference of farmers in municipality *j* for having the largest amount of available land cultivated with coffee, which is a perennial crop. This preference may be attributed to the use of comparative advantages related to geographical factors (altitude, temperature, precipitation and soil), as well as the market behavior of coffee prices based on differential quality. The measurements were made for the years 2018 and 2021.

3. *Spatial autocorrelation (Moran's I)*: is a geostatistical analysis tool that measures the autocorrelation of spatial units based on the locations and values of entities simultaneously, assessing whether the variable is clustered, dispersed or random (Siabato & Guzmán-Manrique, 2019). We start from the *null hypothesis* (H0) which states that the values of the polygons on the map are randomly distributed. Once the statistical analysis is performed, two parameters are obtained: *p and z*, where *p* represents a probability and a small p-value allows for the rejection of the null hypothesis H0. On the other hand, the *z* parameter represents the standard deviations. Typically when z is close to zero, it indicates insufficient statistical evidence to reject the H0; for this reason, a small p value implies high values of *z* that can be positive or negative (GEASIG, 2016).

The analysis of the Moran index for spatial autocorrelation reveals the spatial distribution of the values of a specific variable. Thus, if the values tend to be spatially clustered (high values near high values), the Moran index will be positive. On the contrary, if the values are dispersed (high values near low values), the index will be negative. If the values of *p* and *z* indicate the rejection of H0 it implies that the Moran index is greater than zero and also a tendency towards *agglomeration*, and conversely, if the index is less than zero, the tendency indicates *dispersion* (GEASIG, 2016).

4. *Coffee production and multidimensional poverty*: using the database DANE (2018), we select the information corresponding to the *populated rural centers and dispersed rural areas* (PRCDRA) of the coffee-growing municipalities. We schematize the variables in bivariate thematic mapping and obtain a Spearman correlation matrix. We expect that the municipalities with the highest coffee production will have low multidimensional poverty rates. The availability of data for this analysis includes the year 2018.
5. *Coffee production and environmental variables*: Arabica coffee is a tropical plant that requires temperatures between 15°C and 24°C, and *annual precipitation* between 1,500 mm and 3,000 mm depending on the retention capacity of the soil, atmospheric humidity, cloud cover, and cultivation practices (ICO, 2022). Using the IDEAM database (2022), and having as reference the work of Aragón and Rud (2023), we implemented a Spearman correlation to identify the relationship between coffee production, LQ, HHI, *average annual temperature* (AAT) and *average annual precipitation* (AAP) (Aragón & Rud, 2023). We used a reduced sample due to the limited availability of data on temperature and precipitation for the coffee-growing municipalities.

Table N°1.

Nomenclature of the variables used in this study

Section	Variable	Description
Topic of specialization in coffee production and correlation of variables	Produ%Coffee	Percentage participation in national coffee production.
	LQcoffe	Location Quotient (LQ) of coffee production.
	HHIcoffe	Herfindahl-Hirschman Index for coffee crop.
	GDP1_GDPtotal	Percentage share of GDP by primary activities (agriculture, livestock, forestry, fishing and mining and quarrying) as a proportion of total municipal GDP (at current 2018 prices).
	MPI	Multidimensional Poverty Index.
	PRCDRA	Populated rural centres and dispersed rural areas.
	MPI_PRCDRA	Percentage of population with multidimensional poverty index (MPI) in populated rural centres and dispersed rural areas.
Environmental variables topic (temperature and precipitation)	AACP	Average annual coffee production.
	AAT	Average annual temperature.
	AAP	Average annual precipitation.

Source: own elaboration.

Results

Coffee production in Colombia between 2007 and 2021

According to statistical information from Minagricultura-UPRA (2022; 2020), in 2021 Colombia registered 695,246.9 harvested hectares with a total coffee production of 754,656.4 tons (t), reaching a regional average yield of 1.09 t/ha. A total of 85.1% came from 9 departments: Huila (18.6%), Antioquia (14.3%), Cauca (12.8%), Tolima (11.9%), Caldas (6.4%), Santander (6.4%), Valle del Cauca (5.7%), Risaralda (4.8%), and Nariño (4.3%), revealing a new geographical distribution of coffee production, that shifts away from the traditional "*eje cafetero*" formed by Caldas, Risaralda, Quindío, north of Tolima, southwest of Antioquia and north of Valle del Cauca.

Longitudinally, the data allow calculating a total variation between 2007 and 2021 of coffee production of -8.9%, of harvested area of -9.3%, and of planted area of -2.2%. Similarly, it is important to highlight that coffee participation as a proportion of national agriculture decreased from 19.2% in 2007 to 15.6% in 2021. In this regard, the *National Federation of Coffee Growers of Colombia* (FNC) has promoted the strategy "*more agronomy, more productivity, more quality*", which encourages better agricultural practices and the planting of resistant and higher yielding varieties (FNC, 2021b; FNC, 2021c).

By 2021, 630 municipalities registered areas planted with coffee, of which 629 reported production, and 197 concentrated 80% of the total production. Pitalito was the main producer accounting for 2.14% of national production, followed by Acevedo (2.06%), Planadas (1.93%), La Plata (1.4%), El Tambo (Cauca) (1.36%), and Garzón (1.24%). Between 2007 and 2021, the number of producing municipalities increased in 6.4%. Moreover, in 2021, eight municipalities were identified where coffee represents more than 50% of agricultural production: Toledo (71.0%), Betania (69.7%), Santa Fe de Antioquia (62.4%), Armenia (58.9%), Toribío (57.6%), Sabaneta (56.5%), Sabanalarga (56.0%), and Inzá (52.2%). Additionally, in this work we contrasted the municipality's production and yields (t/ha) within bivariate cartography and found that the relationship does not always have a high - high correspondence (*Figure 1)*. Thus, the mapping for 2021 shows that the municipalities with the highest production and highest yields (t/ha) are in Huila, Tolima, Cauca, and southwestern Antioquia.

Table N°2.

Percentage variation of coffee production (t) by department between 2007 - 2021

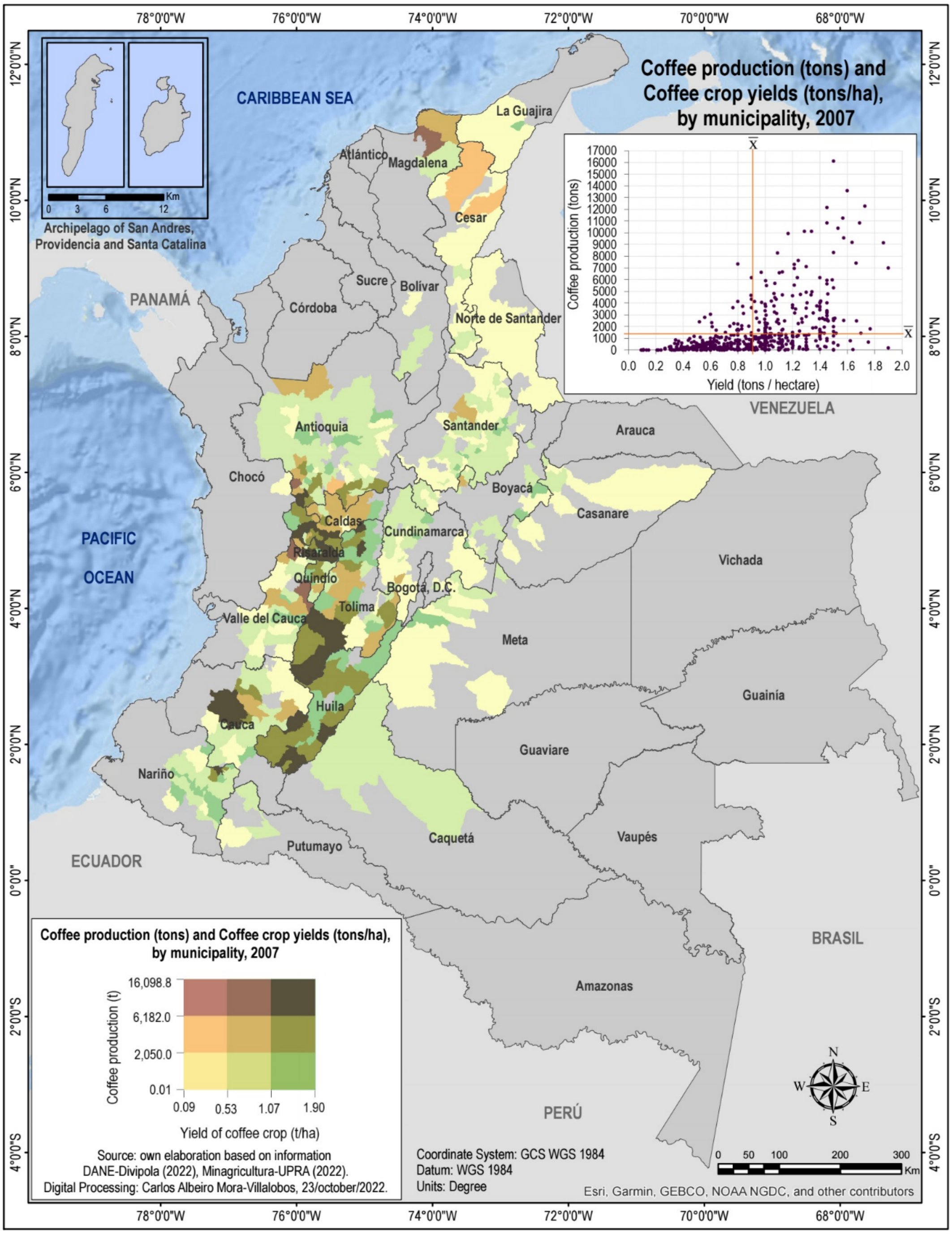
Coffee production (tons): percentage change between 2007 and 2021							
Extraordinary increase		**Outstanding increase**		**Moderate increase**		**Reduction**	
Putumayo	544.1%	Cauca	87.5%	Meta	21.9%	Casanare	-4.3%
Bolívar	104.9%	Santander	63.0%	Caquetá	15.8%	Chocó	-8.6%
		Cesar	54.6%	Huila	8.5%	Antioquia	-10.3%
		Norte de Santander	52.6%	Boyacá	3.5%	La Guajira	-14.4%
				Nariño	2.4%	Tolima	-20.0%
						Cundinamarca	-24.1%
						Magdalena	-29.1%
						Valle del Cauca	-38.5%
						Quindío	-39.6%
						Caldas	-47.9%
						Risaralda	-50.5%

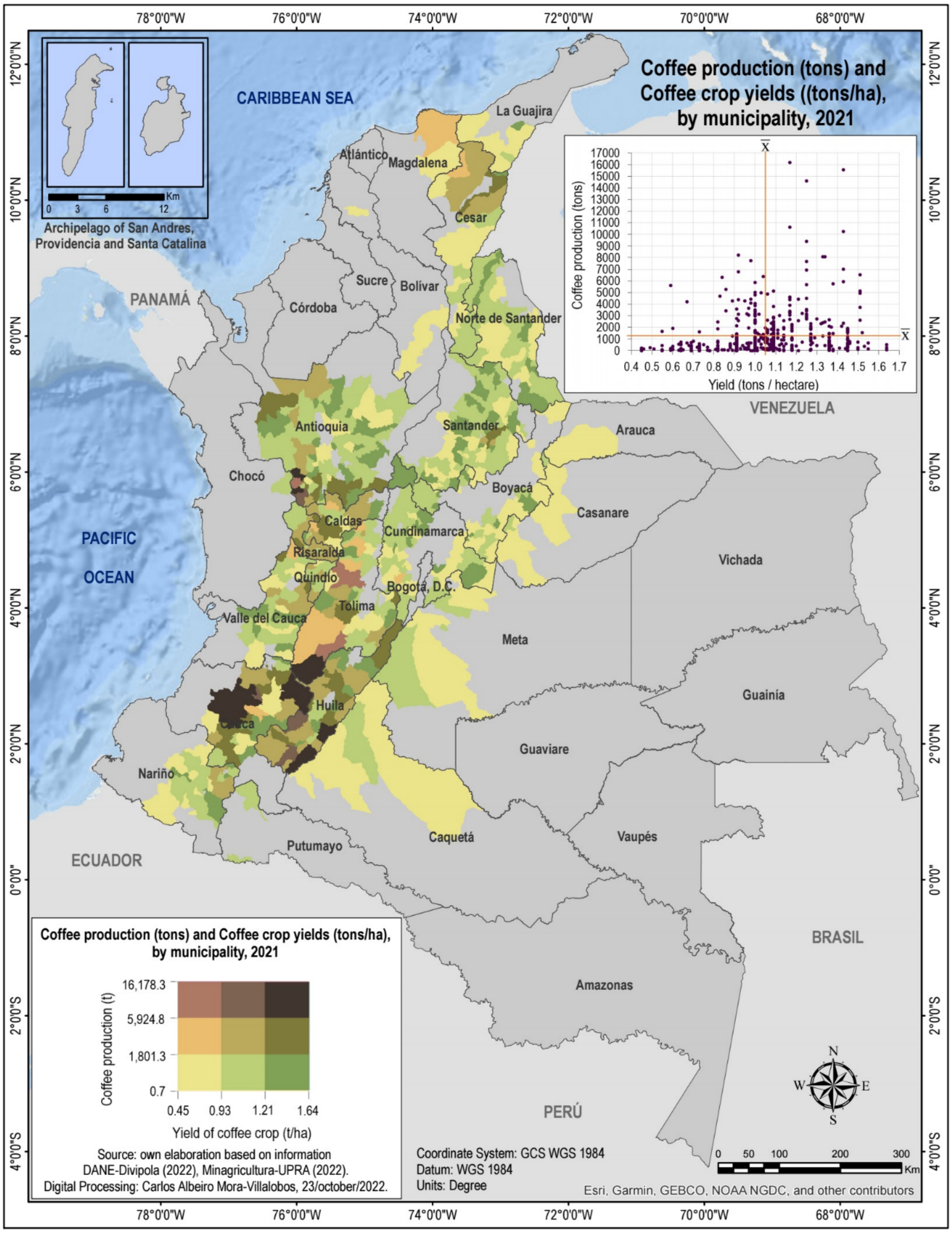
Source: own elaboration based on data from Minagricultura-UPRA (2022), Minagricultura-UPRA (2020).

Note: department of Arauca is not included because in 2007 and 2014 it did not report coffee production. Putumayo and Bolívar show high percentages of change because they are not traditionally coffee producing regions.

Figure N°1.

Coffee production (tons) and yield (t/ha) by municipality, 2007 and 2021





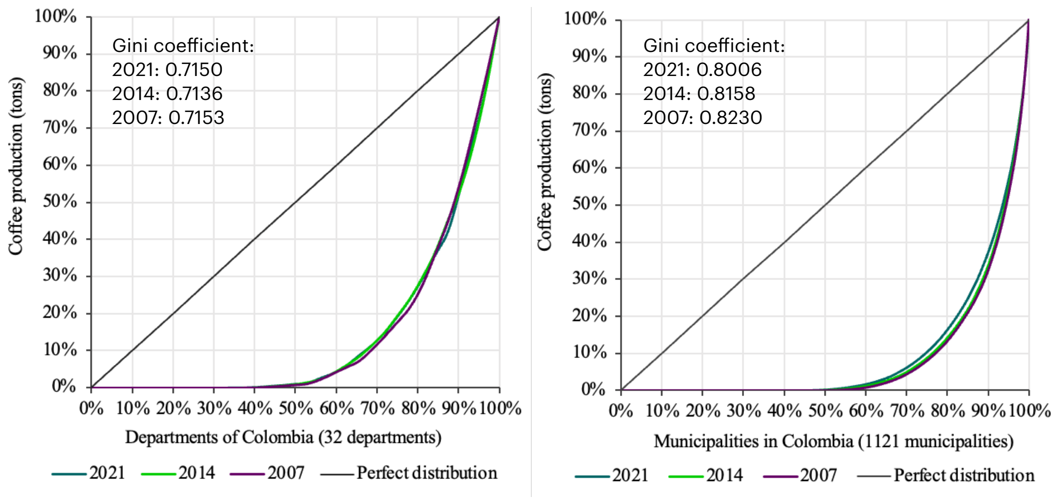
Source: own elaboration based on data from Minagricultura-UPRA (2022), DANE-Divipola (2022).
Note: intervals use Natural Breaks (Jenks) methodology, ArcGIS version 10.7.

Concentration of coffee production

Figure 2 shows a high concentration of coffee production at departmental level in terms of the Gini index which yields 0.7153 in 2007, 0.7136 in 2014 and 0.7150 in 2021. For the last year studied, 12.5% of departments produce 57.6% of the total coffee. At the municipal level, the Gini index reported higher values than the departmental level with 0.8230 in 2007, 0.8158 in 2014 and 0.8006 in 2021, with a variation of -2.7% between 2007 and 2021. In general terms,17.6% of Colombian municipalities are responsible for 80% of national coffee in 2021.

Figure N°2.

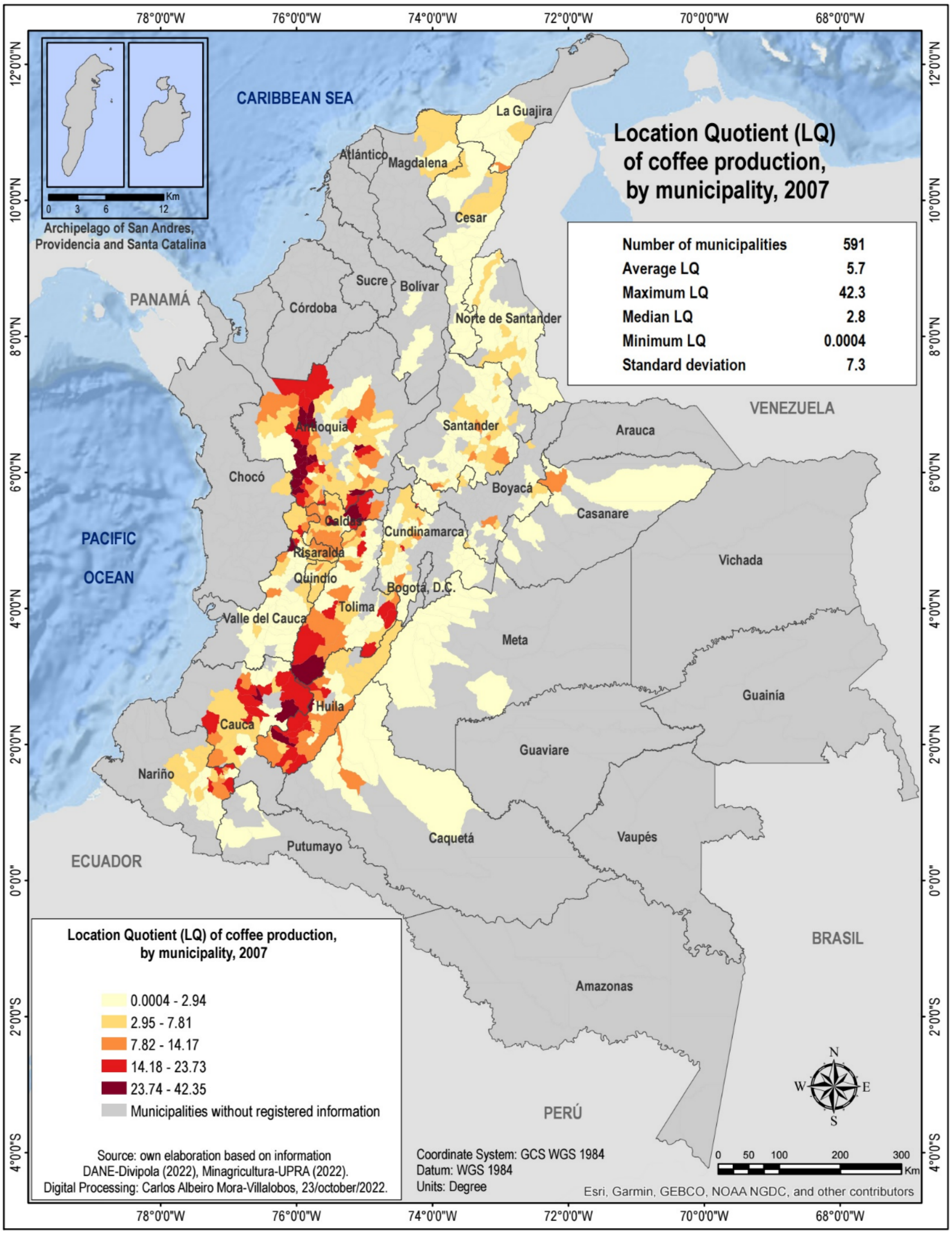
Lorenz Curve for coffee production, by department (left) and by municipality (right): 2007, 2014 and 2021

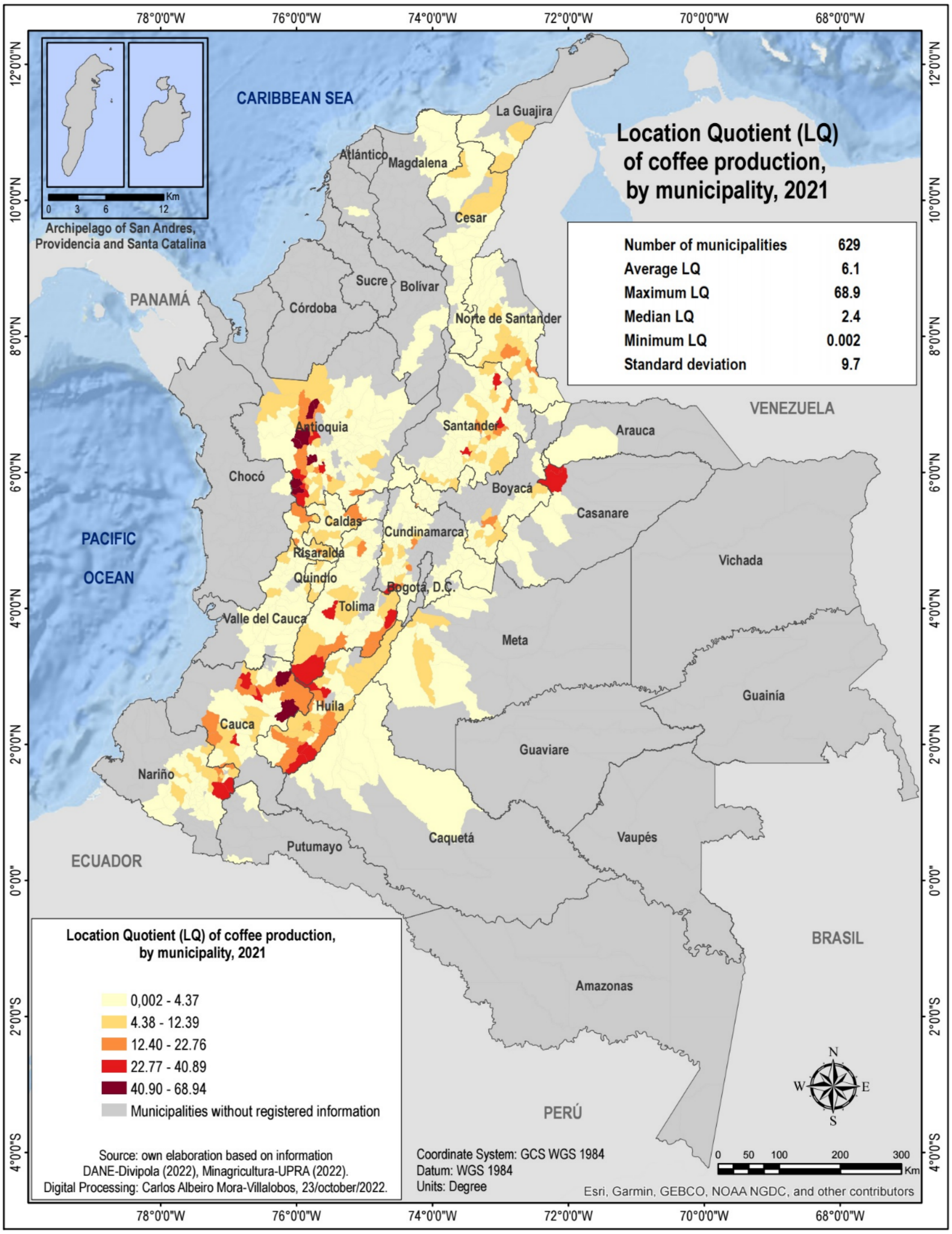


Source: own elaboration based on data from Minagricultura-UPRA (2022), Minagricultura-UPRA (2020).

On the other hand, the location coefficient (LQ) shows that in 2021, 65.3% of the municipalities (n=411) had an LQ greater than 1.0 and nine municipalities (1.4%) had an LQ equal to 1.0. The remaining 209 municipalities, representing 33.2%, had values lower than 0.94. The LQ values in the 411 municipalities with significant values ranged between 1.11 and 68.94, and it is possible to identify that 81.0% of the frequencies fluctuate between 1.11 and 15.07. The remaining 19% corresponds to 78 municipalities with the highest values (between 15.23 and 68.94). The five municipalities with the highest LQ values were Toledo (68.94), Betania (67.66), Santa Fe de Antioquia (60.58), Armenia (57.12), and Toribio (55.91). Comparatively, the five municipalities with the highest coffee production in 2021 reached the following LQ values: Pitalito (18.4), Acevedo (27.17), Planadas (30.38), La Plata (12.18), and El Tambo (Cauca) (3.19).

Figure N°3.
Location Quotient (LQ) of coffee production, by municipality, 2007 and 2021





Source: own elaboration based on data from Minagricultura-UPRA (2022), DANE-Divipola (2022).
Note: intervals use Natural Breaks (Jenks) methodology, ArcGIS version 10.7.

Herfindahl-Hirschman Index (HHI), 2021

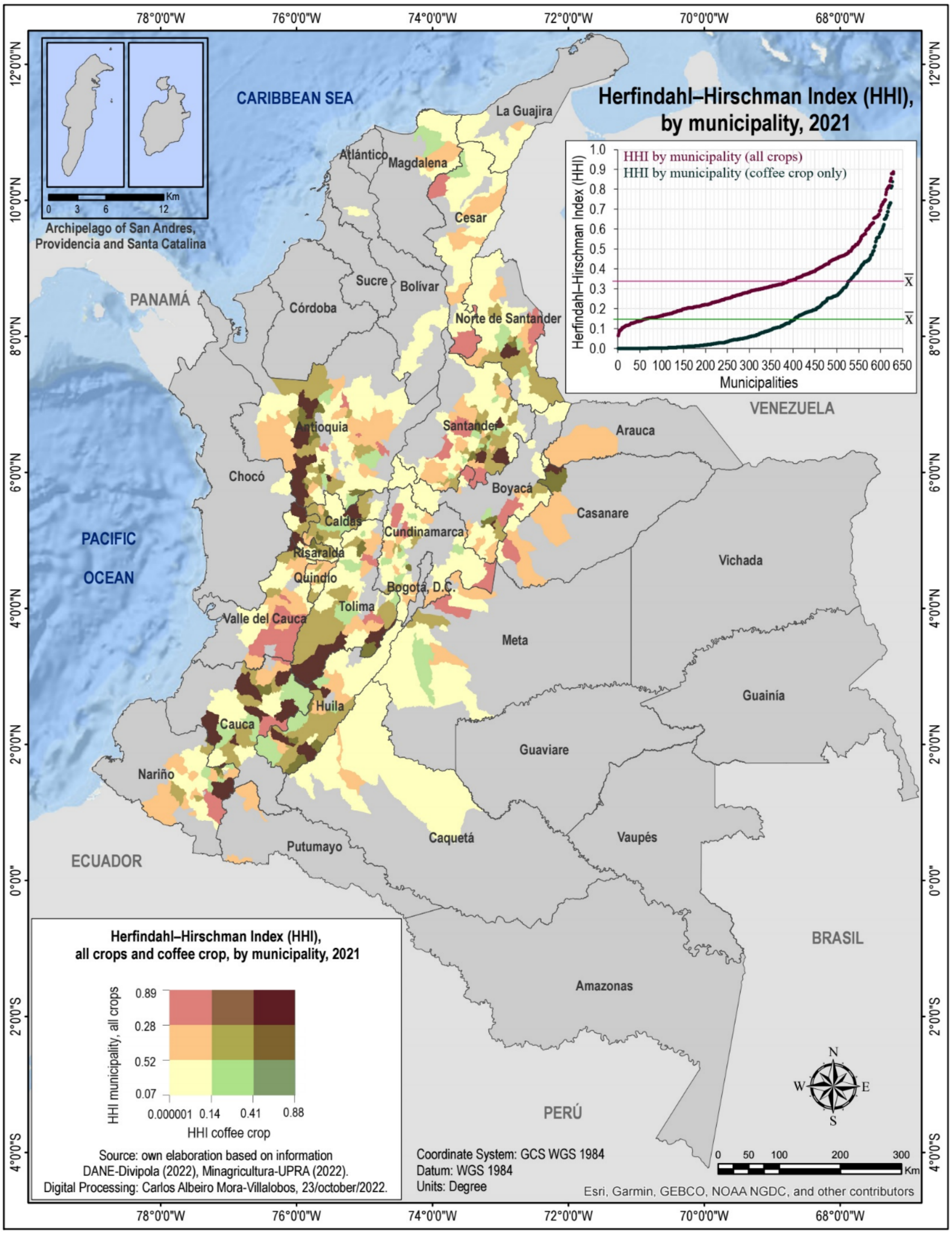
This section focused its attention on coffee crops (sowing), therefore, specialization should be understood as farmers' preference in a particular municipality to sow coffee. Among the 629 coffee-producing municipalities registered in 2021, the average HHI index for coffee crop was 0.151 with a maximum value of 0.879 and a minimum of 0.0000001. Five categories of specialization (quintiles) are observed: very-high (greater than 0.801), high (between 0.601 and 0.80), medium (between 0.401 and 0.60), low (between 0.201 and 0.40), and very-low (between 0.001 and 0.20). We found 6 municipalities (1.0%) with very-high specialization; 19 municipalities (3.0%) with high specialization; 53 municipalities (8.4%) with medium specialization; 98 municipalities (15.6%) with low specialization; and 453 municipalities (72.0%) with very-low specialization. The 6 municipalities with very high specialization in coffee cultivation were: Santa Fe de Antioquia (0.808), Betania (0.838), and Ciudad Bolívar (0.814) in the department of Antioquia; and Piendamó (0.879), Inzá (0.879), and Toribío (0.816) in the department of Cauca. Thematic cartography (*Figure 4*) allows the identification of municipalities with very-high and high specialization, located in the departments of Antioquia, Nariño, Cauca, Huila, Tolima, Santander, and Norte de Santander.

On the other hand, between 2021 and 2007, a variation of 6.1% is observed in the number of municipalities that have an area cultivated with coffee, which is equivalent to 36 new municipalities in 2021 that did not have cultivation in 2007. Although the planted area at the national level (all crops), shows a variation of 20.4% between 2007 and 2021, the same does not occur with coffee, which decreased -2.2% (from 860,244.6 hectares in 2007 to 841,154.9 in 2021). Additionally, the HHI calculation show that between 2007 and 2021, the very-high and high specialization segment had a variation of only 4.2%; average specialization shows a variation of -14.5%; low specialization had a variation of -18.3%; and very low specialization had a variation of 17.1%. These results show a reduction in the planted area in municipalities with medium and low specialization, and a considerable increase in municipalities with very low specialization in coffee cultivation. This trend could suggest that traditionally coffee municipalities are in an eventual stage of substitution of the crop.

Figure *4* shows HHI data for 2021, in which two quantitative variables intersect: *HHImunicipality_2021* indicates the level of specialization of agricultural production by municipality without identifying the specialization crop. *HHIcoffe_2021* indicates the level of specialization in coffee cultivation by municipality. An intercept of the two variables, (HHImunicipality_2021 and HHIcoffe_2021), reveals a municipality with a specialization in coffee production.

Figure N°4.

Herfindahl-Hirschman Index (HHI), all crops and coffee crop (planted area), by municipality, 2021



Source: own elaboration based on data Minagricultura-UPRA (2022), DANE-Divipola (2022).

Note: intervals use Natural Breaks (Jenks) methodology, ArcGIS version 10.7.

Spatial autocorrelation (Moran's I), 2021

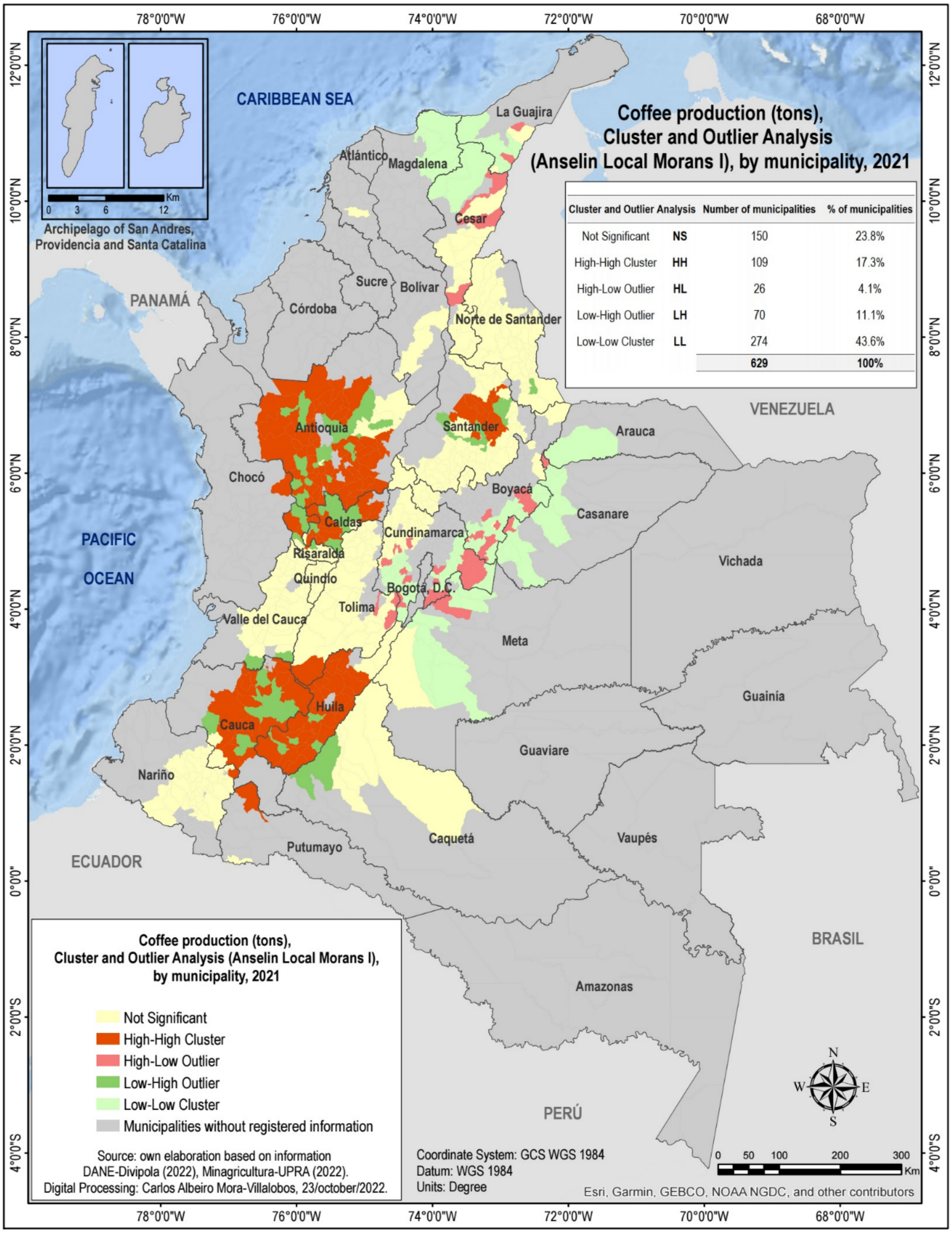
In accordance with the theoretical principles of Moran's I and considering that the *p-value* is equal to 0.0000001 with a *z* parameter equal to 31.241230, the null hypothesis (H_0) which states that the polygons on the map are randomly distributed, is rejected. It is determined that there is less than a 1% probability that this clustering pattern could have occurred by chance. Consequently, the analysis confirms that municipal-level coffee production in 2021 yields a Moran's I value of 0.213621, indicating spatial agglomeration. This result suggests the presence of clusters of municipalities where spatial contiguity correlates with coffee production, thus identifying a clustered spatial structure (*Figure 5*).

Also, three types of coffee productive agglomerations were found: 1) *high productive agglomeration* located towards the center-south of the country over the departments of Tolima, Huila, Cauca, Caldas, Risaralda, north of Valle del Cauca and south of Quindío; 2) *medium productive agglomeration* located over the departments of Cundinamarca Boyacá, Santander, Norte de Santander, center of Antioquia and several municipalities of the piedmont of the plains; and 3) *low productive agglomeration* distributed in the municipalities located in the mountainous region of the Sierra Nevada de Santa Marta, the Serranía del Perijá, southwestern Antioquia and several municipalities of Nariño and Tolima. Nariño presents a unique case, accounting for 4.3% of national coffee production in 2021. Of its 64 municipalities, 40 reported coffee production, with 11 concentrating the highest production values. This distribution highlights the department's medium to low levels of agglomeration, underscoring the region's untapped productive potential. Similarly, the clusters that appear in the piedmont of the plains, where the municipality of Támara (Casanare) is projected as the productive epicenter of the region, are also noteworthy (*Figure 5*).

By conducting the *High-Low Clustering Report*, which employs *Getis and Ord's GGG index*, it is possible to determine the extent to which municipal units with high values (hotspots) or low values (coldspots) are spatially clustered. This analysis allows for the identification and prioritization of cluster formation (Siabato & Guzmán-Manrique, 2019).

Figure N°5.

Cluster and Outlier Analysis (Anselin Local Morans I), coffee production (tons) by municipality, 2021



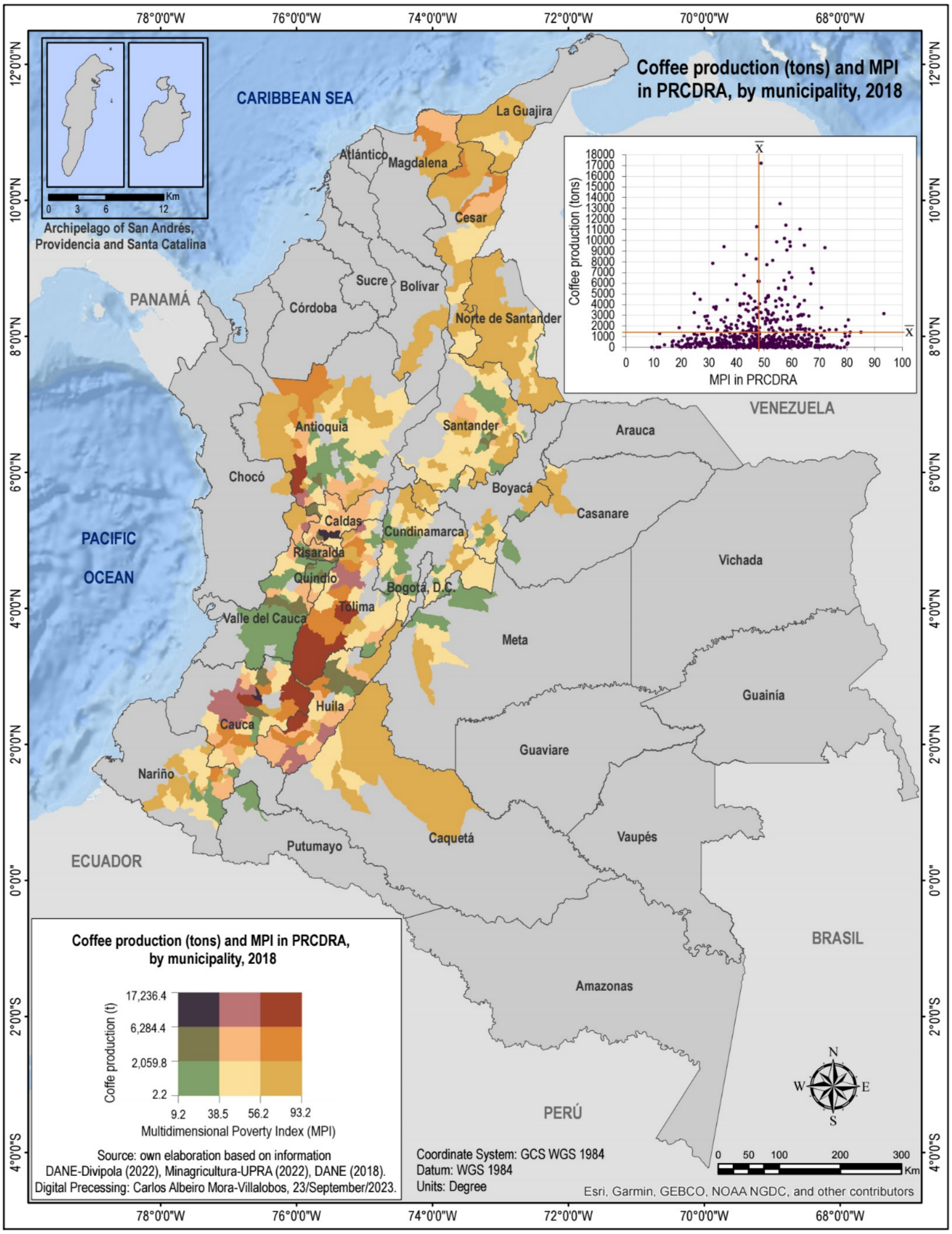
Source: own elaboration based on data Minagricultura-UPRA (2022), DANE-Divipola (2022).

Coffee production and Multidimensional Poverty (PMI) in populated rural centers and dispersed rural areas (PRCDRA), 2018

In this section, the database DANE (2018) was analyzed. DANE shows the MPI disaggregated at the municipal level for the 1,121 municipalities in the country. In 2018, the percentage of people in multidimensional poverty in Colombia was 19.6% of the total, 13.8% in *urban areas*, and 39.9% in PRCDRA (DANE, 2019). Using the coffee-growing municipalities in 2018, Colombia produced 855,840 tons of coffee distributed in 600 municipalities. 80% of national production was concentrated in 191 municipalities, including Pitalito (2.01%), Acevedo (1.57%), Ciudad Bolívar (1.34%), El Tambo (1.32%), and Salgar (1.29%) (Minagricultura-UPRA, 2020).

According to MPI data, the incidence of multidimensional poverty in the population located in PRCDRA of the 600 coffee-growing municipalities was on average 48%, ranging from 93.2% to 9.2%. *Table 3* shows that 14 municipalities (2.3%) had a multidimensional poverty rate of less than 20% (DANE, 2018), and 72.2% of the municipalities had more than 40.1% of the rural population living in multidimensional poverty. Furthermore, it was determined that the variables with the highest incidence were: low educational attainment (mean 80.1%, maximum 96.7%, and minimum 28.2%), informal employment (mean 90.0%, maximum 98.5%, and minimum 66.9%), and lack of access to improved water sources (mean 42.6%, maximum 93.3%, and minimum 0.5%) (DANE, 2018). Although coffee production has traditionally been a distinctive feature of Colombian agricultural production, the analysis indicates that its contribution to improving the quality of life for rural residents, as measured by the variables in the Multidimensional Poverty Index (MPI), is minimal.. Although coffee-growing municipalities possess the potential to generate wealth through this crop, the findings suggest that, on average, they lack the capacity to create a *trickle-down* effect capable of significantly enhancing the quality of life for rural populations.

Figure N°6.
Coffee production (tons) and Multidimensional Poverty Index (MPI) in populated rural centres and dispersed rural areas (PRCDRA), by municipality, 2018



Source: own elaboration based on data from Minagricultura-UPRA (2020), DANE (2018).
Note: intervals use Natural Breaks (Jenks) methodology, ArcGIS version 10.7.

Table N°3.

Incidence of multidimensional poverty in coffee-growing municipalities, 2018

Percentage of population living in multidimensional poverty	Number of coffee production municipalities	Percentage of coffee production municipalities
00,0% to 20,0%	14	2.3%
20,1% to 40,0%	153	25.5%
40,1% to 60,0%	314	52.3%
60,1% to 80,0%	112	18.7%
80,1% to 100%	7	1.2%
	600	**100.0%**

Source: own elaboration based on data from Minagricultura-UPRA (2020), DANE (2018).

In this section, we test the correlational hypothesis proposed:

H1: There is an inverse association between coffee production and the incidence of multidimensional poverty in the *populated rural centers and dispersed rural areas* of coffee production municipalities, which indicates that the municipalities with higher coffee production have lower rates of multidimensional poverty in *populated rural centers and dispersed rural areas*.

For this purpose, a panel data for the coffee-producing municipalities in 2018 was created, and subsequently, Spearman's correlation was estimated for five variables: 1) percentage of population with multidimensional poverty (MPI) in *populated rural centers and dispersed rural areas* (MPI_PRCDRA); 2) percentage participation in national coffee production (Produ%Coffe); 3) LQ of coffee production (LQcoffee); 4) section of the HHI representing coffee crop (HHIcoffee); and 5) percentage share of GDP by primary activities (agriculture, livestock, forestry, fishing and mining and quarrying) as a proportion of total municipal GDP (at current 2018 prices) (GDP1_GDPtotal).

The *Kolmogorov-Smirnov test* ($p > 0.05$) indicates that the variables analyzed do not have a normal distribution ($p < 0.05$). Therefore, Spearman's correlation method was chosen for its robustness in assessing the association between variables when the data do not meet the assumptions of normality. Additionally, it is well-suited for assessing monotonic relationships between two variables (when variable1 increases, variable 2 also increases or decreases, but not necessarily at a constant rate).

Table N°4.

Spearman correlations in pairs by municipality, 2018

Sample 1	Sample 2	N	Correlation	95% confidence interval (CI) for ρ	*p - value*
Produ%Coffee	MPI_PRCDRA	600	0.108	(0.028; 0.187)	0.008
LQcoffee	MPI_PRCDRA	600	0.206	(0.127; 0.282)	0.000
HHIcoffee	MPI_PRCDRA	600	0.094	(0.014; 0.173)	0.021
GDP1_GDPtotal	MPI_PRCDRA	600	0.089	(0.009; 0.168)	0.029
LQcoffee	Produ%Coffee	600	0.630	(0.574; 0.680)	0.000
HHIcoffee	Produ%Coffee	600	0.705	(0.657; 0.747)	0.000
GDP1_GDPtotal	Produ%Coffee	600	0.127	(0.047; 0.205)	0.002
HHIcoffee	LQcoffee	600	0.911	(0.893; 0.926)	0.000
GDP1_GDPtotal	LQcoffee	600	-0.034	(-0.114; 0.046)	0.409
GDP1_GDPtotal	HHIcoffee	600	0.008	(-0.073; 0.088)	0.854

Source: own elaboration based on data from Minagricultura-UPRA (2020), DANE (2018).

Considering the results in *Table 4*, *H0 is accepted and H1 is rejected* because the correlation between the variables is quite low, a positive correlation is identified, and the *p-values* indicate that the Spearman correlation coefficients are statistically significant. Thus, it is concluded that there is no determinant association between coffee production, volume specialization (LQ) and specialization by planted area (HHI), with respect to the incidence of MPI in the rural areas of coffee producing municipalities (MPI_PRCDRA).

Table 4 shows that the variables Produ%Coffe and MPI_PRCDRA exhibit a weak positive correlation of 0.108. At a 95% confidence level, the population correlation coefficient is estimated to lie between 0.028 and 0.187. Generally, a stronger correlation is associated with a narrower confidence interval. It is important to note that there is autocorrelation between the variables LQcoffe and Prod%Coffee. Specifically, LQcoffe is derived from data on annual coffee production at the municipal level, while Prod%Coffee represents the percentage of municipal coffee production relative to national coffee production. A similar autocorrelation exists between GDP1_GDPtotal and Prod%Coffee. However, this pattern does not hold for the relationship between HHIcoffee and Prod%Coffee.

A second Spearman correlation was performed (confidence level = 95%) including 191 municipalities that concentrated 80% of national coffee production in 2018. The results show that Produ%Coffee and MPI_PRCDRA have positive correlation of 0.119 and *p-value* 0.102 (statistically not significant). LQcoffee and MPI_PRCDRA have a positive correlation of 0.444 and *p-value* 0.000 (statistically significant); HHIcoffee and MPI_PRCDRA have a positive correlation of 0,281 and *p-value* 0.000 (statistically significant); GDP1_GDPtotal and MPI_PRCDRA have a positive correlation of 0,153 and *p-value* 0,034 (statistically significant). These results suggest that municipalities with high levels of agglomeration in coffee production (as indicated by LQ and HHI) do not tend to show significant improvements in multidimensional poverty indicators in rural areas.

Table N°5.

Spearman correlations in pairs, 191 municipalities with 80% of national coffee production, 2018

Sample 1	**Sample 2**	**N**	**Correlation**	**95% confidence interval (CI) for ρ**	***p - value***
Produ%Coffee	MPI_PRCDRA	191	0.119	(-0.024; 0.257)	0.102
LQcoffee	MPI_PRCDRA	191	0.444	(0.316; 0.556)	0.000
HHIcoffee	MPI_PRCDRA	191	0.281	(0.142; 0.409)	0.000
GDP1_GDPtotal	MPI_PRCDRA	191	0.153	(0.011; 0.290)	0.034
LQcoffee	Produ%Coffee	191	0.343	(0.208; 0.466)	0.000
HHIcoffee	Produ%Coffee	191	0.361	(0.227; 0.482)	0.000
GDP1_GDPtotal	Produ%Coffee	191	-0.064	(-0.204; 0.079)	0.381
HHIcoffee	LQcoffee	191	0.839	(0.783; 0.882)	0.000
GDP1_GDPtotal	LQcoffee	191	-0.156	(-0.292; -0.013)	0.032
GDP1_GDPtotal	HHIcoffee	191	-0.179	(-0.314; -0.037)	0.013

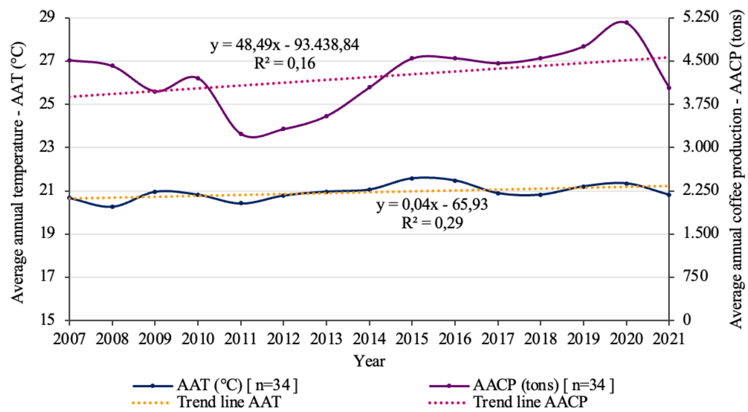
Source: own elaboration based on data from Minagricultura-UPRA (2020), DANE (2018).

Coffee production and environmental variables: temperature and precipitation, 2007 - 2021

A panel data using IDEAM (2022) database was created containing daily *temperature* information from 42 stations located in 34 coffee-growing municipalities that represented 18.2% of national coffee production in 2021. Likewise, we shaped a data panel containing daily precipitation information from 197 stations located in 104 coffee-growing municipalities that accounted for 49.7% of national coffee production in 2021. With this information, an *average annual temperature* (AAT) and *average annual precipitation* (AAP) was computed, which was contrasted with the *average annual coffee production* (AACP). The panel was complemented with LQ and HHI data.

Figure N°7.

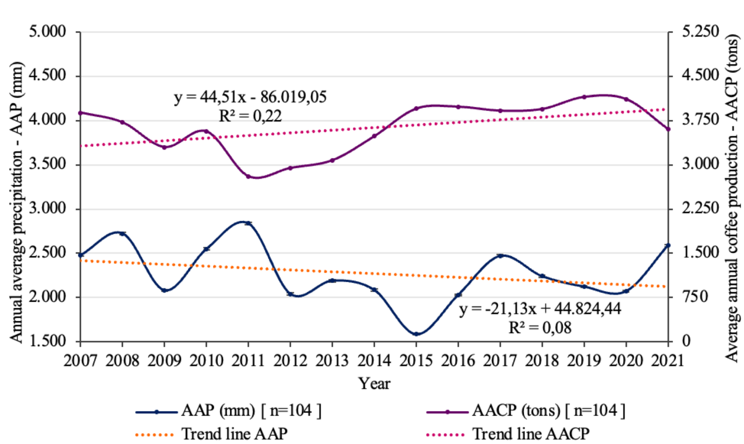
Average annual temperature (AAT) and coffee production (tons), by municipality, 2007 - 2021



Source: own elaboration based on data from IDEAM (2022), Minagricultura-UPRA (2020).
Note: the equation and R^2 correspond to the trend line.

Figure N°8.

Average annual precipitation (AAP) and coffee production (tons), by municipality, 2007 - 2021



Source: own elaboration based on data from IDEAM (2022), Minagricultura-UPRA (2020).
Note: the equation and R^2 correspond to the trend line.

Figure 7 shows parallel trends between the variables, which implies that higher AAT are associated with increased coffee production. Although the results suggest a positive correlation between AAT and AACP, it is not a determinant result because it is necessary to observe additional variables such as precipitation, agronomic practices, age of the coffee plantation, variety of coffee grown, and type of soil, among others. In contrast, *Figure 8* shows a divergent trend, which indicates that lower AAP induces higher coffee production. Taking reference to Aragón and Rud (2023) and Ceballos-Sierra & Dall'Erba (2021), we implemented a correlation analysis to find the degree of association between municipal percentage in national coffee production (Produ%Coffe), LQ, HHI, AAT, and AAP for 2007, 2014 and 2021, therefore, we tested the next correlational hypotheses:

H2: There is an inverse association between coffee crop specialization (HHI) and AAT, indicating that an increase in AAT generates a reduction in the level of specialization by HHI.

H3: There is an inverse association between coffee crop specialization (HHI) and AAP, indicating that an increase in AAP generates a reduction in the level of specialization by HHI.

Table N°6.

Spearman correlations for average annual temperature (AAT), in pairs: 2007, 2014, 2021

Year	Sample 1	Sample 2	N	Correlation	95% confidence interval (CI) for ρ	*p - value*
2021	Produ%Coffee_2021	AAT_2021	34	0.005	(-0.333; 0.343)	0.976
	LQcoffe_2021	AAT_2021	34	0.060	(-0.284; 0.390)	0.737
	HHIcoffe_2021	AAT_2021	34	-0.180	(-0.490; 0.171)	0.309
	LQcoffe_2021	Produ%Coffee_2021	34	0.468	(0.135; 0.705)	0.005
	HHIcoffe_2021	Produ%Coffee_2021	34	0.447	(0.112; 0.691)	0.008
	HHIcoffe_2021	LQcoffe_2021	34	0.721	(0.473; 0.863)	0.000
2014	Produ%Coffe_2014	AAT_2014	34	-0.021	(-0.357; 0.319)	0.905
	LQcoffe_2014	AAT_2014	34	-0.112	(-0.434; 0.236)	0.529
	HHIcoffe_2014	AAT_2014	34	-0.136	(-0.455; 0.213)	0.443
	LQcoffe_2014	Produ%Coffe_2014	34	0.368	(0.022; 0.635)	0.032
	HHIcoffe_2014	Produ%Coffe_2014	34	0.484	(0.154; 0.716)	0.004
	HHIcoffe_2014	LQcoffe_2014	34	0.833	(0.658; 0.923)	0.000
2007	Produ%Coffee_2007	AAT_2007	34	0.033	(-0.309; 0.367)	0.855
	LQcoffe_2007	AAT_2007	34	-0.093	(-0.419; 0.254)	0.601
	HHIcoffe_2007	AAT_2007	34	-0.123	(-0.444; 0.226)	0.489
	LQcoffe_2007	Produ%Coffee_2007	34	0.359	(0.012; 0.628)	0.037
	HHIcoffe_2007	Produ%Coffee_2007	34	0.230	(-0.122; 0.531)	0.190
	HHIcoffe_2007	LQcoffe_2007	34	0.683	(0.417; 0.842)	0.000

Source: own elaboration based on data from Minagricultura-UPRA (2020), IDEAM (2022).

Although the results show an inverse correlation between AAT and HHI, H2 is rejected because the *p-values* are not statistically significant. A possible explanation is that the sample size of the AAT dataset is small, limiting the statistical power and thereby providing insufficient evidence to validate the inverse correlation between AAT and HHI. Also, same correlation increases in the three observation periods, which corresponds to the constant decrease in the area planted since

2013; this information could suggest that the variations in AAT derived from climate change would have some effect on the areas cultivated with coffee. On the other hand, AAT does not exhibit statistically significant p-values in relation to Produ%Coffee and LQ.

Table N°7.

Spearman correlations for average annual precipitation (AAP), in pairs: 2007, 2014, 2021

Year	Sample 1	Sample 2	N	Correlation	95% confidence interval (CI) for ρ	*p - value*
2021	Produ%Coffee_2021	AAP_2021	104	-0.049	(-0.239; 0.145)	0.623
	LQcoffe_2021	AAP_2021	104	-0.152	(-0.336; 0.043)	0.123
	HHIcoffe_2021	AAP_2021	104	0.026	(-0.167; 0.218)	0.791
	LQcoffe_2021	Produ%Coffee_2021	104	0.336	(0.148; 0.501)	0.000
	HHIcoffe_2021	Produ%Coffee_2021	104	0.274	(0.082; 0.446)	0.005
	HHIcoffe_2021	LQcoffe_2021	104	0.768	(0.660; 0.845)	0.000
2014	Produ%Coffe_2014	AAP_2014	104	0.060	(-0.134; 0.250)	0.543
	LQcoffe_2014	AAP_2014	104	0.200	(0.005; 0.379)	0.042
	HHIcoffe_2014	AAP_2014	104	0.218	(0.025; 0.396)	0.026
	LQcoffe_2014	Produ%Coffe_2014	104	0.319	(0.129; 0.485)	0.001
	HHIcoffe_2014	Produ%Coffe_2014	104	0.340	(0.152; 0.504)	0.000
	HHIcoffe_2014	LQcoffe_2014	104	0.851	(0.775; 0.903)	0.000
2007	Produ%Coffee_2007	AAP_2007	104	0.128	(-0.067; 0.314)	0.194
	LQcoffe_2007	AAP_2007	104	0.009	(-0.184; 0.201)	0.930
	HHIcoffe_2007	AAP_2007	104	0.303	(0.113; 0.472)	0.002
	LQcoffe_2007	Produ%Coffee_2007	104	0.291	(0.101; 0.462)	0.003
	HHIcoffe_2007	Produ%Coffee_2007	104	0.271	(0.079; 0.443)	0.005
	HHIcoffe_2007	LQcoffe_2007	104	0.735	(0.617; 0.821)	0.000

Source: own elaboration based on data from Minagricultura-UPRA (2020), IDEAM (2022).

Regarding H3, the results show a positive correlation between AAP and HHI, which decreases considerably in the observed periods, and *p-values* show not significant results in 2021. H3 is rejected and it is concluded that there is insufficient statistical evidence to validate the inverse correlation between AAP and HHI. On the other hand, AAP does not show statistically significant *p-values* with respect to Produ%Coffee and LQ. The findings of the correlation matrix constitute an important input to motivate research regarding coffee production and the effects derived from climate change that may have a causal relationship. For example, the substitution of coffee cultivation as an effect of the increase in production costs due to pest and disease management, the decrease in agronomic yields (t/ha), and the behavior of the internal reference price.

Discussion

This study employed the Gini coefficient to quantify the concentration of coffee production, the Location Quotient (LQ) and Herfindahl-Hirschman Index (HHI) to assess specialization, and Moran's Index to analyze spatial agglomeration. These methodologies have been extensively validated in prior research, including studies by Cosrojas & Eguia (2021), Kartikawati et al., (2019), Castro & Fuentes (2017), Schouten & Heijman (2012), and Chasco Yrigoyen (2010). Our investigation into the spatial distribution of coffee production across municipalities, juxtaposed with multidimensional poverty indices (MPI), revealed a pronounced prevalence of MPI in rural coffee-producing regions. This outcome suggests that coffee production has limited influence on improving rural living standards, a phenomenon likely linked to depressed market prices and the pervasive role of intermediaries in the coffee trade. These findings present significant implications for guild institutions and rural development policy frameworks, particularly given the predominance of smallholder coffee farmers.

Given the context, it is imperative that municipalities with moderate to high levels of production and specialization rank the development and implementation of strategic plans aimed at enhancing the quality of coffee production. These strategic plans, if executed effectively, could not only endow coffee with a competitive edge but also potentially lead to higher market prices. Additionally, optimizing the use of post-harvest by-products, particularly coffee cherries post-pulping, for value-added processes such as food product development, is crucial. The international market's escalating demand for specialty coffee, alongside the rising trade and consumption of coffee cherry derivatives, underscores the importance of this approach (Jacobi et al., 2024).

Concurrently, the impacts of climate change on global agricultural output, with coffee—particularly Arabica varieties—being acutely vulnerable, are well documented (Bianco, 2020; Jacobi et al., 2024). Considering that Colombia exclusively cultivates Arabica varieties and that smallholder farmers dominate the sector; the implications of climate change are especially pertinent. This scenario presents formidable challenges for Colombian agricultural institutions, as the livelihoods of over 540,000 families depend on coffee production, and rural regions within coffee-producing municipalities exhibit high multidimensional poverty rates. Addressing these complex challenges requires coordinated efforts among state entities, guild institutions, and the private sector. Bianco (2020) highlights that, in response to a 20% increase in global coffee demand between 2010 and 2020, major multinational corporations in the coffee supply chain (e.g., Dunkin' Donuts, Starbucks, and Nestlé), have integrated climate change adaptation into their corporate social responsibility (CSR) strategies, advancing shared value creation (CSV) initiatives with producers. Furthermore, the study by Ceballos-Sierra & Dall'Erba (2021) emphasizes that climate variability's impact on Colombian coffee productivity demands adaptive strategies. These strategies should be facilitated by government and coffee institutions to enable farmers to transition to alternative crops without compromising their livelihoods. This insight is pertinent to our research, which identifies a consistent decline in planted coffee areas since 2013, indicative of crop substitution in various municipalities. The primary drivers of this trend appear to be rising production costs, climate change effects, and fluctuations in the New York Stock Exchange's coffee reference price.

Similarly, von Loeben et al., (2023) examined the ramifications of climate change on coffee and corn production chains, noting that Arabica coffee is particularly susceptible, with an anticipated 20% reduction in planted area by 2050. They also identified that climate impacts significantly disrupt value chains by escalating production costs, requiring mitigation strategies considering social dimensions, including gender inequality and land tenure issues. This finding is especially pertinent to our study, as Colombia's coffee sector is characterized by Arabica production on small farms, averaging five hectares, within regions where strong collective action is evident through small producer associations and cooperatives. Additionally, Jacobi et al., (2024) affirm that while coffee cultivation sustains thousands of smallholders, it also presents considerable challenges, as income levels remain low and the climate crisis threatens the viability of most coffee-producing areas.

For future research, examining the agro-industrial processes within rural coffee-growing regions and their potential implications for regional economic development is essential. The study by Qu et al., (2022) in South Korea provides a valuable framework for this exploration. It is essential to emphasize that productive agglomeration requires the identification of value chain components capable of transforming the comparative advantages of localized production into competitive advantages. This process facilitates the formation of business clusters that evolve into agro-industrial clusters (CAI), encompassing value-added transformation processes, rather than being confined to traditional Agricultural Clusters (AC). The principal challenge for developing countries lies in transitioning from CAs to CAIs (Otsuka & Ali, 2020).

The implications of agricultural clusters for the various actors within the production chain warrant careful consideration. This would enhance the understanding of the flows within the coffee value chain, both upstream and downstream. In this context, "Value Stream Mapping" analyses for coffee would prove valuable (Silva et al., 2024; Karyani et al., 2019; Parthanadee & Buddhakulsomsiri, 2012). Other topics to consider would be:

- AC and the linkages with diverse actors in the value chain: supply of agricultural inputs, production on farms, marketing with local and international companies, coffee processing and industrialization, education/instruction/training institutions related to coffee growing, institutions for the dissemination of innovation and technology, financial entities and access to agricultural credit, among others (Venus et al., 2024; Molina et al., 2021).
- AC and the strengthening of public policies to address climate change and its socioeconomic impacts on coffee producers (Poncet et al., 2024; Herrera et al., 2024). In this regard, it would be interesting to explore the concept of "*ecosystem services / environmental services*". This value would represent retribution to the coffee grower for the care of the "coffee landscape, the production of oxygen, the capture of CO2, the management of soils, the care of surface water sources, and the conservation of the biodiversity of birds.
- AC and the inclusion of women in the global coffee marketing chain (Jacobi et al., 2024) and generational change in coffee farms (Bavorová et al., 2024).

Conversely, the findings of this research can contribute to agricultural policies and economies reliant on coffee production through:

- Promote programs and projects focused on "coffee quality clusters" (MinCIT-Confecámaras, 2023; Cepal, 2023).
- Strengthen strategies that link the production of Peasant, Family and Community Agriculture (ACFC). This is important considering that in Colombia 96% of coffee producers are small (they have farms of less than 5 ha). In the same line, strengthen marketing channels promoting direct producer-consumer relationship mechanisms. This would significantly contribute to strengthening the marketing channels for small coffee brands, which are often entrepreneurship of coffee-growing families, associations/cooperatives of coffee

producers, or initiatives of young entrepreneurs, who seek to add value to the product for national marketing (Jacobi et al., 2024).

- Promote short-cycle intercropping of vegetables, legumes, fruit trees, and tubers that are allelopathic with coffee crops and that contribute to ensuring food and nutritional security in the homes of producers; e.g., yucca, arracacha, plantain, beans, squash, onion, cilantro, peas, corn, orange, banana, and avocado (Moreira et al., 2024).
- Strengthen research into the adaptation of tropical agriculture to climate change, especially studies on Arabica coffee varieties (Bro et al., 2017).
- Disseminate innovation and technology to improve value chain processes, especially in production and post-harvest marketing and in regional coffee industrialization projects.
- Strengthen agricultural credit access programs in the municipalities where agricultural clusters have been identified (Wanzala et al., 2024).
- Promote strategies for cooperatives and associations of small producers to access international markets and obtain differential prices based on coffee quality (Jacobi et al., 2024).
- Promote the strategic use of post-harvest organic waste for compost production.
- The analysis of the effects of climate change on the cost of production and the spread of coffee pests and diseases, especially in municipalities where agricultural clusters were identified (Ayalew et al., 2024).
- Motivate generational change by promoting "*coffee-culture*" as a way of life that promotes social well-being and the profitability of the crop, through agricultural credits at low interest rates, training in the production of high-quality coffee, access to formal higher education, rural housing improvement programs, access to technology and innovation to improve production and post-harvest processes, marketing strategies with differential prices, among others (Bavorová et al., 2024).
- Analyze women's participation in coffee production to improve gender equity relations and well-being in rural populations (Jacobi et al., 2024). In this regard, it is important to highlight that there is information on women coffee growers (e.g., Yoshioka et al., 2023), but there is a large information gap on women's participation in the other links of the production chain: supply, training/education, marketing, industrialization, research, among other topics.

It is important to note that a determining factor in this work was the lack of official statistical information on temperature and precipitation in several municipalities of relevant importance for coffee production, especially in the departments of Huila, Cauca, Nariño, Valle del Cauca, Antioquia, Caldas, Risaralda, Cundinamarca, and Santander. In this sense, it is necessary to expand the analysis between temperature and precipitation in coffee production due to the economic importance of coffee growing for the country and for 540,000 growing families. This would contribute significantly to the design of public policies and strategies for adapting agriculture to climate change. The absence of data on monetary poverty at the municipal level hinders the conduct of robust statistical analyses that could reveal the influence of coffee income on the welfare and quality of life of the rural population in coffee-producing municipalities. This data would facilitate a comparison with the Multidimensional Poverty Index (MPI) and enable the implementation of statistical modeling to assess the impact of "coffee income on the quality of life of coffee growing families".

Conclusions

This study analyzed the concentration and specialization of coffee production in Colombian municipalities between 2007-2021 to identify Colombian coffee's AC. The regional concentration of coffee production -measured using the Gini coefficient- reported a value of 0.7153 in 2007, 0.7136 in 2014, and 0.7150 in 2021 (start-middle-end of the database analyzed). The departments of Huila, Cauca, Nariño, Santander, and Norte de Santander have gained a greater share of national coffee production over the last fifteen years. Similarly, it was determined that coffee production is highly concentrated at the municipal level, with the Gini coefficient reaching 0.8230 in 2007, 0.8158 in 2014, and 0.8006 by 2021. This situation can be explained by the expansion of coffee cultivation to municipalities where production was not previously recorded, such as the plains-foothills (Arauca, Casanare, and Meta), the Amazon-foothills (Caquetá and Putumayo), the Serranía del Perijá, and the foothills of the Sierra Nevada de Santa Marta (Cesar, Magdalena, and La Guajira). The Gini coefficient was used to validate the concentration of production among the producing municipalities. Agricultural production is strongly influenced by environmental and geographic conditions, which explains why several non-producing municipalities lack the necessary environmental factors for coffee cultivation. Other variations that are important to highlight in the analysis periods 2007, 2014, and 2021 (start-middle-end of the database analyzed):

- The national area planted with coffee in 2007 was 860,244.6 (ha), increasing to 948,477.3 (ha) in 2014, and ending with 841,201.9 (ha) in 2021, to register a percentage variation between 2007 and 2021 of -2.2%.
- The total harvested area in 2007 was 766,476.8 (ha), increasing to 795,563.2 (ha) in 2014, and ending with 695,246.9 (ha) in 2021, to register a percentage variation between 2007 and 2021 of -9.3%.
- National coffee production in 2007 was 828,898.2 (t), reducing to 728,400.0 (t) in 2014, and ending with 754,656.5 (t) ha in 2021, to register a percentage variation between 2007 and 2021 of -8.9%.
- Agronomic yields (t/ha) in 2007 were 1.08, reducing to 0.92 in 2014, and ending at 1.09 in 2021.
- The number of municipalities with an area planted with coffee in 2007 was 593, increasing to 595 in 2007, and ending in 629 municipalities in 2021, registering a 6.1% percentage variation between 2007 and 2021.

The measurement of productive specialization found that coffee production is strongly concentrated in the central-southern regions of the country, particularly in the departments of Huila, Tolima, Cauca, Caldas, and Risaralda. By 2021, 416 municipalities were identified with a Location Quotient (LQ) greater than 1.0, of which 78 were among the top 20% of values (ranging from 15.1 to 68.9). Additionally, Moran's Index identified that coffee production at the municipal level tends to cluster, and in the High-Low Clustering Report, that uses the Getis-Ord G index, three types of clusters were found: 1) high agglomeration located in the center-south of the country; 2) medium agglomeration located in the departments of Cundinamarca, Boyacá, Santander, Norte de Santander, central Antioquia, and several municipalities in the foothills of the plains; and 3) low agglomeration distributed in the municipalities of the mountainous region of the Sierra Nevada de Santa Marta, the Serranía del Perijá, southwestern Antioquia, and several municipalities in Tolima and Nariño.

Also, the specialization in coffee production (as measured by LQ and HHI) is not significantly associated with multidimensional poverty in rural areas. Although coffee is a representative product of Colombian agriculture, there is no evidence of a significant correlation between coffee production and the reduction of multidimensional poverty in populated rural centers and dispersed rural areas in the 600 coffee-producing municipalities in 2018. The information was corroborated with a second Spearman correlation that included only 191 municipalities that concentrated 80% of national coffee production in 2018. Again, the results indicate that municipalities with high agglomeration in coffee production (LQ and HHI), do not have a significant effect on improving multidimensional poverty indicators in rural areas. This outcome suggests that coffee production exerts a limited influence on improving rural living standards, a phenomenon likely linked to market prices, the role of intermediaries in the coffee trade, production costs, the state of rural roads, the informality of rural work, rural housing conditions, access to improved water sources, low educational achievement, among others. Although coffee is a product of economic importance in Colombian agricultural production with the capacity to generate wealth for the producing municipalities, it is not possible to identify spillover effects for the rural areas of these municipalities in relation to the variables contained in the MPI.

Regarding the environmental variables analyzed for 2021, it was found that variations in average annual temperature (AAT) and average annual precipitation (AAP) have a low association with production specialization (LQ and HHI). In conclusion, we recommend continuing to study the socioeconomic aspects of coffee production, considering its economic importance for Colombian agriculture. We suggest addressing issues related to the value chain, the socioeconomic impacts of climate change, the contribution of coffee plantations to CO2 absorption, the management of pests and diseases through biological control mechanisms, rural poverty, coffee origin denominations, and organic coffee production, among other related topics.

Conflicts of interest

The authors have no conflict of interest related to this document.

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