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Credit and municipal agricultural production in the Northeast: A spatial econometric approach

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ABSTRACT
The mechanisms of reach and the expansion of credit granted to Brazilian agriculture have become determinants of production in the sector on a national scale. Thus, this study aims to analyze the effects of agricultural credit on the gross value of agricultural production (GDP) in the Northeast region. Through an exploratory analysis of spatial data and spatial econometrics, it is possible to verify the significant and positive impact of credit, both granted through the Constitutional Financing Funds and the National Development Bank (BNDES), on the GDP of agriculture in the Northeast. The Durbin Spatial Model of Error (SDEM) was estimated and chosen from the tests of Robust Lagrange Multipliers, the Moran Index of the residuals under randomization, and the Monte Carlo simulation of Moran's I. The results unequivocally demonstrate that credit, along with the amount of rainfall, the number of agricultural pieces of machinery, and the use of fertilizer in the soil, has positively impacted the agricultural GDP in the northeastern municipalities over the years analyzed. These findings have significant implications for the agricultural sector, particularly in the Northeast region, and can inform policy and practice.

KEYWORDS
Agricultural economics, Production, Spatial econometrics

Crédito e produção agrícola municipal no Nordeste: uma abordagem econométrica espacial

RESUMO
Os mecanismos de alcance e a expansão do crédito concedido à agricultura brasileira tornaram-se determinantes da produção no setor em escala nacional. Assim, este estudo tem como objetivo analisar os efeitos do crédito rural sobre o valor bruto da produção agrícola (PIB) na região Nordeste. Por meio de uma análise exploratória de dados espaciais e de econometria espacial, é possível verificar o impacto significativo e positivo do crédito, tanto concedido por meio dos Fundos Constitucionais de Financiamento quanto pelo Banco Nacional de Desenvolvimento Econômico e Social (BNDES), sobre o PIB da agricultura no Nordeste. O Modelo Espacial de Erro de Durbin (SDEM) foi estimado e escolhido a partir dos testes de Multiplicadores de Lagrange Robustos, do Índice de Moran dos resíduos sob randomização e da simulação de Monte Carlo do I de Moran. Os resultados demonstram inequivocamente que o crédito, juntamente com a quantidade de chuvas, o número de máquinas agrícolas e o uso de fertilizantes no solo, impactou positivamente o PIB agrícola nos municípios nordestinos ao longo dos anos analisados. Esses achados têm implicações significativas para o setor agrícola, particularmente na região Nordeste, e podem orientar políticas e práticas.

PALAVRAS-CHAVE
Economia agrícola, Produção, Econometria espacial

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1. Introduction

Agricultural production in Brazil occupies a relevant space in the national economic activity. Agriculture is one of the leading Brazilian export sectors, and its development takes place on a greater or lesser scale throughout the national territory, with a high diversity of productive crops (Abbade, 2014; Bragagnolo and Barros, 2015; Freitas and Mendonça, 2016; Reis et al., 2020). Both permanent and temporary crops are produced in all regions and are essential in inducing economic growth and regional development (Scherer and Porsse, 2017).

In the Northeast region, agricultural activities accounted for 7.2% of the value added between 2002 and 2020, according to Trece and Considera (2023). Agriculture in the region is quite diversified, including the production of sugarcane, corn, soybeans, and cotton, as well as irrigated fruit growing, especially in the São Francisco Valley and the Açú Valley, aimed at export (Castro, 2012). In addition, the vast agricultural activity carried out by family farmers covers a wide range of crops (Aquino and Bastos, 2015; Bacelar and Favareto, 2020).

Its most recent dynamics have occurred through production in the Cerrado region, especially in Bahia, Piauí, and Maranhão. This production includes grains such as soybeans, corn, cotton, and sugarcane. These activities are expanding in part of the Matopiba region, with a focus on the production of agricultural products for export (Bolfe et al., 2016; Buainain et al., 2018; Pereira et al., 2018; Bahiense et al., 2022).

There is a diversity of factors that influence the performance of agricultural production in the Northeast, from the granting of credit for agriculture (Santos and Braga, 2013), the use of soil correction factors for various crops (Costa et al., 2014; Saldanha et al., 2017), the process of mechanization of activities to increase productivity (Vasconcelos et al., 2013), to climatic factors, such as rainfall or the lack of it (Campos, 2014; Marengo et al., 2016; Carlos et al., 2019). Thus, this study focuses on credit policy but also recognizes the importance of the other variables mentioned as determinants of agricultural production, considering them as potential influences in this context.

However, these studies do not combine all elements in a single analysis considering the spatial factor. Concerning credit, the productive dynamics of the Northeast region have been encouraged by its activities since the creation of the Constitutional Financing Funds of the Northeast (FNE), which is responsible for financing productive activities, including regional agricultural production (Souza et al., 2013; Giovenardi et al., 2019). Agricultural financing mechanisms are substantially relevant to regional production since credit is among the most important for fostering productive activities in the Northeast (Silva-Filho et al., 2023; Silva Filho et al., 2024).

The contribution of the study focuses on two fundamental points. First, the analysis covers both place-based policies (such as subsidized credit from the Constitutional

Financing Fund of the Northeast (FNE) for companies) and non-place-based policies (such as subsidized credit from the National Bank for Economic and Social Development (BNDES) . Thus, the spatial factor is essential to explain the effects of credit, rain, fertilizer, and machinery on the Gross Value of Agricultural Production (GDP) in the Northeast. This justifies using spatial econometrics, enabling new results for agricultural literature. The literature presents isolated studies on the possible influences of the GDP, such as those by Santos and Braga (2013); Costa et al. (2014); Saldanha et al. (2017); Carlos et al. (2019). The second contribution is the use of the Durbin Spatial Error Model (SDEM), which incorporates components of spatial spillover of local scope, manifesting itself in exogenous explanatory variables (X), and components of global spatial spillover, which affect the error term. Thus, the analysis covers both production spillovers at a local and global level, associated with the variables above. This allows a better understanding of the possible production scenarios in the Northeast and their concentration.

Based on this analytical perspective, this study seeks to analyze the effects of agricultural credit and other production-related variables on the Gross Value of Agricultural Production (GDP) in the municipalities of the Northeast in 2019. In addition to these initial considerations, the second section describes the methodological procedures adopted; the third section reviews the literature on the conditioning factors of agricultural production in the Northeast; the fourth section presents the results and discussions; and, finally, the last section offers the final considerations.

2. Methodological Procedures

The central idea underlies this approach, which concerns the proper use of mechanisms available to producers and those available in due course. Thus, the strategy of analysis of the constraints to municipal agricultural production used in this study considers credit as the primary determinant, followed by mechanisms of soil improvement, mechanization, and the supply of natural water resources. A series of studies (Santos and Braga, 2013; Costa et al., 2014; de Medeiros et al., 2017; Saldanha et al., 2017) sought to analyze the performance of Brazilian agricultural production, considering credit as one of the main inducers of the product. In addition to credit, it is well known that droughts are one of the leading natural obstacles to the low performance of agriculture in this region due to the vast area exploited without irrigation and the rainfall irregularities that affect much of the region, especially the semi-arid area. In this context, considering the supply of water resources as an essential factor in agricultural production is pertinent, as indicated by the literature on the subject (da Silva et al., 2011; Silva et al., 2012; Rocha et al., 2020).

Likewise, the mechanization process increases agricultural productivity, allowing a larger area to be worked at a lower cost and greater technical efficiency in land use. Therefore, analyzing the number of properties that use agricultural machinery is an essential mechanism for understanding municipal agricultural production, as evidenced in the literature (Vasconcelos et al., 2013; Araújo et al., 2021; Dias et al., 2021; de Lima et al., 2024).

In addition, the specialized literature (Silva et al., 2012; Costa et al., 2014; Saldanha et al., 2017) indicates that using soil correctives is an important mechanism to increase land productivity in various crops. In the Northeast region, studies have shown positive effects of this use on sugarcane production (Almeida Júnior et al., 2011; Simões Neto et al., 2015; da Costa et al., 2019), maize (de Souza Gomes et al., 2019; Rezende et al., 2021), beans (de Oliveira and Wander, 2023) and soybeans (Matias et al., 2019), among others (Francisco et al., 2017; de Oliveira et al., 2018; de Matos et al., 2019; do Nascimento et al., 2019). Therefore, it is relevant to investigate whether using soil correctives in properties contributes to increased production value in the Northeast municipalities.

Thus, other variables are included as controls in the estimates. However, the variables mentioned are considered essential for the analysis of this study, as they broadly cover the determinants of municipal agricultural production and are frequently cited in the literature on the subject, given their importance in justifying the phenomenon in question. The following table presents the variables used in this study, their respective sources, and the expected signs for each variable.

Table 1. Database, description of variables, sources, and expected results in the estimates

Variable	Description	Expected Effect	Unit of Measurement	Source
log(per_capita_vbp_16)	Natural logarithm of the agricultural gross domestic product per inhabitant in 2016		Logarithm of the GDP per capita	IBGE
log(b_vbp)	Natural logarithm of the gross value of total agricultural production in 2019		Logarithm of the GDP per capita	IBGE
log(fundo_per_capita)	Constitutional Financing Funds of the North and Northeast in the municipalities of the regions where the Constitutional Funds operate in per capita terms in the years 2016, 2017, and 2018.	+	The logarithm of per capita credit granted to the municipality (in R$ 2023)	MIDR
log(bndes_per_capita)	In per capita terms, public credit from BNDES was received in the municipalities of the regions where the Constitutional Funds operate in the years 2016, 2017, and 2018.	+	The logarithm of per capita credit granted to the municipality (in R$ 2023)	BNDES
log(chuv_ml)	Millimeters of rain in the municipalities of the regions of operation of the Constitutional Funds in 2019.	+	The logarithm of millimeters of annual rainfall in the municipality	ANA
log(chuv_ml²)	Millimeters of rain squared in the municipalities of the regions where the Constitutional Funds operate in 2019.	–	The logarithm of millimeters of rainfall squared annually in the municipality	ANA
Semi-arid	We included a semi-arid dummy that includes the northeastern municipalities in the driest area of the country.	–	1 for municipalities in the semi-arid region, 0 otherwise	
log(estab_maqagri_17)	Several agricultural establishments in the municipality used machines in production in 2017.	+	The logarithm of the number of agricultural machineries by municipalities in the Northeast	IBGE
log(estab_corPHsolo_17)	The number of municipal and agricultural establishments that used soil PH correction for production in 2017 was high.	+	The logarithm of the number of establishments that used soil PH factor correction by the municipality in the Northeast	IBGE
log(raz_pibagr_pib_16)	The ratio of agricultural GDP to total GDP of municipalities.	+	The logarithm of the ratio of agricultural GDP to total GDP of the municipalities of the Northeast	IBGE

Source: elaboration by the authors.

By demonstrating the table above, the analysis of the results considers the variables of credit, soil correction, millimeters of rainfall, and use of machinery in agriculture as the central core of this analysis, with the others being only controls for the non-bias of the regression parameters. Thus, the approach below presents the analytical treatment given to the object of study.

The use of GDP data from 2016 and 2019 is justified by the need to capture distinct moments in the productive dynamics of the agricultural sector, allowing for a comparison between periods with different economic and sectoral contexts. Both values were deflated correctly, as were the data related to BNDES and the analyzed funds, ensuring comparability in real terms.

Regarding the nature of the credit provided by the funds and BNDES, it is important to clarify that the resources are not exclusively allocated to the agricultural sector. However, it is one of the main beneficiaries, particularly under certain credit lines. In this study, the values considered refer to credit disbursements, not to outstanding balances, as the analysis focuses on the recent allocation of resources and their relationship with the sector's productive performance.

2.1 Exploratory Analysis of Spatial Data

Initially, it is necessary to verify the data spatially, that is, if the spatial effects generate complications. This is essential before spatial econometric modeling(Almeida, 2012). The process consists of describing and associating the spatial distribution of the GDP among the units evaluated in space, perceiving patterns and forms of spatial instability, and identifying possible outliers. For this, Moran's I statistic was used for the variable of interest. Moran's index is a statistic and one of the most widespread in the analytical field for measuring spatial autocorrelation based on the product of deviations from the variable's mean (Alves and Justo, 2021). According to Gallo and Ertur (2003), Moran's I statistic gives the formal indication of a linear association between the variable of interest subtracted from the mean (z) about itself spatially lagged (Wz).

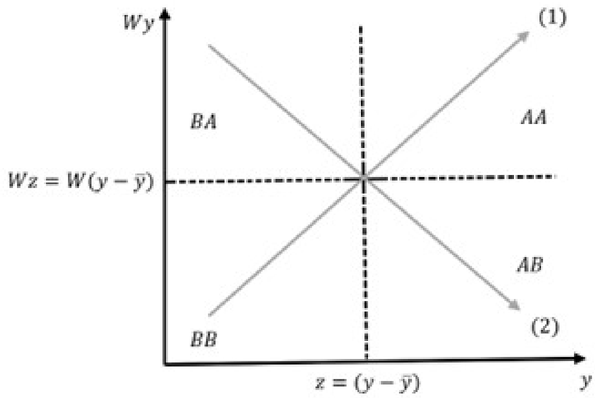
It is a global index of spatial autocorrelation and indicates each data set's degree of spatial association. In terms of the present study, it is the spatial correlation presented by the total and per capita GDP in the Northeast in 2019, which is exempt from the possible impacts of COVID-19 on the performance of this sector. In formal terms, Moran's I is presented with the following equation:

$$I = \frac{n}{S_0}\frac{z'Wz}{z'z} \tag{1}$$

Where n represents the number of municipalities, z refers to the normalized GDP values, S_0 refers to the sum of the weights of the spatial weighting matrix, and W represents the spatial weighting matrix, Wz corresponds to the means of the normalized values of the GDP among neighboring municipalities (Anselin and Bera, 1998). Moran's I can vary between positive, null, or negative values. A positive Moran's I value higher than the expected value suggests that the GDP variable presents positive spatial autocorrelation, indicating a positive effect on neighboring municipalities, which suggests spatial effects and cluster formation. On the other hand, Moran's I may present a negative value for this variable of interest concerning the expected value, which suggests that there are no spatial autocorrelation effects associated with that municipality's GDP. Therefore, if positive, it indicates similarity between municipalities, and conversely, it indicates dispersion. This is the basis of Moran's I as an initial analysis, considering that it is already possible to evaluate whether the proposed research problem has relevance within a spatial analysis .

After analyzing the global statistics, the Scatter Plot of the Moran Index, which reveals its distribution, Can Be Examined. In Figure 1, the first and third quadrants suggest agglomerations, while the second and fourth indicate dispersion. In addition, Figure 1 shows the lines that indicate grouping effects (1) and dispersion effects (2).

Figure 1. Illustration of Moran's Scatter Diagram



Source: Authors' elaboration.

Specifically, the High-High (AA) and Low-Low (BB) quadrants reflect positive spatial autocorrelation, indicating similarities. In contrast, the Low-High (BA) quadrant and the High-Low (AB) quadrant indicate spatial dispersion. Thus, quadrants AA and BB are associated with positive spatial autocorrelation, and BA and AB reflect spatial dispersion. In the context of the present study, results that suggest positive spatial autocorrelation in the variable of Gross Value of Production per capita of the northeastern municipalities are expected to be observed.

However, while Moran's Index provides a global view of the data, it is crucial to investigate and understand local spatial patterns through LISA (Local Indicators of Spatial Association). According to Anselin and Bera (1998), the Local Moran's Index breaks down the global autocorrelation indicator into four categories (AA, BB, AB, and BA), allowing the evaluation of the local contribution of each observation. The AA quadrant represents the municipalities with a high concentration of Gross Production Value compared to the average, while the BB quadrant indicates a low concentration. According to Gallo and Ertur (2003), for LISA indicators to be valid, two conditions must be met: a) each observation must reveal statistically significant spatial groupings, and b) the sum of the local indicators in all regions must be proportional to the corresponding global spatial autocorrelation indicator.

2.2 Empirical strategy

Considering the objective of analyzing the effects of agricultural credit on the gross GDP in the municipalities of the Northeast region, the present study used the estimation of the general spatial model. In formal terms, (Anselin and Bera, 1998; Almeida, 2012; Elhorst and Elhorst, 2014; Alves and Justo, 2021) consider the following structure of the general spatial dependence model or GSM model:

$$y = \rho W y + X\beta + WX\tau + \varepsilon \tag{2}$$

$$\varepsilon = \lambda W \varepsilon + \epsilon \tag{3}$$

Or

$$\varepsilon = \gamma W \epsilon + \epsilon, \epsilon \sim Normal(0, \sigma^2 I_n) \tag{4}$$

This model represents a highly complex spatial process involving spillover components of global and local reach. Where Wy is an n by 1 vector of spatial lag for the dependent variable, ρ the spatial autoregressive coefficient. The constraint on the coefficient of spatial lag X is the matrix of exogenous explanatory variables. It should be noted $W\varepsilon$, and $W\epsilon$ that can be matrices with different spatial weights, constituting a more general case. If you impose restrictions on spaceboats, other models will be obtained.

To identify the most appropriate model for the proposed research problem, a set of tests, such as the Lagrange multiplier (LM) test, Moran's I test under randomization, and Moran's I Monte Carlo Simulation, was used to estimate the per capita VBP of agriculture in the Northeast.

After considering the estimates for OLS (Ordinary Least Squares), SLX (Spatial Lag Model of X), SAR (Autoregressive Spatial Regression Model), SDEM (Durbin Spatial Model of Error), and SEM (Spatial Error Model) models . Thus, through the results of the tests of Robust Lagrange Multipliers and the Moran Index of the residuals under randomization and the Monte Carlo simulation of Moran's I, the most appropriate model was the Durbin Spatial Model of Error (SDEM), in formal terms, we have:

$$y = X\beta + WX\tau + \epsilon \tag{5}$$

$$\varepsilon = \lambda W \varepsilon + \epsilon \tag{6}$$

This model incorporates components of spatial spillover of local range that manifest themselves in exogenous explanatory variables (X): credit, rainfall, machinery fertilizer, etc. Moreover, components of global spatial spillover affect the error term (ϵ).

By specifying equation 6, the explanatory variables have a local effect, affecting only the direct neighbors, while the random error term has a global effect, influencing all municipalities in the Northeast. Another relevant point, according to Almeida (2012), is that there are no identification problems. Thus, the same weighting matrix can be used to lag both the explanatory variables and the error term (ε).

The results section presents the results of the tests and estimates the different models. However, the most appropriate model was the SDEM, which is therefore considered the reference base of the research, and its results are used as a point of comparison.

3. Literature review

The literature review carried out here aims to highlight the main questions raised that are inherent to agricultural production in the Brazilian Northeast. Thus, issues related to credit to agriculture, the amount of rain or droughts in the region, the use of fertilizers in the soil as mechanisms to improve productivity, and the use of agricultural machinery in regional production stand out. Thus, it seeks to show the relevance of these fundamental issues in the literature, which are essential to the performance of northeastern agricultural production, even recognizing that the determinants of regional agricultural production are not exhausted here.

In this sense, the study by Khan et al. (2005) sought to evaluate the effects of drought in 2001 on production, income, and employment in agriculture, considering the Geographic Microregion of Brejo Santo, a municipality located south of the State of Ceará, as the area of coverage. The authors analyzed agriculture based on a comparative analysis between the droughts of 1998 and 2001 to the year 2000, which is considered a regular rainy season. The data is from several sources, such as IBGE, Statistical Yearbook of Ceará, Iplance, Ematerce, SDR, and Funceme. Likewise, productive performance indicators were constructed, and the main results show that the drought of 2001 caused a significant drop in the agricultural production of all the crops analyzed, especially rice, which suffered a reduction of 80.18% in the State of Ceará and 84.75% in the Microregion studied. Agricultural income was also severely affected, with losses of up to 70.67% in Ceará and 81.32% in Brejo Santo and its Microregional surroundings. Regarding employment, the drought of 2001 freed up 70.54% of the agricultural workforce in Ceará and 78.21% in the Micro-region compared. Based on the results, the authors suggested more effective public policies to mitigate the impacts of droughts in the analyzed region.

From another analytical perspective, but which dialogues directly with the objective analyzed here,Aquino and Teixeira (2005) listed and analyzed the main operational and institutional factors that hinder the access of family farmers to rural credit from the National Program for the Strengthening of Family Agriculture (PRONAF) in the Northeast region of Brazil, highlighting an empirical evaluation in the municipality of São Miguel, State of Rio Grande do Norte. The methodology and the databases include data collection through field research and document analysis, comprising the time frame between 1996 and 2001. The main results listed by the authors suggest that PRONAF has a selective and exclusionary character in the analyzed region since its operational performance mainly elects the most capitalized family farmers, with a concentration of resources in the wealthiest regions. As problems with the insufficiency of the effectiveness of the policy, the authors highlight the insufficient and uncoordinated performance of local social development agents, as well as the indiscriminate application of the national criteria of PRONAF (rigid, excluding, and centralizing), which perpetuate the social and economic exclusion of the poorest family farmers, especially in coverage investigated.

By another analytical route of those highlighted above, Lacerda and Silva (2007) sought to compare the efficiency of no-tillage and conventional tillage and the residual effects of cattle and chicken manure on soil moisture and cotton yield in a Fluvic Neosol. The authors searched for evidence on soil fertilizer and productivity through an experimental study conducted at the Experimental Farm of the Federal University of Ceará in the municipality of Pentecoste. The experiment was controlled by comparing different doses of cattle manure (50 and 100 t ha-1) and chicken manure (14.3 t ha-1) in the two management systems. The variables of interest of the research were: height reached by the plants in each of the systems, number of apples (green cotton fruit) per plant, dry matter of the aerial part of the plant, boll mass (ripe fruit of the cotton plant) per plant, number of seeds per plant, seed mass, and soil moisture, comparing these variables according to the objective control of the experiment. The results found by the authors show us that no-tillage surpassed conventional tillage in cotton yield, improving water and soil conservation and plant use. However, the area fertilized with chicken manure provided the most significant increases in all the variables analyzed, showing that this is a critical fertilizer in soil improvement in the agriculture analyzed. As a limitation of the study, the variability of the results as a function of the specific characteristics of the soil and local climatic conditions can be emphasized.

For the optical credit analysis, Souza et al. (2011) analyzed the behavior of the credit policy aimed at Brazilian agriculture in the last decade (1999 to 2009), distinguishing two segments, namely family and non-family farming. As an objective approach to the study, the authors resorted to analyzing data from the 2006 Agricultural Census of the IBGE and the statistical yearbooks of rural credit of the Central Bank of Brazil. The authors gave analytical highlights to the Brazilian mesoregions (North, Northeast, Southeast, South, and Midwest). The primary evidence highlighted in the study shows that, although the number of credit agreements increased until 2006, there was a reduction in rural credit agreements in the subsequent years of the analyzed period, thus highlighting a greater concentration of credit destined for non-family farming. Thus, the authors highlight insufficient financial resources, especially for family farmers, who already face challenges such as a lack of technical assistance and bureaucratic barriers to granting credit resources.

On the other hand, Vasconcelos et al. (2013) sought to calculate the mechanization index in the Northeast region states based on the identification of demand for agricultural machinery in the region's states. The authors focused on the descriptive analysis of data, using as a source the data from the statistical yearbooks of the National Association of Automotive Vehicle Manufacturers (ANFAVEA) in the time frame that comprises the years 2009 and 2011, as well as the data of the Municipal Agricultural Production (PAM) of the Brazilian Institute of Geography and Statistics (IBGE), covering the years 2007 to 2010. The main results found by the authors show that the State of Sergipe has the best rate of mechanization of agricultural activities. In contrast, the State of Paraíba has the worst rates, mainly due to the prevalence of traditional cultivation practices in this state. Likewise, the analysis of elasticities showed us that some crops, such as sugarcane, oranges, bananas, and cassava, are agricultural activities that can induce a more excellent mechanization process. The authors concluded that there is a need for a more significant promotion of equality in the agricultural modernization of the states of the northeast region, given the variability in the levels of mechanization among the federative units, as well as suggesting the need for more effective public policies to promote agricultural modernization in the states of this region.

From the perspective of the soil improvement process for cultivation, the study by Costa et al. (2014) sought to analyze, through an experiment, whether it is possible to determine the agricultural productivity of sugarcane in the first two crop cycles, from its submission to different doses of phosphorus (P) in the plant sugarcane, combined with phosphate fertilization of cover in ratoon cane, in Ultisols of different textures in the Northeast region of Brazil. The experiment was carried out in three locations, namely, Japungu Distillery in the State of Paraíba, Carpina Sugarcane Experimental Station in the State of Pernambuco, and the Bom Jesus Sugar Mill, also in this state. The study used six P rates (0, 40, 80, 120, 160, 200 kg ha-1 of P2O5) applied to the bottom of the planting furrow and 40 kg ha-1 of P2O5 in ratoon cane. As the main results of the experiment, the authors highlight that the productivity of sugarcane plant was up to 34% higher when phosphate fertilization was applied at planting, with maximum agronomic efficiency doses of 107 kg ha-1 in PAdx, 120 kg ha-1 in PVAd2, and 130 kg ha-1 in PVAd1. Likewise, ratoon cane responded satisfactorily to topdressing phosphate fertilization only in medium-textured ultisols. In contrast, there was no yield increase in clayey and weathered ultisols, restricting its recommendation in these soils. The authors suggest that more extended evaluations are needed to understand the residual effect of phosphorus better. However, it is possible to see that soil fertilizer can be a favorable factor for increasing productivity.

Likewise, the study by Simões Neto et al. (2015) aimed to evaluate the availability of phosphorus (P) in representative soils for sugarcane cultivation in the Pernambuco forest zone region and to establish a new recommendation for fertilization with the nutrient for the crop in these soils. The experiment used five types of soils: Dystrocohesive Yellow Ultisol, Dystrophic Yellow Ultisol, Dystrophic Yellow Latosol, Eutrophic Haplic Gleisol and Ortic Humiluvic Spodosol. The authors evaluated the application of seven P doses, based on each soil's maximum P adsorption capacity (P-rem). After 30 days of fertilization, the authors sought to evaluate the P contents in the soils from the Mehlich-1, Mehlich-3, Bray-1 extractors, and anion exchange resin. As a result, the authors highlight that Mehlich-1 and anion exchange resin are the most appropriate extractors to represent the availability of P in the evaluated soils. Likewise, the critical P levels were calculated, and five fertility classes were defined for different soil clay contents. Finally, the authors suggest broader correlations with other agronomic and climatic factors to generalize fertilization recommendations. Thus, it is possible to see that fertilization in the soil can improve agricultural performance, leading to greater productivity.

Using the credit approach, the study by Aquino and Bastos (2015) sought to evaluate the evolution, results, and limits of the Agroamigo Program in the Northeast region of Brazil between 2005 and 2015, focusing on strengthening family farming. The authors conducted the approach by analyzing secondary data from program reports and case studies. The results highlighted in the study indicate that Agroamigo positively impacted expanding access to credit for family farmers, contributing to the increase in agricultural production and income. However, the authors point out that the program faces limitations related to bureaucracy, inequality in the distribution of resources, and insufficient technical assistance, which compromises its effectiveness and the sustainability of the benefits in the long term.

Through the analytical route of agricultural credit, Galdino et al. (2019) aimed to analyze the results of the National Land Credit Program (PNCF) in the Brazilian Northeast from 2005 to 2015. Its analytical approach was based on tabular and descriptive data analysis: the number of beneficiary families, proposals, financed area, and the values of the Subprojects for Collective Infrastructure (SIC) and Land Acquisition (SAT). As the main results, the authors highlighted that the Northeast had the most significant number of families served. Piauí and Alagoas had the highest and lowest number of benefited families, respectively. Likewise, the Northeast had the most financed area and the highest value in obtaining the SAT compared to the other Brazilian regions. In addition, the authors highlight an oscillation in the results during the period analyzed, with a significant decrease in the data when comparing 2005 with 2015. Finally, the authors suggested that there is a need for a more detailed analysis of regional particularities to understand the impacts of the PNCF better.

Using the climatological approach, Santana and Santos (2020) analyzed the impacts of the 2012-2017 drought on agricultural production in the semi-arid region of the Brazilian Northeast. The authors reported in their approach to analytical mechanisms based on quantitative data from the Municipal Agricultural Survey (PAM) and the Municipal Livestock Survey (PPM) of the IBGE, complemented by qualitative analyses on the effects of water scarcity on agricultural production and regional livestock. The study was carried out through an analytical-comparative approach, comparing the years of drought with the previous ones and highlighting the states of the Northeast and the municipalities of the semi-arid region. As a main result, it is possible to highlight that the drought caused significant drops in the production of several agricultural products, especially corn, beans, and cassava, with a partial recovery in some cases until 2017. However, the authors suggest that the data should be interpreted cautiously since these impacts should not be attributed exclusively to drought due to other factors such as producer profile and technological level that may have affected the observed results over the years.

In another analytical way, Lima et al. (2022) aimed to build an Agricultural Modernization Index (IMA) to verify the constraints of the agricultural modernization process in the municipalities of the Northeast region based on census information from the 2017 Agricultural Census. The authors used methodological resources to apply Factor Analysis and Cluster Analysis to find indicators associated with agricultural activity and, subsequently, to agglomerate similar municipalities according to the results found by the IMA. The main results highlighted from the study show that 88.42% of the analyzed municipalities have a low agricultural propensity, while only 0.91% presented an index considered good. The authors conclude by suggesting a need for public policies that equalize the disparities between localities, stimulate the use of irrigation systems in more productive areas, and expand the use of machinery and equipment to improve the modernization of agriculture in the region.

Using the credit approach, Dias et al. (2023) sought to estimate the effect of rural credit for family farmers (Pronaf) on the total production of temporary crops in the Northeast region of Brazil, differentiating between regions with semi-arid and non-semi-arid climates, as well as municipalities with and without irrigation centers. As methodological procedures were adopted, it is possible to highlight the analysis of panel data with random effects applied to data from PAM, IBGE, BCB, MDA, INMET, and Global Climate Monitor from 2012 to 2017. As the main results addressed by the authors, it is possible to highlight that rural credit positively affected the gross value of production. However, the number of family farmers did not have a significant influence. Likewise, municipalities with irrigation centers presented better results than those in the semi-arid region. Thus, the authors suggest a need for more effective agricultural policies to counterbalance the impacts of water scarcity, especially in the northeastern semi-arid region.

4. Results and discussions

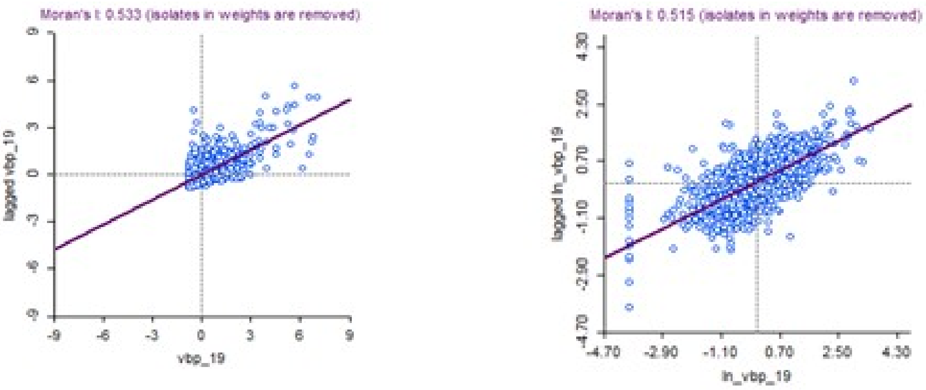
The study's primary results are presented below, organized as follows: first, the exploratory analysis of spatial data, including Moran's scatter plot; then LISA; and, finally, the results of the tests and econometric models.

4.1 Spatial analysis

Spatial data analysis explores variables with dense or intense spatial distribution. As discussed in the previous section, an alternative approach to visualizing spatial autocorrelation is the Moran scatter plot, which presents the spatial lag of the variable of interest on the vertical axis and the value of the variable of interest on the horizontal axis. Figure 2 shows the Moran Global dispersion map for the northeastern municipalities' total and per capita agricultural GDP in 2019. It is worth noting that the index can vary between -1 and 1.

Figure 2. LISA index for total GDP and GDP per capita in the municipalities of the Northeast — 2019

(a) Total GDP **(b)** GDP per capita



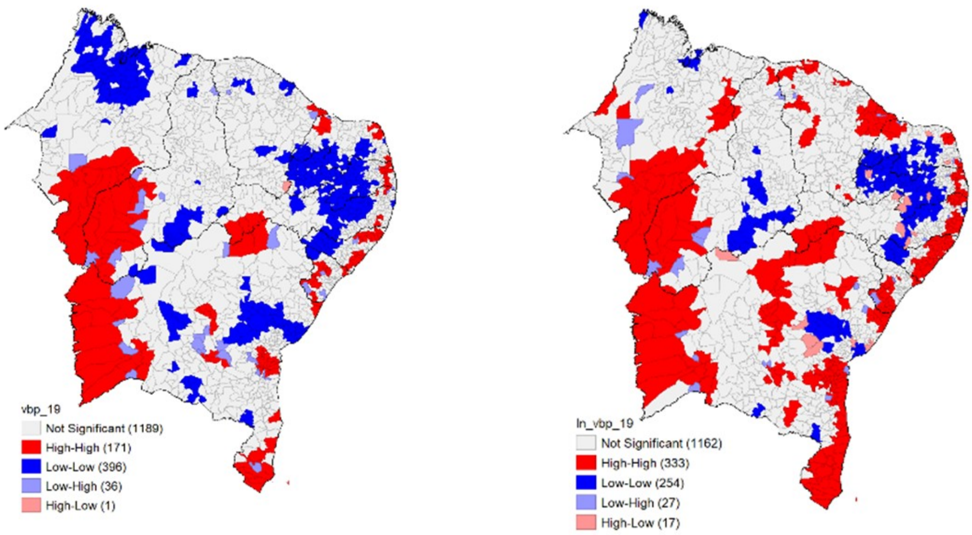
Source: Authors' elaboration.

The index for total GDP was 0.533, and the GDP per capita was 0.515, suggesting high spatial autocorrelation in the variable of interest, both in total and per capita terms, for the northeastern municipalities. In other words, municipal agricultural production presents autocorrelation in the municipalities of this region.

Figure 3 shows the LISA maps for the total GDP (map on the left) and the GDP per capita (map on the right), highlighting the formation of clusters. The results show the presence of spatial autocorrelation, with the formation of High-High clusters predominantly in the areas of agro-export production. It is possible to identify municipalities in Bahia, Maranhão and Piauí belonging to agribusiness in the Matopiba region (Bolfe et al., 2016) in these clusters, as well as municipalities in the São Francisco region, producers of irrigated fruit growing.

Figure 3. Global Moran's Index for total GDP and GDP per capita in the municipalities of the Northeast — 2019

(a) Total GDP **(b)** GDP per capita



Source: Authors' elaboration.

In addition, the coastal region in the south of Bahia, known for cocoa production (Franck et al., 2016; Carvalho et al., 2018; Campos, 2019), and the states with sugarcane cultivation (Dias et al., 2021), as well as the production of melon for export in the Apodi region (Ceará and Rio Grande do Norte)(Santos and Braga, 2013; Penha and Alves, 2018; Lisbinski et al., 2023), were identified in the clusters. Also noteworthy are the municipalities of Vale do Assu in Rio Grande do Norte. In addition, the Low-Low cluster included municipalities in the hinterland areas of all the states of the Northeast, as well as municipalities in the northernmost region of Maranhão.

4.2 Descriptive Statistics

Table 2 below presents some of the descriptive statistics of the variables – mean, standard deviation, minimum, and maximum. The years used in this study were highlighted to illustrate the data.

Table 2. Descriptive statistics of the variables – mean, standard deviation, minimum and maximum – 2016-2019

Variables	Average	Standard deviation	Minimum	Maximum
vbp_19	36116.60	192839.80	1.00	4845016.66
vbp_per_2019	1.79	8.91	0.00	171.63
raz_pibagr_pib_16	1.15	0.13	1.00	2.30
capita_bndes_16	37.47	240.73	0.00	4445.31
capita_bndes_17	43.10	324.17	0.00	8488.34
capita_bndes_18	44.02	366.04	0.00	8828.67
capita_fundos_16	144.75	1211.59	0.00	28592.81
capita_fundos_17	151.66	1139.02	0.00	31068.37
capita_fundos_18	168.44	1232.40	0.00	24984.88
chuva_ml	983.43	531.63	214.24	5036.83
chuva_ml²	1249761.82	1642305.07	45897.58	25369696.74
estab_corPHsolo_17	95.34	183.07	0.00	2379.00
estab_maqagri_17	67.39	168.92	2.00	3211.00

Source: Authors' elaboration.

The statistics above show that some municipalities in the Northeast region received very low per capita credit from the funds and the BNDES in some years.

4.3 Econometric model results

Tables 3, 4, and 5 present the econometric results, as suggested by the specialized literature, including tests for model choice, estimates, and validation of estimates. Table 3 shows the robust LM and LM tests for the OLS and SLX models. According to Burridge (1980); Almeida (2012); Anselin and Bera (1998); Elhorst and Elhorst (2014), these tests allow us to identify the existence of spatial heterogeneity and verify whether it corroborates the spatial autocorrelation of the residuals of the estimated model.

Table 3. LM test for the OLS and SLX models for the GDP per capita of agriculture in the Northeast.

OLS			SLX		
LMerr =602.49	df=1	p-value<2.2e-16	LMerr = 539.29	df=1	p-value <2.2e-16
LMlag = 376.82	df=1	p-value <2.2e-16	LMlag = 574.92	df = 1	p-value <2.2e-16
RLMerr =235.41	df=1	p-value <2.2e-16	RLMerr = 11,311	df = 1	p-value <0.0007703
RLMlag = 9.7364	df=1	p-value =0.001807	RLMlag = 46,945	df = 1	p-value = 7.302e-12

Source: Authors' elaboration.

The results of the robust LM and LM tests indicate the presence of spatial heterogeneity, which suggests that the choice of models should consider those that include corrections for spatial errors. Thus, the SDEM and SEM models were identified as the most appropriate for the estimates of spatial regressions (Anselin and Bera, 1998; Gallo and Ertur, 2003; Elhorst and Elhorst, 2014), as they correct problems of spatial errors and can be selected based on additional tests.

After estimating the regressions (Table 5), the criteria of Moran's I test were applied under randomization and then the Monte Carlo simulation of the regression residuals (Table 5), as described by Mrkvička et al. (2016). The models tested were OLS, SLX, SAR, SDEM, and SEM, as shown in Table 3.

Table 4. Moran's Test I under randomization and Monte Carlo's Simulation of Moran's I test for estimates of per capita GDP of agriculture in the Northeast.

Model	OLS Level	SLX Level	SAR Level	SDEM Level	NO Level
Moran's I statistic st dev	24.637	23.308	7.557	-1.2564	-1.6121
p-value	0.000	0.000	0.000	0.8955	0.9465
Moran's I Monte Carlo Simulation					
Model	OLS Level	SLX Level	SAR Level	SDEM Level	NO Level
Statistic	0.34699	0.32829	0.10601	-0.018277	-0.023291
p-value	0.001	0.001	0.001	0.914	0.944

Source: Authors' elaboration.

The results of the tests indicated that the data structure analyzed here was the most appropriate for models with SDEM and SEM spatial error correction, confirming the robust LM and ML tests presented in Table 3 above. Thus, the choice between the two models was based on the criterion of minimization of AIC and maximization of Log Likelihood, as suggested in the literature. After all the robust tests are carried out, the SDEM model will be used to analyze them.

Finally, Table 5 shows the estimates. Only the SDEM model is suitable for analyzing the results after the robust tests are applied to choose the best model. In addition, it is noteworthy that using the lagged dependent variable ($ln_v bp_1 6$) is an essential mechanism for endogeneity correction that was also applied to result in reliable and robust estimates.

The results indicate that the credit granted in 2016, 2017, and 2018 impacted the GDP of agriculture in the northeastern municipalities in 2019, evidencing a temporal overflow of credit in this region. In addition, although the coefficients are low, both BNDES and FNE credit positively impact the GDP. However, these results do not confirm the existence of spatial credit spillovers. Contrary to the findings of Resende et al. (2017), the lag of the SDEM model did not show statistical significance in any year. In other words, the effect of the credit is limited to the municipality that receives it, without spillover to neighboring municipalities. This suggests that there is no significant interconnection in the agricultural production chain between the municipalities in the region.

Table 5. The impacts of the Constitutional Financing Funds on the VBP of the municipalities of MATOPIBA—OLS, SLX, SAR, SDEM, and SEM.

Variables	Dependent variable: ln_vbp_per_capita						
	(OLS)	(SLX)	SLX(lag)	(SAR)	(SDEM)	SDEM(lag)	(SEM)
ln_vbp_16	0.093***	0.082***	0.034***	0.069***	0.082***	0.036***	0.078***
	(0.006)	(0.008)	(0.012)	(0.006)	(0.006)	(0.014)	(0.006)
log(capita_bndes_16)	0.016**	0.016**	-0.017	0.008	0.017**	-0.007	0.020***
	(0.008)	(0.008)	(0.016)	(0.007)	(0.007)	(0.019)	(0.007)
log(capita_bndes_17)	0.017**	0.017**	-0.037**	0.010	0.020**	0.010	0.019***
	(0.009)	(0.009)	(0.019)	(0.008)	(0.008)	(0.021)	(0.007)
log(capita_bndes_18)	0.064***	0.056***	0.073***	0.042***	0.048***	0.024	0.046***
	(0.008)	(0.009)	(0.017)	(0.008)	(0.008)	(0.020)	(0.007)
log(capita_fundos_16)	0.049***	0.036***	0.058***	0.031***	0.034***	0.023	0.034***
	(0.009)	(0.010)	(0.020)	(0.009)	(0.009)	(0.023)	(0.008)
log(capita_fundos_17)	0.035***	0.030***	-0.010	0.022**	0.031***	0.030	0.029***
	(0.011)	(0.011)	(0.024)	(0.010)	(0.010)	(0.027)	(0.009)
log(capita_fundos_18)	0.043***	0.037***	0.007	0.044***	0.038***	-0.018	0.043***
	(0.010)	(0.010)	(0.021)	(0.009)	(0.009)	(0.024)	(0.008)
chuva_ml	2.017***	1.399***	0.015	0.989***	1.449**	-0.156	1.785***
	(0.415)	(0.437)	(0.147)	(0.375)	(0.600)	(0.133)	(0.603)
chuva_ml²	-0.154***	-0.096***	-0.018	-0.075***	-0.106**	0.004	-0.135***
	(0.030)	(0.034)	(0.015)	(0.028)	(0.045)	(0.014)	(0.045)
Semi-arid	0.013	-0.177***	0.201***	0.065**	-0.105**	0.143*	-0.054
	(0.029)	(0.064)	(0.075)	(0.026)	(0.051)	(0.076)	(0.040)
estab_maqagri_17	-0.009	0.007	-0.034*	-0.004	0.007	-0.020	0.008
	(0.009)	(0.012)	(0.018)	(0.008)	(0.010)	(0.021)	(0.010)
estab_corPHsolo_17	-0.016*	-0.006	-0.032*	-0.021**	-0.009	-0.017	-0.005
	(0.009)	(0.012)	(0.016)	(0.008)	(0.010)	(0.019)	(0.010)
raz_pibagr_pib_16	1.642***	1.794***	-0.446**	1.462***	1.780***	-0.465*	1.827***
	(0.107)	(0.117)	(0.201)	(0.098)	(0.101)	(0.244)	(0.099)
Constant	-7.339***	-5.241***		-3.954***	-5.028**		-6.517***
	-1.406	-1.413		-1.273	-2.021		-2.037
Observations	1,794	1,794		1,794	1,794		1,794
R2	0.637	0.654					
Adjusted R2	0.634	0.648					
Log Likelihood				-722.329	-634.302		-650.918
sigma2				0.127	0.110		0.111
Akaike Inf. Crit.				1,476.659	1,326.604		1,333.837
Residual Std. Error	0.397 (df = 1780)	0.390 (df = 1767)					
F Statistic	240,272*** (df = 13; 1780)	128,191*** (df = 26; 1767)					
Wald Test (df = 1)				353.245***	561.688***		647.206***
LR Test (df = 1)				320.886***	413.322***		463.707***

Source: Authors' elaboration.

Table 5 presents the results regarding the impacts of the Constitutional Financing Funds on the GDP of the municipalities of the Northeast between 2016 and 2019. The increase in BNDES credit in 2016 and 2017 resulted in a 2% growth in the agricultural GDP of the municipalities of the Northeast in 2019. In 2018, the growth was 5%, indicating a significant positive impact of this financing on the agricultural sector in the region, as studied by Silva-Filho et al. (2023).

In this case, the value of funds per capita in 2016 and 2017 impacted agricultural GDP growth by 3%, while in 2018, the growth was 4%. This indicates that per capita funds have had an increasing positive effect on agricultural GDP over these years. It is concluded that both BNDES credit and constitutional funds have a temporal overflow, impacting 2019 and subsequent years.

An increase of 1% in the number of millimeters of rain impacts 140% of the GDP, indicating that rain in the Northeast is essential to increasing the GDP of agricultural production, since the activity is predominantly rainfed. However, rainfall values increase to a certain extent and then begin to fall (negative expected value), meaning that rain is beneficial up to a specific limit. However, after that limit, it harms the crop.

Municipalities in the semi-arid region tend to have lower GDPs; however, a municipality in the semi-arid region close to another municipality (presumably more economically active) shows the highest GDP among them. The number of establishments that had agricultural machinery in 2017, with an increase of 1 percentage point, impacts the growth of agricultural GDP by 1%. Meanwhile, the number of establishments that corrected the soil PH hurt the GDP per capita of the Northeast municipalities in 2017. This means that despite being a critical agricultural practice, it may have presented adverse effects, possibly due to inadequate practices, high costs, or other factors not directly captured by the variable. It is important to emphasize that the ratio of agricultural GDP to total GDP in 2016 shows that a higher proportion of agricultural GDP to total GDP in 2016 is strongly associated with a significant increase in the GDP per capita of the municipalities in the Northeast. This impact is positive and highly significant, indicating that the importance of the agricultural sector in 2016 had a lasting and beneficial effect on the regional agricultural economy, with influences extending across neighboring municipalities.

The results indicate that BNDES credit and constitutional funds have a positive and lasting impact on agricultural GDP in the municipalities of the Northeast. The amount of rainfall is essential for rainfed agriculture, with a significant positive impact up to a specific limit, after which the excess becomes harmful. In addition, agricultural machinery increases agricultural GDP, while poor practices such as soil pH correction can have adverse effects. The importance of the agricultural sector is evidenced by the lasting impact of higher agricultural GDP in 2016, which continues to benefit the regional economy in the following years. These results highlight the relevance of financing, appropriate climatic conditions, and efficient agricultural practices for regional economic development (Mendes Resende et al., 2018).

In addition, Resende et al. (2017) also used panel data to examine the effect of constitutional funds on the increase in GDP per capita from 2004 to 2010. The results showed that constitutional funds favorably impact GDP per capita growth at the municipal level. The spatial estimates, however, did not point to the presence of spatial spillovers resulting from the constitutional funds.

5. Final Thoughts

This article's objective was to analyze the impacts of credit, rainfall, use of agricultural machinery, and soil correction factors, among others, on the GDP of the municipalities of the Northeast in 2019. Methodological procedures of exploratory analysis of spatial data and spatial econometrics were adopted.

The results show spatial autocorrelation of the agricultural GDP in the northeastern municipalities, forming high-high clusters in the areas that predominate in exporting agribusiness. These areas are predominant in the region's agricultural production and significantly impact the agricultural GDP of the Brazilian Northeast. Municipalities in the region of cerqueiro agriculture in the states' interior were grouped into the Low-Low clusters.

The tests pointed to the adequacy of the SDEM model. The results indicate that the credit granted in 2016, 2017, and 2018, both from BNDES and FNE, positively impacted the GDP of the municipalities in the Northeast in 2019. This demonstrates the importance of credit for agricultural production in the region and highlights the temporal overflow of resources over the agricultural GDP.

In addition, the amount of rainfall substantially impacts the region's agricultural GDP. However, no evidence was confirmed that soil PH correction or agricultural machinery significantly affects the agricultural GDP of northeastern municipalities.

These results suggest that credit is an essential mechanism for agricultural production in northeastern municipalities. In addition, the amount of rainfall has a relevant impact on production, indicating the need for mechanisms to mitigate the effects of droughts and improve the performance of agricultural GDP in the region.

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