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Spatial Analysis Of Sugarcane Productivity In The State Of São Paulo, Brazil

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Abstract:
In Brazilian agriculture, sugarcane cultivation has a great contribution, due to high production, sugar exports, car combustion via ethanol, and the energy generated by bagasse. Considering the evolution of sugarcane production techniques and the economic importance of this crop, the objective of the study is to carry out a spatial analysis and evolution of sugarcane productivity in the municipalities of the state of São Paulo. In the period 1974-2008, state production rose from 50 million tons to close to 400 million tons. The evolution of sugar cane productivity was initially around 50 tons per hectare in the 1970s and has grown and stabilized at around 80 tons per hectare, which may be due to the use of new technologies, biotechnologies, and the like, but there was no change in spatial patterns (Moran's I index and regions with clusters). In 2021, there were 56 locations with productivity above 85.5 tons per hectare, a figure above 74 tons that was the state average for the same year. The mesoregions of Piracicaba, Campinas, Ribeirão Preto, Araraquara, and São José do Rio Preto have the highest municipal values and productivity clusters.

Key Words*: Saccharum officinarum; mesoregions; ethanol.*

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I. Introduction

The main economic importance of sugarcane is its ability to store sucrose, and it is linked to three main agro-industries: sugar, alcohol, and energy. In the 2020/21 harvest, Brazil, the world's largest sugarcane producer, was responsible for the production of 654.5 million tons destined to produce 41.2 million tons of sugar and 29.7 billion liters of ethanol. The largest producing state is São Paulo, accounting for around 54.1% of production in the harvest, with around 48.4% going to ethanol and 63.2 of total production to sugar.

As the main raw material for the sugar-alcohol industry, sugar cane goes through stages of production in the agro-industry, supplying the material to the industry; and managing inputs, waste, and by-products. In addition, it provides flexibility to the market, and there can be sugar and alcohol production, storage, and marketing of the end products. All stages need to be carried out using efficient management techniques. The stages: harvesting, loading, transportation, weighing, paying for the quality of the cane, unloading, and washing must be carried out in sync with industrial operations so that there is no congestion in the supply of material, thus demanding storage space, leading to a depreciation in quality or a shortage of cane for crushing, resulting in production delays.

In the 2023/24 harvest, sugarcane production is expected to grow by around 4.4% in relation to the 2022/23 harvest, with around 637.1 million tons expected. The increase is due to better crop yields and the allocation of more land to the crop. Conab (National Supply Company) carried out a survey and found that sugar production could reach 38.77 million tons, in the historical series, the second highest ever recorded, losing out to the 2020/21 harvest, which was estimated at 41.25 tons. In addition to the larger harvest expected for the raw material in the current crop year, the promising market for the sweetener has led to more sugarcane being used.

The process of mechanizing sugarcane plantations in São Paulo began in the mid-1970s, due to a shortage of labor. Law 11.241 was enacted on September 19th, 2002, regulated by Decree 47.700 of March 11th, 2003, establishing a timetable for excluding burning as a way of eliminating sugarcane straw for harvesting purposes. In 2007, an agreement of intent formulated by the São Paulo state government began, with the main aim of bringing forward the timetable for eliminating the use of fire in manual sugarcane harvesting.

Since 1975, the mechanization of sugarcane has leveraged a methodology of continuous development, improving the standardization of operations, matching tractor power to implements with greater working capacity, programming for maintenance control, operator training, insertion of new equipment for planting, application of cake and elimination of ratoons, among others. All this technological progress has contributed to Brazil having lower production costs compared to other countries in the world. The attributes of the machines and implements used in sugarcane cultivation are diverse, depending on the planting, cultivation, and harvesting system used. The systems used in Brazil can be segmented into semi-mechanized and mechanized, with the proportions of workers, machines, and implements employed varying between them.

Various types of mechanical technology are used in sugarcane agricultural production, such as soil preparation, planting, tending, and harvesting. The processes described are known as the mechanization of production. Considering the evolution of sugar cane production techniques and the economic importance of this crop, especially for the state of São Paulo, which is the largest producer, the study aims to carry out a spatial analysis and evolution of sugar cane productivity in the municipalities of the state of São Paulo. The database is provided by the Brazilian Institute of Geography and Statistics (IBGE) and contains production, harvested area, and productivity figures for sugar cane in the municipalities of the state of São Paulo. The results will provide a better understanding of the spatial distribution of productivity and can be used to target public and private investments to improve the production system.

II. Material And Methods

The data was obtained from Sidra (2023), which is a set of tables provided by the Brazilian Institute of Geography and Statistics (IBGE), where we obtain information on the area harvested in the municipalities, as well as sugarcane production and productivity. The Exploratory Spatial Data Analysis (ESDA) method is used to demonstrate spatial distributions, model atypical localities, explain patterns of spatial association, and propose different spatial regimes and different forms of instability in space (Almeida; Perobelli; Ferreira, 2008). According to Almeida (2012), exploratory spatial data analysis (ESDA) addresses the effects of spatial dependence and heterogeneity. Spatial dependence or spatial autocorrelation occurs when the value of a given variable in a region i, for example, is related to the value of the same variable, but in another region, for example, region j. Spatial heterogeneity appears when data from divergent spatial units is used to explain the same phenomenon (Anselin, 1988).

Exploratory spatial data analysis is an econometric tool, a series of statistical tools used to show and figure spatial distributions, exemplify unusual localities, inform spatial association patterns (spatial clusters) and suggest different spatial regimes and other forms of instability in space (Almeida; Perobelli; Ferreira, 2008). The first stage of the ESDA study begins with hypothesis testing, intending to ascertain whether the data or spatial variables being analyzed are randomly distributed. According to Almeida (2012), spatial randomness means that the values of a variable in each region do not depend on the values of this variable in other neighboring regions. Therefore, spatial data or variables can be defined as the observation of these (data or variables) which are associated with a location in geographical space (Sabater, Tur and Azorín, 2011). It is worth noting that the analysis described is more suitable for looking at spatially compact or intensive variables, i.e. those that are divided by some indicator of intensity (Almeida, 2012).

Exploratory Spatial Data Analysis makes it possible to collect measures of global and local spatial autocorrelation, investigating the interference of spatial results through the mediation of quantitative methods (Anselin, 1988). To develop the ESDA, however, it is recommended that, beforehand, an arrangement is assigned that allows the measurement of coefficients that portray the notion of the degree of interaction or mutual influence between the spatial units analyzed (Neto and Medeiros, 2011).

Moran’s I index shows the spatial relationship of productivity between localities, whereby a positive relationship (I>0) indicates the predominance of High-High and Low-Low clusters. On the other hand, a negative Moran's I index indicates the existence of High-Low and Low-High clusters. There are also Low-Low and Low-High clusters. The method described was used to identify clusters of municipalities in the state of São Paulo with sugar cane productivity differentials. High-High clusters show that they have high productivity (tons per hectare) and are neighbors of municipalities with the same characteristics. High-low clusters show municipalities with high productivity characteristics around low-productivity localities. The neighborhood pattern was the municipalities around the localities, determined as "queen".

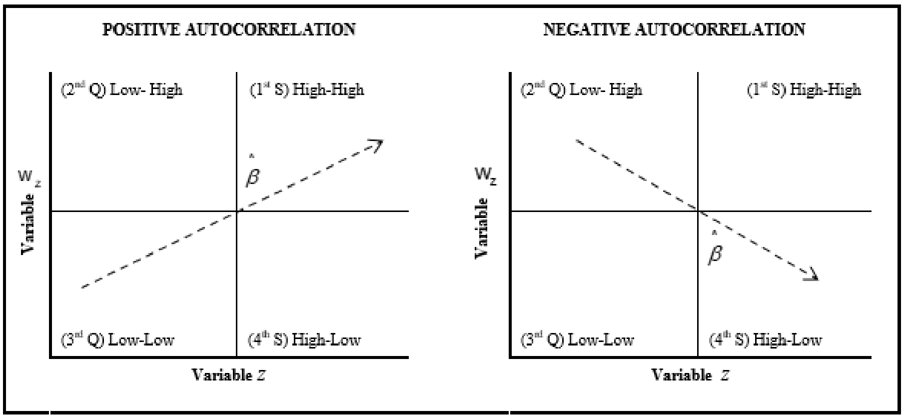
Univariate spatial association

According to Almeida (2012), Moran's scatter diagram is an alternative for visualizing spatial autocorrelation, where the value of the variable of interest (Z) is found on the horizontal axis and the spatial lag of the variable of interest (W_z) is found on the vertical axis. To obtain the slope of the line, a simple linear regression by ordinary least squares (OLS) is estimated, specified as:

$$Wz = \alpha + \beta z + \varepsilon \tag{1}$$

Given that α is the regression constant, β is the angular coefficient and ε is a random error term. Thus, Moran's I is represented by the angular coefficient of the line of the spatial lag (W_z) against the variable of interest (Z), estimated by (OLS) and represented by the line in Figure 1.

Figure 1. Univariate Moran's I scatter diagram.



Source: adapted from Almeida (2012).

Using equation 5, the estimated $\hat{\beta}$ coefficient is equivalent to the Moran's I formula represented in the equation. When $\hat{\beta} > 0$, the regression line is positively inclined, and when $\hat{\beta} < 0$ the regression line is negatively inclined.

$$\hat{\beta} = I = \frac{z'Wz}{z'z} \tag{2}$$

It is worth noting that in addition to the overall measure of spatial linear association, the scatter diagram shows us other information, such as quadrants representing four types of spatial linear association: High-High (HH), Low-Low (LL), High-Low (HL) and Low-High (LH). An example of Moran's scatter diagram is shown in Figure 2 above.

In the first quadrant of the diagram, a High-High (HH) cluster is identified, in which the spatial units (municipalities) have high values of the variable of interest (IPDU) analyzed and are called (neighbors) by spatial units that have values in the same proportion, also becoming high. A High-Low (HL) cluster denotes a cluster in which a spatial unit (municipality) with a high value of the variable of interest (UDI) is close in the same locality to spatial units with a low value of the variable of interest, as shown by the fourth quadrant of the diagram. A Low-High (LH) cluster belongs to a cluster in which a spatial unit (municipalities) has a low value of the variable of interest (IPDU) and is surrounded by spatial units (municipalities) with a high value of this variable of interest, which are represented in the second quadrant. In the third quadrant, a Low-Low (LL) agglomeration refers to spatial units that show low values for the variable of interest (IPDU) and are adjacent to spatial units that also show low values for this variable of interest.

Univariate local indicator of spatial association (LISA)

According to Anselin (1995), a Local Indicator of Spatial Association (LISA) should be any statistic that meets two criteria:

1. For each observation, indicate significant spatial clusters of similar values around the observation (municipality) and,
2. The sum of the local indicators, for all regions (municipalities), must be proportional to the global spatial autocorrelation indicator that corresponds to it.

The Local Moran's coefficient I_i decomposes the global autocorrelation indicator into the local contribution of each observation in four categories: high-high (HH), low-low (LL), high-low (HL), and low-high (LH), each of which individually results in a quadrant on the Moran's scatter diagram (Almeida, 2012).

The local Moran's coefficient I_i for a standardized variable y, observed in the region i, Zi, can be expressed by equation (6).

$$I_i = Z_i \sum_{j=1}^{j} w_{ij} Z_j \tag{3}$$

The $I_i$calculation only includes the neighbors of observation i, defined according to a matrix of spatial weights. To I_i be a LISA indicator, it must meet the second condition mentioned above, which is that the sum of the local indicators is proportional to the corresponding global indicator, according to a proportionality factor. So, if you add up IMoran's local indicators, you get:

$$\sum_i I_i = \sum_i Z_i \sum_j w_{ij} Z_j \tag{4}$$

The Local Moran's I equation can be arrived at as proposed by Anselin (1995), depicted by

$$I = \frac{\sum_i I_i}{s_0 \sum_i \frac{z_i^2}{n}} \tag{5}$$

The LISA statistic is used to test the null hypothesis, i.e. the absence of local spatial association. Under the assumption of normality, the expected value, the hope of the statistic I_i is given by: $\mathrm{E}(I_i) = \left[\frac{-1}{(n-1)}\right]$. To obtain an empirical distribution of the test statistics, it must be observed whether the value of the variable of interest is inside or outside the defined critical region. In this way, if the calculated value is greater in magnitude than the mathematical expectation of Moran's I, its results will be statistically significant (Anselin, 1995).

III. Result

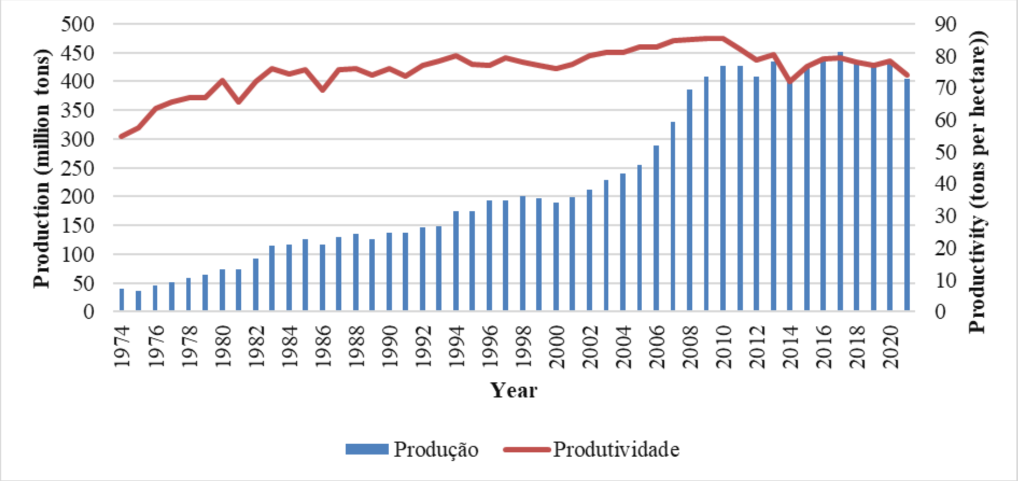
The right time to plant sugarcane is of the utmost importance for its proper development, as it needs ideal climatic conditions for growth and sugar accumulation. The crop requires high water availability, high temperatures, and a high level of solar radiation to thrive. Sugarcane can be planted in three different seasons: the year-and-a-half system, the year system, and winter planting. Sugarcane productivity is determined by the perfect combination of climate, soil, and variety, so the highest yields are achieved by selecting the right variety for the growing environment and cultivating in soils with the appropriate biological, physical, and chemical properties. Agricultural productivity is measured in terms of tons of cane per hectare (TCH), but recently it has also come to mean the volume of sugar and alcohol produced per ton of cane per hectare. To maintain productivity levels, it is essential to diligently control pests and weeds.

According to Nitsch (1991), the 1973 oil crisis sparked interest in the search for alternative energy sources worldwide. In Brazil, a biofuels program was launched in 1975 and has since been consolidated. The global oil crisis in 1973 led to significant technological advances in the automobile industry. That year, OPEC (the Organization of Petroleum Exporting Countries) reduced production, causing a supply shortage and a sharp increase in prices. The price of a barrel rose from around US$1.9 in 1972 to US$11.2 in two years, known as the first oil shock. On November 14, 1975, Brazil responded by creating the National Alcohol Program, Proálcool, in collaboration with car manufacturers, government, and academics, becoming the largest program promoting renewable biofuels derived from sugarcane in the world. The sugar sector had been accustomed to converting surplus production into anhydrous alcohol since the Great Depression of the 1930s, blending it with gasoline up to 22% without issues.

During the second oil price hike in 1979/81, coinciding with the sugar crisis of 1980, an important innovation boosted Proálcool: the feasibility of running a car entirely on alcohol using hydrated ethanol with around 94% alcohol content. The technological breakthrough, led by the Brazilian Air Force's Aerospace Technical Center (CTA), encouraged automakers to produce ethanol-powered cars, with the government ensuring fuel supply and competitive pricing compared to gasoline.

Figure 2 illustrates the evolution of sugarcane production and productivity in São Paulo from 1974 to 2021. Production increased from around 50 million tons in 1974 to nearly 400 million tons by 2008, stabilizing at 400-450 million tons annually since then. Productivity initially averaged around 50 tons per hectare in the 1970s, increasing and stabilizing at around 80 tons per hectare with the adoption of new production technologies, genetic improvements, and the utilization of by-products (vinasse, filter cake, ash, etc.) as fertilizers.

Figure 2. Sugarcane production and productivity in the state of São Paulo, 1974-2021.

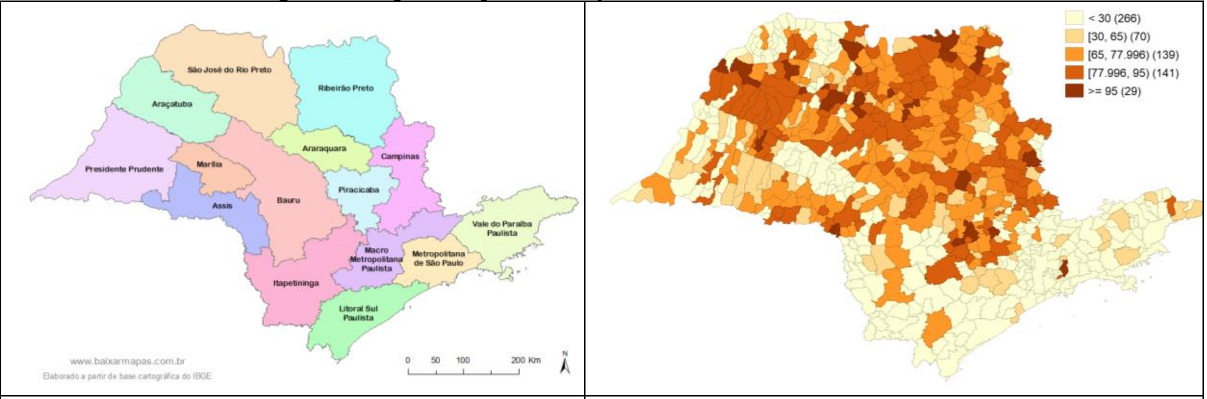


Source: research results.

Productivity is a factor that is not homogeneous between regions. Therefore, it is important to know the differences between regions to understand and draw up strategies for the development of new technologies and the application of investments and policymaking. Figure 3 shows the mesoregions of São Paulo (Figure 3A), a thematic map of sugar cane productivity in the municipalities of the state of São Paulo (Figure 3B), Moran's diagram, and Moran's I index (Figure 3C) and a map of spatial clusters of sugar cane productivity in the municipalities (Figure 3D) in 2000.

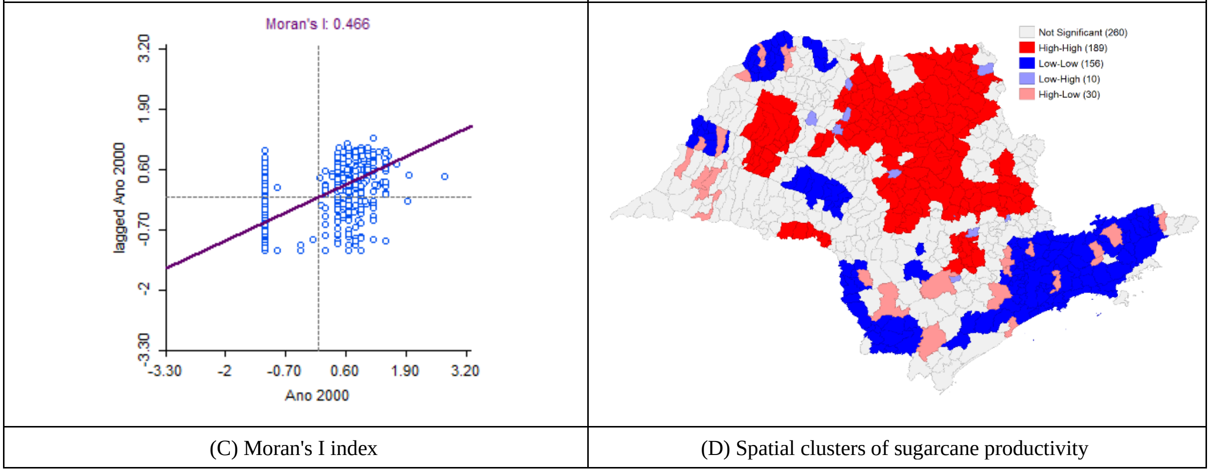
Figure 3A illustrates the mesoregions of São Paulo for a better understanding of the results described. There were 141 localities with productivity in the 78-95 tons per hectare range and 29 municipalities with local averages of more than 95 tons per hectare described in Figure 2B. For the year 2000, these values are above the average, which was around 76 tons per hectare. Figure 3C shows the value of 0.466 by Moran's diagram and Moran's index, which indicates a spatial pattern for the formation of High-High and Low-Low spatial clusters. In the mesoregions of Piracicaba, Campinas, Ribeirão Preto, Araraquara and São José do Rio Preto, Figure 3D shows the formation of spatial clusters of sugar cane productivity with 189 High-High municipalities.

Figure 3. Sugarcane productivity in the state of São Paulo, 2000.



(A) Mesoregions of the state of São Paulo

(B) Thematic map of sugarcane productivity in the state of São Paulo



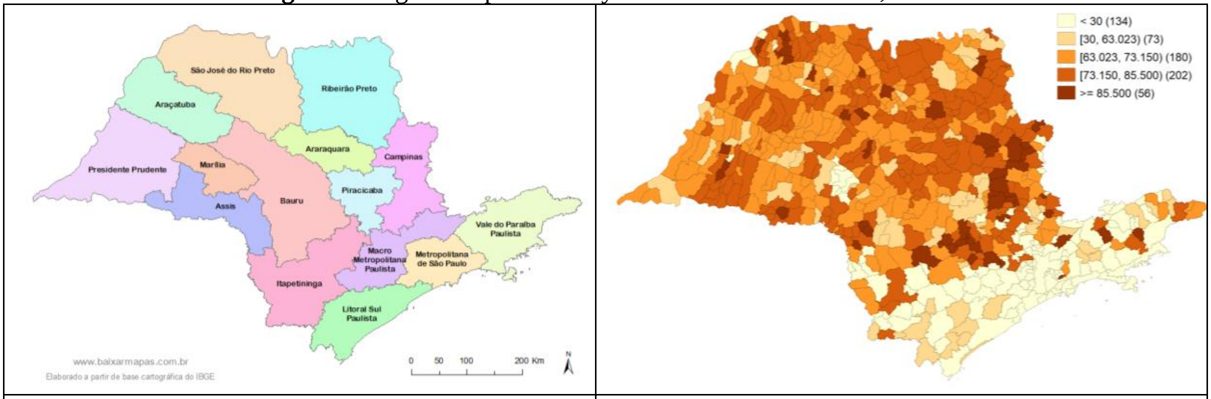
(C) Moran's I index

(D) Spatial clusters of sugarcane productivity

Source: research results.

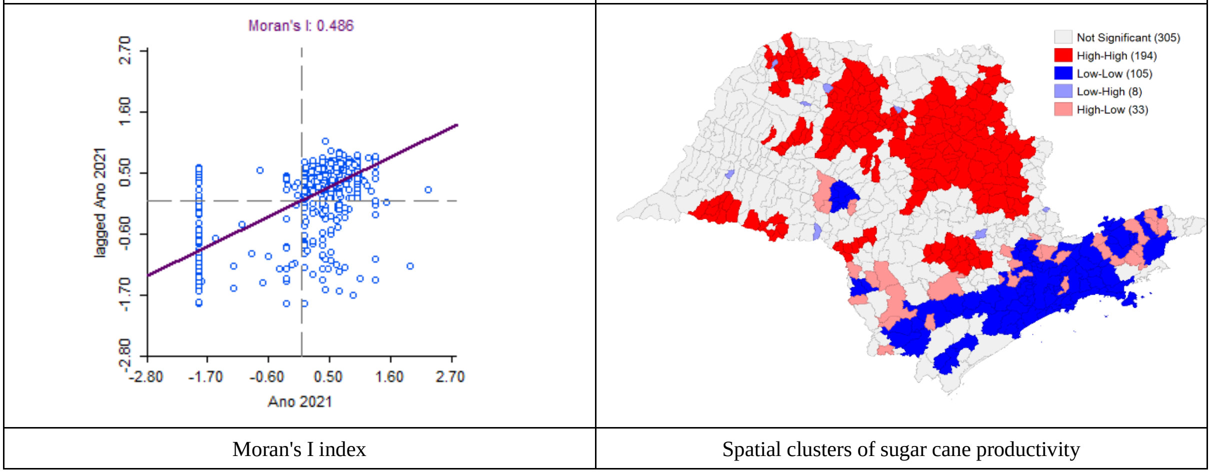
Figure 4A shows the mesoregions of the state of São Paulo to understand the results of the study. Figure 4B shows that there were 56 locations with productivity above 85.5 tons per hectare in 2021, which is above the 74 tons that was the state average for the same year. The productivity range between 73.15 and 85.5 had 202 municipalities, with the rest below 73 (below the state average). Analyzing the Moran Diagram and Moran's I index of 0.486, it indicates the existence of a spatial pattern for the formation of High-High and Low-Low spatial clusters. Figure 4D shows the formation of spatial clusters of sugar cane productivity with 194 High-High municipalities, which are concentrated in the mesoregions of Piracicaba, Campinas, Ribeirão Preto, Araraquara, and São José do Rio Preto. Consequently, the mesoregions with the highest productivity and production have a concentration of processing industry (sugar and alcohol) due to the perishability of the raw material, which must be delivered in a short space of time to avoid deterioration and loss of sucrose.

Figure 4. Sugarcane productivity in the state of São Paulo, 2021.



(A) Mesoregions of the state of São Paulo

(B) Thematic map of sugar cane productivity in the state of São Paulo



Moran's I index

Spatial clusters of sugar cane productivity

Source: research results.

IV. Conclusions

In the period 1974-2008, state production rose from 50 million tons to close to 400 million tons. Since 2008, state production has been stagnating in the 400-450 million tons per year range. The evolution of sugar cane productivity was initially around 50 tons per hectare in the 1970s and has grown and stabilized at around 80 tons per hectare. In the period 2000-2021, productivity figures increased, which may be due to the use of new technologies, biotechnologies, but there was no change in spatial patterns (Moran's I index and regions with clusters). In 2021, there were 56 locations with productivity above 85.5 tons per hectare, a figure above 74 tons that was the state average for the same year. The mesoregions of Piracicaba, Campinas, Ribeirão Preto, Araraquara, and São José do Rio Preto have the highest municipal values and productivity clusters.

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