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Evolution Of Wheat Production And Productivity In Brazil: An Exploratory Analysis Of Spatial Data

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Abstract:
Wheat (Triticum aestivum L.) is one of the most cultivated grains in the world, being the second most produced cereal. In Brazil, wheat has been cultivated for more than 6 centuries. However, it has an irregular production history due to phytosanitary, climatic, and economic factors that make the country insufficient to meet domestic demand. From this, it becomes interesting to analyze the expansion of wheat production in Brazil to understand the problem of Brazil being dependent on imports of this cereal. The objective of the study is to carry out a spatial analysis of the production and productivity of wheat crops in Brazil between the years 1990 and 2019 to identify the shift in the production area and groupings of regions with different productivity per area. With the exploratory analysis of spatial data, it was possible to conclude that the expansion of cultivated area and increased productivity of wheat crops is directly linked to the use of genetic improvement to select adapted and productive varieties and new production technologies.
***Key Words**: Triticum aestivum L.; cereal; marketplace; self-sufficiency; demand.*

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I. Introduction

Wheat (*Triticum aestivum L.*) is one of the most widely grown grains in the world and the second most-produced cereal. In the 2019 harvest, the global cultivated area was 216.5 million hectares, resulting in a production of 764.3 million tons (USDA, 2020). Allied to this, it stands out for its great economic and food importance (Moraes, 2011). In Brazil, the cultivation of the crop has an irregular production history due to phytosanitary, climatic, and economic factors. At the beginning of the 20th century, the federal government played a key role in the production chain. Through financial incentives and the creation of two research stations, it encouraged wheat growers through information.

Agreements to buy American wheat in the first half of the 20th century were responsible for discouraging the Brazilian chain, leading to a devaluation. It was only in the 1960s that policies were created to encourage wheat production through guaranteed prices, agricultural credit linked to lower interest rates, and the creation of infrastructure. However, the chain was subject to minimum prices set for farmers and the exchange ratio between the price of the grain and the product, such as flour. In this way, the State was responsible for financing the price difference by centralizing the chain.

The area under cultivation has increased in recent harvests. Data from the Brazilian National Supply Company (CONAB) shows that between 2009 and 2019, cultivation reached an area of approximately 2.2 million hectares of wheat per harvest, with an average production of 5.4 million tons. This information indicates the extent of the area dedicated to wheat cultivation and the average amount of wheat produced during this period.

The largest area of cereal production is concentrated in the south of the country, accounting for 87.3% of Brazilian production (CONAB, 2020). This is because wheat is classified as a winter crop, meaning it needs low temperatures for its establishment, development, and production. In addition, wheat is a crop that is vulnerable to climatic changes such as variations in relative humidity, rainfall close to the harvest period, frosts during crop development, as well as demanding soils that are suitable for cultivation. However, after record-breaking harvests in 2015 and 2016, the southern region is facing difficulties in growing cereal due to the fall in grain prices and climatic conditions such as excessive rainfall during sowing and the occurrence of frosts and periods of prolonged water deficits during crop development, thus causing productivity losses, which combined with the low price, have made the crop unprofitable (CONAB, 2018).

Currently, Brazil is responsible for the production of approximately 10 million tons. It produces around 62% of the country's demand, given that Brazilians consume 13 million tons a year. With the prospect of record production next year, Brazil is expected to become self-sufficient in grain production within the next ten years

(EMBRAPA, 2022). The Ministry of Agriculture and Livestock (MAPA) projects Brazilian production at 7.2 million tons of wheat in 2028. In contrast, domestic consumption of the grain will be 14.3 million tons. In this scenario, it will be necessary to import 7.3 million tons of wheat to meet domestic market demand (Gasques et al., 2019).In order to regain self-sufficiency in wheat production in Brazil, it is necessary to identify the Brazilian regions that have suitable conditions for growing this cereal. The Brazilian Cerrado has proved to be a viable alternative for growing adapted varieties, thanks to studies carried out by research institutes such as Embrapa Brasileira de Pesquisa Agropecuária (EMBRAPA). It is also worth noting that the region allows for an earlier harvest than major production centers such as the South and Argentina. In addition, the organized production chain in some states, such as Minas Gerais, favors wheat production in the region (Coelho et al., 2011). This makes it interesting to analyze the expansion of wheat production in Brazil to understand the problem of Brazil's dependence on imports of this cereal.

The aim of the study is to carry out a spatial analysis of wheat production and productivity in Brazil between 1990 and 2019 to identify the displacement of the production area and groupings of regions with different productivity per area. The data was obtained from Sidra (2023), which is a set of tables provided by the Brazilian Institute of Geography and Statistics (IBGE).

II. Material And Methods

Research classified as exploratory spatial data analysis (ESDA) is a tool used to describe the distribution and identification of spatial associations, as well as to assess the possibility of different spatial regimes or other forms of variation in space (non-stationarity). To do this, it is important to consider the interrelationship and spatial heterogeneity of the variable under analysis (Almeida, Perobelli, and Ferreira, 2008).

The data was obtained from the IBGE (Brazilian Institute of Geography and Statistics) and analyzed using the GeoDA program, a free software tool that serves as an introduction to spatial data science.

The definition of the weight matrix is carried out through the study of contiguity, which represents the neighborhood between observations based on spatial and/or socioeconomic distance (Almeida, 2004). The set of non-stochastic and exogenous elements in the model are based on the geographical arrangement of the observations or the contiguity between them and thus make up the spatial weight matrix (Anselin, 1999). The purpose of using the matrix is to capture the effects of the environment on the data by applying weightings. This means that the variable observed in each region receives a weighting when it is in the same environment as the proven region. Almeida (2004), Anselin (1988), and Tyszler et al. (2006) explain how to obtain these matrices.

wij = {1 if i and j are neighbors; 0 if i and j are not neighbors} (1)

For this work, we sought a model based on the contiguity pattern, also known as Queen, illustrated in image 1, whose premise is to use the convention of including both borders with a non-zero extension and vertices (nodes) in the map visualization as contiguous (Almeida, 2004). Pinheiro (2007) points out that Figure 1 shows that the common edges related to cell A and adjacent cells can be considered in different directions. Cell A can be adjacent to a cell called B, or continuity can be associated with a cell called C, or it can simply be a combination of both restrictions.

Moran's I statistic is the formal estimator of spatial dependence and is used to calculate spatial autocorrelation (Almeida, 2004), which is depicted by the equation:

$$I = \frac{n}{\sum\sum w_{ij}} \frac{\sum\sum w_{ij}(y_i - \bar{y})(y_j - \bar{y})}{\sum(y_i - \bar{y})^2} \quad (2)$$

n: number of spatial units or observations in the data set;
y_i: variable of interest for a specific spatial unit i;
$\bar{y}$: average of the variable of interest in all spatial units;
w_{ij}: spatial weight of the pair of spatial units i and j, which measures the degree of interaction or proximity between them.
Matrix-wise, (2) can be written as:

$$I = \frac{n}{S_0} \frac{z'Wz}{z'z} \quad (3)$$

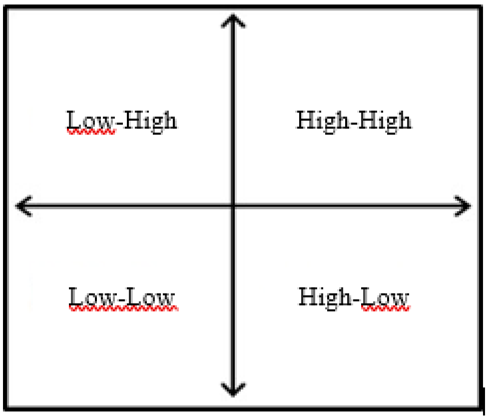
Where:
n: number of regions or spatial units in the analysis;
z: standardized variable of interest;
W_z: standardized variable of interest for neighboring regions, weighted according to a matrix of spatial weights "W";
S_0 is $I = \sum\sum wij$, so all the elements of the W matrix must be added together.

Moran's I statistic stipulates the degree of linear autocorrelation between the values observed over time and the weighted average of the neighboring values (Almeida, Perobelli, and Ferreira, 2008). The value of - [1⁄((n-1)], is expected, i.e. indicating the value that could be obtained if there were no patterns. From this, values exceeding -1/(n-1) indicate positive spatial autocorrelation, suggesting clustering or spatial dependence of similar values, and below indicates negative spatial autocorrelation, suggesting dispersion or spatial segregation of dissimilar values (Almeida, 2004). The presence of positive spatial autocorrelation indicates that there is a similarity between the values of the variable considered and its spatial location. This means that neighboring areas tend to have similar values. On the other hand, negative spatial autocorrelation reveals dissimilarity between the values of the attribute and its spatial location. In this case, neighboring areas tend to have different values (Almeida, 2004).

Moran's scatter plot is an alternative way of interpreting Moran's I statistic. It is a graphical representation that shows the spatial lag of the variable of interest on the vertical axis and the value of the variable of interest on the horizontal axis (ALMEIDA, 2004). Divided into four quadrants (high-high, low-low, high-low, and low-high) as illustrated in Figure 2, these quadrants represent four patterns of local spatial association between regions and their neighbors, indicating the formation of spatial clusters or agglomerations (Almeida, Perobelli and Ferreira, 2008).

A High-High (HH) cluster, represented by the upper right quadrant (Figure 2), indicates that the regions within this cluster and their neighboring regions have values above the average for the variable studied. A Low-Low (LL) cluster, represented by the lower left quadrant, indicates that the regions within this cluster and their neighboring regions have low values compared to the average. A High-Low (HL) cluster, represented by the lower right quadrant, refers to a cluster where regions with high values are surrounded by regions with low values. A Low-High (LH) cluster, represented by the upper left quadrant, refers to a cluster where regions with low values are surrounded by regions with high values. These cluster patterns provide insights into the spatial distribution and relationships of the variable being studied.

Figure 2. Illustration of Moran's scatter diagram Moran



Source: Prepared by the authors.

The regions located in the high-high and low-low quadrants show positive spatial autocorrelation, i.e. these regions form clusters with similar values. There is negative spatial autocorrelation in the low-high and high-low quadrants, i.e. the regions form clusters with different values (ALMEIDA, PEROBELLI, and FERREIRA, 2008).

Anselin and Floxax (1995) were responsible for suggesting Moran's I statistic to obtain local patterns of linear association that are statistically relevant, and it is common to use the LISA statistic (Local Indicators of Spatial Association). This statistic is shown by the following formula:

$$I_i = \frac{(y_i - \bar{y}) \sum w_{ij}(y_j - \bar{y})}{\sum_i (y_i - \bar{y})^2 / n} \quad (4)$$

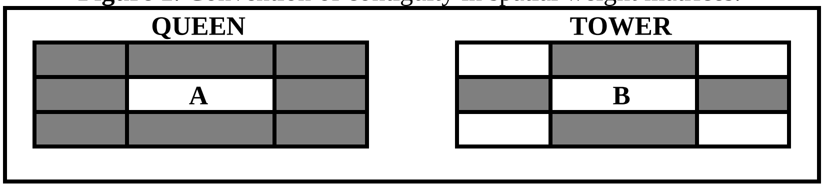
$$I_i = z_i \sum_j w_{ij} z_j \quad (5)$$

z_i and z_j represent the standardized variables and the summation over j is such that only the values of the neighbors j and J_i are included.

The set w_{Ji} comprises the neighbors of observation i, and w_{ii}=0.

The local Moran's I spatial autocorrelation indicator is a method that breaks down the global autocorrelation indicator into four categories based on the local contribution of each observation. Each category represents a quadrant in the scatter plot, this composition helps to understand spatial patterns and identify clusters of similar values in the data set (Anselin, 1995). It measures the degree of clustering of similar values in the observed region and identifies statistically significant spatial groupings. It helps to identify areas where values are more similar to each other than would be expected by chance alone (Almeida, 2004). This information is valuable for understanding spatial patterns and can be used in various areas, such as urban planning, epidemiology, and environmental studies (Almeida, 2004). According to Perobelliet al. (2007), measures of local spatial autocorrelation, such as the Moran Scatter plot and Local Indicators of Spatial Association (LISA) statistics, are used to observe the existence of local spatial clusters, whether they have high or low values, and which geographical regions are most significant for the presence of spatial autocorrelation. Moran's scatter plot visually represents the spatial distribution of values and their spatial relationships, while LISA statistics provide quantitative measures of local spatial association, narrowing down which areas have patterns of clustering or dispersion.

Figure 1. Convention of contiguity in spatial weight matrices.



Source: Almeida (2012, p. 77).

III. Result

Table 1 shows the data from the survey of wheat supply and demand in Brazil for the period 2011-2022. Imports accounted for around 46% of annual supply on average over the period, which shows the country's external dependence on wheat and wheat flour, mainly from Argentina, the United States, Canada, Russia, and Europe. Domestic production normally supplies between one and two-thirds of consumption and is increasing over the period, mainly due to rising prices and import difficulties caused by the COVID-19 pandemic and the Ukrainian War. The market situation has stimulated an increase in production and self-sufficiency, with the ratio between national production and consumption rising from 38% in 2017 to 86% in 2022.

Table 1. Supply and demand balance. Values in thousands of tons.

Harvest	Initial stock	Production	Import	Supply	Consumption	Export	Final stock
2001	715.8	3,194.2	7,045.7	10,955.7	10,180.2	2.4	773.1
2002	773.1	2,913.9	6,853.2	10,540.2	10,240.5	4.0	295.7
2003	295.7	6,073.5	5,707.5	11,732.4	10,314.1	1,372.3	390.3
2004	390.3	5,845.9	5,311.0	11,547.2	10,433.0	1.8	1,112.4
2005	1,112.4	4,873.1	6,266.1	12,251.6	10,989.8	786.1	475.7
2006	475.7	2,233.7	7,933.3	10,642.7	10,393.4	2.0	247.3
2007	247.3	3,836.7	6,666.7	10,750.7	10,450.0	2.0	298.7
2008	895.7	5,884.0	5,676.4	12,456.1	9,398.0	351.4	2,706.7
2009	2,706.7	5,026.2	5,922.2	13,655.1	9,614.2	1,170.4	2,870.5
2010	2,870.5	5,881.6	5,771.9	14,524.0	10,242.0	2,515.9	1,766.1
2011	1,766.1	5,788.6	6,011.8	13,566.5	10,444.9	1,901.0	1,220.6
2012	1,220.6	4,379.5	7,010.2	12,610.3	10,584.3	1,683.8	342.2
2013	342.2	5,527.9	6,700.0	12,570.1	11,431.4	61.0	1,077.7
2014	1,077.7	7,373.1	5,500.0	13,950.8	12,192.2	500.0	1,258.6
2015	1,731.4	5,534.9	5,517.6	12,783.9	10,312.7	1,050.5	1,420.7
2016	1,420.7	6,726.8	7,088.5	15,236.0	11,470.5	576.8	3,188.7
2017	3,188.7	4,262.1	6,387.5	13,838.3	11,244.7	206.2	2,387.4
2018	2,387.4	5,427.6	6,738.6	14,553.6	11,360.8	582.9	2,609.9
2019	2,609.9	5,154.7	6,676.7	14,441.3	11,860.6	342.3	2,238.4
2020	2,238.4	6,234.6	6,007.8	14,480.8	11,599.0	823.1	2,058.7
2021	2,058.7	7,679.4	6,080.1	15,818.2	12,049.8	3,045.9	722.5
2022*	722.5	10,554.4	5,500.0	17,076.9	12,394.1	2,800.0	1,582.8

Source: Conab (https://www.conab.gov.br).

Table 2 shows national production data by state for the years 1990 and 2021. The main producing states are Paraná and Rio Grande do Sul, which account for around 86% of national production. The states of Minas Gerais, São Paulo, Santa Catarina, Goiás, the Federal District, and Bahia increased production, driven by the offer of new varieties and technologies that made it possible to expand the area with productivity gains.

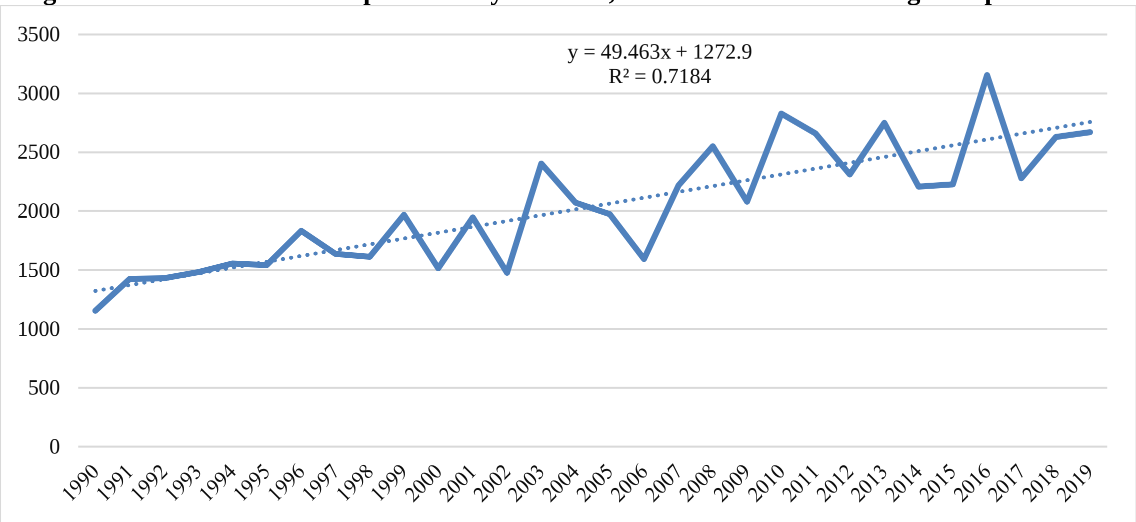
Table 2. Federal units' share of wheat production, 1990-2021. Values in tons.

Region	1990		2021	
	Production	Share (%)	Production	Share (%)
Bahia	-	0.0%	17737	0.2%
Minas Gerais	14562	0.5%	207262	2.6%
São Paulo	203000	6.6%	435413	5.5%
Paraná	1394052	45.1%	3231985	41.0%
Santa Catarina	108288	3.5%	317969	4.0%
Rio Grande do Sul	1168628	37.8%	3547866	45.1%
Mato Grosso do Sul	204035	6.6%	21470	0.3%
Mato Grosso	11	0.0%	288	0.0%
Goiás	920	0.0%	84035	1.1%
Federal District	295	0.0%	10500	0.1%
Brazil	3093791	100.0%	7874525	100.0%

Source: IBGE (2023).

Figure 3 illustrates the evolution of wheat productivity (yield) in Brazil in kilograms per hectare over the period 1990-2019. The trend equation shows that the calculated R square was 0.72, i.e. the equation explains 72% of the variation in productivity over the period. The estimated equation of 49.46x + 1272.9 indicates that initial productivity was close to 1273 kilograms per hectare and, annually, productivity increased by around 49.6 kilograms per hectare between 1990 and 2019, reaching a value close to 2700 kilograms per hectare. The increase in yield is the result of factors related to improved cultivation techniques and genetic improvement.

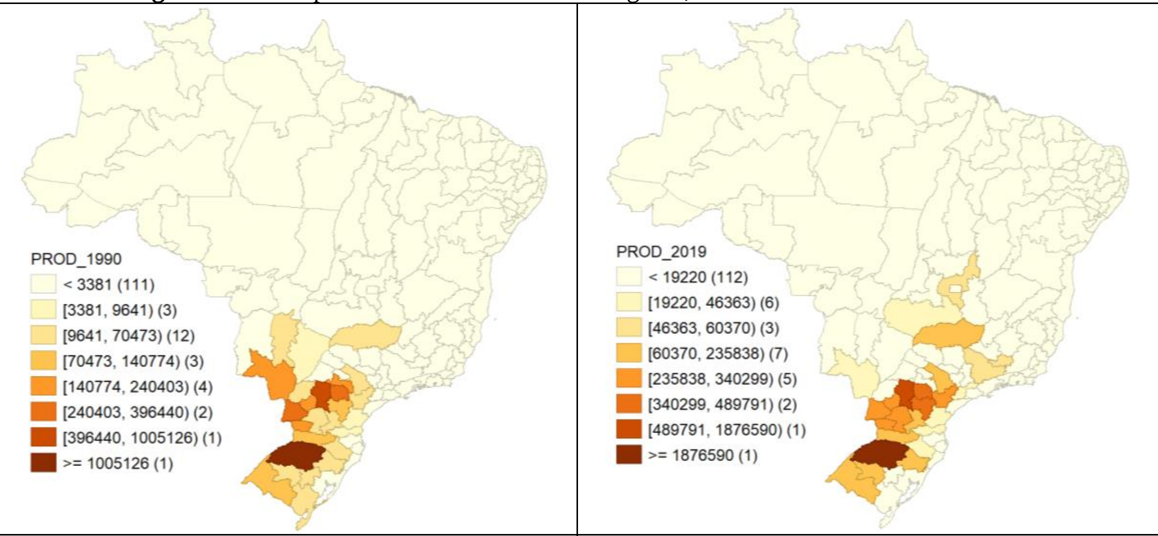
Figure 3 – Evolution of wheat productivity in Brazil, 1990-2019. Values in kilograms per hectare.



Source: research results.

Figure 4 illustrates wheat production in tons in the Brazilian mesoregions in 1990 and 2019. In 1990, Paraná and Rio Grande do Sul concentrated production and it was present in Mato Grosso do Sul, São Paulo, Minas Gerais, and Goiás. In 2019, although the main producers are still Paraná and Rio Grande do Sul, the crop has expanded significantly to the north, mainly Minas Gerais and Goiás.

Figure 4. Wheat production in Brazil's mesoregions, 1990-2019. Thousands of tons.

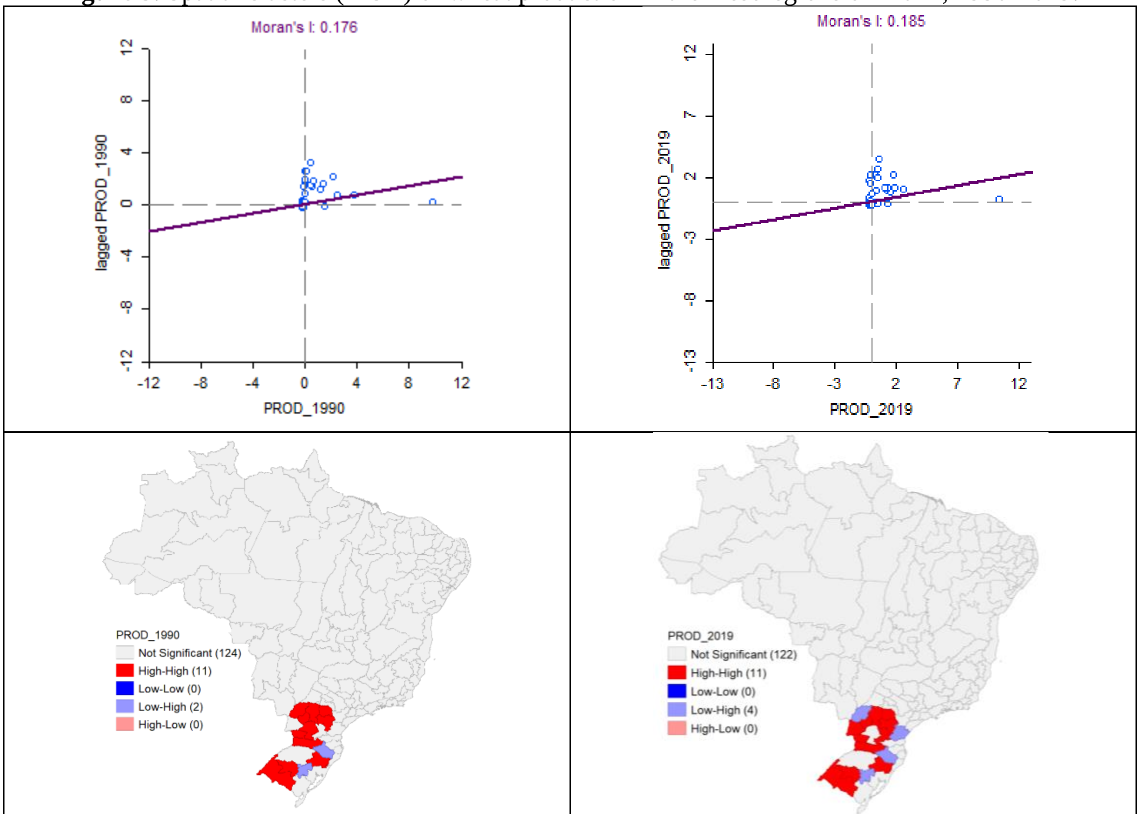


1990	2019

Source: research results.

Figure 5 illustrates the Moran scatter diagrams and spatial cluster maps of wheat production in Brazil's mesoregions in 1990 and 2019. The values achieved for Moran's I statistic were 0.176 (year 1990) and 0.185 (year 2019), indicating possible HH and LL clusters for wheat production in Brazil's mesoregions. The results showed that, despite expansion into the Southeast and Midwest, production remained concentrated in the states of the Southern Region, which had 11 mesoregions with High-High clusters, i.e. mesoregions with high production with neighbors with the same characteristic. Logistical difficulties in distributing wheat production to the rest of the country mean higher costs and prices, as well as losses in the marketing process.

Figure 5. Spatial clusters (LISA) of wheat production in the mesoregions of Brazil, 1990-2019.



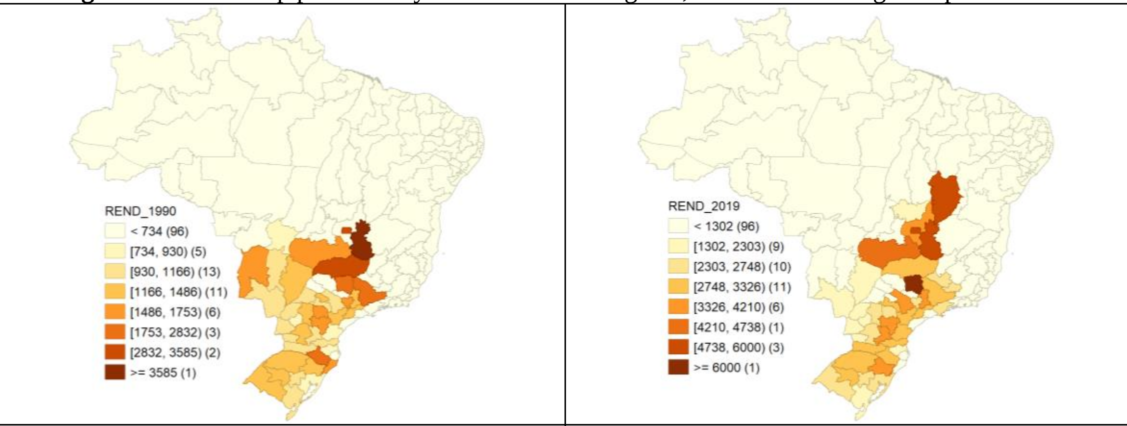
1990	2019

Source: research results.

Figure 6 illustrates the wheat crop productivity maps in Brazil's mesoregions in 1990 and 2019 in kilograms per hectare. In 1990, there were three mesoregions with yields above 2,832 kilograms per hectare and, later in 2019, there were 22 mesoregions with yields above 2,748 kilograms per hectare. The results show an increase in wheat productivity and the territorial expansion of planting. In addition, productivity was higher in the mesoregions of Minas Gerais, Goiás, and Bahia in the two years analyzed with wheat production in the Midwest and Northeast regions.

The expansion of the planting area and higher productivity of the wheat crop in the Midwest and Northeast regions was possible due to the development of the BRS 264 cultivars, which are more widely planted in the region, and the BRS 404 rainfed variety, which is adapted to the Brazilian cerrado. Genetic improvement and the adaptation of cultivation techniques have played an important role in increasing agricultural productivity in regions with low water availability and higher temperatures, as in some regions of Brazil.

Figure 6. Wheat crop productivity in Brazil's mesoregions, 1990-2019. Kilograms per hectare.



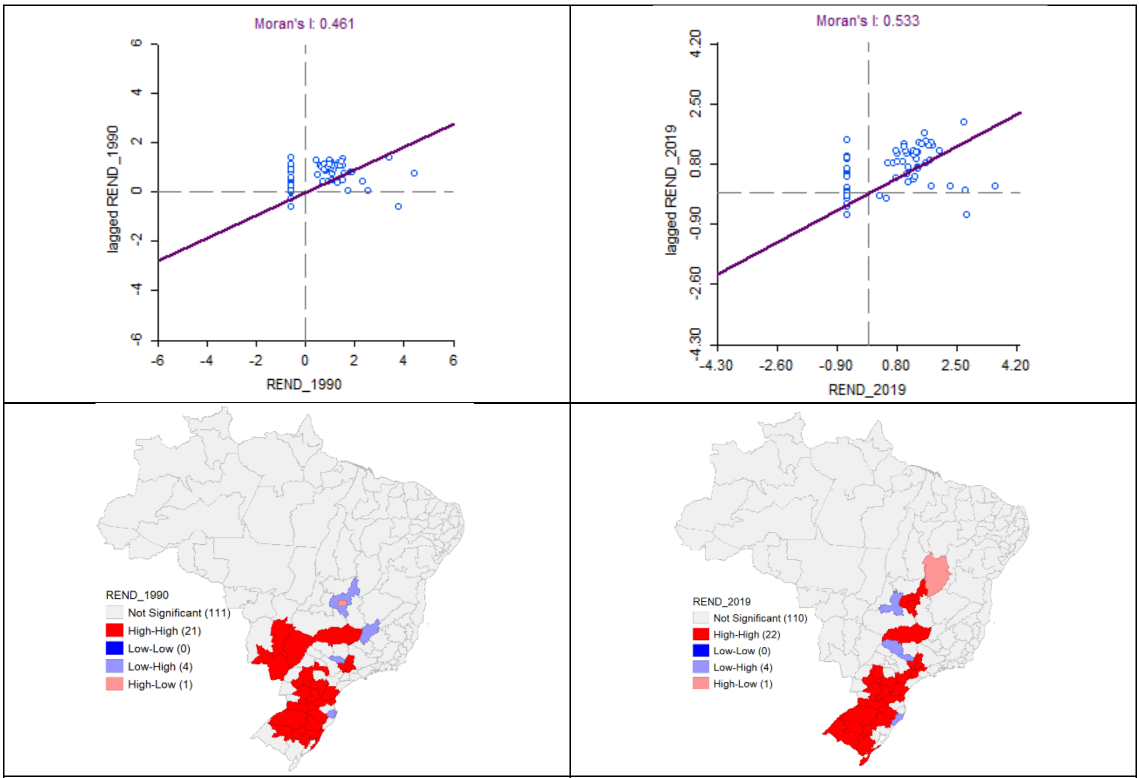
1990	2019

Source: Research results.

Figure 7 illustrates Moran's scatter diagrams and spatial clusters of wheat crop productivity in the producing mesoregions. The positive values of Moran's I statistic for the years 1990 (0.46) and 2019 (0.53) indicate the existence of HH and LL clusters of wheat-producing mesoregions, which can be seen in the maps in Figure 7. In 1990, there were 21 AA mesoregions with high productivity characteristics with equal neighbors. They were mainly located in the Southern Region and Mato Grosso do Sul. For 2019, 22 producing mesoregions were found in the High-High clusters in the Southern Region, São Paulo, Minas Gerais, and Goiás, and one High-Low mesoregion in Bahia.

The expansion of wheat production to the Midwest and Northeast is accompanied by a process of increasing productivity (kilograms per hectare), which makes self-sufficiency in wheat production possible in the future. Therefore, the previously existing difficulties of new technologies and varieties adapted to the climate and soil are not limiting in the recent period for the expansion of the wheat cultivated area in drier and hotter climates and in the cerrado soil.

Figure 7. Spatial clusters (LISA) of wheat productivity in the mesoregions of Brazil, 1990-2019. Kilograms per hectare.



1990	2019

Source: research results.

The expansion of wheat cultivation to the Northeast and Midwest depends on the availability of inputs and the development of the production chain in the regions, which includes processing and the marketing system. Table 4 shows data on wheat milling in the different regions of Brazil, and the majority (around 62%) of milling takes place in the South and Southeast. Therefore, increasing processing capacity in the other regions is an important point for the development of the crop in the Northeast and Midwest.

Table 4. Estimated wheat milling in Brazil.

Region	2018	2019	Variation (%)
	Total milling (tons)	Total milling (tons)	
Paraná	3,618,585	3,719,864	2.8%
Rio Grande do Sul	1,832,625	1,913,568	4.4%
Santa Catarina	498,811	466,027	-6.6%
São Paulo	1,653,452	1,611,042	-2.6%
North and Northeast regions	3,410,236	3,485,476	2.2%
Midwest, Minas Gerais, Rio de Janeiro and Espírito Santo	1,160,898	1,209,933	4.2

Source: Abitrigo - May/2020. Available at https://www.abitrigo.com.br/wp-content/uploads/2020/05/2-ABITRIGO-MOAGEM-2019.pdf.

IV. Conclusion

The purpose of this article was to analyze the manufacturing and refining sugar sector and its economic impacts on the Brazilian economy using data from the input-output matrix of the 2018 year. The context of the sugar agribusiness within the national productive chain was outlined. The results showed that the manufacturing and refining sugar sector had the highest participation in GDP generation by inputs (aggregate I), representing 46.61% of the total value. This aggregate was also the largest job creator, accounting for 57.87% of the total. However, despite this, aggregate I had the lowest remuneration, with only 22.5 billion reals paid, of which just 5.3 billion was allocated to inputs, equivalent to 9,486 reals on average annually. The expansion of the area under cultivation and the increase in wheat productivity are directly linked to the use of genetic improvement to select adapted and productive varieties and to improve cultivation practices. Production is still concentrated in the South of Brazil, but increased production and productivity in the Southeast, Midwest, and Northeast present the possibility of achieving self-sufficiency in production in the future. This is justified by the ratio between national production and domestic consumption, which rose from 38% in 2017 to 86% in 2022. Productivity in 1990 was close to 1273 kilograms per hectare, which increased by 49.6 kilograms per hectare, and in 2019 reached a value close to 2700 kilograms per hectare. Further research can be carried out to make forecasts and draw up policies for self-sufficiency in supplying the domestic wheat market by expanding production areas in the Midwest and Northeast regions.

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