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SPATIAL APPROACH TO YIELD OF SECOND CORN CROP IN PARANÁ STATE

ABSTRACT

This study aimed to investigate factors that increase corn crop yield in the second crop in Paraná State, Brazil. For that purpose, we used a spatial approach to evaluate the correlation between second corn crop yield and the variables of labor force, mechanization, technical guidance, access to financing, and soybean crop yield (crop succession system). We used data from the Agricultural Census and the Municipal Agricultural Survey for the years 2006 and 2017. The methodological approach includes Exploratory Spatial Data Analysis and spatial regressions by unrestricted and restricted samples (spatial regimes). The findings show that mechanization, technical guidance and soybean yield positively affect second corn crop productivity in Paraná. The robustness of these positive effects is also found in regressions by spatial regimes. In conclusion, the study highlights the importance of crop succession systems and regional production arrangements in generating productivity gains in the second corn crop.

Keywords: Second corn crop; Agricultural Census; Spatial correlation; SAR Model; Crop yield.

RESUMO

Este estudo teve como objetivo investigar fatores que aumentam a produtividade da cultura do milho na segunda safra no estado do Paraná, Brasil. Para tanto, utilizamos uma abordagem espacial para avaliar a correlação entre a produtividade da segunda safra de milho e as variáveis força de trabalho, mecanização, orientação técnica, acesso a financiamento e produtividade da cultura da soja (sistema de sucessão de culturas). Utilizamos dados do Censo Agropecuário e da Pesquisa Agropecuária Municipal para os anos de 2006 e 2017. A abordagem metodológica inclui Análise Espacial Exploratória de Dados e regressões espaciais por amostras irrestritas e restritas (regimes espaciais). Os resultados mostram que a mecanização, a orientação técnica e a produtividade da soja afetam positivamente a produtividade da segunda safra de milho no Paraná. A robustez desses efeitos positivos também é encontrada em regressões por regimes espaciais. Em conclusão, o estudo destaca a importância dos sistemas de sucessão de culturas e dos arranjos regionais de produção na geração de ganhos de produtividade na segunda safra de milho.

Palavras-chave: Segunda safra de milho; Censo Agropecuário; Correlação espacial; Modelo SAR; Produtividade agrícola

Código JEL: C21; Q10.

INTRODUCTION

In Brazil, the second corn crop, or winter crop, or even called in portuguese “milho safrinha”, is one of the main developments in the Brazilian agricultural sector in the last decades. The purpose of second corn crop is to optimize the use of land and machinery, as well as labor force, in agricultural farms. It is a new production model established with the crop succession system that comprises the planting of soybean in the summer crop and corn in the winter crop. The establishment of two crop seasons a year has helped boost grain production in Brazil; however, analyses of crop performance and assessments of factors that influence yield of the second corn crop remain unclear.

In the literature, agricultural yield is usually related to soil and climate conditions, cultivation methods, mechanization, rural credit, genetic improvement, among others (Eckert *et al.*, 2018). In this study, we aimed to analyze yield of second corn crop in Paraná State, Brazil, using a spatial approach. This analytical perspective can contribute to highlight a grain that has become the main alternative for the second crop in Brazil, a system with great potential for yield growth. The spatial approach also emphasizes differences in crop yields between regions, an issue of great interest to the academic community (Bustos; Caprettini; Ponticelli, 2016).

Corn is the object of study in this article, as it has been ranked as the most produced cereal worldwide since the late 1990s, attributed mainly to its adaptability to different ecosystems, genetic improvement, and variety of uses in the food and feed industries as well as raw material for biofuel production (García-Lara; Serna-Saldivar, 2019).

The study spatial delimitation is based on the fact that Brazil has been the world's third-largest corn producer since the 2011/12 crop (Eckert *et al.*, 2018) and Paraná State is a major corn producer in the country, located in the region where the second corn cultivation system originated. Since the late 1980s, the first corn crop (summer crop) started to be sown earlier in the year, which allowed for the planting of the second corn crop (winter crop) between the months of February and March in Paraná State and in the other southern states in Brazil (Ramalho; Marques; Lemos, 2021). Moreover, climate conditions, such as high altitudes and moderate temperatures, in Paraná State are highly favorable for the second corn crop (Gonçalves *et al.*, 2002).

In the present study, the overall objective is to identify the presence and direction of the spatial correlation between yield of the second corn crop in Paraná State and the elements discussed in the literature, such labor force, mechanization, technical guidance, access to financing, and soybean yield. Further, the methodological approach comprised the application of Exploratory Spatial Data Analysis (ESDA) in conjunction with global spatial regressions and spatial regimes. The spatial approach used in this article is justified by the heterogeneity present among the municipalities of Paraná. The municipalities are distributed across different edaphoclimatic zones, with varying soil types and different landforms.

We use data from the Agricultural Census and the Municipal Agricultural Survey from 2006 and 2017, as these years were the most recent years of the Agricultural Census publication. In the 2011/12 crop year, production of the second corn crop in Brazil surpassed that of the summer crop for the first time in history (Souza *et al.*, 2018); thus, the time cutoff encompasses a period of an important temporal displacement movement of corn production in Brazil.

The original contribution is to evaluate, within a spatial framework, factors historically correlated with increased crop yield, such as the use of skilled workforce (Buainain; Dedecca, 2010), mechanization and rural credit (Eckert *et al.*, 2018), as well as access to technical guidance (Pereira; Castro, 2020). These factors, despite being previously examined in the literature, are

expected to present spatial correlation owing to the disparate distribution of agricultural infrastructure, institutional support, and socioeconomic conditions among municipalities. In addition, the approach proposed also includes soybean yield; thus, corn is assessed as an integral part of a crop succession system throughout the agricultural year. Crop yield is a hot topic, directly and indirectly affecting social, economic, and environmental aspects, while impacting food security.

This article is organized into five sections, including this introduction. Section 2 describes the data and methodology, encompassing exploratory spatial data analysis, the SAR, SEM, and SDM models, and spatial regime delineation. Section 3 reviews the theoretical foundations and empirical literature on the determinants of maize productivity, such as labor, mechanization, rural credit, technical assistance, and the soybean-maize crop succession. Section 4 presents and discusses the results considering the literature, emphasizing direct and indirect effects. Finally, Section 5 offers the conclusions, highlighting the study's key contributions and its implications for public policy and agricultural practice.

MATERIAL AND METHODS

Data

The data used in this research are at the municipal level and referring to the year crops of 2006 and 2017 were obtained predominantly from the Agricultural Census conducted by the Brazilian Institute of Geography and Statistics (IBGE) and from the Municipal Agricultural Survey (PAM). These years were chosen because they were the most recent years until the publication of the Agricultural Census. The variables used in this study (Table 1) were chosen based on the literature on corn crop yield in Brazil.

Table 1: Variables assessed

Variable	Definition
Productivity ¹	Productivity of second corn crop (tons per hectares) in each municipality of Paraná.
Labor ²	Ratio between the number of people employed by agricultural farms for production of temporary crops and the number of total agricultural farms in each municipality of Paraná.
Mechanization ²	Ratio between the number of farms with harvesters dedicated to temporary farming and the number of total agricultural farms in each municipality of Paraná.
Financing ²	Ratio between the number of farms dedicated to temporary farming that obtained financing from any source and the number of total agricultural farms in each municipality of Paraná.
Technical guidance ²	Ratio between the number of farms dedicated to temporary farming that received some type of technical assistance and the planted area (hectares) of the second corn crop in each municipality of Paraná.
Soybean ¹	Productivity of soybean crop (tons per hectares) in each municipality of Paraná.

Source: Prepared by the authors.

Note: Data sources: ⁽¹⁾ Municipal Agricultural Production (IBGE) and ⁽²⁾ Agricultural Census (IBGE)

Corn production underwent changes Paraná State in the period between the last two Agricultural Censuses (2006 and 2017), with an increase in the production of the second corn crop (winter crop) with a concomitant reduction in the first corn crop (summer crop). Overall, in Brazil, first crop production has not decreased significantly; nevertheless, the second corn crop has grown substantially over the last three decades, mainly since the 2005/06 crop (Table 2).

Table 2: Evolution of corn production of the selected crops in Paraná State and Brazil, in millions of tons.

Harvest	Paraná		Brazil		Total Production share (%)	
	1st crop	2nd crop	1st crop	2nd crop	1st crop	2nd crop
1990/91	4,600.8	368.1	23,040.6	1,055.5	20.0%	34.9%
1995/96	6,546.8	1,368.0	28,895.1	3,509.6	22.7%	39.0%
2000/01	9,445.7	2,929.2	35,833.0	6,456.7	26.4%	45.4%
2005/06 ⁽¹⁾	7,678.3	3,561.7	31,484.7	11,176.9	24.4%	31.9%
2010/11	6,046.5	6,201.3	34,946.7	22,460.3	17.3%	27.6%
2016/17 ⁽¹⁾	4,686.3	12,856.4	29,814.9	40,772.7	15.7%	31.5%
2020/21	3,124.0	6,490.2	24,726.5	60,741.6	12.6%	10.7%
2021/22	2,995.6	13,425.9	25,026.0	85,613.5	12.0%	15.7%
2022/23*	3,829.5	14,205.2	27,076.2	96,309.6	14.1%	14.7%

Source: CONAB (2022), IBGE (2022)

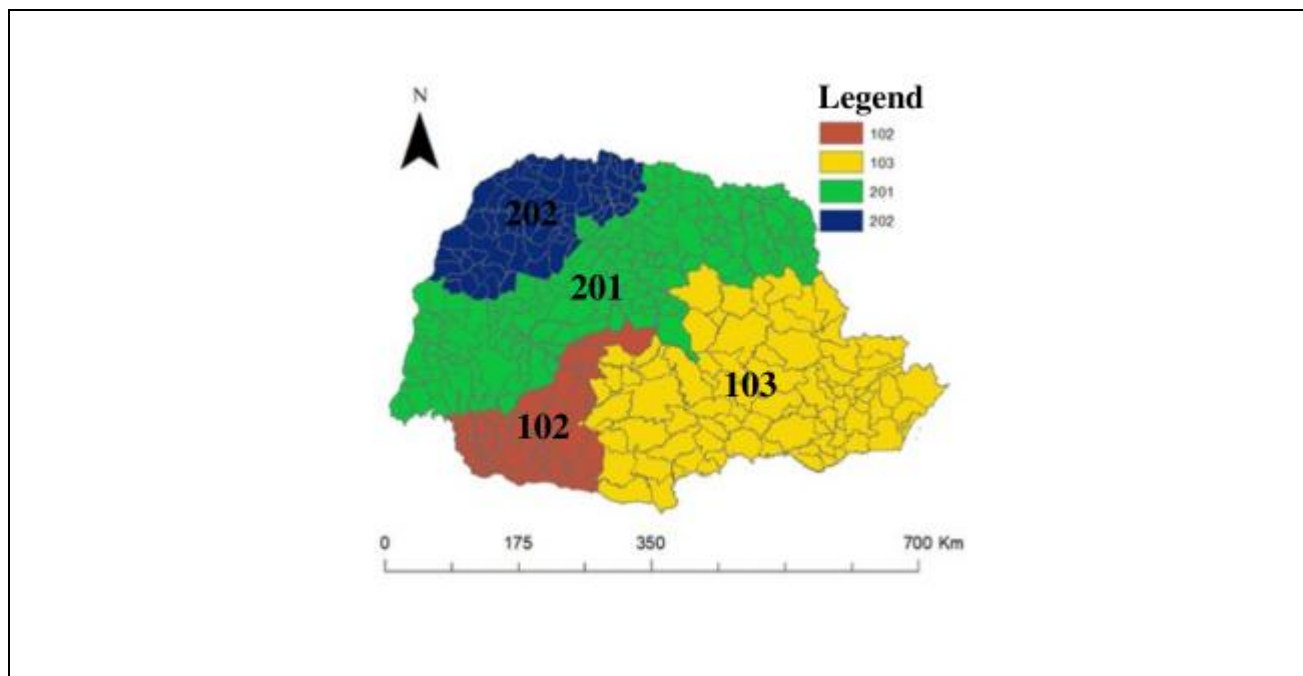
Note: ⁽¹⁾ Agricultural Census data; (*) Estimated data. Unit of measurement: 1,000 tons; (**) Share in total production (%) indicates the portion of total production represented by the 1st and 2nd crops, respectively.

The Agricultural Climate Risk Zoning of the Ministry of Agriculture, Livestock and Supply was used as an indicator of the soil and climate in the regions of Paraná State (Figure 1). This instrument was developed based on the results of research carried out by the Brazilian Agricultural Research Corporation (EMBRAPA Soja), the Brazilian Association of Plant Breeders (BRASPOV), and the Brazilian Seed and Seedling Association (ABRASEM). The regions for Paraná State are defined according to soil and climate factors favorable to soybean production and, consequently, suitable for the succession system with the second corn crop.

Paraná State has four edaphoclimatic regions. Region 102 primarily encompasses the Southwest of the state and extends to parts of the Central-South. This region is characterized by diverse topography, including plains and mountainous areas. The regional soil shows a diversity of types ranging from clay to sandy soils. The topographical and edaphoclimatic variability poses specific challenges to agricultural practices, as higher areas may be prone to erosion problems, while low-lying areas may face excessive moisture retention.

Region 103 is a transitional area that covers parts of the Central-South, Central-East, Southeast and includes the Metropolitan Region of the capital city of Curitiba. This results in a wide diversity of soil and climatic conditions; for instance, the proximity to Curitiba City brings specific urban and climatic influences. Some areas may have soils that are more fertile, while others may be prone to drainage issues.

Figure 1: Soybean crop regions in Paraná State, Brazil



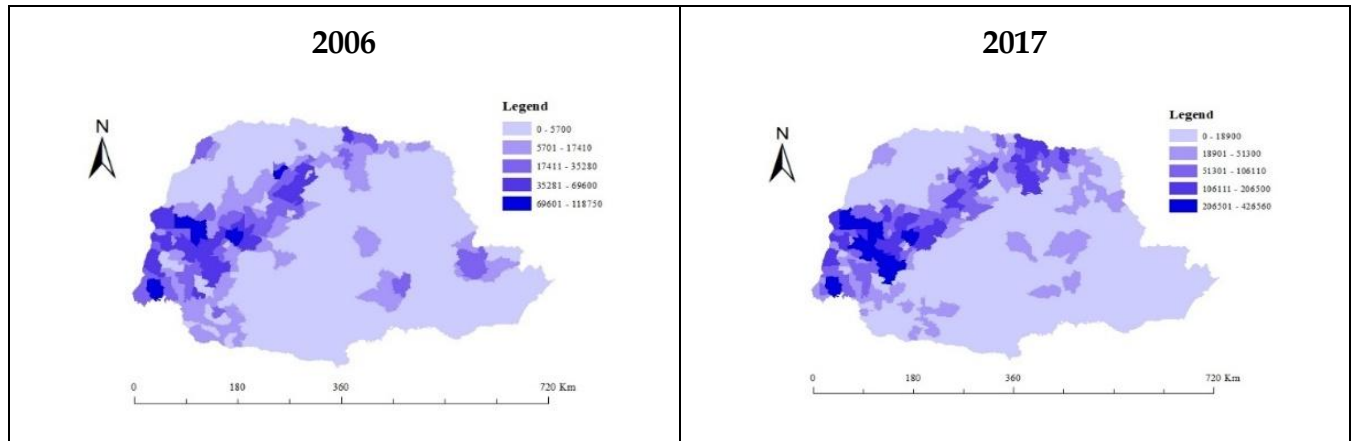
Source: Secretary of Agricultural Planning (Brasil, 2012).

Region 201 encompasses the Norte-Pioneiro, Central-North, Central-West, and West of Paraná State. This region is characterized by a broad variation in edaphoclimatic conditions. The presence of fertile soils in some areas, such as the Norte-Pioneiro, offers good conditions for intensive agriculture. However, the Central-West and West regions may face challenges related to water availability and seasonal climatic variations, including drought periods, demanding specific management strategies, such as the use of irrigation systems and the selection of drought-resistant crops.

Region 202 encompasses the Northwest of Paraná and parts of the Central-North. This region is characterized by a great diversity of soils, including sandy and clayey soils. The presence of rivers and water bodies, such as the Paraná River, can influence agriculture, providing natural irrigation in some areas. However, climate variability, with alternating periods of rain and drought, requires careful water management and the selection of crops adapted to seasonal conditions.

The spatial distribution of corn productivity in Paraná State shows a concentration in region 201 (Figure 2). Crop yield has a greater dispersion among the municipalities in the state, influenced by the size of the planted area. Region 102 and 103 presents an increase in crop productivity.

Figure 2: Spatial distribution of the second corn crop productivity in Paraná State, Brazil



Source: Municipal Agricultural Production, IBGE (2022).

Econometric Method

The econometric method used has an intrinsically spatial nature. In this context, to investigate the complex spatial relationships between the variations involved in the study, we used the technique known as Exploratory Spatial Data Analysis (ESDA). The ESDA plays a key role to thoroughly examine the existence of spatial correlations, both on a global and local scale, achieved through the application of Local Indicators of Spatial Association (LISA). As described by Almeida (2012), Moran's I statistic is an essential component of this analysis and can be represented in a matrix form, as follows:

$$I_{GU} = \frac{n}{S_0} \frac{z'Wz}{z'z} \quad (1)$$

where: n is the number of municipalities, z is the value of the variable in question, Wz is the value of the variable with a weighting by the spatial weight matrix, and S_0 is the sum of the elements of the weight matrix. In addition, $z'Wz$ represents the spatial autocovariance.

The bivariate global Moran's I statistic is calculated with the following equation:

$$I_{GB} = \frac{z_1'Wz_2}{z_1'z_1} \quad (2)$$

where: observations of two variables in question are considered.

Given that the global Moran's I statistic is not sufficient to capture specific effects in the spatial correlation, the LISA approach is indicated (Anselin, 1995), as it allows identifying local spatial correlation. The Moran's I statistic for local univariate (I_{LU}) and bivariate (I_{LB}) analysis are calculated as follows:

$$I_{LU} = z_{1i}Wz_{1i} \quad (3)$$

$$I_{LB} = z_{1i}Wz_{2i} \quad (4)$$

Therefore, clusters are observed between both variables weighted by the chosen matrix. Agglomerations that are not Non-Significant (NS) may be types: High-High (HH), Low-Low (LL), Low-High (LH), or High-Low (HL). Where the first term (left) refers to variable x in municipality i and the second term (right) represents variable y in municipality j .

After ascertaining the spatial correlations, regressions are performed to verify which explanatory variables have significant effects on yield of the second corn crop. First, spatial regressions are performed by OLS considering the spatial weights matrix. If the value of the robust Lagrange Multiplier test shows a higher value of $LM\rho$ than the value of $LM\lambda$, a new regression is performed by the spatial lag model (SAR). Otherwise, the new regression is made by the spatial autoregressive error model (SEM), which in this case is the most suitable (Almeida, 2012).

The SAR Model is defined as follows:

$$y = \rho W_y + X\beta + \varepsilon \quad (5)$$

where: ρ is the spatial lag coefficient of variable y , W_y is a vector of lags for dependent variable y , X are independent variables, β is the coefficient of independent variables, and ε is the error term.

The SEM model is as follows:

$$y = X\beta + \mu \quad (6)$$

$$\mu = \lambda W_\mu + \varepsilon \quad (7)$$

where: μ is the error term with effects that are not modeled because of unobserved information, λ is the coefficient of autoregressive error, and W_μ is the lagged error in space.

According to Almeida (2012), if the null hypothesis of the Jarque-Bera test is rejected, indicating the absence of normality of errors, the estimator used of Maximum Likelihood is no longer adequate and the coefficients should be estimated by Least Squares in Two Stages (MQ2E).

After verifying the incorporation of spatial dependence in the model through the Anselin and Kelejian test (1997), it is possible to estimate a model considering the lags of the explanatory variables. This model, called Durbin spatial (SDM), allows analyzing the robustness of coefficients when introducing overflow effects by discrepancies of explanatory variables (Almeida, 2012).

The SDM model is written as follows:

$$y = \rho_1 W_y + X\beta + \rho_2 WX + \varepsilon \quad (8)$$

where: WX represents the spatially lagged explanatory variables and ρ_2 is the overflow effect of these lagged variables. In the comparison of the estimated coefficients between the SAR and

SDM models, coefficients with a lower value in the Akaike criterion (Almeida, 2012) are better adjusted.

Therefore, regressions are estimated to verify which variables influenced second-crop corn productivity in 2006 and 2017:

$$Productivity = f(labor, mechanization, financing, technical guidance, soybean) \quad (9)$$

Following the spatial regressions for the 399 municipalities (unrestricted sample), regressions by soybean region (restricted sample according to Figure 1) are applied in the form of spatial regimes. According to Anselin (1990), the statistic follows an F distribution and can be verified as follows:

$$C = \frac{\left(\frac{e_R' e_R - e_{IR}' e_{IR}}{K} \right)}{\left(\frac{e_{IR}' e_{IR}}{N-2K} \right)} \sim F_{K, N-2K} \quad (10)$$

where: e_R is a vector with the errors of the regressions restricted by subsamples, referring to each soybean region, e_{IR} is a vector of errors of the regression with the general sample, K is the number of explanatory variables and N is the number of municipalities.

DETERMINING FACTORS OF CORN PRODUCTION IN BRAZIL

The corn production chain in Brazil has undergone profound structural changes since the end of the 1970s, reaching an average annual growth of around 4% in crop yield between the 1960/61 and 2021/22 crop years (USDA, 2022). In this period, changes in factor endowment, technical capacity, and demand for commodities promoted an array of institutional modifications in agribusiness (Ruttan; Hayami, 1984) and corn was one of the most benefited crops (Ramalho; Marques; Lemos, 2021).

Between the 1980s and 1990s, the no-till farming (zero-tillage) system was initiated to reduce soil erosion and minimize environmental impacts caused by the conventional cultivation system. In no-till, crop remnants (haystacks) left on the soil surface contributed to the emergence of the second corn crop (Zambrzycki; Vale; Dantas, 2013). The no-till system has contributed to biodiversity balance by increasing soil fertility and reducing costs with agricultural inputs (Salomão *et al.*, 2020).

No-till farming created conditions for the development of corn production in the winter crop, which started in the southern region of Brazil (Silva *et al.*, 2015). The success of the second corn crops in that region fostered public and private investment in new management strategies, as well as in genetic improvement, formulation of appropriate fertilizers, among others, essentially aiming to increase yield of the second corn crop (Mattos; Silveira, 2018). The onset of the second corn crop introduced changes in three broad categories that explain yield differentials: availability and endowment of resources, technological resources, and human capital (Hayami; Ruttan, 1970).

After the model was consolidated, the early 2000s were marked by the growing participation of the central-western region in Brazil in the production of the winter corn crop and the region became the leader in terms of planted area, reaching a significant 9.0 million hectares in the

2019/2020 crop, about 5.2% of the total area planted worldwide with corn for the winter crop (Battisti *et al.*, 2020). The protagonism of the central-western and southern regions of Brazil, especially Mato Grosso and Paraná States, actively contributed to the increase in the national average yield, raising from 2.7 t/ha in the 2000/2001 crop to 5.7 t/ha in the 2014/2015 and 2018/2019 crops, the highest yields achieved based on the last available data update (CONAB, 2022).

In Paraná, the northern and western regions of the state have the highest concentration of corn production, accounting for more than 70% of planted areas (SEAB, 2014). Yield gains of the second corn crop in Paraná State is explained essentially by the continuous improvement process in the cropping system since its implementation, relying on several initiatives from the public and private spheres (Ramalho; Marques; Lemos, 2021).

Besides the technical evolution resulting from the change in the production model, genetic improvement also contributed to increasing corn crop yield. In this context, the use of genetically improved seeds provided hybrid cultivars adapted to different soil types and soil and climate conditions (Costa *et al.*, 2015). In Brazil, this process began in the mid-1930s through research conducted mainly by the Luiz de Queiroz College of Agriculture (ESALQ/USP), Agronomic Institute of Campinas (IAC), and partner institutes (Amabile; Vilela; Peixoto, 2018). However, from the 1990s onward, with the release of legal commercial access to Genetically Modified Organisms (GMOs), more competitors and cultivars have been made available in this market (Cordeiro; Perez; Guazzelli, 2007).

Another important factor in our analysis is the mechanization in agricultural production. Mechanization allowed for cost reduction, mainly in terms of handling time and unskilled labor, providing substantial gains in efficiency and yield (Queiroz *et al.*, 2004). In corn crops, the main mechanized operations are linked to sowing and harvesting, involving the use of machines with capacity for longitudinal distribution of seeds in the soil combined with the correct depth of seed deposition (Weirich Neto *et al.*, 2015) and machinery to harvest cobs and separate the grains in the same stage (Loureiro *et al.*, 2012).

Rural credit is also crucial as it enables investments in new technologies, adapted cultivars, machinery, and equipment that are essential to increase the second corn crop yield (Sanches; Alves; Barros, 2019). The policy of democratizing access to credit for farmers in Brazil has been carried out since the 1930s (Santos; Braga, 2013). The Brazilian rural credit incentive policy is characterized by the stimulus to increase agricultural production, with direct impact on crop yield as well as on expansion and management of available technologies (Pereira; Castro, 2021).

Rural credit can also be an instrument for technical guidance or Technical Assistance and Rural Extension (ATER) to promote crop yield associated to sustainability of the agricultural farm (Bianchini, 2015). ATER is complementary to credit and thus has become an instrument of rural development over the years and an important tool for strategic development of agriculture in Brazil, offering education on sustainable practices and soil management, crop rotation, pesticide use, and others (Marschall, 2009).

In Brazil, the southern region presents the greatest coverage of technical guidance due to the large number of agricultural cooperatives, associations, and public and private technical assistance institutions, among other factors (Castro; Resende; Pires, 2014). This capillarity in the network of knowledge transmission also contributes to labor force qualification, reflected in increased marginal productivity per worker and greater efficiency in the use of available inputs (Del Grossi; Silva, 2006).

In sum, several factors contribute to yield of the second corn crop, such as soil and climate conditions also favorable to soybean cultivation, development of regular and highly productive biotechnological products, advancement of mechanized operations, access to rural credit lines, access to ATER, and employment of qualified human capital. Paraná State, forerunner of winter corn crop in Brazil, has a major production of the second corn crop, with significant yield gains year after year. Therefore, understanding the determinants of corn crop yield in Paraná State is relevant for an assertive planning by producers and for directing incentive public policies.

RESULTS AND DISCUSSION

Table 3 presents the spatial weighting matrix used Exploratory Spatial Data Analysis. According to the calculation of Moran's I statistics, the five neighbors (K-5) is the most suitable matrix for the spatial analysis. The calculated Moran's I was statistically significant and greater than the expected Moran's I indicating an overall positive spatial correlation in the second corn crop yield, where the correlation line has an upward slope.

Table 3: Choice of weight matrix

Matrix	Moran's I 2006	Moran's I 2017
Rook	0.568***	0.660***
Queen	0.570***	0.675***
K-5	0.577***	0.682***
K-7	0.557***	0.658***

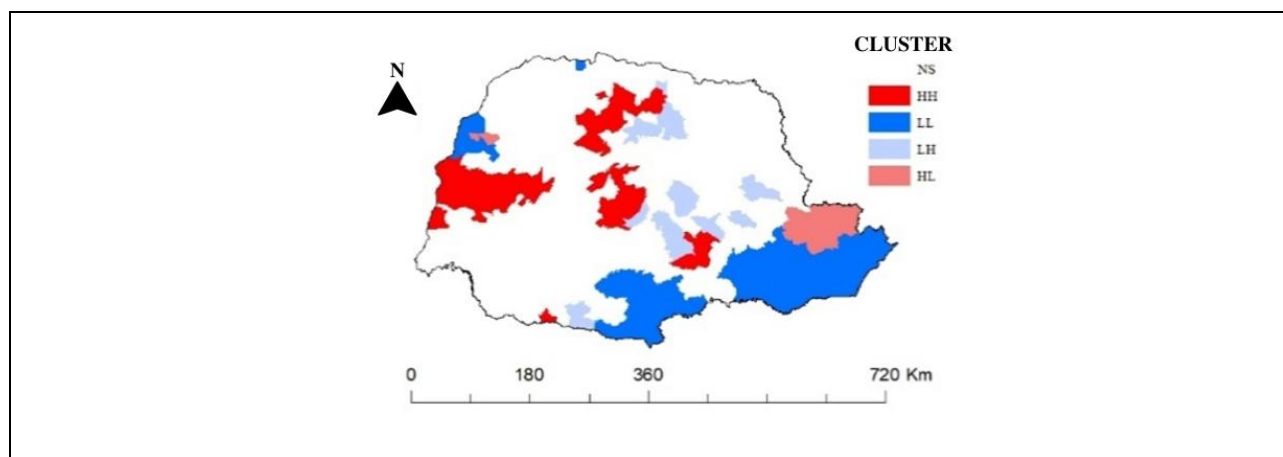
Source: Prepared by the authors.

Note: Expected Moran's I = -0.0025. *** Statistically significant at 0.01.

Figure 3 presents the spatial distribution of the LISA approach for yield of the second crop corn in Paraná State, analyzing the bivariate relationship between the variables referring to the years 2006 and 2017, respectively. There is a predominance of High-High (H-H) and Low-Low (L-L) clusters in Paraná.

In this context, in the western and central-northern regions of Paraná show H-H clusters, indicating that the municipalities in these clusters had high yield levels of the second corn crop in 2006 and kept high yield levels in 2017. While L-L clusters in the eastern part of region 103 and in the central-southern region of the state show that the municipalities, in these regions had low yield in the second corn crop in 2006 and kept the low level in 2017.

Figure 3: Spatial distribution of the bivariate LISA approach of the second crop corn productivity in 2006 and 2017 in Paraná State, Brazil



Source: Prepared by the authors.

Concerning the identification of clusters created from the spatial correlation of second corn crop yield with the explanatory variables (Figure 4), the H-H cluster in 2006 in western Paraná State in the analyses for labor and mechanization reduced in size in 2017. In this context, new H-H clusters emerged in other parts of the state, mainly in the edaphoclimatic regions 103 and 201.

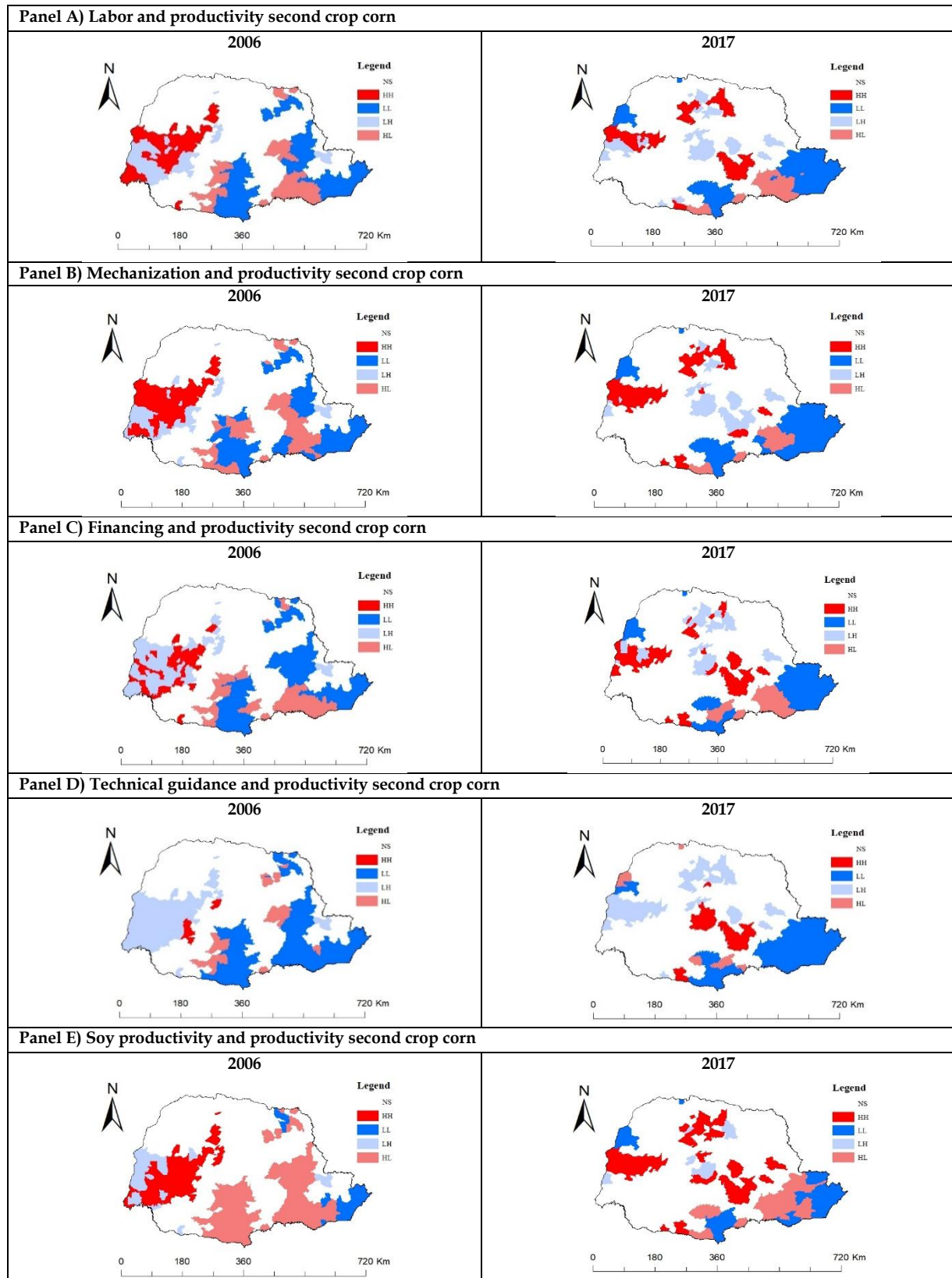
Regarding the L-L clusters, a pattern can be identified for the different bivariate analyses (Panels A to D). In 2006, there were L-L clusters in the eastern part of region 103, in Norte-Pioneiro, central-southern, and central-eastern regions. In 2017, these clusters became more intensely concentrated in two particular parts, in the central-southern and eastern parts of region 103. This means that these clusters were formed by municipalities with low levels of variables labor force, mechanization, financing, and technical guidance, and were neighbors of municipalities with low levels of the second corn crop yield.

In turn, regarding Panel E, which evaluates the spatial correlation between soybean and corn yields, a small number of L-L clusters can be identified. In this cut of the analysis, there is a predominance of H-L clusters in different regions of Paraná State and H-H clusters concentrated in region 201 in 2006 and distributed in different regions in 2017.

In addition to the spatial distribution of the LISA bivariate approaches, it is important to analyze the cluster composition in Paraná State, showing the number of municipalities that each cluster comprises, in addition to the displacement of clusters between points in the state. Table 4 presents the numbers of municipalities that formed the clusters in 2006 and 2017.

In direct correlations, that is, H-H and L-L, spatial correlations between the second corn crop yield with mechanization, financing, and soybean yield increased the number of municipalities in these direct spatial correlation clusters. In the case of inverse spatial correlations, L-H clusters showed a reduction in the number of municipalities in all the spatial correlations analyzed. On the other hand, the other type of cluster with inverse spatial correlation, that is, H-L cluster, did not show a reduction in the number of municipalities only in the spatial correlation between the second corn crop yield and mechanization.

Figure 4: Spatial distribution of the bivariate LISA approach of explanatory variables and the second crop corn yield in 2006 and 2017



Source: Prepared by the authors.

Table 4: Composition of clusters of bivariate LISA in Paraná State (number of municipalities)

Cluster	Year	Independent Variables (x)				
		Labor	Mechanization	Financing	Tech. guidance	Soybean yield
HH	2006	39	45	31	3	47
	2017	37	47	39	13	63
LL	2006	41	40	39	54	14
	2017	41	48	41	51	32
LH	2006	34	28	42	70	26
	2017	33	23	31	57	7
HL	2006	25	26	27	12	52
	2017	16	29	16	6	25

Source: Prepared by the authors.

Note: Dependent variable (y) is yield of second corn crop.

Another point to be highlighted is the role of mechanization and soybean yield in direct spatial correlations. In both correlations of yield with the second corn crop of the 399 municipalities in Paraná State, 95 municipalities formed H-H and L-L clusters in 2017, indicating a productive framework favorable to corn yield in municipalities with a high level of mechanization and soybean yield.

Table 5 presents the tests for choosing the type of spatial model, based on the tests after regression by OLS. In this case, we found that the most suitable family is the SAR type. It is also observed that the errors are not normal, requiring regressions by 2SLS.

Table 5: Tests of choice model in OLS

Tests	2006	2017
Jarque-Bera	17.55***	152.20***
Breusch-Pagan	5.780	21.819***
Koenker-Bassett	8.928	12.478
Lagrange Multiplier (ρ)	303.46***	347.85***
Robust LM (ρ)	16.15***	45.21***
LM (λ)	287.34***	303.89***
Robust LM (λ)	0.037	1.254

Source: Prepared by the authors.

Note: Moran's I test for residuals from OLS regressions indicated that the queen matrix is the most suitable for regressions.

*** Statistically significant at 0.01.

Table 6 presents the total effects in the regressions for the unrestricted sample (399 municipalities) in each year analyzed. The weighting matrix used is of the queen type. Since the objective here is to analyze only the direction of the effects of the explanatory variables on the dependent variable, the direct, indirect and total effects were not disaggregated in this Table.

Table 6: Total effects in regressions for unrestricted sample in the years 2006 and 2017

Variables	2006		2017	
	SAR	SDM	SAR	SDM
Labor	-0.0001	-0.0009	0.0001	-0.0001
Mechanization	0.0254***	0.0155	0.0201***	0.0122**
Financing	-0.0156	-0.0051	-0.0235	-0.0053
Tech. guidance	0.0001	0.0005	0.0020**	0.0015
Soybean	-0.0001	0.0002	0.0026***	0.0009
ρX	No	Yes	No	Yes

Source: Prepared by the authors.

Notes: Lower Akaike criterion in the SAR model than in the SDM model.

ρ component statistically significant at 0.01 and positively related to the dependent variable.

The logarithm was applied to the dependent variable and, to present the effects, they were divided by 100.

*** Statistically significant at 0.01. ** Statistically significant at 0.05.

The signs of the total coefficients of the SAR model indicate that, in both years, mechanization influenced the productivity of the second corn crop in the state of Paraná. Furthermore, in 2017, technical guidance and soybean productivity became statistically significant and positively related to the productivity of the second corn crop. The lagged dependent variable, as predicted and announced in the note, had a positive effect on the dependent variable, that is, the productivity of the second corn crop in the neighboring municipality affected the productivity of the second corn crop in the municipality in question.

Table 7 presents the effects found in the regressions for regions 102, 103, 201 and 202 in Paraná. The regressions for the restricted samples were performed by 2SLS in the SAR model, as previously in the unrestricted sample.

The results of regressions by spatial regimes show that in region 102, mechanization and technical guidance had no significant effect on second-crop corn productivity in 2006, but showed a positive effect in 2017. In region 103, technical guidance also showed a significant effect on the dependent variable after 11 years. In the case of region 201, mechanization, which already had a positive effect on second-crop corn productivity, maintained the direction of the effect. While in region 202, in addition to mechanization, soybean productivity also maintained the positive effect after 11 years.

The fact that mechanization has a positive effect on the second corn crop yield in the SAR model was attributed to the massive use of mechanized operations, mainly at sowing and harvesting, corroborating Weirich Neto *et al.* (2015). The positive spatial relationship between mechanization and yield also validated the result found by Queiroz *et al.* (2004). The authors reported substantial gains in efficiency and yield, as well as reduction of costs and management time with the advance of mechanization in agricultural production. Furthermore, the high mechanization degree contributed to the reduction of the labor force employed in the production process, helping to explain the lack of statistical significance of variable labor in both years.

Table 7: Direct, indirect and total effects of restricted sample regressions

102						
Variables	2006			2017		
	Direct	Indirect	Total	Direct	Indirect	Total
Labor	0.0016	0.0007	0.0023	-0.0014	-0.0001	-0.0015
Mechanization	-0.0691	-0.0310	-0.1002	0.0128**	0.0002	0.0131**
Financing	-0.0562	-0.0252	-0.0814	0.0100	0.0001	0.0102
Tech. guidance	0.0005	0.0002	0.0008	0.0005***	0.0001	0.0006***
Soybean	-0.0011	-0.0005	-0.0016	0.0016	0.0001	0.0017
Observations	52	52	52	52	52	52
103						
Variables	2006			2017		
	Direct	Indirect	Total	Direct	Indirect	Total
Labor	-0.0012	0.0106	0.0094	-0.0006	-0.0011	-0.0018
Mechanization	0.0076	-0.0672	-0.0596	0.0205	0.0341	0.0547
Financing	0.0178	-0.1578	-0.1399	-0.0020	-0.0034	-0.0055
Tech. guidance	0.0001	-0.0012	-0.0011	0.0049***	0.0081*	0.0130**
Soybean	-0.0003	0.0030	0.0026	0.0006	0.0010	0.0017
Observations	86	86	86	86	86	86
201						
Variables	2006			2017		
	Direct	Indirect	Total	Direct	Indirect	Total
Labor	-0.0002	0.0001	-0.0001	0.0002	0.0001	0.0003
Mechanization	0.0124**	0.0048**	0.0172**	0.0060***	0.0001	0.0061***
Financing	0.0199	0.0077	0.0277	-0.0039	-0.0001	-0.0040
Tech. guidance	-0.0010	-0.0004	-0.0014	0.0003	0.0002	0.0005
Soybean	-0.0003	-0.0001	-0.0004	-0.0001	-0.0001	-0.0002
Observations	181	181	181	181	181	181
202						
Variables	2006			2017		
	Direct	Indirect	Total	Direct	Indirect	Total
Labor	-0.0001	-0.0001	-0.0002	-0.0002	-0.0001	-0.0003
Mechanization	0.0554***	0.0060	0.0615***	0.0143*	0.0017	0.0161*
Financing	0.0273	0.0030	0.0303	0.0175	0.0021	0.0197
Tech. guidance	-0.0012	-0.0001	-0.0014	0.0003	0.0001	0.0004
Soybean	0.0021***	0.0002	0.0023***	0.0025***	0.0003	0.0028***
Observations	80	80	80	80	80	80

Source: Prepared by the authors.

Notes: ρ component statistically significant at 0.01 and positively related to the dependent variable.

The logarithm was applied to the dependent variable and, to present the effects, they were divided by 100.

Wald test statistically significant at 0.05.

*** Statistically significant at 0.01. ** Statistically significant at 0.05. * Statistically significant at 0.10. *

The lack of statistical significance of the financing variable in the regressions (in the unrestricted and restricted samples) is possibly explained by the fact that second-crop corn producers generally do not use this source of credit with the same intensity and need as small farmers, since agricultural credit systems are, in large part, aimed primarily at small farmers, according to Henig and Santos (2016).

Another factor that can help explain this lack of statistical significance of financing is that producers of the second corn crops in Paraná State also produce soybean in another period of the year and, as soybean crops are highly profitable and dissipated across large properties in the state, the owners are generally producers with less need to take loans (Igreja, 2019). To reinforce this, the data from the Agricultural Census (2017) show that among the temporary crop producers, 38,682 producers with properties of area up to 100 ha sought and obtained some type of financing, while only 8,992 producers with properties of area above 100 ha obtained some type of financing.

In the case of the positive relationship between technical guidance and yield in the SAR model, Bianchini (2015) points out that rural technical assistance is an essential tool to disseminate knowledge that boosts production, reflecting in gains in yield and efficiency for agricultural farms.

Soybean productivity became significant in the unrestricted sample after 11 years, in addition to the maintenance of the effect in the restricted sample for region 202. This reflects the advancement of the second corn harvest in the state of Paraná. In 2006, the most cultivated type of corn was the first harvest; however, with the change in direction to the second harvest production system, space was opened for soybean cultivation, since the competitor for planting the first corn harvest in Brazil is soybean (Prestes Junior, 2020). Furthermore, according to Pereira Filho and Borghi (2020), the technology used in soybean cultivation spills over to the second corn harvest in municipalities that apply succession between crops, increasing the productivity of the second corn harvest in an environment favorable to soybean cultivation.

CONCLUSION

The domain of production techniques and the emergence of new technologies have caused the production of the second corn crop (winter crop) to surpass that of the traditional first crop (summer crop) in Brazil and in Paraná State. This increase in production is due to the allocation of planted area corn to the second crop, as well as to yield gains in the spatial regressions, mechanization and technical guidance had a positive effect on the productivity of the second corn harvest in Paraná and in the edaphoclimatic regions favorable to soybean cultivation.

Moreover, between 2006 and 2017, soybean yield started to influence the second corn crop yield in Paraná State. This means that producers that adopted crop succession, with cultivation of soybean in the summer crop and corn in the winter crop, implemented changes such as acquisition of new machinery, cultivars adapted to the edaphoclimatic region, among others, observed yield gains in both year crops.

Finally, this article contributes to the discussion in the literature about which factors have only spatial correlation, and which factors impact yield of the second corn crop. For Paraná State, this study shows local production arrangements, especially in the western and central-northern parts of the state, a region known locally as the “terra roxa”. Thus, there is a new perspective of analysis of these regions to understand which characteristic aspects of this

region, such as soil and climate conditions, cooperativism and associativism, may also be contributing to yield gains of the second corn crop.

Moreover, since mechanization, technical guidance, and succession with soybean cultivation contribute to yield gains of the second corn crop, information on these variables should also be considered in the decision-making process by producers who want to produce corn in the winter crop in other productive regions.

About the formulation of public policies and management strategies in the private sector, the identification of factors such as mechanization and technical guidance, which positively affect yield in the second corn crop, suggests the importance of encouraging investments in training and access to agricultural machinery. This can be achieved through public policies that promote the modernization of agriculture, with an emphasis on the second corn crop.

Additionally, the positive correlation between soybean yield and yield of second crop corn emphasizes the advantage of crop rotation. These findings are essential for guiding public policies aimed at the sustainable development of agriculture, promoting the adoption of practices, such as crop rotation and technical training of producers.

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