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ORIGINAL ARTICLE

Spatial autocorrelation of soybean plant populations and physical attributes of Oxisol[1]

Autocorrelação espacial de populações de plantas de soja e atributos físicos de um Latossolo

Job T. de Oliveira[2*], Fábio H. R. Baio[2], Eder E. da Silva[2], Suzany S. de Moura[2], Domingos S. Valente[3] & Paulo E. Teodoro[2]

[1] Research developed at Universidade Federal de Mato Grosso do Sul, Chapadão do Sul, MS, Brazil
[2] Universidade Federal de Mato Grosso do Sul/Campus CPCS/Departamento de Agronomia, Chapadão do Sul, MS, Brazil
[3] Universidade Federal de Viçosa/Departamento de Engenharia Agrícola, Viçosa, MG, Brazil

HIGHLIGHTS:
Maps with the use of bivariate techniques are important tools for exploratory studies of agricultural fields.
The soybean crop yield does not increase or decrease according to the variation of the adopted plant population.
Sowing planning with plant population reduction is important to increase the producer's profit.

ABSTRACT: Among the necessary phytotechnical adjustments, the correct recommendation of the plant population of each soybean cultivar is of paramount importance for success in crop production. Thus, the objective of this study was to analyze the distribution and spatial autocorrelation of the soybean plant population according to the spatial variability of the physical and chemical attributes of Oxisol in the Brazilian Cerrado region. The attributes studied were plant population, soybean grain yield, apparent soil electrical conductivity, soil organic matter content, cation exchange capacity, hydrogenionic potential, and clay content in the soil. The plant population varied inversely as a function of apparent soil electrical conductivity. The areas with the highest values of apparent soil electrical conductivity, soil organic matter content, cation exchange capacity, and clay content had the lowest plant populations. Soybean yield was not influenced by increase or decrease in the plant population. Thus, it is economically viable to plant with lower plant density to improve the farmer's profit margin.

Key words: *Glycine max*, moran index, precision agriculture, spatial dependence

RESUMO: Dentre os ajustes fitotécnicos necessários, a correta recomendação da população de plantas de cada cultivar de soja é de suma importância para o sucesso na produção desta cultura. Assim, o objetivo deste estudo foi analisar a distribuição e autocorrelação espacial da população de plantas de soja de acordo com a variabilidade espacial de atributos físicos e químicos de um Latossolo na região do Cerrado brasileiro. Os atributos estudados foram: população de plantas, produtividade de grãos de soja, condutividade elétrica aparente do solo, teor de matéria orgânica do solo, capacidade de troca catiônica, potencial hidrogeniônico e teor de argila no solo. A população de plantas variou inversamente em função da condutividade elétrica aparente do solo. As áreas com os maiores valores de condutividade elétrica aparente do solo, teor de matéria orgânica do solo, capacidade de troca catiônica e teor de argila apresentaram as menores populações de plantas. A produtividade da soja não foi influenciada pelo aumento ou diminuição da população de plantas, por isso é economicamente viável plantar com menor densidade de plantas para melhorar a margem de lucro do agricultor.

Palavras-chave: *Glycine max*, índice de Moran, agricultura de precisão, dependência espacial

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* Corresponding author - E-mail: job.oliveira@hotmail.com
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Introduction

With the increase in agricultural production costs, driven by the price of inputs, almost entirely imported, and with the instability in the economic policy of the Brazilian economy, one way to maintain profitability is to increase yield (Matos et al., 2021).

The availability of the same resource shared between two competing plants is difficult to assess, and it is necessary to explain the temporal variations and spatial distributions of these resources. Therefore, several variables, such as soil chemical and physical properties, the genetics of the crop, weather conditions, and crop population, influence the crop's final yield (Deretti et al., 2022) in each cultivation environment, which may present a greater or lesser risk of reaching the maximum potential yield of soybean.

Evaluating the spatial correlation between the soybean plant population per hectare and soil attributes is an important technique for optimizing agricultural inputs. This assessment can be done using various tools, such as georeferencing, spatial distribution, and the interpretation of thematic maps in productive fields (Oliveira et al., 2020a). Spatial autocorrelation can be defined as the coincidence of similar values in nearby locations or the absence of randomness of a variable due to its spatial distribution. They can occur in two ways: positive autocorrelation, when high or low values for a random variable tend to cluster in space, and negative autocorrelation, when there is a dissimilarity in the data between high and low values (Anselin et al., 2006; Oliveira et al., 2021). Currently, it is common to use a single population of soybean seeds throughout the area; however, it is known whether there is spatial variability in the physical and chemical characteristics of the soil in the field.

The spatial distribution of indicators is an instrument that can contribute to understanding the processes involved in a particular phenomenon to be studied, allowing for the analysis of the characteristics and differences of each production plot (Oliveira et al., 2020a). Thus, the objective of this study was to analyze the distribution and spatial autocorrelation of the population of soybean plants according to the spatial variability of the physical and chemical attributes of Oxisol in the Brazilian Cerrado region.

Materials and Methods

This work was carried out in the Chapadões region, a locality in the Brazilian Cerrado comprising the northwest of the State of Mato Grosso do Sul, the south of the State of Goiás, and the southeast of Mato Grosso, in two agricultural seasons, comprising the agrarian years 2019 and 2020. In the first agricultural year, the experiment was carried out in Chapadão do Sul/MS municipality at the approximate geographic coordinates of 22 S, 329139.00 m E; 7923631.00 m S (WGS84 - UTM) at an altitude of 826 m. Furthermore, in the following year, the experiment was conducted in the municipality of Chapadão do Céu/Go, at geographic coordinates of 22 S, 305866.30 m E; 7958615.07 m S (WGS84 - UTM) at an altitude of 828 m.

According to the Köppen classification, the region's climate is tropical at altitude (Cwa), with a rainy season in the summer and a dry season in the winter. The annual temperature varies between 13 and 28°C (daily measurements), and rainfall is around 1850 mm per year. The soil in which the experimental meshes from the two different agricultural years were installed was classified as sandy, clayey Red Yellow Oxisol (Santos et al., 2018).

The experimental design was completely randomized, with 33 sampling points in the 2019 crop season and 48 experimental sampling points in the 2020 crop season. The difference in the sampling points is based on the different fields cropped over the years. Four soybean populations of randomized seeds were installed in the plots, with 280, 320, 360, and 400 thousand seeds ha^{-1}. This variation was a 42.86% increase in seed density. The measurement of the response variables was performed at the center of each plot, allocated by a sampling point. Eight subsamples were taken around 1 meter from the central sampling point, thus reducing local variability. The chemical and physical soil attributes were measured by sampling at the same sampling points, at a depth of 0.0-0.2 m. The experiment used soybean cultivars (*Glycine max* L. Merrill) Desafio 8433 RR, and Foco IPRO 74i77RSF (Brasmax corporation) in the first and second crop seasons, respectively; these cultivars had an indeterminate growth habit and an average cycle of 110 days. Plants were spaced at 0.45 m between the crop rows. The spacing between plants varied according to the plant population.

The attributes studied were plant population (POP), soybean grain yield (SGY), apparent soil electrical conductivity (EC), soil organic matter (OM) content, cation exchange capacity (CEC), hydrogen potential (pH), and clay content in the soil (CLA), following the methodology described by Teixeira et al. (2017). For each attribute studied, the mean, median, minimum, and maximum values, standard deviation, coefficient of variation (CV), and data normality were calculated using the Shapiro-Wilk method, with the aid of the statistical program Rbio version 17 (Bhering, 2017).

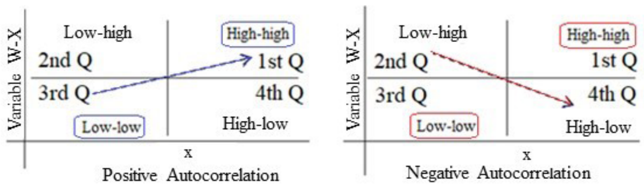
Prescription maps containing seeding rates (different populations of plants) were processed using the geographic information systems (GIS) program ArcGis 10.5. The sowing of the crop containing soybean populations at a variable rate was carried out by a John Deere DB model seed drill (Horizontina, Brazil). Soybean cultivation was carried out according to fertilizer recommendations, based on soil analyses, and phytosanitary control, according to the pest management required for the region.

Veris Q1000 equipment was used to measure the EC. This sensor has four electrodes connected to smooth metal discs, which make contact with the soil and are arranged side by side (Peralta & Costa, 2013), performing a reading of the soil profile from 0.00 to 0.40 m deep. An electronic central control coordinates the emission and reception of electrical loads from the disks to measure the EC. The measured value was connected to the coordinates from the global navigation satellite system (GNSS) to georeference the collected data (model GA 38, Garmin). The EC readings were mapped, taking one point per second in parallel lines in the field every 20 m between the lines of soybeans.

Global and local Moran indexes (LISA) were used as statistical tools to assess spatial autocorrelation. The global indicators of spatial autocorrelation (Moran I and II) provide measurements for the set of all points of the geostatistical grid, characterizing the entire study field. One possibility of visualizing global spatial autocorrelation is through the Moran scatter diagram (Figure 1).

The variable of interest (X) is allocated to the horizontal axis, and the spatial lag of the variable of interest (W_X) is on the vertical axis. The diagram verifies the pattern of data concentration divided into four types of associations: high-high (AA), low-low (BB), low-high (BA), and high-low (AB). When the result presents a positive spatial association, the regression line increases, and the values of soil attributes tend to cluster in the first and third quadrants; when the relationship is negative, the line decreases, and the units are predominantly grouped in the second and fourth quadrants (Almeida, 2012).

The pseudo-significance level of the Moran bivariate index was tested by GeoDa software using randomization with 999 permutations. These permutations were performed to make a statistical pseudo-test based on the Monte Carlo method (Anselin et al., 2006) at $p \leq 0.05$.



Adapted from Almeida (2012)

Figure 1. Moran scatter plot

Results and Discussion

The analyzed variables were divided by the year of the experiment and are shown in Table 1. From the analysis of the minimum and maximum values, the mean, and the variance of the attribute values, it is possible to establish that there was variation in the measured values. However, knowing this variation is not enough to identify where an attribute's high and low values are found (Oliveira et al., 2021). The attributes generally showed low variability or a coefficient of variation lower than 10% in the 2019 harvest. In the 2020 crop season, SGY and EC attributes presented a coefficient of variation (CV) classified as medium (ranging from 10 to 20%), which classifies the variability of an attribute according to the magnitude of its CV. These low CVs are due to the fact that, in the region where the experiment was carried out, the soils present less spatial variability, as they are flatter and very uniform when compared to other regions in Brazil, such as in sloping regions in the state Paraná. In addition, they were cropped in a no-tillage system for more than 15 years in the two areas where the experiment was carried out.

Through the regression equations adjusted according to the data analysis, positive and non-significant differences were found in the two years of experiments between attributes EC, OM, and CEC and between OM and CEC.

Different regressions were obtained in this study between EC and CEC for the 2019 harvest ($CEC = 0.3065^{*}EC + 7.9547$, $R^2 = 0.2176$); EC and OM for the 2019 harvest ($OM = 16.103^{*}EC^{0.2477}$, $R^2 = 0.2183$); and OM and CEC for the 2020 harvest ($CEC = 0.0514^{*}OM + 6.4719$, $R^2 = 0.2000$). The regressions between SGY and POP for the 2019 and 2020 harvests were not significant.

As already presented in the literature (Serrano et al., 2017), there is a positive and direct relationship between EC and CEC and other attributes. In this work, despite the R^2 value not being high, it showed a positive relationship between the attributes. Therefore, increasing the EC increased the nutrient concentrations available in the soil. According to the evaluation of the regression curves, it was possible to identify that in the two harvests, the EC versus CEC relationship presented a significant positive linear correlation. These EC values are closely related to salinity, CEC, and available nutrients. Amorim Neto et al. (2020) showed a positive correlation between the EC variable and salinity. In Brazil, many regions have salinity problems (arid regions). Moran's bivariate analysis technique can relate these regions to indicate the best and most adequate plant populations as a function of salinity. Soil salinity can be determined through the EC of the soil.

Table 1. Descriptive analysis of the attributes evaluated in the two harvests of soybean crops

Attribute [(a)]	Average	Minimum	Maximum	Standard deviation	Coefficient of variation (%)	Pr < w	FD
Harvest 2019							
POP	360,000.00	311,000.00	422,000.00	3.24	8.99	3.46×10^{-6}	NN
SGY	3925.10	3218.50	4506.10	254.80	6.49	0.61	NO
EC	4.79	3.99	5.27	0.34	7.10	0.07	NO
OM	23.74	21.43	26.25	0.92	3.86	0.11	NO
CEC	9.42	8.95	9.85	0.22	2.37	0.01	NN
pH	4.38	4.26	4.57	0.09	2.05	0.03	NN
CLA	450.97	441.52	471.73	10.50	2.31	2.52×10^{-3}	NN
Harvest 2020							
POP	311,000.00	290,000.00	336,000.00	21752.00	6.95	1.95×10^{-8}	NN
SGY	4723.24	4095.52	6258.39	558.76	11.42	3.21×10^{-3}	NN
EC	5.33	3.44	6.47	0.66	12.44	0.51	NO
OM	39.08	34.73	41.43	1.14	2.91	0.02	NN
CEC	8.48	8.25	8.72	0.13	1.54	0.13	NO
pH	5.04	4.98	5.11	0.03	0.59	0.40	NO
CLA	437.96	371.35	553.71	36.95	8.35	0.04	NN

POP - Plant population; SGY - Soybean grain yield in kg ha^{-1}; EC - Apparent soil electrical conductivity in mS m^{-1}; OM - Soil organic matter in g kg^{-1}, CEC - Cation exchange capacity in $cmol_c$ dm^{-3}; pH - Hydrogen potential (pH); CLA - Clay content in the soil in g kg^{-1}, FD - Frequency distribution: NO - Of the normal type; NN - not normal

The regression referring to the two harvests, according to the POP versus SGY relationship, did not influence yield. Therefore, for the adopted variation patterns, this had no influence. Nevertheless, for the studied patterns, varying higher percentages in POP had a negligible negative impact on yield in the soybean crop. This was also verified by Vazquez et al. (2008), in which variations of +42.00 and −75.00% concerning the average differences in soybean crop yield were significant, but variations smaller than 21.42 and −27.27% in POP did not influence yield. Tourino et al. (2002) reported that there was no significant effect of spacing between rows or plant density in rows on soybean yield. In a study by the same authors, variations in plant populations close to the average did not influence the yield results. However, when the plant population doubled, there were effects on the yield.

The regions with the highest plant population have a higher cost of planting per hectare, as the seeds are inputs that represent about 10% of the cost, according to Oliveira et al. (2020b). In addition, crop yield can be affected by the efficiency of the combine harvester. Its efficiency is inversely proportional to the plant population once an increase in the number of plants implies an increase in the number of branches and leaves to be processed by the machine, affecting the displacement speed of the combine harvester, and lost grains. Corroborating this analysis, Procópio et al. (2018) reported that a greater population of plants causes soybean crops to present plants with greater height, which may imply lodging, making it difficult to harvest fallen pods and reducing the yield of the harvester. According to Vazquez et al. (2008), the adoption of populations below the recommended one favors the development of weeds and can result in very branched plants and reduced height, which also increases the losses at the time of harvest since the process of separation and grain cleaning is hampered with the increase in weed green mass inside the harvester.

An adequate number of soybean plants in a population is controversial, as some farmers plant more seeds per hectare, while others do the opposite. Factors that influence this recommendation, such as seed availability, are critical factors in determining the population density. However, both in the regression analyses and in the Moran bivariate analysis technique, the results showed that the plant population can be reduced, saving seeds without changing crop yield. Figure 2 presents a Moran scatterplot of soil attributes that have global bivariate indices.

After adjusting the scatter diagrams (Figures 2A-F) in relation to soil attributes, plant population and soybean yield maps of the two crop seasons studied were estimated using cluster maps. Therefore, it was possible to elaborate maps with the concentration patterns for the variables of this study (Figures 3A-F), which allowed visualization, showing where significant spatial clusters were formed.

In the 2019 crop season, the points were concentrated in the extremes (south and north regions) when analyzing the cluster maps of EC in relation to soil CEC (Figures 3A and 3B). In the 2020 crop, points in the northern region showed similar results, with "high-high" autocorrelation. A high-high cluster indicates high CEC values, which are high EC values.

The same reasoning can be verified for the maps of Figures 3C and 3D, illustrating "high-high" autocorrelation in the same

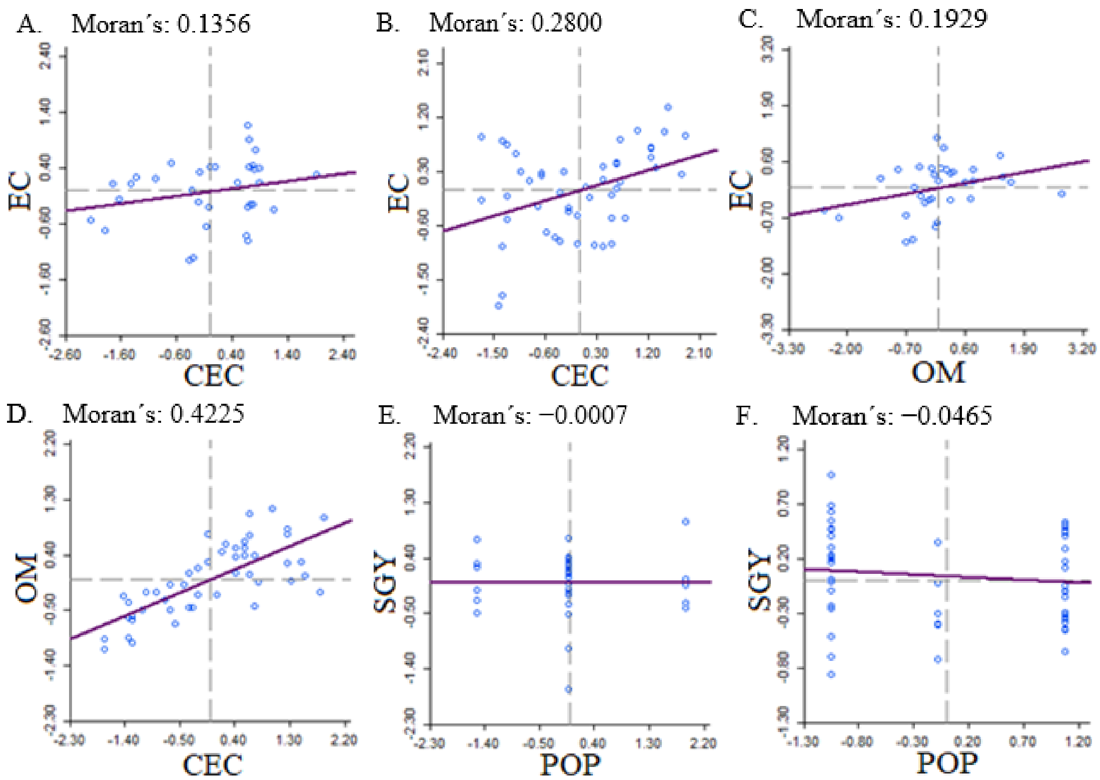


Figure 2. Moran scatter diagram between apparent soil electrical conductivity (EC) and cation exchange capacity (CEC) for the 2019 harvest (A); EC and CEC for the 2020 harvest (B); EC and soil organic matter (OM) for the 2019 harvest (C); OM and CEC for the 2020 harvest (D); soybean grain yield (SGY) and plant population (POP) for the 2019 harvest (E); and SGY and POP for the 2020 harvest (F)

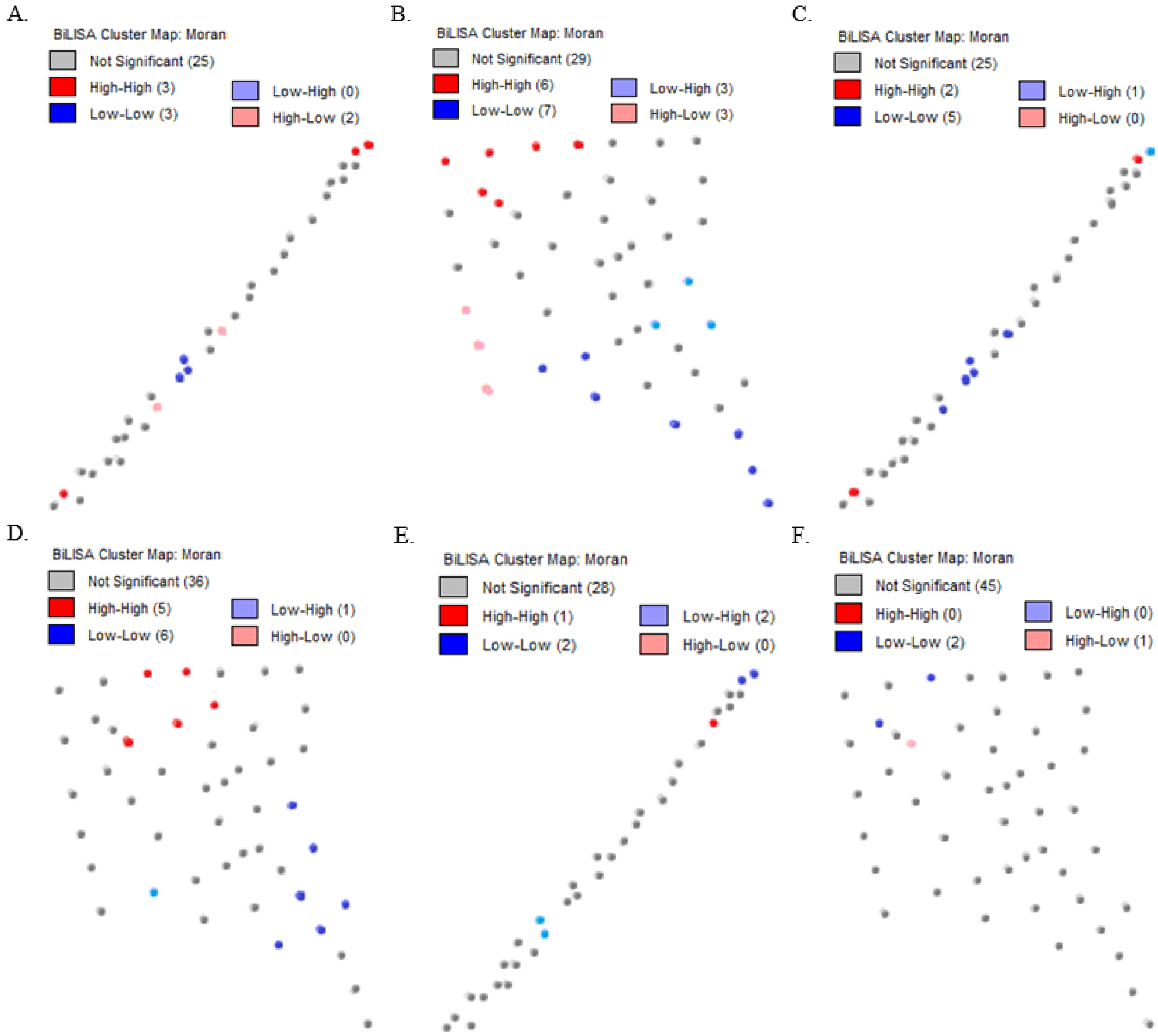


Figure 3. Cluster maps of Moran bivariate indices for apparent soil electrical conductivity (EC) versus cation exchange capacity (CEC) in the 2019 harvest (A); EC versus CEC in the 2020 harvest (B); EC versus soil organic matter (OM) in the 2019 harvest (C); OM versus CEC in the 2020 harvest (D); soybean grain yield (SGY) versus plant population (POP) in the 2019 harvest (E); and SGY versus POP in the 2020 harvest (F)

regions. However, Figures 3E and 3F do not show significant "high-high" correlations in any region. These results showed that the samples with the highest concentrations of nutrients were those with the lowest plant populations, and this reduction did not negatively affect soybean yield. Deretti et al. (2022) demonstrated that for the same fertilizer dosage, the tested soybean cultivars supported reductions in POP without affecting grain yield and productivity. In this way, a reduction in plant density can be recommended for cultivated soybean.

The observation of these cluster maps and field observations contributes to finding the reasons for the occurrence of variability in soybean yield. This work can serve as a basis for adequate sowing or soil management planning with the application of inputs at different rates by measuring the EC of the soil.

The maps of bivariate regimes allow adequate geographic visualization of the concentration degree of the studied variables, referring to local bivariate Moran indices or local spatial autocorrelation analysis (Moran LISA). It is possible to observe which regions have spatial clusters formed, representing the relationship between indicators of soil attributes related to the maps of bivariate clusters (Figure 3). These analyses were carried out in two experimental areas with dozens of sampling points in the present work. Such techniques are essential tools for exploratory studies of agricultural fields. Further studies in this area are suggested, as statistics can add much knowledge to soybean cultivation (Rodrigues et al., 2021). It is important to relate soybean plant population, crop yield, combine harvester efficiency with different populations, and availability of seeds on the market.

Conclusions

1. Through Moran's bivariate analysis, the spatial analysis tool in area units made it possible to verify that regions with higher concentrations of nutrients in the planting area can receive smaller plant populations without affecting crop productivity.

2. The increase or decrease in the plant population did not influence soybean crop yield.

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