Spatial variability of soil penetration resistance in cotton growing areas

Variabilidad espacial de la resistencia del suelo a la penetración en las zonas algodoneras

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ABSTRACT

Resistance to soil penetration is a problem in cotton growing areas; this harms plant development and crop productivity. An analysis of spatial variability allows studying the variability of soil physical properties, especially those related to compaction and resistance to penetration. The hypothesis of this study was based on the possibility of evaluating soil compaction in areas cultivated with cotton crops through an analysis of spatial variability. Thus, the aim of the study was to evaluate the spatial variability of soil resistance to penetration and its effects on cotton productivity. The research was carried out in Paraíso das Águas, Mato Grosso do Sul, Brazil, in an agricultural area belonging to Fazenda Indaiá II. The experimental area consisted of a plot of 60 ha, where cotton seeds of the FM 978 6LTP cultivar were planted. The *x* and *y* directions of the Cartesian coordinate system were defined and the experimental mesh was staked, spaced 9.9 m apart. Cotton productivity was evaluated (t ha^{-1}) as well as gravimetric soil moisture at a depth of 0 to 0.20 m as well as mechanical resistance to penetration in the following layers: 0 to 0.10 m (RP1), 0.10 to 0.20 m (RP2), 0.20 to 0.30 m (RP3), 0.30 to 0.40 m (RP4), 0.40 to 0.50 m (RP5), 0.50 to 0.60 m (RP6), including average penetration resistance (RPM). For each evaluated variable, classical descriptive analysis and analysis of spatial variability were carried out, with the construction of semi-variogram and later kriging and cokriging maps. To analyze the dependence and spatial interdependence between the variables, the soil resistance to penetration showed spatial variability in the cotton crops; and there was an inversely proportional relationship between cotton productivity and soil resistance to penetration, where the lower the penetration resistance, the higher the cotton productivity.

Key words: soil compaction, geostatistics, *Gossypium hirsutum*, kriging.

RESUMEN

La resistencia a la penetración del suelo es un problema en las zonas de cultivo de algodón, ya que perjudica el desarrollo de las plantas y la productividad de los cultivos. El análisis de variabilidad espacial permite estudiar la variabilidad de las propiedades físicas del suelo, especialmente aquellas relacionadas con la compactación, como la resistencia a la penetración. La hipótesis de este trabajo se basó en la posibilidad de evaluar la compactación del suelo en áreas cultivadas con cultivos de algodón a través del análisis de variabilidad espacial. Así, el objetivo del trabajo fue evaluar la variabilidad espacial de la resistencia a la penetración y sus efectos sobre la productividad del algodón. El trabajo se realizó en Paraíso das Águas, Mato Grosso do Sul, Brasil, en una zona agrícola perteneciente a la Fazenda Indaiá II. El área experimental estuvo compuesta por una parcela con una superficie de 60 ha, donde se sembraron semillas de algodón del cultivar FM 978 6LTP. Se definieron las direcciones *x* y *y* del sistema de coordenadas cartesianas y se plantó la malla experimental, espaciada 9,9 m. Se evaluó la productividad del algodón (t ha^{-1}), la humedad gravimétrica del suelo a una profundidad de 0 a 0,20 m y la resistencia mecánica a la penetración en las capas: de 0 a 0,10 m (RP1), de 0,10 a 0,20 m (RP2), 0,20 a 0,30 m (RP3), 0,30 a 0,40 m (RP4), 0,40 a 0,50 m (RP5), 0,50 a 0,60 m (RP6) y resistencia media a la penetración (RPM). Para cada variable estudiada se realizó un análisis descriptivo clásico y un análisis de variabilidad espacial, con la construcción de semivariograma y posteriormente mapas de kriging y cokriging, para analizar la dependencia e interdependencia espacial entre las variables. La resistencia a la penetración del suelo presentó variabilidad espacial en áreas algodoneras y existió una relación inversamente proporcional entre la productividad del algodón y la resistencia a la penetración del suelo, donde a menor resistencia a la penetración, mayor es la productividad del algodón.

Palabras clave: compactación de suelo, geoestadística, *Gossypium hirsutum*, kriging.

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Introduction

Cotton (*Gossypium hirsutum* L.) has economic and social importance for Brazilian agriculture. It is cultivated to obtain seeds and fiber and is widely used in the production of feed and the textile industry (INDEA, 2023). In the 2022/23 harvest, production exceeded 3,150.1 million t, with a forecast increase in the planted area in the 2023/24 harvest (CONAB, 2023).

An expansion of cotton cultivation in Brazil occurred in the early 1990s, extending across the biome with intense application of technology (Sari *et al*., 2023). Knowledge of the factors that affect cotton production is important for defining regions with potential for the production of seeds and fiber of high quality; differences in production are associated with cultivars and physical quality of the soil (Ramos *et al*., 2022).

Soil management implies knowing its physical, chemical, and biological characteristics, aiming at practices for agricultural production by understanding its potential and limitations (Silva *et al*., 2020). Soil compaction is a limiting factor in agricultural production. It impacts the reorganization of particles and aggregates, limiting the adsorption and absorption of nutrients, infiltration, and redistribution of water and gas exchange; and these factors limit agricultural productivity (Moraes *et al*., 2020).

Resistance to soil penetration is an indication of the physical quality of soils; it is a property related to compaction, and it mechanically quantifies the impediment of root growth (Jamali *et al*., 2021). Penetration resistance is a practical and complete parameter related to texture, soil density and water content that is used to monitor the state of soil compaction. Critical values varying between 1.5 and 4.0 MPa (Cortez *et al*., 2018) define a compacted soil with necessary assessment depending on the crop to be planted. Responding to resistance to penetration, plants reduce leaf area so that photoassimilates are redirected to the roots, to mitigate the effects of resistance. This harms the productivity of the cotton plants (Nikkel & Lima, 2020).

Soil resistance to penetration is evaluated with a penetrometer, equipment that measures the resistance of soil layers. It is characterized as one of the main tools for diagnosing and evaluating soil compaction (Vogel *et al*., 2017). Oliveira *et al*. (2023) emphasize the importance of knowing gravimetric soil moisture, as it is closely related to soil resistance to penetration.

The analysis of the spatial variability of soil resistance to penetration through geostatistics allows detection of the variation and spatial distribution of soil properties, especially those related to compaction (Cortez *et al*., 2018). The use of spatial variability promotes recurrent monitoring of the state of soil compaction in a practical way, characterizing the compaction caused by soil use and management in agricultural cultivation areas (Machado *et al*., 2015). Thus, it is classified as a precision agriculture technique.

Based on the above, the hypothesis of this study was based on the possibility of evaluating soil resistance to penetration in areas cultivated with cotton crops using the analysis of spatial variability. Thus, the objective of the work was to evaluate the spatial variability of gravimetric water contents in soil, soil resistance to penetration, and their effects on cotton productivity.

Materials and methods

The study was carried out in Paraíso das Águas, Mato Grosso do Sul, Brazil, in an agricultural area belonging to Fazenda Indaiá II, close to the geographic coordinates 19º1’33” S, 53º0’37” W and an altitude of 608 m a.s.l. According to Köppen and Geiger, the climate is humid tropical (Aw), characterized by a mean temperature varying between 14°C and 31°C and mean annual rainfall of 1303 mm.

The soil in which the experimental meshes were measured was classified as Entisols (USDA, 1987) with a sandy texture, containing 12% clay. The physical characteristics of soil were determined in the 0-0.20 m depth layer as follows: particle size distribution (%) of clay, silt, sand, 12, 5, 83; soil density of 1.3 g cm^{-3}; water content (g g^{-1}) of 0.088 and 0.053 for soil field capacity and permanent wilting point, respectively, determined by the Richards method. All soil physical analysis followed the methods described in Teixeira *et al*. (2017).

The following soil chemical characteristics were determined in the Soil Laboratory of the Brazilian Institute of Analysis (IBRA), where all the analysis followed the methods described in Teixeira *et al*. (2017): pH: 5.020; soil organic matter OM (g kg^{-1}): 57.100; phosphorus P (mg dm^{-3}): 10.190; potassium K (mg dm^{-3}): 0.060; calcium Ca (mg dm^{-3}): 1.540; magnesium Mg (mg dm^{-3}): 0.710; aluminum Al (mg dm^{-3}): 0.000; potential acidity H+Al: ($cmol_c$ dm^{-3}): 0.011; sum of bases SB ($cmol_c$ kg^{-1}): 0.041; effective cation exchange capacity ECEC ($cmol_c$ kg^{-1}): 0.045; cation exchange capacity CEC (meq 100 g^{-1}): 0.020; base saturation BS (%): 43.020.

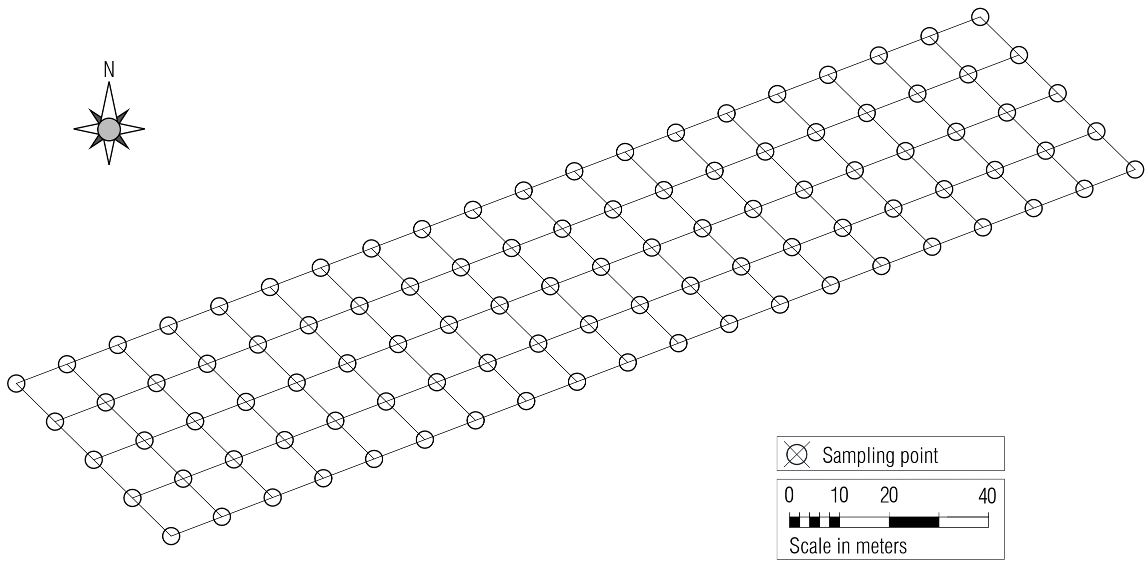

FIGURE 1. Sampling mesh with 100 points, from the experimental grid.

In the experimental area of 60 ha, we planted cotton seeds of the cultivar FM 978 6LTP. Planting was carried out on November 20, 2022, with a spacing of 90.0 cm x 11.7 cm, totaling a population of 95,000 plants ha^{-1}.

The x and y directions of the Cartesian coordinate system were defined and grid, spaced 9.9 m apart (Fig. 1). Each experimental mesh consisted of three transects measuring 49.5 m x 198.0 m. Transects were spaced 9.9 m apart, with sample points squared at 9.9 m x 9.9 m, containing 100 of them. The area corresponding to each experimental mesh was 0.98 ha.

The mechanical resistances of soil to penetration were: RP1, RP2, RP3, RP4, RP5, RP6, and RPM, where the number that accompanies the soil property referred to the soil depth as follows: 1 – depth from 0 to 0.10 m; 2 – depth of 0.10 to 0.20 m; 3 – depth of 0.20 to 0.30 m; 4 – depth of 0.30 to 0.40 m; 5 – depth of 0.40 to 0.50 m; 6 – depth of 0.50 to 0.60 m; RPM referred to the resistance to soil penetration in the layer from 0 to 0.60 m calculated by the average of all readings taken. The determination of soil resistance to penetration was measured up to 60 cm deep as this is an effective depth of the root system of the cotton crop.

To determine soil resistance to penetration, a Falker digital penetrometer model PenetroLOG–PLG 1020 was used. It was configured to record readings at constant penetration speed with the unit in kilopascal (kPa). The measurements were taken one week before the cotton harvest, during the dry season.

To determine gravimetric soil moisture content (W) at each sampling point, soil samples were collected at a depth of 20 cm and taken to the laboratory. The samples were placed in capsules and weighed to obtain the moist soil weight (MSW). They were then placed in an oven at 105ºC for 24 h to obtain the dry soil weight (DSW). Finally, the gravimetric moisture content W was determined using Equation 1.

$$W = \left[\frac{(MSW - DSW)}{MSW} \right] \times 100 \quad (1)$$

Cotton productivity (CP) was determined by harvesting all bolls (fiber and seeds) from three randomly harvested plants at each sampling point. The material was weighed on a precision scale to determine the average per plant in grams. The value was transformed from g per plant to t. The results were multiplied by the number of plants per ha and the cotton productivity (yield) was presented in t ha^{-1}. Khamidov *et al.* (2023), Pereira *et al.* (2023), and Ferreira and Resende (2023), among other authors, carried out experiments with cotton and measured its productivity in t ha^{-1}.

Statistical analysis

For each soil property and for cotton productivity, a classic descriptive analysis was carried out, with the statistical program Rbio (biometrics in R) version 17, in which the mean, median, minimum and maximum values, standard deviation, coefficient of variation, and kurtosis were calculated. Skewness and analysis of the frequency distributiwere carried out. To test the hypothesis of normality or lognormality of the productive components (x), the Shapiro and Wilk test (1965) at 5% was used. In it, the null hypothesis as tested, which is judged to be the sample coming from a population with normal distribution.

Spatial correlation analysis was performed using free and open source software using the Gamma Design Software package (GS+, 2004). For each variable (soil property or plant productivity), its spatial dependence was analyzed by calculating the simple semivariogram which presents the spatial dependency evaluator (SDE). However, for those that showed spatial interdependence, their crossed semivariograms were also calculated, based on the stationarity assumptions of the intrinsic hypothesis. For each variable, the nugget effect (Co), range (Ao) and threshold (Co + C) were related (GS+, 2004).

Working to obtain the ideal number of neighbors, kriging and cokriging maps were obtained, through interpolation, to analyze the dependence and spatial interdependence between the variables.

Results and discussion

Table 1 presents the descriptive analysis of soil properties. From this analysis, it is possible to observe a variation in relation to the evaluated data. Cotton productivity showed a high standard deviation due to the data dispersion, as it is a sampling grid with a large number of points (100). A greater number of sample points provides greater solidity in the resul

Soil resistance to penetration with high values, is the principal symptom resulting from soil compaction creating an impediment from root growth, water and nutrient availability for cotton cultivation (Anghinoni *et al*., 2019). According to Aime *et al.* (2019), in situations of soil compacted in the 0.0-0.25 m layer, the volume of cotton roots is greater on the soil surface, regardless of the cultivar used, due to the limitation of root growth in deeper layers.

Table 2 presents the correlation matrix between productivity and gravimetric moisture and soil resistance to penetration.

Results show the presence of a high correlation between the soil resistance to penetration RP1xRP2, RP1xRPM, RP2xRP3, RP2xRPM, RP3xRP4, RP3xRPM, RP4xRPM, and RP5xRP6. Positive correlations were observed between all penetration resistance depths studied. This result indicates that, at different depths, penetration resistances are correlated with each other in this soil. According to Oliveira *et al.* (2020), who studied resistance to penetration in Oxisols, the same behavior is known.

The correlation matrix also shows a negative correlation between cotton productivity and RP1, RP2, and RP3. This indicates that the greater the soil compaction, that is, the greater soil resistance to penetration, the lower the cotton productivity. The productivity of agricultural crops is affected by soil compaction (Cortez *et al*., 2018). Cotton is a crop susceptible to soil compaction (Nouri *et al*., 2019).

Geostatistical analysis showed the occurrence of a negative spatial correlation between productivity and RP1 (Tab. 3). This result demonstrates an inversely proportional relationship between penetration resistance and cotton productivity, where the lower the resistance to soil penetration, the higher the crop productivity.

TABLE 1. Descriptive analysis of cotton productivity, gravimetric soil moisture content, and soil resistance to penetration in cotton growing area.

Property	Mean	Minimum	Maximum	Standard deviation	Kurtosis	Skewness
CP	3.755	1.311	8.924	93.940	1.154	0.889
RP1	0.644	0.069	1.756	0.380	0.145	0.656
RP2	2.250	0.486	4.302	0.762	-0.367	0.090
RP3	2.665	0.542	4.244	0.845	-0.475	-0.490
RP4	3.035	1.268	4.335	0.637	0.179	-0.394
RP5	3.061	1.906	4.023	0.451	-0.462	-0.246
RP6	2.622	1.646	3.896	0.477	0.197	0.586
RPM	2.343	1.469	3.031	0.346	-0.392	-0.268
W	2.338	1.014	3.779	0.597	-0.778	0.021

CP: cotton productivity, t ha^{-1}; RP1: soil resistance to penetration in 0.0-0.10 m, kPa; RP2: soil resistance to penetration in 0.10-0.20 m, kPa; RP3: soil resistance to penetration in 0.20-0.30 m; RP4: soil resistance to penetration in 0.30-0.40 m, kPa; RP5: soil resistance to penetration in 0.40-0.50 m; RP6: soil resistance to penetration in 0.50-0.60, kPa m; RPM: medium soil resistance to penetration, kPa; W: gravimetric soil moisture content.

TABLE 2. Correlation matrix between cotton productivity, gravimetric soil moisture content, and soil resistance to penetration in cotton growing areas.

	CP	RP1	RP2	RP3
CP	1	-	-	-
RP1	-0.095	1	-	-
RP2	-0.108	0.505**	1	-
RP3	-0.041	0.122	0.556**	1
RP4	0.041	0.155	0.335*	0.690**
RP5	0.151	0.018	-0.200	-0.098
RP6	0.181	-0.068	-0.209	-0.067
RPM	0.012	0.450**	0.686**	0.795**
W	0.041	-0.143	0.024	0.021
	RP4	**RP5**	**RP6**	**RPM**
RP1	-	-	-	-
RP2	-	-	-	-
RP3	-	-	-	-
RP4	1	-	-	-
RP5	0.196	1	-	-
RP6	0.069	0.499**	1	-
RPM	0.785**	0.277*	0.239*	1
W	-0.070	-0.147	-0.032	-0.068

CP: cotton productivity, t ha^{-1}; RP1: soil resistance to penetration in 0.0-0.10 m, kPa; RP2: soil resistance to penetration in 0.10-0.20 m, kPa; RP3: soil resistance to penetration in 0.20-0.30 m; RP4: soil resistance to penetration in 0.30-0.40 m, kPa; RP5: soil resistance to penetration in 0.40-0.50 m; RP6: soil resistance to penetration in 0.50-0.60 m, kPa; RPM: medium soil resistance to penetration, kPa; W: gravimetric soil moisture content. * significant at the 5% level and ** significant at the 1% level according to the Tukey´s test.

TABLE 3. Estimated parameters for the simple and crossed semi-variogram of the components in relation to cotton productivity, gravimetric soil moisture content, and soil resistance to penetration in cotton growing areas.

Property	Adjust -ment	Nugget effect	Level	Range (m)	SSR	SDE (%)	Class
CP	Exp	0.336	2.1	38	0.1400	0.840	Strong
RP1	Gau	0.035	0.150	15	8.74E-04	0.767	Strong
RP2	PNE	x	x	x	x	x	x
RP3	PNE	x	x	x	x	x	x
RP4	Exp	0.160	0.425	25	0.0158	0.624	Moderate
RP5	Exp	0.085	0.205	27	2.25E-03	0.585	Moderate
RP6	Sph	0.140	0.228	34	5.70E-03	0.386	Moderate
RPM	Gau	0.063	0.125	17	7.60E-04	0.496	Moderate
W	PNE	x	x	x	x	x	x
CP x RP1	Gau	-0.003	-0.080	35	1.19E+01	0.934	Strong

CP: cotton productivity, t ha^{-1}; RP1: soil resistance to penetration in 0.0-0.10 m, kPa; RP2: soil resistance to penetration in 0.10-0.20 m, kPa; RP3: soil resistance to penetration in 0.20-0.30 m, kPa; RP4: soil resistance to penetration in 0.30-0.40 m, kPa; RP5: soil resistance to penetration in 0.40-0.50 m; RP6: soil resistance to penetration in 0.50-0.60 m, kPa; RPM: medium soil resistance to penetration, kPa; W: gravimetric soil moisture content. CPxRP1 – correlation between cotton productivity and penetration resistance in 0-0.10 m; SSR – the sum of squared residuals; SDE – spatial dependency evaluator; Exp = exponential; Gau = gaussian; Sph = spherical; PNE = pure nugget effect.

Soil in ideal conditions for root development is explored homogeneously by plant roots and its volume is relatively greater than in soils with compaction problems since compacted soils have increased density, reduced porosity, and increasing resistance to root penetration (Cortez *et al*., 2018). Therefore, the formation of compacted surface layers, especially in relation to the continuous traffic of agricultural machinery, affects root formation, harming plant development and cotton productivity (Ramos *et al*., 2022).

Figure 2 presents the simple semi-variograms and kriging maps of penetration resistance at different depths and cotton productivity.

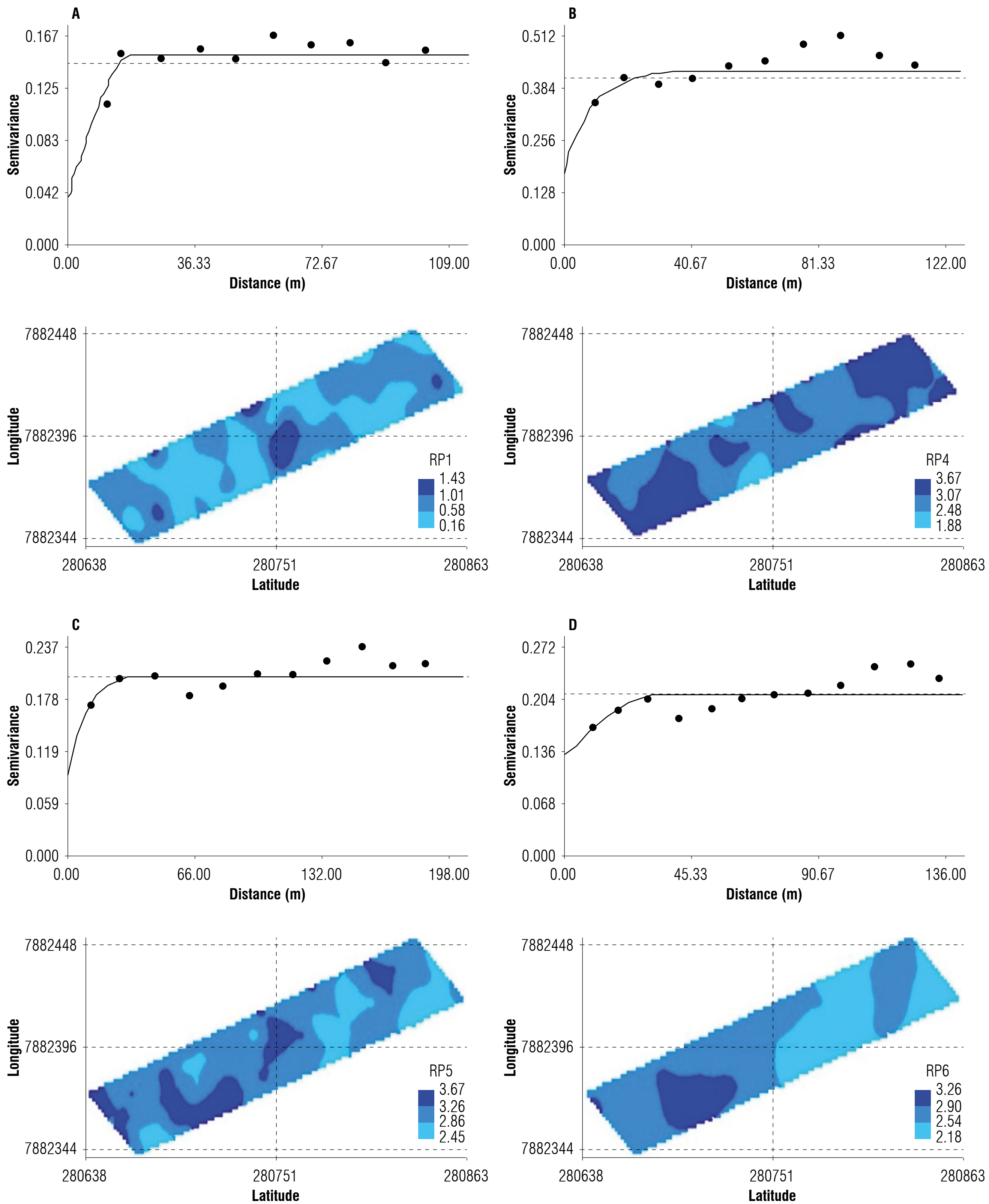

FIGURE 2. Semivariograms and kriging maps: (A) RP1: resistance to soil penetration in 0.0-0.10 m; (B) RP4: resistance to soil penetration in 0.30-0.40 m; (C) RP5: resistance to soil penetration in 0.40-0.50 m; (D) RP6: resistance to soil penetration in 0.50-0.60 m. Continue in the next page

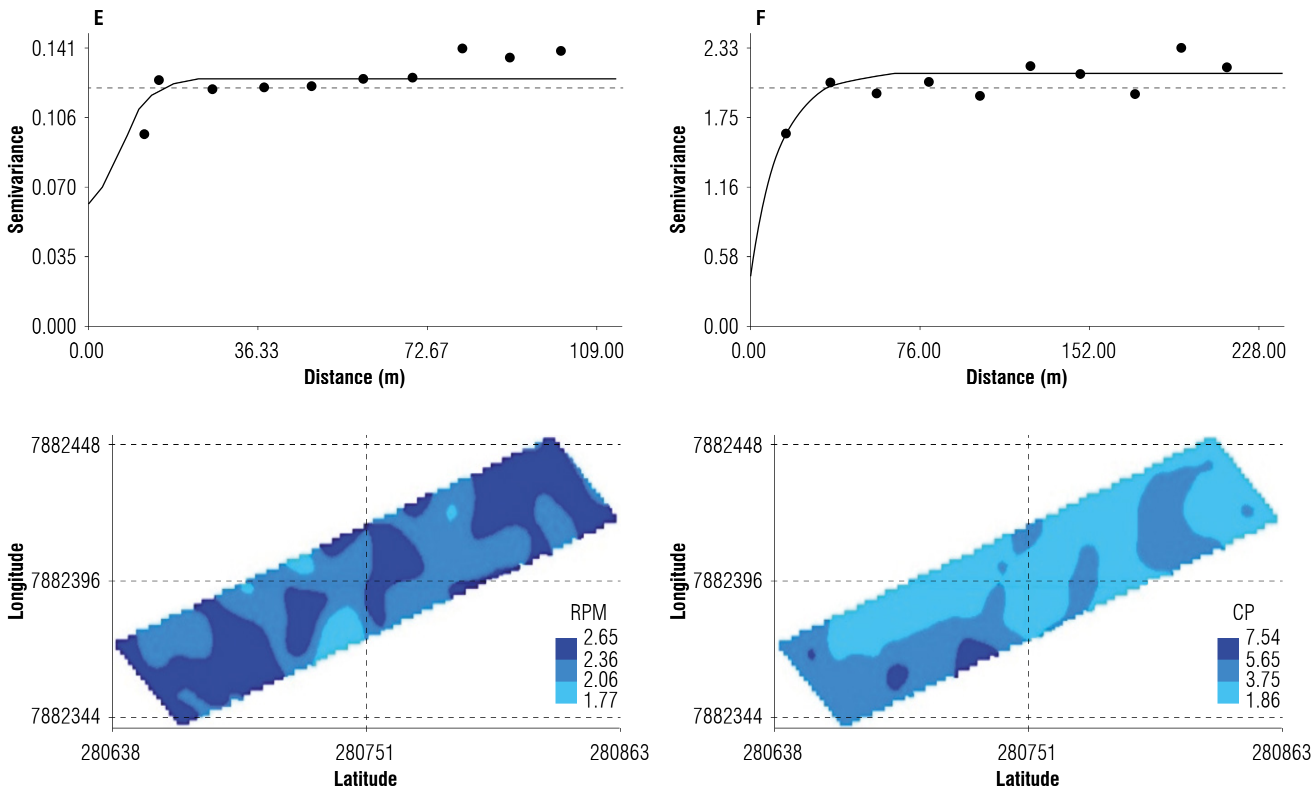

FIGURE 2 continuation. Semivariograms and kriging maps: (E) RPM: medium soil resistance to penetration; (F) CP: cotton productivity.

Analyzing the map (RP1), it is possible to observe that the central part presents higher soil resistance to penetration values in the 0-0.10 m layer, while the southwest region presented the lowest values (Fig. 2A).

On the map that represents the RP4 property, we noted that in the northeast region there are higher penetration resistance values, while in the southwest the values are lower (Fig. 2B). In RP5, the northeast region had the lowest values for soil resistance to penetration in the 0-0.50 m layer, while the central and southwest regions had the highest values (Fig. 2C).

The study area has been cultivated for many years. In addition to cotton cultivation, corn and beans, among other crops, have been planted; and the area has also been used as pasture for cattle. There is a possibility that the traffic of heavy machinery or of animals may have had a strong influence on increasing the soil resistance to penetration. These are reasons why some regions on the maps present higher values of soil compaction.

The RP6 property had the lowest soil resistance to penetration values in the northeast and southeast regions, while the southwest region had the highest values (Fig. 2D). The kriging map that had the average resistance to soil penetration in the center and right and left margins had the highest values (Fig. 2E).

In relation to crop productivity, the lowest values were observed in the central, north and northeast, while the southwest region had the highest values (Fig. 2F).

Figure 3 presents the crossed semi-variograms and kriging and cokriging maps of cotton productivity.

The regions on the map where the highest values of cotton productivity were presented are precisely those in which there was better interaction between the crop and the physical aspects of the soil. That is, regions where the soil presented the lowest mechanical resistance to soil penetration had greater productivity of cotton. This fact was verified in the crossed semi-variogram (CP x RP1) of cotton productivity as a function of the soil's mechanical resistance to penetration at a depth of 0-0.10 m where the semivariogram curve is turned downwards, indicating a negative correlation. This implies that the higher the CP, the lower the RP1 (Fig. 3).

Soil resistance to penetration with high values is a negative and unwanted characteristic that concerns compaction, negatively influencing plant root growth (Silva *et al.*, 2021).

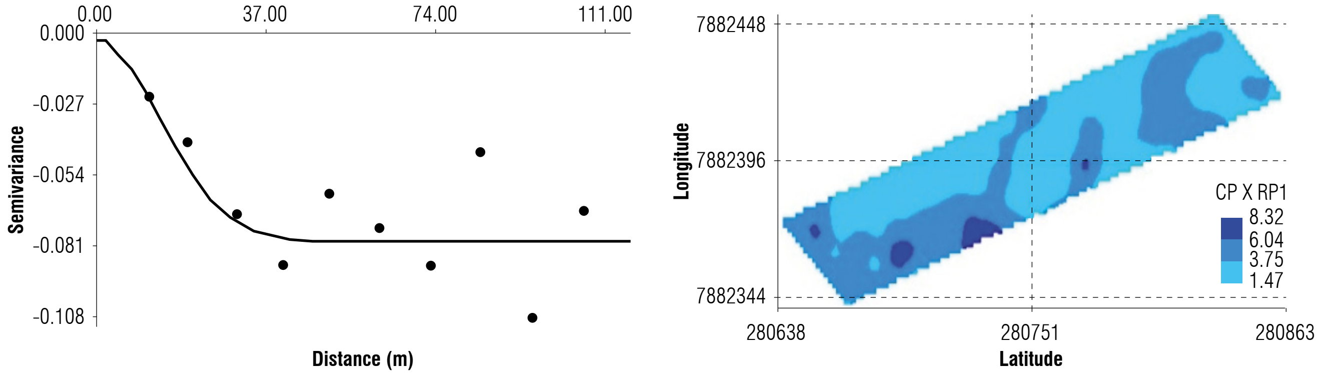

FIGURE 3. Cross semi-variogram and cokriging map. CPxRP1 represents a correlation between cotton productivity and soil resistance to penetration in 0-0.10 m.

The main problem with high resistance of soil to penetration consisted in that it caused negative effects on root growth; and, thus, it reduces the number of leaves, plant height and dry matter (Gubiani *et al*., 2017).

Soils that are resistant to penetration are characterized by roots found in the superficial layers, where plants aim to maximize the absorption of water and nutrients due to the difficulty of exploring deeper layers (Gabriel *et al*., 2021). However, the surface layers of the soil easily lose water through evaporation, subjecting plants to water deficit (Nouri *et al*., 2019). Additionally, compacted soils have lower infiltration rates, leading to waterlogging, which is harmful to crops such as cotton that have low tolerance to waterlogging (Aime *et al*., 2021).

In this study, the variability of soil resistance to penetration in areas cultivated with cotton and its influence on productivity was observed; the greater the resistance to soil penetration, lower the cotton productivity is found. Future perspectives are based on the possibility of continuing the study in the same areas, observing the increase or decrease in soil resistance to penetration using the methods to minimize soil compaction.

Conclusions

Cotton productivity (CP), soil resistance to penetration (RP1), and correlation between cotton productivity and soil resistance to penetration (CPxRP1) showed spatial variability in cotton growing areas presenting a strong degree of spatial dependence.

The penetration resistances RP4, RP5, RP6, and RPM showed spatial variability in cotton growing areas varying in degrees of spatial dependence from higher to moderate. There is an inversely proportional relationship between cotton productivity and soil resistance to penetration, where the lower the soil resistance to penetration, the higher the cotton productivity, indicating that adequate soil management, prioritizing the maintenance of straw and consequently organic matter and avoiding the movement of heavy machinery, are paths to less compacted and more productive soil.

Conflict of interest statement

The authors declare that there is no conflict of interests regarding the publication of this article.

Author's contributions

JPOR: conceptualization, methodology, validation, formal analysis, research, writing - original draft; JTO designed the experiment, analyzed the data, wrote, and edited the manuscript; TRC: resources, writing, review and editing; CGR: validation, resources, writing – review and editing; FFC: validation, writing - review and editing. All authors approved the final version of the manuscript.

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