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Spatial dependence of attributes of rainfed maize under distinct soil cover conditions

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ABSTRACT: Maize crop under rainfed conditions is widely grown in the Brazilian Northeast on community farms for human and animal consumption. The application of mulch could be adopted to enhance rainwater harvesting and soil moisture levels, although such practice is rarely applied in rainfed cultivation. This study aimed to evaluate the spatial variability of maize productivity, based on soil physical attributes and plant growth and yield, under a rainfed regime in the presence and absence of mulch in the Brazilian semi-arid region. The study was conducted from May to September 2016 in Pesqueira - PE (locality of the Semiarid of Pernambuco State, Northeast, Brazil), during which the development and production of maize in experimental plots were evaluated, and maize was grown using the traditional cropping system with and without mulching. Two grids with 40 points in a 4 × 10 m mesh were established, with spacing of 1 m for soil sampling and maize biometric evaluation. For statistical analysis, 30 samples were randomly selected from each plot. Maize cultivated in the presence of mulch showed higher development, with symmetrical distribution for all variables except for soil moisture and stem diameter. Sand content, soil moisture, height of the first cob, number of leaves, leaf length, plant height, and cob weight presented moderate to strong spatial scale dependence for the two cropping conditions, with higher spatial dependence consistently observed for the development parameters in the covered area.

Key words: rainfed agriculture, kriging, coconut powder, mulching, cultivar São José

Dependência espacial de atributos do milho em sequeiro sob distintas condições de cobertura do solo

RESUMO: O cultivo de milho em sequeiro é amplamente explorado no Nordeste Brasileiro pela agricultura familiar, para alimentação humana e animal. Para melhorar a captação da água da chuva e a umidade do solo, pode-se adotar a cobertura morta, embora essa prática ainda seja raramente aplicada no cultivo de milho de sequeiro. Neste contexto, o objetivo deste estudo foi avaliar a variabilidade espacial da produtividade do milho, com base nos atributos físicos do solo e no crescimento e produção da planta, sob regime de sequeiro na presença e na ausência de cobertura morta na região semiárida. O estudo foi realizado de maio a setembro de 2016 em Pesqueira-PE, avaliando o desenvolvimento e a produção de milho em parcelas experimentais, adotando-se o sistema tradicional sem cobertura morta e com cobertura. Estabeleceu-se dois grids com 40 pontos em malha de 4 x 10 m, com espaçamento de 1 m para amostragem de solo e avaliação biométrica. Para análise estatística, foram sorteadas trinta amostras aleatoriamente em cada parcela. O milho cultivado na presença de cobertura apresentou maior desenvolvimento, com distribuição simétrica para todas as variáveis, exceto para a umidade do solo e o diâmetro do colmo. O teor de areia, a umidade do solo, a altura da primeira bifurcação, o número de folhas, o comprimento da folha, a altura da planta e o peso da espiga apresentaram de moderada a forte dependência espacial para as duas condições, com maior dependência espacial sempre observada para os parâmetros de desenvolvimento na área com cobertura morta.

Palavras-chave: agricultura de sequeiro, krigagem, pó de coco, cobertura morta, cultivar São José

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Introduction

As one of the main agricultural products in the Brazilian Northeast, maize is highly relevant to human nutrition and animal livestock. However, maize productivity in the semiarid northeast is sensitive to rainfall regimes, cultivation practices, and climate conditions (Brito et al., 2005; Neves et al., 2015).

In the semiarid region of Pernambuco State, maize is usually cultivated on hillslopes during the rainy season. Maize presents high water use efficiency and high dry matter production per unit of absorbed water (Borges et al., 2014).

In order to enhance crop production under rainfed conditions, soil management adopting conservation practices is highly recommended, especially in areas with high evapotranspiration rates (Sales et al., 2016). In particular, mulching with dry bean straw (Santos et al., 2010) and rice straw (Montenegro et al., 2013; Abrantes et al., 2015) presents high performance for soil and water conservation.

The adoption of mulching by soil water management practices is fundamental for soil moisture control and crop development, soil water storage enhancement, infiltration, and crop transpiration (Zhang & Shao, 2013; Borges et al., 2014; Vereecken et al., 2014). Performance of mulching is influenced not only by vegetation cover, topography, soil texture, and agricultural activity (Lei et al., 2011; Santos et al., 2011), but also by the straw material and cover density (Montenegro et al., 2013; Yang et al., 2014).

Due to the spatial variability of interdependent variables affecting crop production, predicting maize productivity under rainfed conditions is a challenge (Hurtado et al., 2009). Hence, the present study aimed to investigate the content of soil moisture pattern and green maize productivity in a rainfed field cultivation in the semiarid Brazilian Northeast, evaluating the impact of mulching on such variables, and consider small-scale spatial variability.

Material and Methods

This study was conducted in Pesqueira municipality - Pernambuco State, in the representative basin of Alto Ipanema, in an area of 183 km^2 located in the Semiarid Agreste, Northeast Region, Brazil, between 8°34'17" and 8°18'11" latitude South and 37°1'35" and 36°47'20" longitude West. The climate is steppe-type semiarid and very hot, according to Köppen. The annual mean rainfall is 703 mm, mean temperature is 23 °C, and the potential evapotranspiration is 1,683 mm annualy (Santos et al., 2012). The dominant vegetation is hypoxerophilous Caatinga (Montenegro & Montenegro, 2006).

The experiment was conducted on a hillslope in the basin with a 5% slope. The soil of the area was classified as abruptic eutrophic Yellow Argisol (EMBRAPA, 2011), with a clay loam texture, exhibiting an impediment layer at 75 cm depth. The soil density was 1.48 kg dm^{-3} and had volumetric moisture contents of 0.16 and 0.10 cm^3 cm^{-3} for the field capacity and wilting point, respectively (Borges et al., 2014).

Maize (cultivar São José) developed by the Pernambuco State Agricultural Corporation (IPA) was grown in experimental plots 4.5 m wide and 11 m long, corresponding to an area of 49.5 m^2, with the larger dimension along the slope. The monitoring was performed along the X and Y axes, totaling 40 (10 × 4) points per area. Area 1 was under bare soil condition (no mulch), and Area 2 was provided mulching with 8 t ha^{-1} of coconut straw, following the recommendation of Montenegro et al. (2013) for both infiltration enhancement and soil temperature control. Figure 1 presents the experimental maize plots and the experiment location at the Ipanema River Watershed.

Maize sowing was carried out on May 6, 2016: three seeds were sown per pit at a depth of 2.5 cm, rows were spaced 1 m apart, and plants were spaced 0.5 m apart. Thinning was conducted 30 days after sowing (DAS), leaving one plant per pit. Border plants were not included in the analysis. At 120 DAS, plant biometrics were taken for: crop height (CH), crop stalk diameter (CSD), number of leaves (NL), length of the A3 leaf (DA3L), weight of green cob (WGC), and height of the first cob insertion (HFC), following the methodology of Borges et al. (2014).

Rainfall and climate variables for reference evapotranspiration estimation (ETo) using Penman-Monteith Method (FAO56) were measured in a Campbell Scientific automatic weather station installed at the representative catchment.

The antecedent one-month total rainfall before cropping was 80.1 mm, and during the experiment it was 179.8 mm. The average temperature was 22.9 °C, ranging from 19.8 to 27.5 °C.

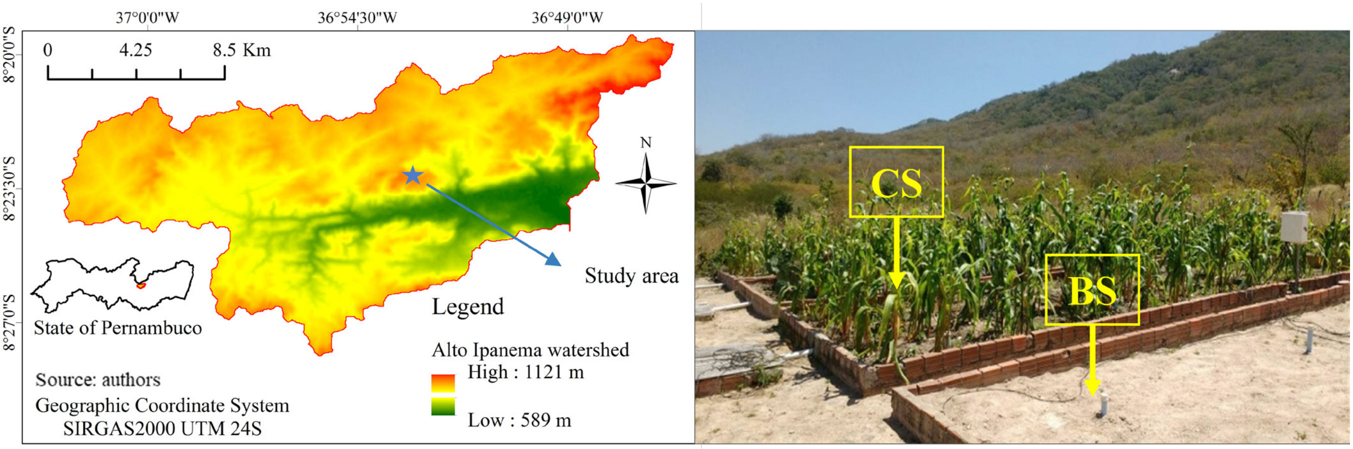

Figure 1. Digital elevation map of Alto Ipanema Representative Basin, and view of the experimental plot, in Pesqueira municipality, Pernambuco State, Brazil

The cumulative reference evapotranspiration was 368.41 mm during the experimental period.

Soil moisture was evaluated in soil samples collected near each plant by the gravimetric method, in the 0-20 cm layer. Soil samples were exposed to 105 ºC for 24 h at the Soil and Water Laboratory of the Federal Rural University of Pernambuco State (UFRPE). Soil texture was evaluated following the methodology of EMBRAPA (2011).

Classic statistical analysis was carried out and normality was evaluated by the Kolmogorov-Smirnov test at 0.05 probability level. Thirty soil samples were randomly selected from each field, as suggested by Castro et al. (2016), in order to conduct the statistical analysis. The coefficient of variation (CV) was classified according to Warrick & Nielsen (1980) criteria as follows: Low variability (CV < 12%), intermediate variability (12 ≤ CV ≤ 60%), and high variability (CV > 60%).

For geostatistical analysis, a classical estimator for the experimental semivariance was adopted according to Montenegro & Montenegro (2006). Thus, semivariance theoretical fits were tested for the Gaussian, Spherical, and Exponential models. Forty sampling points (40 plants) were analyzed for both PC and SD treatments using a regular 1 x 1 m mesh. Outliers were detected and removed based on the Hoaglin et al. (1983) criteria, which classify outliers as values lower than Li (Li = Qi - 1.5 Ai) or higher than Ls (Ls = Qs + 1.5Ai), where Qi and Qs are the lower (25^{th}) and upper (75^{th}) quartiles, respectively, and Ai = Qs - Qi represents the interquartile range. The Spatial Dependence Index (SDI) calculated according to Cambardella et al. (1994) as the ratio between the nugget effect and the sill of the theoretical semivariograms, which represent the nugget semivariance as the percentage of total semivariance. This criterion establishes strong dependence when a given ratio is lower than 25%, moderate for a ratio between 25 and 75%, and weak when the ratio is higher than 75%. The adjusted models were validated using the Jack-Knifing geostatistical technique.

Results and Discussion

Characteristics of the classical statistical analysis for both bare soil (BS) and covered soil (CS) can be verified by inspection of the box plots, shown in Figure 2. The sand content (SC), median values for soil moisture (SM), crop stalk diameter (CSD), height of the first cob insertion (HFC), number of leaves (NL), length of the A3 leaf (DA3L), plant height (PH), and weight of the green cob (WGC) for both plots are represented.

The first and third quartiles exhibit adequate symmetry around the median value, which is located approximately at the center of the boxes and is consistent with the normal distribution hypothesis. It is worth mentioning that the mean soil moisture at the covered plot (0.055) was 59% higher than it was in the bare soil plot (0.022), indicating the effectiveness of the 8 t ha^{-1} coconut straw mulching density in increasing soil moisture content. Such results are in accordance with those obtained by Santos et al. (2010) and Borges et al. (2014) for previous experiments at the same plots and with those of Montenegro et al. (2013) obtained in laboratory experiments. Montenegro et al. (2013) showed that mulching increases soil moisture, enhances infiltration and, hence, contributes to agrosystem service at the Caatinga Biome.

The Table 1 presents the classical statistics for the soil physical attributes and crop development variables for the experimental plots at 120 DAS.

Mulching (CS) positively affected ($p < 0.05$) variables SM, HFC, NL, DA3L, and PH. Similar results were found by Borges et al. (2014), who attributed their findings to higher rainfall retention between rainfall intervals which subsequently influenced crop development.

Statistical interactions among the variables SC, CSD, and WGC for both conditions were not verified.

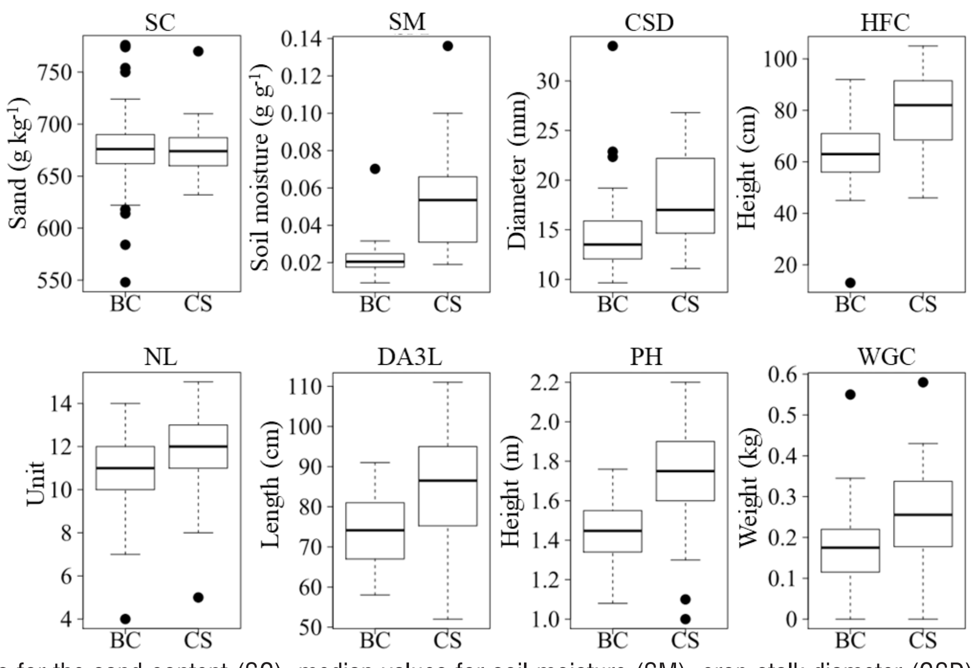

Figure 2. Box plots for the sand content (SC), median values for soil moisture (SM), crop stalk diameter (CSD), height of the first cob insertion (HFC), number of leaves (NL), length of the A3 leaf (DA3L), plant height (PH), and weight of the green cob (WGC) for bare soil (BS) and covered soil (CS) plots

Table 1. Classical statistics for sand content, soil moisture, maize development parameters, and maize production for the absence (BS) and for the presence of mulching (CS) at 120 days after sowing

	Treatments	Variables							
		SC	SM	CSD	HFC	NL	DA3L	PH	WGC
Mean	CS	675.30	0.05	18.08	79.37	11.82	83.83	175	0.25
	BS	677.73	0.02	14.64	64.47	10.52	74.14	144	0.17
P		0.08	<0.001	0.406	0.01	0.004	0.006	<0.001	0.07
CV (%)	CS	3.47	48.63	25.13	19.38	16.57	17.18	15.77	52.73
	BS	6.50	40.56	28.52	21.59	15.75	12.26	11.66	55.78
SDI (%)	CS	33.33	12.96	----	33.33	37.50	1.96	11.36	11.11
	BS	15.12	39.22	----	12.69	0.01	5.37	10.00	44.44

CV - Coefficient of variation; SDI - Spatial dependence index; SC - Sand content, (g kg^{-1}); SM - Soil moisture, g g^{-1}; CSD - Crop stalk diameter, mm; HFC - Height of the first cob insertion, cm; NL - Number of leaves; DA3L - Length of the A3 leaf, cm; PH - Plant height, m; WGC - Weight of the green cob, kg; Significance level of $p < 0.05$ by the F test

Spatial dependence varied from moderate to strong for soil variables and for crop characteristics (Table 1), meaning that such measurements were not randomly distributed at the experimental plots that were not fertilized. Analyzing the impact of fertilization on spatial dependence of rainfed maize production, Hurtado et al. (2009) reported that SDI was moderate to strong when crops were not fertilized, which is consistent with our findings.

Mulching increased the mean values for CSD, HFC, NL, DA3L, PH, and WGC by 19, 19, 11, 12, 18 and 32%, respectively, when compared to treatment without conservation practice. For all crop variables evaluated, moderate variability was observed under mulching.

The highest rainfall rates occurred during the begin of the of the cycle, with a cumulative value of 98.8 mm between May 9 and 10, 2016; the remaining 81 mm of total rainfall was approximately distributed throughout the rest of experimental period. The highest values of daily ETo occurred in the final period of cultivation with 5.99 mm, and the total cumulative value was 368.41 mm.

Green cob production of 10.2 t ha^{-1} under mulching was higher than it was for the bare soil condition (BS) (6.9 t ha^{-1}), with a total precipitation of 179.8 mm in the crop cycle. Reference values proposed by IPA (1995) for the São José cultivar ranged from 8 to 12 t ha^{-1} for the weight of the green cob. Therefore, the experimental values verified that the rainfed mulching treatment was adequate. Thus, only PC treatment promoted production according to the proposed range. Recent research on this variety in the Agreste region of Pernambuco produced 22 t ha^{-1} of total green matter under dry conditions, with 183 mm of precipitation in the crop cycle (Tabosa et al., 2014). Borges et al. (2014) examined mulch cover (7 t ha^{-1}) and rock barriers under natural rainfall condition using the maize variety São José; with 487 mm of total precipitation during the entire cycle, they obtained a green cob matter productivity of 3.24 t ha^{-1} (52.47%) higher than treatment with bare soil.

A Spearman correlation matrix for soil moisture and crop development parameters was constructed. High correlations were observed only between crop characteristics, such as between the height of the first cob insertion (HFC) and the plant height (PH), in both BS and CS conditions, with a correlation coefficient equal to 0.74. In general, Spearman coefficients express weak classical correlation. Indeed, the correlation coefficient between soil moisture and plant height was 0.07 and 0.11 for BS and CS, respectively. Such a result does not necessarily mean that variables are not correlated from a spatial point of view. This issue will be discussed in the next section regarding the geostatistical analysis of field data.

Experimental and theoretical semivariograms are presented in Figure 3A for soil physical attributes and biometric maize variables for both BS and CS conditions. Only the crop stalk diameter (CSD) exhibited random variation and then

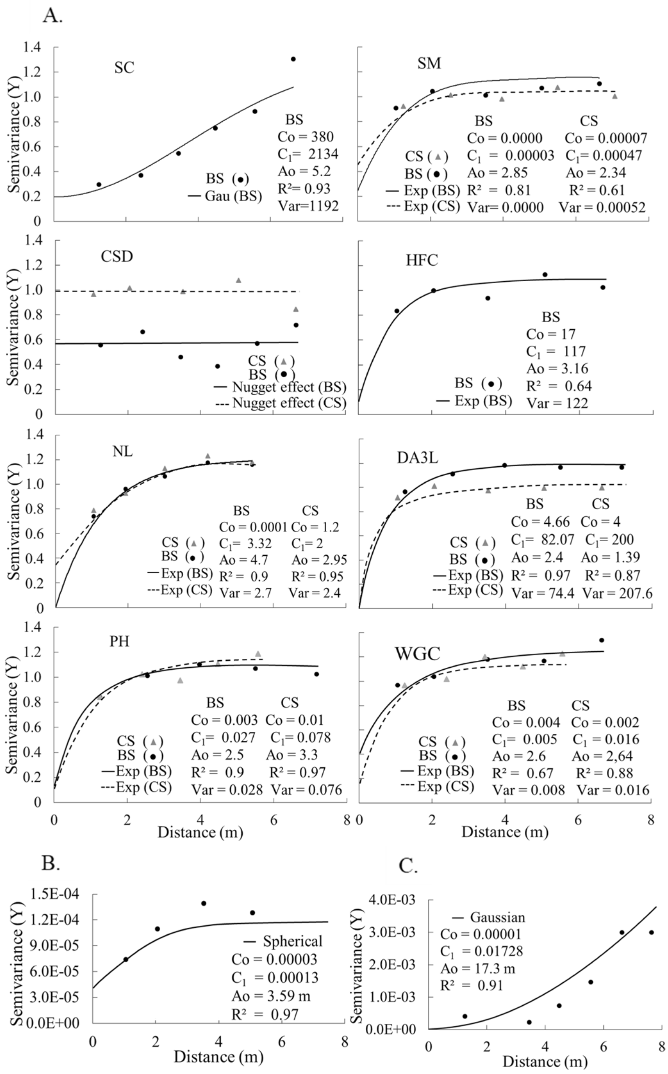

Figure 3. Scaled experimental and theoretical semivariograms for sand content - SC (g kg^{-1}), soil moisture - SM (g g^{-1}), crop stalk diameter - CSD (mm), height of the first cob insertion - HFC (cm), number of leaves - NL (Unit), length of the A3 leaf - DA3L (cm), plant height - PH (m), productivity (kg), for the absence (BS) and the presence (CS) of mulching. (A) Crossed semivariograms for soil moisture (SM) versus plant height (PH) for plots BS (B) and CS (C)

a pure nugget effect pattern. For all other variables, spatial dependence was detected. Except for the sand content (SC) (which was fitted to a Gaussian model), all variables with spatial dependence exhibited exponential behavior.

To investigate the spatial correlation between soil moisture and crop height, cross semivariograms were produced for the experimental plots (Figures 3B and C). Although the point-to-point correlation was weak, spatial correlation was detected for both plots and, exhibiting an exponential (Exp) behavior in BS and a Gaussian (Gau) pattern for CS. The scale of dependence for the cross-correlation increased significantly for the covered plot, and the spatial dependence changed from moderate to strong.

The CS treatment was adjusted to the exponential model, but with R^2 lower than 0.6, with adjusted parameters (Co, C1, Ao, R^2, and Var) for SC (317, 634, 6.7, 0.54, and 552) and HFC (15, 250, 0.87, 0.54, and 237).

Semivariograms for the variables SC, SM, HFC, NL, DA3L, PH, and WGC were validated according to the standard deviation of the residual statistics for CS (1.130, 1.068, 1.037, 1.120, 1.068, 1.000, and 1.071) and BS (1.107, 1.064, 1.150, 0.999, 1.048, 0.971, and 1.040), as well as for average errors of CS (-0.005, 0.043, 0.011, 0.006, 0.007, 0.028, and 0.049) and BS (-0.050, 0.001, 0.021, 0.019, 0.017, 0.055, and 0.030).

Crop stalk diameter (CSD) did not exhibit spatial dependence in either plot, thus presenting a pure nugget effect behavior. All other crop variables presented spatial dependence at the sampled scale, and the experimental semivariance was best fitted to an exponential model. It is noteworthy that the highest scales of dependence were obtained for the height of the first cob insertion (HFC) and plant height (PH), and for both variables the scale of dependence increased when mulching was adopted.

Lima et al. (2015) found that mulching is an effective practice in controlling runoff and thus enhances infiltration and soil moisture. At the same plots adopted in this study, Borges et al. (2014) verified that soil moisture highly increased rainfed maize production.

Strong spatial dependence was observed for the variable SM with the variable HP in US ($R^2 = 0.97$) and CP ($R^2 = 0.91$). The spatial variation by kriging mapping of the plant variables, soil moisture, and texture in plots BS and CP are displayed in Figure 4. The cover plot promoted higher values for SM and other plant variables compared to the plot with BS. This result is likely associated with the presence of coconut powder, which may enable the soil to retain greater moisture for a longer period of time.

The map of SC in BS presented higher values and variability, mainly at the upper left portion of the map. Compared to SM, lower values of this variable are observed at the end of maize cultivation (0.008 to 0.034 g g^{-1}), and only a small portion of the area in the median to direct corner with values from 0.034 to 0.086 g g^{-1}. In the area with CP, SM presented values in the range of 0.008 to 0.112 g g^{-1}. There was a greater variability in SM for the BS area.

The highest values of PH in CS (1.8 to 2.05 m) occurred at the central and northern portions of the area, while the highest values in BS (1.3 to 1.55 m) were distributed in the

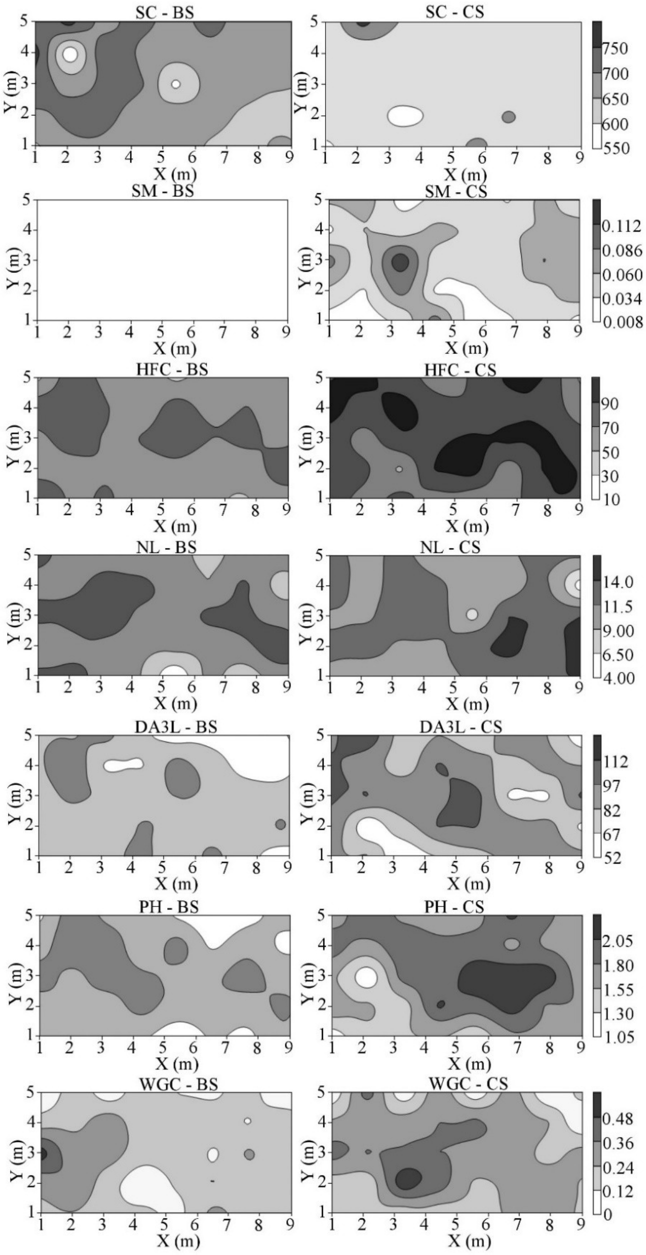

Figure 4. Isoline maps for the sand content - SC (g kg^{-1}), soil moisture - SM (g g^{-1}), height of the first ear - HFC (cm), number of leaves - NL, length of the A3 sheet - DA3L (cm), plant height - PH (m), and weight of green cob - WGC (kg) for the absence (BS) and the presence of mulching (CS)

western central portion of the study area. The lack of mulch resulted in lower infiltration and surface retention of water in BS. Meanwhile, in CS the presence of mulch promoted higher infiltration and water retention, consequently resulting in higher water content in the soil. This result can be verified in the map of SM-CS, wherein the highest values were observed compared to SM-BS. Borges et al. (2014) also observed higher soil moisture with mulching compared to plots without mulching.

The areas with the highest WGC in PC had a strong relationship with the highest ranges of HP and SM, highlighting the strong relationship between mulching and agricultural production. The biometric variables of maize (HFC, NL, DA3L, PH, and WGC) presented moderate to high spatial dependence for treatment with coconut powder (CP). Silva

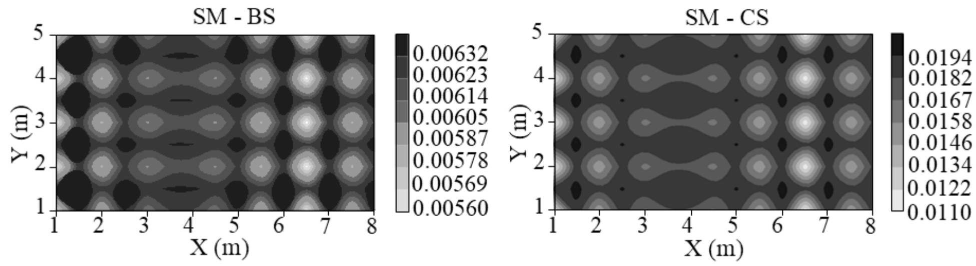

Figure 5. Map of the standard deviation of kriging for soil moisture for the absence (BS) and the presence of mulching (CS)

et al. (2010) emphasized that the spatial variability of soil physical attributes influences the developmental factors and production of agricultural crops. Abrantes et al. (2015) reported that mulching is an essential management practice for the maintenance of a sustainable agroecosystem, as planting in bare soil can promote its degradation. Teame et al. (2017) reinforced that mulching practices promote soil conservation, contribute to water infiltration, reduce evapotranspiration, and improve the local microclimate.

The reliability of the soil moisture mappings can be evaluated on the basis of the kriging standard deviation, as shown in Figure 5. A spatially similar pattern of uncertainty can be noted for both uncovered and mulch conditions.

The standard error maps demonstrate that the soil moisture map estimates were reliable, as the errors were relatively low (mainly in sites closer to the sample points where smaller standard errors are observed). Similar error values were observed by Ferraz et al. (2017) in coffee plantations.

Conclusions

1. Maize grown with mulch (8 t ha^{-1}) presented superior development for all plant variables compared to cultivation in bare soil.

2. The soil and plant variables of the corn cultivar São José presented moderate to strong small-scale spatial dependence for both covered soil and bare soil.

3. Mulching increased the cross-correlation spatial dependence scale between SM and PH from moderate to strong; notwithstanding, such variables have not presented classical correlation.

Acknowledgments

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