Spatial variability of carbon and nitrogen stocks in integrated management systems and pasture in a cerrado region

Variabilidade espacial dos estoques de carbono e nitrogênio em sistemas de manejo integrados e pastagem em região de cerrado

Variabilidad espacial de las existencias de carbono y nitrógeno en los sistemas de manejo integrado y pastizales en la región del cerrado

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Abstract

The conversion of the native Cerrado into agricultural systems promotes a reduction in the input of organic residues on the soil, which can compromise the contents of soil organic carbon. The spatial distribution of carbon and nitrogen stocks in the soil is normally influenced by environmental and anthropogenic factors. This research aimed to map and evaluate the spatial variability of carbon and nitrogen stocks in the soil, in different integrated systems and pasture areas in the edaphoclimatic conditions of the Cerrado biome, in the state of Maranhão. The work was set up in a Red-Yellow Latosol with different management methods: crop-livestock integration with no-till farming, crop-livestock integration with patch scarification and harrowing, crop-livestock-forest integration, and pasture. The samples were removed at a depth of 0.0-0.20 m, in a grid with a regular interval of 50 m, totaling 193 points. The data were subjected to descriptive statistics, geostatistics, and kriging interpolation. The mean and median values are similar for the carbon and nitrogen stocks, in their respective management systems, indicating symmetric data distribution, confirmed by the asymmetry and kurtosis values close to zero. The spatial distribution of the carbon stocks is more homogeneous in the crop-livestock integration with no-till farming, whereas the crop-livestock integration with patch scarification and harrowing presents greater homogeneity in nitrogen distribution.

Keywords: Geostatistics; Soil management; Surface maps.

Resumo

A conversão de Cerrado nativo em sistemas agrícolas promove redução no aporte de resíduos orgânicos ao solo, o que pode comprometer os teores de carbono orgânico do solo. A distribuição espacial dos estoques de carbono e nitrogênio do solo são influenciados normalmente por fatores ambientais e antropogênicos. O objetivo desta pesquisa foi mapear e avaliar a variabilidade espacial dos estoques de carbono e nitrogênio do solo em diferentes sistemas integrados e pastagem nas condições edafoclimáticas do Cerrado maranhense. O trabalho foi montado em um Latossolo Vermelho-Amarelo com diferentes formas de manejo: integração lavoura-pecuária em plantio direto, integração lavoura-pecuária com escarificação e gradagem, integração lavoura-pecuária-floresta e pastagem. As amostras foram retiradas em uma profundidade de 0,0-0,20 m, em uma malha com intervalo regular de 50 m, totalizando 193 pontos. Os dados foram submetidos à estatística descritiva, geoestatística e interpolação por krigagem. Os valores de média e mediana são semelhantes para os estoques de carbono e nitrogênio em seus respectivos sistemas de manejo indicando distribuição simétrica dos dados, confirmado pelos valores de assimetria e curtose próximos a zero. A distribuição espacial dos estoques de carbono é mais homogênea no sistema de integração lavoura-pecuária em plantio direto, enquanto a integração lavoura-pecuária com escarificação e gradagem apresenta maior homogeneidade na distribuição do nitrogênio.

Palavras-chave: Geoestatística; Manejo do solo; Mapas de superfície.

Resumen

La conversión del Cerrado nativo en sistemas agrícolas promueve una reducción en el suministro de desechos orgánicos al suelo, lo que puede comprometer el contenido de carbono orgánico del suelo. La distribución espacial de las reservas de carbono y nitrógeno en el suelo suele estar influenciada por factores ambientales y antropogénicos. El objetivo de esta investigación fue mapear y evaluar la variabilidad espacial de las reservas de carbono y nitrógeno del suelo en diferentes sistemas integrados y pastos en las condiciones edafoclimáticas del Cerrado de Maranhão. La obra se instaló en un Latosol Rojo-Amarillo con diferentes formas de gestión: integración cultivo-ganadería bajo labranza cero, integración cultivo-ganadería con escarificación y desgarrado, integración cultivo-ganadería-bosque y pasto. Las muestras se tomaron a una profundidad de 0,0-0,20 m, en una malla con un intervalo regular de 50 m, totalizando 193 puntos. Los datos fueron sometidos a estadística descriptiva, geoestadística e interpolación por kriging. Los valores medios y medianos son similares para las existencias de carbono y nitrógeno en sus respectivos sistemas de gestión, lo que indica una distribución simétrica de los datos, confirmada por los valores de asimetría y curtosis cercanos a cero. La distribución espacial de las reservas de carbono es más homogénea en el sistema de integración cultivo-ganadería bajo labranza cero, mientras que la integración cultivo-ganadería con escarificación y desgarrado presenta mayor homogeneidad en la distribución del nitrógeno.

Palabras clave: Geoestadística; Manejo de suelos; Mapas de superficie.

1. Introduction

Knowledge of the variation of soil attributes in space in time is necessary for the improvement of techniques that aim at increasing production without expanding farmable areas. However, in order to identify this variation, it is necessary to understand its causes and effects in agriculture. These causes and effects are mostly associated with the interaction between intrinsic and extrinsic factors, which act in different intensities along the landscape, resulting in the spatial variability of the chemical and physical attributes of the soil (Oliveira Junior et al., 2011).

In this context, the evaluation of the spatial variability in of soil organic matter can aid in the understanding of the cause and effect of this variation in different areas since it is considered one of the main soil components, able to provide nutrients and also modify the carbon reserves, which may lead to significant changes in the atmospheric concentration of CO_2, playing an important role in the global C cycle (Sacramento et al., 2018).

The quantification of carbon (C) and nitrogen (N) stocks can be performed using spatial variability. This methodology facilitates the understanding of the heterogeneity of management systems, which may be linked to factors such as immobilization, mineralization, lixiviation, and fertilizers, which interact in a complex way and determine the productive capacity of an agricultural area. For N, it should be considered that its main form of application is through nitrogen fertilization, which may generate spots with high N values (Li et al., 2018). This characteristic can lead to a reduction in productivity and the lixiviation of nitrate into underground waters, especially in soils with sandy texture (Singh et al., 2019).

The use of the geostatistics technique can aid in the identification of the cause and effect of the management, using spatial variability and facilitating the application of inputs at a variable rate (Richart et al., 2016). This type of study has already been employed in several research lines within the soil sciences, such as in the chemical, physical, biological, and mineralogical attributes (Oliveira Junior et al., 2011; Resende et al., 2014; Alho et al., 2014; Li et al., 2018), involving landscape positioning, agricultural crops, soil classes, and management systems.

In integrated management systems, however, woks employing geostatistics are still scarce, and even more notably if the aim is the observation of the behavior of C and N stocks. Studies such as that by Soares et al. (2020), in a Cerrado-Amazon transition region, which approached the spatial variability of the crop-livestock integration system, verified an increase in the C stocks on the soil. Coser et al. (2018), when studying the chemical attributes of the soil in a crop-livestock-forest integration system, reported that geostatistics was useful to reveal the management strategies to be adopted.

This research aimed to map and evaluate the spatial variability of carbon and nitrogen stocks on the soil in different integrated and pasture systems in the edaphoclimatic conditions of the Cerrado biome, in the Maranhão state, in a Red-Yellow Latosol.

2. Material and Methods

The study was developed at the Santa Luzia Farm, in the municipality of São Raimundo das Mangabeiras, MA (6º 49' 48" S and 45º 23' 52" w, 475 m of elevation) inserted in the Cerrado biome. According to the classification by Koppen, the climate of the region fits the Aw type (rainy tropical), with a dry winter and a rainy summer, mean annual temperature of 26.4 ºC, and an annual rainfall of 1,154 mm, with the rainy season between the months of November and April. The soil was classified as a dystrophic Red-Yellow Latosol with clayey texture (Jacomine et al., 1986).

The evaluated areas were named as native Cerrado forest (NCF), crop-livestock-forest integration (ICLF), crop-livestock integration with no-till farming (ICL-1), crop-livestock integration with recent patch scarification and harrowing (ICL-2), and pasture (PA). The chemical and granulometric analysis of the management system areas analyzed in the study is described in Table 1, and the respective management histories are described in Table 2.

Table 1. Chemical and granulometric analysis of the Red-Yellow Latosol subjected to different management systems in the Cerrado region of the Maranhão state, at a 0.0-0.20 m depth.

Areas	pH	P	K^+	Ca^{+2}	Mg^{+2}	Al^{+3}	Ds	Sand	Silt	Clay
	$CaCl_2$	Mg dm^3	----------cmol$_c$ dm^3----------				Kg dm^{-3}	--------g kg^{-1}--------		
NCF	4.9	9.3	0.25	3.7	1.0	0.3	1.25	465	138	397
ICLF	4.5	6.9	0.14	3.8	1.0	0.4	1.27	437	91	472
ICL-1	4.2	27.5	0.4	3.7	0.7	0.6	1.14	449	64	487
ICL-2	4.5	20.1	0.29	4.6	0.7	0.3	1.28	409	111	480
PA	3.9	2.2	0.2	0.4	0.3	1.7	1.44	640	115	245

NCF – Native Cerrado forest; ICLF – Crop-livestock-forest integration; ICL-1 – Crop-livestock integration with no-till farming; ICL-2 – Crop-livestock integration with recent patch scarification and harrowing; and PA – Pasture. P – phosphorus; K^+ – potassium; Ca^{+2} – calcium; Mg^{+2} – magnesium; Al^{+3} – aluminum; Ds – soil density. Source: Authors.

Table 2. Management history of the area at the Santa Luzia Farm, municipality of São Raimundo das Mangabeiras, MA.

Description
Native Cerrado forest
Native forest with Cerrado vegetation, without anthropic interference.
Crop-livestock-forest integration
2003: deforestation, eucalyptus seedlings were implanted and rice was cultivated between the rows; soybean cultivation in the second year; maize - palisade grass (*Brachiaria decumbens* cv. Basilisk) in the third year. After maize harvest, the cattle were introduced, with a stocking rate of 4 animals per ha. The palisade grass remained until 2016.
Crop-livestock integration with no-till farming
1986: deforestation; 1986 to 2000: conventional planting; 2001 to 2005: no-till farming; 2006 to 2017: ICL-1, soybean cultivation with later planting of millet for four consecutive years, two consecutive years of maize intercropped with palisade grass (*Brachiaria brizantha* cv. MG5). After maize harvest, the cattle introduction was performed, with a stocking rate of 2.3 animals per hectare; 2009 to 2016: no soil tillage.
Crop-livestock integration with recent patch scarification and harrowing
1986: deforestation; 1986 to 2000: conventional planting; 2001 to 2007: no-till farming; 2007 to 2017: ICL-2, soybean cultivation with later planting of millet for four consecutive years, two consecutive years of maize intercropped with palisade grass (*Brachiaria brizantha* cv. MG5). After maize harvest, the cattle introduction was performed, with a stocking rate of 2.3 animals per hectare; 2004 to 2015: ICL-2 no soil tillage; 2016: the area was scarified and harrowed.
Pasture
2001: deforestation, rice was cultivated in the 2001/02 cropping season, followed by palisade grass in the next year (*Brachiaria brizantha* cv. MG5), the area kept with pasture until the collection of the samples. Fertilization no longer occurred in the area after the cultivation of palisade grass. The stocking rate is 4 animals per hectare.

Source: Authors.

This is an experimental research with descriptive statistics and geostatistical statistics, with soil collections carried out with the aid of a sampling mesh. Each point collected was georeferenced to assemble the kriging maps (Warrick and Nielsen, 1980; Matheron, 1971; Cambardella et al., 1994; Pereira et al., 2018).

A total of 193 deformed and undeformed soil samples were collected in November 2016, at a 0.0-0.20 m depth, divided as follows: 50 samples for the ICL-1; 50 samples for the ICL-2; 50 samples for the PA; and 38 samples for the ICLF, in a 50 x 50 m sampling grid, totaling 10 hectares for each management system, except for the ICLF, which presented 6.5 hectares, and for the native Cerrado forest 5 compound samples were taken for the comparison of C and N stocks. Each sampling point was georeferenced in order to demarcate the study area and elaborate soil maps with the aid of geostatistical tools.

All samples were stored in identified plastic bags. The soil density analysis was performed in the undeformed samples according to the methodology recommended by Teixeira et al. (2017).

The undeformed soil samples were air-dried, homogenized, and sieved through a 2 mm mesh sieve. For the determination of the contents of total organic carbon and total nitrogen, the soil samples were ground in a mortar and passed through a 0.2 mm mesh sieve. In the determination of the C and N contents, the 990.03 combustion method was used (AOAC, 2002) by employing a LECO® CN628 elemental analyzer (Leco Corp., St. Joseph, Mi, EUA). The C and N stocks were calculated for each soil sample (Mg ha^{-1}) by multiplying the content obtained in % by the soil density (g cm^{-3}) and layer thickness (cm).

The C and N stocks were obtained by correcting the mass of the soil using the soil layer and equivalent mass through the reference soil mass (Ellert and Bettany, 1995). For the calculation of the equivalent mass, the relative soil mass was considered in the different forms of use by the following expression: Msoil= ds x E x A, in which: Msoil = soil mass, expressed in Mg ha^{-1}; ds = soil density, expressed in Mg m^{-3}; E = thickness, expressed in m; A = area, 10,000 m^{2}. After the soil mass definition, the native Cerrado area was considered as a reference area. For the calculation of the areas to be added or subtracted, equation 1 was employed:

$$\text{Ead/sub}=(\text{Mref}-\text{Marea}) \times \text{fha/ds}, \quad \text{(Equation 1)}$$

In which: Ead/sub = soil thickness of the layer to be added (+) or subtracted (-), expressed in m; Mref = equivalent soil mass of the reference area, expressed in Mg ha^{-1}; Marea = equivalent soil mass of the area, expressed in Mg ha^{-1}; fha = conversion factor from ha to m^{2} (0.0001 ha·m^{-2}); ds = soil density, expressed in Mg m^{-3}. The C and N stocks in equivalent mass were obtained by equation 2:

$$Est=cc \times ds \times (E \pm Ead/sub) \times A \times Fkg, \text{ (Equation 2)}$$

In which: Est = C or N stock per unit of area in an equivalent layer, expressed in Mg ha^{-1}; cc = concentration of C or N, expressed in g·kg^{-1}; ds = soil density, expressed in Mg·m^{-3}; E = thickness of the soil layer studied, expressed in m; Ead/sub = thickness of the soil layer to be added (+) or subtracted (-), expressed in m; A = area, considering 1 ha, that is, 10,000 m^2; Fkg = conversion factor from kg to Mg (0.001 Mg ha^{-1}).

The results obtained were analyzed based on descriptive statistics by calculating the measures of position (mean, median, minimum, and maximum), variability (coefficient of variation – CV), and central tendency (asymmetry and kurtosis), in order to verify the normality of the evaluated attributes. For the analysis of the CV, the classification by Warrick and Nielsen (1980) was adopted, with low variability for values lower than 12%, average variability for values between 12 and 60%, and high variability for values above 60%.

Spatial dependence was analyzed by adjusting the semivariograms, based on the presupposition of stationarity of the intrinsic hypothesis. The GS$^{+®}$ software was used to obtain the semivariograms. The spherical, exponential, and Gaussian models were adjusted to the data. The choice of the theoretical models was performed by observing the residual sum of squares and the coefficient of determination (R^2). Through the models it was possible to perform the prediction of each attribute in non-sampled zones through kriging, represented in contour maps, using the Surfer® software for the C and N stocks.

The classification of the degree of spatial dependence (GDE) was performed based on the ratio between the nugget effect and the sill through the mathematical formula $(C_0/C_0+C_1)^*100$, with values under 25% being considered as high, moderate between 25% and 75%, and week when above 75% (Cambardella et al., 1994).

3. Results and discussion

3.1 Descriptive statistics

The mean and median values are similar for the C and N stocks (Table 3) in their respective management systems, indicating symmetrical data distribution, confirmed by the values of asymmetry and kurtosis close to zero. When these measures coincide, the use of geostatistics is perfectly applicable (Alho et al., 2014; Corado Neto et al., 2015). However, some attributes have distant values from zero, indicating an asymmetrical distribution.

Table 3. Descriptive statistics for the C and N stocks (Mg ha^{-1}), in a Red-Yellow Latosol under different management systems, at a 0.0-0.20 m depth.

Variable	Mean	Median	Min.	Max.	CV (%)	Asy.	Kur.	w
	Crop-livestock-forest integration							
Carbon stock	37.30	35.20	27.65	54.19	20.63	0.84	-0.27	*
Nitrogen stock	2.59	2.43	1.21	4.08	27.18	0.35	-0.40	ns
Crop-livestock integration with no-till farming								
Carbon stock	68.30	68.26	53.86	82.85	9.22	-0.17	-0.11	ns
Nitrogen stock	4.04	4.11	2.88	4.90	12.18	-0.44	-0.22	ns
Crop-livestock integration with patch scarification and harrowing								
Carbon stock	68.50	67.66	49.16	86.15	12.60	0.24	-0.49	ns
Nitrogen stock	3.80	3.96	0.71	5.58	27.74	-1.24	1.74	*
Pasture								
Carbon stock	54.46	53.15	36.94	76.63	17.81	0.64	-0.14	ns
Nitrogen stock	1.31	1.20	0.06	5.78	77.90	2.17	7.01	*
Native Cerrado Forest								
Carbon stock	32.00	-	-	-	-	-	-	-
Nitrogen stock	2.20	-	-	-	-	-	-	-

Asy.: asymmetry; Kur.: kurtosis: Min.: Minimum: Max.: Maximum; CV: coefficient variation; w – Shapiro-Wilk Test; *: non-normal distribution ($p < 0.05$), ns: normal distribution ($p > 0.05$). Source: Authors.

When analyzing the chemical attributes of the soil in an area of agricultural production, Matias et al. (2015a) observed similar results in the Cerrado region of the Piauí state, confirming that the attributes could be represented by the mean since they had demonstrated a normal frequency distribution, that is, the mean and the median with similar values and asymmetry and kurtosis close to zero.

Based on the kurtosis coefficient, which shows the dispersion of the distribution in relation to a normal curve (mesokurtic), the C stocks data for all management systems presented a platykurtic distribution lower than the normal curve, with a smooth flattening close to zero, in which the values varied from -0.49 to -0.11. The N stocks in the systems of crop-livestock integration with recent patch scarification and harrowing (ICL-2) and pasture (PA) presented a leptokurtic behavior, that is, with a peak of data distribution above the normal, especially for the PA (Table 3), which distanced from the zero value (the closest to zero the better is the data distribution of kurtosis) (Silva et al., 2018).

The coefficient of variation (CV), according to the classification proposed by Warrick and Nielsen (1980), ranged from 12 to 60% for the C stocks in the systems of crop-livestock-forest integration (ICLF), ICL-2, and PA, thus being considered as a moderate variation. However, the C stocks of the crop-livestock integration with no-till farming (ICL-1) presented low variability, with a CV of 9.22%. For the N stocks, the variability was moderate for the ICLF, ICL-1, and ICL-2 systems. The highest concentration amplitude of the element on the soil was verified for the PA system, varying from 0.06 to 5.78, indicating a (high) variability that cannot be detected due to the distance between the sampled points (Richart et al., 2016). The works by Matias et al. (2015b), Matias et al. (2015a), and Corado Neto et al. (2015) found low and moderate CV for the chemical attributes of the soil in the Cerrado. The variability of the chemical attributes is the reflection of the interactions of formation processes, soil management practices, and crops, with a marked impact at superficial soil depths (Matias et al., 2015a).

Conversely to the results verified in this study, Wollenhaupt, Mulla and Crawford (1997) reported that a moderate CV is not necessarily a good indicator of spatial variability due to the occurrence of extremely low and high values, which applies to the present study when observing the disparity between the minimum and maximum values (Table 3).

The large amplitude observed in the N stock in the PA system is probably related to the lack of fertilization throughout time, leading to soil exhaustion and resulting in a predominance of values close to the mean 1.31 Mg ha^{-1}. Braz et al. (2013), when comparing different pastures in Chapadão do Sul, MS, found N stock values varying from 1.61 to 1.78 Mg ha^{-1} in a degraded pasture, at a 0.0-0.30 m depth.

When evaluating the chemical attributes of the soil in an ILP system in the Cerrado-Amazon transition region, Soares et al. (2020) verified amplitude values for the C and N stocks varying from 7.47 to 32.59 Mg ha^{-1} and from 0.54 to 2.37 Mg ha^{-1}, respectively, at a 0.0-0.10 m depth. Matias et al. (2015b) observed an amplitude from 12.0 to 17.0 $g{\cdot}kg^{-1}$ for organic matter, at a 0.0-0.20 m depth, in a no-till planting system in the conditions of the Cerrado biome, in the Piauí state.

The results generated by the Shapiro-Wilk test confirmed the normal distribution for the C stocks of the ICL-1, ICL-2, and PA systems, whereas for the N stocks the normality was verified for systems ICLF and ICL-1. Although the Shapiro-Wilk test concluded that the C stocks of the ICLF system and the N stocks of the ICL-2 and PA systems did not present normality, they possess a tendency towards normality due to the asymmetry and kurtosis values close to zero and to the similarity between the mean and median values (Table 3) (Soares et al., 2020).

Although the normality test is not an imposition for geostatistics application, it is recommended that the distribution does not present heavy tails so that the analyses are not compromised, considering that the kriging estimations present better results when data normality is satisfactory, presenting a symmetrical distribution (Corado Neto et al., 2015).

3.2 Geostatistics

According to the parameters of geostatistics (Table 4), all analyzed variables present spatial dependence, indicating that the performance of the regionalized variables was not random and that the distance between the points used in the sampling grid was satisfactory for the study of spatial variability, in this area.

Table 4. Parameters of the semivariogram models adjusted for the C and N stocks in a Red-Yellow Latosol under different management systems, at a 0.0-0.20 m depth.

Variable	C_0	$C_1 + C_0$	A_0 (m)	GDE (%)	R^2	Modelo
	Crop-livestock-forest integration					
Carbon stock	23.3	87.60	714.3	26.60	0.82	Exp.
Nitrogen stock	0.03	0.42	106.4	7.14	1.00	Exp.
Crop-livestock integration with no-till farming						
Carbon stock	2.51	32.61	82.80	7.70	0.99	Exp.
Nitrogen stock	0.03	0.25	95.70	12.00	0.90	Exp.
Crop-livestock integration with patch scarification and harrowing						
Carbon stock	47.3	247.5	838.60	19.11	0.92	Gau.
Nitrogen stock	0.05	0.51	132.60	9.80	0.82	Exp.
Pasture						
Carbon stock	17.20	75.15	140.60	22.89	0.90	Exp.
Nitrogen stock	0.26	2.08	1577.70	12.50	0.85	Gau.

C_0 – pure nugget effect; $C_1 + C_0$ – sill; A_0 – range; R^2 – coefficient of determination; GDE ((C_0/(C_1 + C_0) * 100)) – degree of spatial dependence, strong < 25%, moderate from 25 to 75%, weak > 75%; Exp.: Exponential; Gau.: Gaussian. Source: Authors.

The spatial dependence was considered strong for all variables in their relative management systems, except for the C stocks of the ICLF system, which exhibited a moderate spatial dependence (26.60%), according to the classification by Cambardella et al. (1994) (Table 4). The strong spatial dependence suggests that the model was sufficient to detect the existing variability in the area, indicating that the soil attributes are not randomly distributed in space and that these attributes are intrinsically influenced by intrinsic factors of the soil, such as the source material, mineralogy, relief, organisms, and time. A weak spatial dependence can be attributed to factors such as soil preparation, machinery traffic, and fertilization (Cambardella et al., 1994).

The semivariograms were calculated to determine any spatially-dependent variation within the field, adjusting to two models: exponential and Gaussian (Table 4), agreeing with Alho et al. (2014) and Oliveira et al. (2018), when studying C stocks in native field and agroforestry areas, respectively, and obtained the best adjustment for the exponential model.

The range is an important parameter in the study of semivariograms since it leads to the understating of the maximum distance in which one variable undergoes interference by another, that is, it is spatially correlated. Above this value, the distribution of the sampling points becomes independent, with no interference between samples. The more homogenous is the cultivation area, the wider is the range (Resende et al., 2014; Matias et al., 2015a).

The management system that presented the widest range was the PA (1,577.70 m for the N stocks), whereas the lowest was the ICL-1 system (82.80 m for the C stocks), values that determine the limit that spatial dependence can reach, from which it will cease existing (Resende et al., 2014). Corado Neto et al. (2015) reported that the shorter the range, the greater the independence between samples, attributing this factor to possible management practices adopted in each evaluated area.

It is imperative to observe that the management systems in this study possess specific characteristics, such as the eucalyptus in the ICLF system, the constant presence of animals in the PA system, soil tillage and nitrogen fertilization in the ICL-2 system, and the absence of soil tillage for 8 years in the ICL-1 area. These factors can make the range present different behaviors between systems, such as described by Oliveira et al. (2018). When studying the spatial variability of soil chemical attributes, such as the C stocks in the PA and agroforestry systems, as well as in the cultivation of cassava and sugarcane, the authors observed that the range was different for each of these areas and that the soil chemical attributes are altered according to the cultivated species and the management adopted.

According to Resende et al. (2014), the landscape areas under the same soil class and similar management are influenced by the shape and slope of the soil, presenting different spatial variability patterns of soil chemical attributes, considering the landscape as a strategic factor in the study of spatial variability.

Wide ranges indicate the opportunity to perform a more spaced sampling. However, this does not mean that the sampling will manifest high precision when performed in the same distances of the ranges. It is known that shorter distances result in greater spatial dependence and, as they increase, they gradually reduce dependence to the range limit (Isaaks and Srivastava, 1990).

Semivariograms are analyzed through the decreasing ratio of their respective coefficients of determination (R^2) (Table 4), which indicated a good adjustment for all management systems. The model with better adjustment was the exponential, with R^2 of 1.00 for the N stocks of the ICLF system and 0.99 for the C stocks of the ICL-1 system. The Gaussian model also presented good adjustments, with R^2 of 0.92 for the C stocks of the ICL-2 system.

3.3 Kriging – maps

Based on the results obtained from the semivariograms, the spatial distribution maps of the attributes of the C (Figure 1) and N stocks (Figure 2) were made. The kriging technique allows estimating the C and N values in non-sampled spots.

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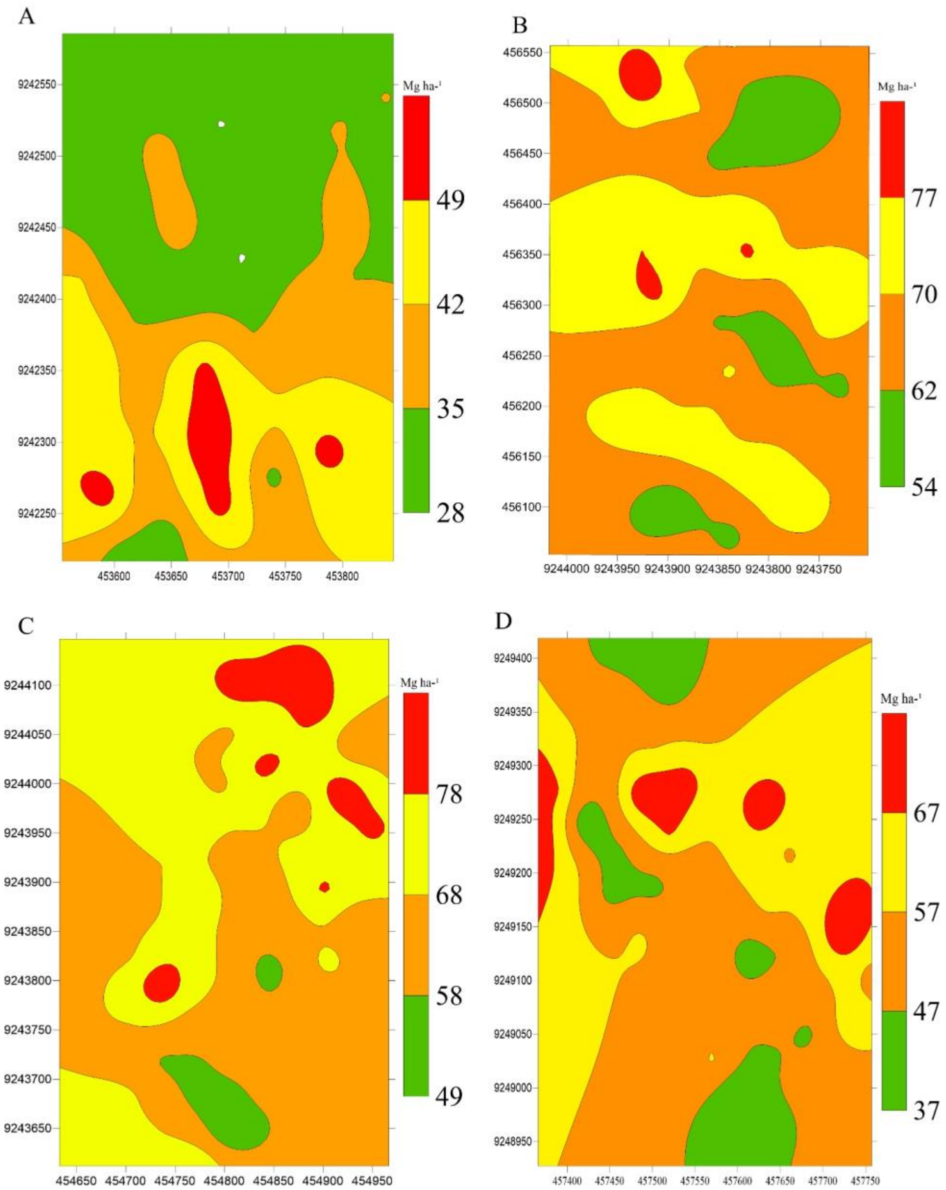
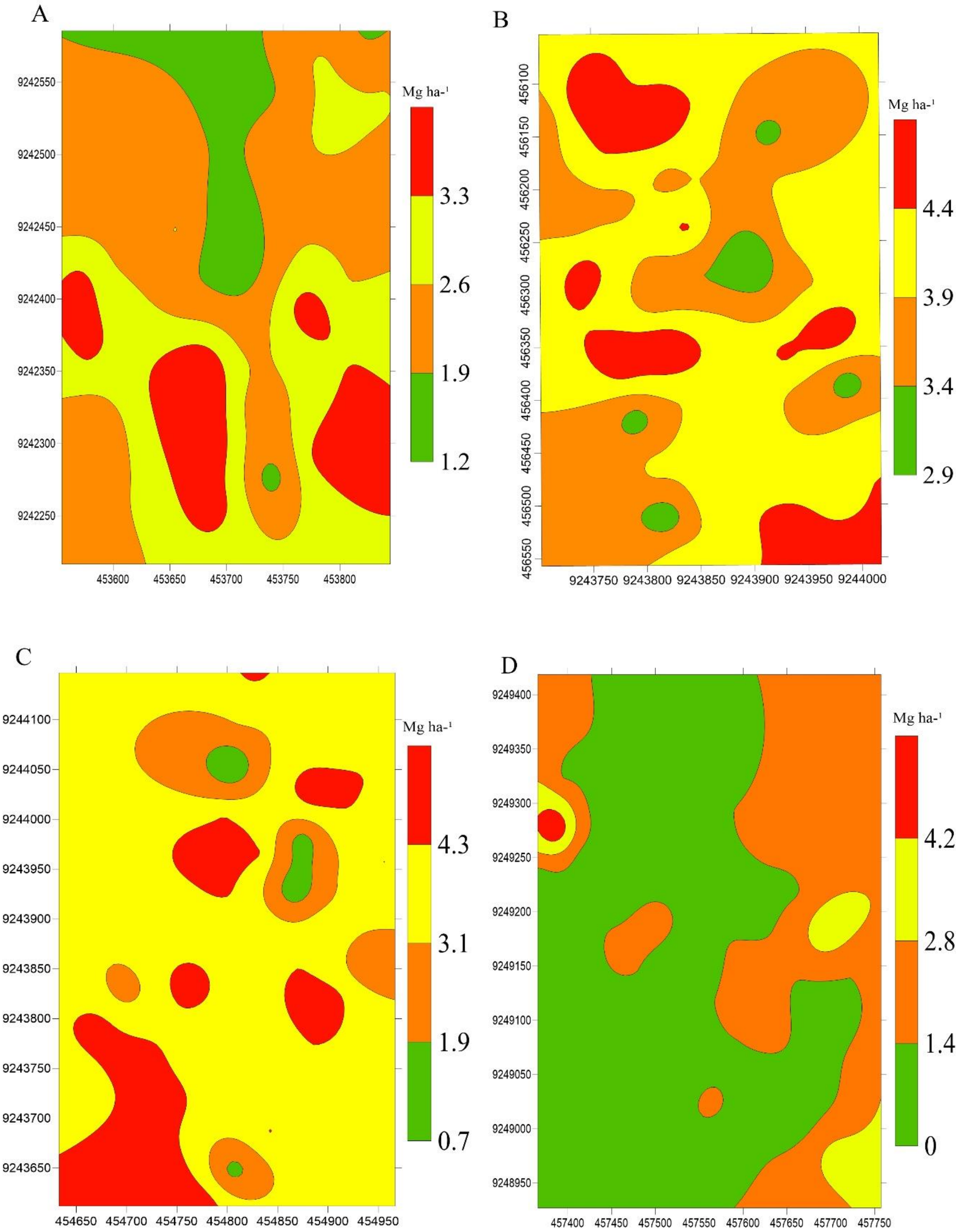
Figure 1. Distribution maps of the carbon stocks for the ICLF (A), ICL-1 (B), ICL-2 (C), and PA (D) management systems, at a 0.0-0.20 m depth.



Source: Authors.

Figure 2. Distribution maps of the nitrogen stocks for the ICLF (A), ICL-1 (B), ICL-2 (C), and PA (D) management systems, at a 0.0-0.20 m depth.



Source: Authors.

The isolines that compose the maps indicate the degree of variability of the C and N stocks; the closed and close lines characterize an area of greater variability, and the spaced lines expose conditions of lower variability (Figures 1 and 2). The maps generated through kriging can be used as a tool to identify specific management areas according to the color distribution in the maps (Matias et al., 2015b). In the individual case of the N stocks, the areas that possess greater color variation indicate that the form of management may be resulting in lower nutrient utilization by the plants, except for the PA area (Figure 2d), whose predominant values are under 1.4 Mg ha^{-1}.

For the ICLF system, an abrupt division of the C stock values is observed, with one range varying from 28 to 35 Mg ha^{-1} and another from 35 to 42 Mg ha^{-1} (Figure 1a). Likewise, the lowest N stock values were also verified in the same areas with lower C stocks. This is an important situation to be observed for the ICLF system since it does not receive nitrogen fertilization, justifying the importance of the deposition of residues on the soil by the eucalyptus, pasture, and animals (manure), and highlighting the need to review nitrogen fertilization strategies between the eucalyptus rows.

Regarding the ICL-1 system, the variation of the values above de 77 Mg ha^{-1} is represented in a more punctual way, being surrounded by the C stocks close to the mean (68 Mg ha^{-1}). Lower values between 54 and 62 Mg ha^{-1} also occurred as smaller spots in the map (Figure 1b), in which the ICL-1 system is highlighted for presenting a uniform aspect in the spatial distribution of C, due to the predominance of values above 62 Mg ha^{-1}. This fact is probably related to the 8 years in which no soil tilling was performed in the area, to the cultivation of crops with a higher C/N ratio, such as millet (after the soybean harvest), and the intercropping of maize with palisade grass, which minimized C losses throughout time (Pacheco et al., 2013), resulting in greater uniformity, such as expressed on the map.

In the ICL-1 system, the highest N stock values were observed in the areas with higher C concentration, which reinforces the relation between N and soil organic matter. It is worth noting that nitrogen fertilization did not occur in the area. Li et al. (2018) studied the impact of nitrogen fertilization on the microbiological variables of the soil and found heterogeneity in the spatial distribution of C and N of the microbial biomass, which is caused by the uneven application of the nitrogen fertilizer. Thus, above-average N stock spots (4.0 Mg ha^{-1}), between 3.9 and 4.4 Mg ha^{-1}, are noticeable on the map (Figure 2b).

The distribution of C in the ICL-2 system (Figure 1c) presented a different behavior from the ICL-1 system, although the mean values were close (Table 3). In the ICL-2 system, the isolines that delimit values between 58 and 68 Mg ha^{-1} and between 68 and 78 Mg ha^{-1} occupy an expressive area of the map. The values between 49 and 58 Mg ha^{-1}, which are below the average (68.5 Mg ha^{-1}), are presented in a punctual form on the map, and there was a greater merging of isolines, which can be attributed to the process of scarification and harrowing performed in the area.

In the ICL-2 system, the nitrogen fertilization (broadcast fertilization) allowed greater homogeneity, in which the spots with values between 0.7 and 1.9 Mg ha^{-1} were less representative on the map, promoting a higher frequency of values close to the mean (3.8 Mg ha^{-1}) (Figure 2c).

For the C stock of the PA area, the values between 47 and 57 Mg ha^{-1} (Figure 1d) prevailed on the map and run along its entire extension. These values do not indicate a reduction in the C stock values if considering the NCF as a parameter, which possesses a mean C stock value of 32 Mg ha^{-1}. However, the PA map shows that high C stock values C (>67 Mg ha^{-1}) are represented by closed isolines, suggesting the isolation of these values and a tendency towards the reduction of the C stocks over time.

It is worth noting that the PA of the present work is neither corrected nor fertilized and the presence of cattle is constant. Besides the low animal productivity, poorly-managed pastures contribute to losses in soil organic matter due to reductions in the quantity and quality of the biomass deposited on the soil (Soares et al., 2020). For the N stocks, the values were grouped around the mean (1.31 Mg ha^{-1}) and filled almost the totality of the map, whereas values from 1.4 to 2.8 Mg ha^{-1} are less representative and occupy marginal areas of the map (Figure 2d).

With this work, it is verified that even in a well-managed area there is a possibility to find variations in the C and N stocks, originated from the input of residues in the shoot and root parts of the crops.

4. Conclusions

The geostatistics technique identified variations in the contents of carbon and nitrogen in areas with the same management system, indicating the need for a more specific control in determined places.

The spatial distribution of the carbon stocks is more homogenous in the crop crop-livestock integration with no-till farming, whereas the crop-livestock integration with recent patch scarification and harrowing presents greater homogeneity in the distribution of nitrogen.

For future research, the use of spatio-temporal geostatistics is recommended, which will enable greater robustness to the results. Test kriging in areas with a history of conventional planting and in eucalyptus forests and observe the behavior of carbon and nitrogen stocks.

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