IJANR
International Journal
of Agriculture
and Natural Resources

*Int. J. Agric. Nat. Resour. 50(2):58-74. 2023*
*www.ijanr.cl*

ENVIRONMENTAL AND ECOLOGY

DOI 10.7764/ijanr.v50i2.2446

RESEARCH PAPER

# Spatial variability of soil organic carbon fractions in areas under cultivation of Amazonian species in the southern region of Amazonas state, Brazil

José Igor Silva Praça[1], Bruna Firmino Enck[1], Milton César Costa Campos[2], Marcos Gervásio Pereira[3], Fernando Gomes de Souza[4], Bruno Campos Mantovanelli[1], Elilson Gomes de Brito Filho[2], Laercio Santos Silva[5], and José Maurício da Cunha[1]

[1]Universidade Federal do Amazonas, Humaitá, Amazonas, Brasil.
[2]Universidade Federal da Paraíba, Areia, Paraíba, Brasil.
[3]Universidade Federal Rural do Rio de Janeiro, Seropédica, Rio de Janeiro, Brasil
[4]Universidade Federal de Roraima, Boa Vista, Roraima, Brasil.
[5]Universidade Federal de Rondonopolis, Rondonopolis, Mato Grosso, Brasil.

## Abstract

**J. I. Silva Praça, B. F. Enck, M. C. Costa Campos, M. G. Pereira, F. Gomes de Souza, B. Campos Mantovanelli, E. Gomes de Brito Filho, L. Santos Silva, and J. M. da Cunha. 2023. Spatial variability of soil organic carbon fractions in areas under cultivation of Amazonian species in the southern region of Amazonas state, Brazil. Int. J. Agric. Nat. Resour. 58-74.** Soil organic carbon (OC) is heterogeneous and sensitive to agricultural management, so knowledge of its spatial variability can improve the monitoring of areas under anthropogenic influence, as OC can serve as a sensitive indicator of changes in the environment. The objective of this study was to evaluate the spatial variability of soil OC fractions in areas of cultivation with Amazonian species in the southern region of Amazonas state. A total of 256 georeferenced data points were collected in the 0.0–0.05 m and 0.05–0.10 m layers in the following agricultural systems: areas with cultivation of Guaraná, Annatto, Cupuaçu and forest. The OC contents were analyzed, and the chemical fractionation of soil organic matter was performed. The analytical results were evaluated through descriptive statistical analysis, and the spatial pattern was evaluated through geostatistical analysis. The conversion of natural ecosystems to agricultural systems affected the rates of addition and decomposition of soil organic matter. Changes in soil organic carbon stocks (SOC stock) due to the uses of different agricultural systems were determined by evaluating the free light fraction of soil organic matter. For the chemical fractions of organic matter, there was a predominance of the humin fraction (C-HU) in relation to the fractions of humic acid (C-FAH), fulvic acid (C-FAF) and OC associated with minerals (COAM) in the different land uses and soil layers analyzed. The geostatistical procedures proved to be important in determining the degree of carbon dependence and its fractionation in the context of spatial variability, and this information is useful in soil quality monitoring.

**Keywords**: soil attributes, chemical fractionation, forest, geostatistics, mapping.

---

Received Ago 09, 2022. Accepted Ago 01, 2023
Corresponding mcesarsolos@gmail.com

## Introduction

Soil is considered an essential natural resource for agricultural production and the provision of ecosystem services (Melo et al., 2021). Human actions have modified soil attributes over time, and these modifications can cause a loss of fertility, changes in physical attributes and decreases in organic matter content, which can lead to soil degradation (Oliveira et al., 2015; Paris et al., 2020).

In the Amazon region, soils are greatly influenced by climatic components (rainfall and temperature) that, together with the relief, culminate in the formation of different soil classes, with a predominance of Ultisols and Oxisols, which are physically suitable for agricultural use; however, these soils have poor fertility, with high aluminum contents and low pH (Campos et al., 2012). Even so, several plant species, notably those native or better adapted to the region, manage to develop well and achieve satisfactory production.

The soil organic matter in the Amazon becomes important and is strategic for sustainable soil (or land) use, as changes in this fraction have consequences for other soil attributes. In several studies addressing soil organic matter, with an emphasis on Rodrigues et al. (2017), the conversion of forests into agroecosystems tends to modify the dynamics of organic matter and nutrient cycling in the Amazon biome. Thus, knowledge of the levels and fractions of organic carbon is fundamental in the management of soil organic matter, especially in environments where areas of native forest are converted into cultivated areas (Owuor et al., 2018; Gomes et al., 2017; 2018; Silva et al., 2021).

Moreover, some studies have noted that this conversion of forest into agroecosystems may have little effect on carbon levels (Gomes et al., 2017). However, it depends greatly on the management of the area (Araújo et al., 2011; Oliveira et al., 2017; Boy et al., 2018). Thus, in the management of soil organic matter, it is important to consider the culture, cultural practices, and use of inputs. In this context, monitoring the spatial variability of organic carbon fractions is necessary to obtain a representative diagnosis of the study site since the use of more accurate methods makes it possible to verify how the soil attributes behave spatially using geostatistical techniques (Rodrigues et al., 2017; Gomes et al., 2018; Zhang et al., 2022).

Recent concepts of soil organic matter formation indicate that its formation is a continuous process by which soil fauna and microbes gradually transform large plant residues into small molecules that bind to mineral surfaces or enter soil aggregates and stabilize (Cotrufo & Lavallee, 2022). While it may be difficult to delineate clear stages for these processes, exploring the different fractions can reveal formation mechanisms (Li et al., 2021).

According to soil organic matter formation concepts and previous studies (Lehmann & Kleber, 2015; Li et al., 2021), its fractions can be broadly classified into different groups, including plant-associated, water/salt soluble, associated with microorganisms and associated with minerals. Understanding the changes in the fractions can reveal the formation mechanisms, even in terms of the conversion of natural environments into conservationist agricultural ecosystems. There is a need to better investigate the response of organic matter fractions with different origins, formation mechanisms and functions to cover crops and the environmental factors that influence them.

Finally, it is understood that in areas of forest conversion to agricultural use, even with the cultivation of native species in the Amazon, there are changes in the soil properties, especially in regard to organic matter, which is a fraction that is quite sensitive to environmental changes. When combined with tools that monitor these changes, tools gain even more importance once they favor a timely assessment of impacts on soil carbon levels (Souza et al. 2020). Thus, the objective of this study was to evaluate the spatial variability of soil organic carbon fractions in areas of cultivation with Amazonian species in the southern region of Amazonas, Brazil.

## Material and methods

The study was carried out in the São Francisco settlement located in the municipality of Canutama, Amazonas state, Brazil, under the geographic coordinates 8° 11’ 22’’ S and 64° 00’ 83’’ W (Figure 1); the study included four areas, three of which had agricultural uses of Urucum (*Bixa orellana* L.), Cupuaçu (*Theobroma grandiflorum* (Wild. ex. Spreng) Schum) and Guaraná (*Paullinia cupana* (Mart.) Ducke) cultivation, and one area of native forest (Table 1).

Soils were classified according to criteria established by the Brazilian Soil Classification System (Santos et al., 2018) as Argissolo Vermelho-Amarelo Distrófico and the World Reference Base of Soils (IUSS Working Group WRB, 2015) as Chromic Abruptic Acrisol, located on the Amazonian Plain that is associated with recent alluvial sediments from the Quaternary period, being contained between the Purus and Madeira Rivers. In addition, it is characterized by the presence of large tabular reliefs, defined by thalwegs of very weak depth; that is, the relief has very gentle slopes, and the natural drainage is poor (Embrapa, 2011). The climate of the region is tropical rainy, with a short dry period. The average partial rainfall varies between 2250 and 2750 mm per year, with the rainy season spanning between October and June. The annual average temperatures vary between 25 and 27 °C, and the relative humidity of the air varies between 85 and 90% (Brasil, 1978).

Soil sampling was carried out in the dry period in two different layers in the four study areas, which resulted in 64 samples per area, where sampling grids of 70×30 m were established with regular spacing of 10 m between points. Soils were sampled in a preserved manner at the crossing points of the meshes in the 0.0-0.05 m and 0.05-0.10 m layers, for a total of 256 samples (Figure 2). These points were georeferenced with GPS equipment to build the digital elevation model (DEM). Analyses of total organic carbon (OC), as well as their fractionations, were performed in the areas cultivated with Cupuaçu (*Theobroma grandiflorum* (Wild. ex. Spreng) Schum), annatto (*Bixa orellana* L.) - Urucum, guarana (*Paullinia cupana* Mart.) Ducke) and native forest. The organic carbon (OC) content was determined by the Walkley-Black method, modified by Yeomans

**Table 1.** Description of use and history of areas of forest and agroecosystems in the southern region of Amazonas.

| Land use | Use history |
|---|---|
| Guaraná (*Paullinia cupana*) | Area resulting from felling and burning of forest, with manual stump cleaning to clean the area in the first year of cultivation. There has never been any fertilization or liming in the cultivated areas, regular spacing of 5.0 × 5.0 m is used, with pruning and periodic cleaning to control pests, and it has been in effective cultivation for 7 years. |
| Cupuaçu (*Theobroma grandiflorum)* | Area resulting from felling and burning of forest, with manual stump cleaning to clean the area in the first year of cultivation. There was never any fertilization or liming in the cultivated areas, regular spacing of 7.0 × 7.0 m is used, with pruning and periodic cleaning to control pests. It has been in effective cultivation for 7 years. |
| Urucum (*Bixa orellana)* | Area resulting from felling and burning of forest, with manual stump cleaning to clean the area in the first year of cultivation. There has never been any fertilization or liming in the cultivated areas, regular spacing of 4.0 × 4.0 m is used, with pruning and periodic cleaning to control pests. It has been in effective cultivation for 3 years. |
| Forest | Characterized as a dense tropical rainforest, whose vegetation is evergreen, consisting of dense and multi-stratified trees between 20 and 50 m in height. |

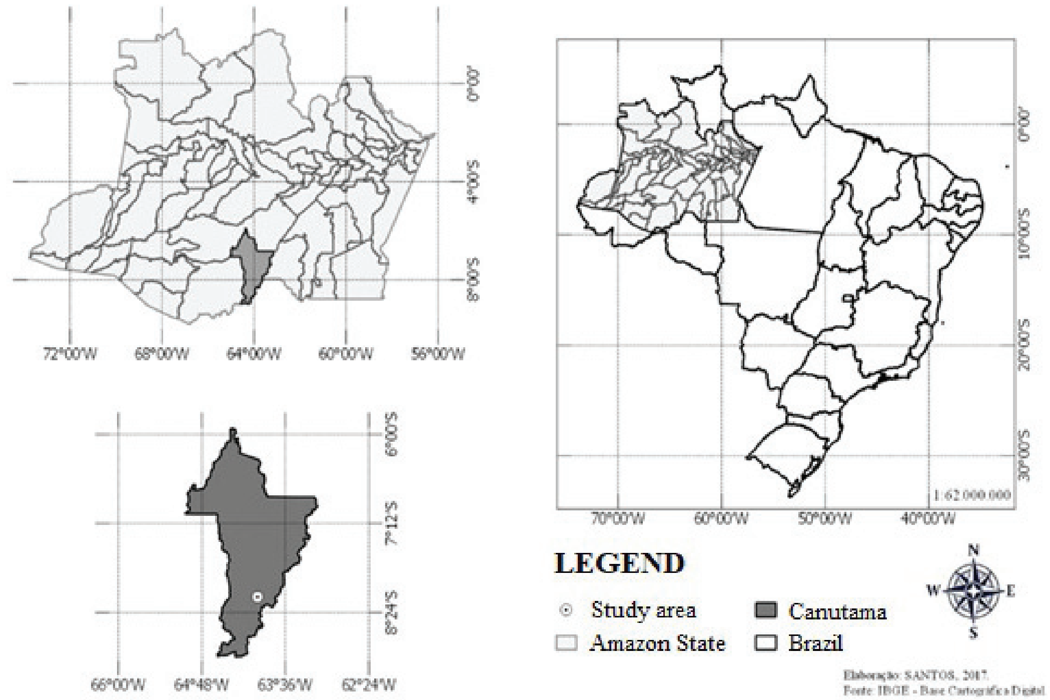

**Figure 1.** Location of the study area. Map of Brazil, highlighting the state of Amazonas and the study area on the map of the municipality of Canutama, Amazonas state.

& Bremner (1988), with digestion in an acidic medium with potassium dichromate under external heating for a period of 5 minutes after total heating at 150 °C. For chemical fractionation, the differential solubility technique was used (Swift, 1996), obtaining the organic carbon in the fulvic acid fraction (C-FAF), humic acid fraction (C-FAH) and humin fraction (C-HUM) for only the 0.0-0.05 m and 0.05-0.10 m layers, as these were the layers with the highest carbon content.

A soil mass obtained from air-dried soil samples (ADSS) containing 30 mg of organic carbon was quantified, and 20 ml of NaOH 0.1 mol $L^{-1}$ was added for 24 hours (AE). The separation between the alkali extract (AE) (AE=FAF+FAH) and the residue was performed by centrifugation at 5000 × g for 30 minutes. Another wash was performed with the same solution, adding the extract to the initial solution, resulting in a final volume of approximately 40 ml. The residue was kept for determination of C–HUM, and the pH of the alkaline extract (EA) was adjusted to 1.0 with 20% H2SO4, followed by decantation for 18 hours. The precipitate (C–FAH) was separated from the soluble fraction (C–FAF) by filtration, and both volumes were adjusted to 50 ml with distilled water. The COAM fraction was determined from the differences between the other quantifications of the determined organic matter fractions.

The quantitative determination of organic carbon in C–FAF and C–FAH was performed using 5.0 ml of extract, 1.0 mL of 0.042 mol $L^{-1}$ potassium dichromate and 5.0 ml of concentrated $H_2SO_4$ in a digester block at 150 °C (30 minutes) and titration with 0.0125 mol $L^{-1}$ ferrous ammonium sulfate. In the residue, the organic carbon of C–HUM was determined after drying the material in an oven at 65 °C (complete drying); 5.0 ml of potassium dichromate 0.1667 mol $L^{-1}$ and 10.0 ml of concentrated $H_2SO_4$ were added in a digester

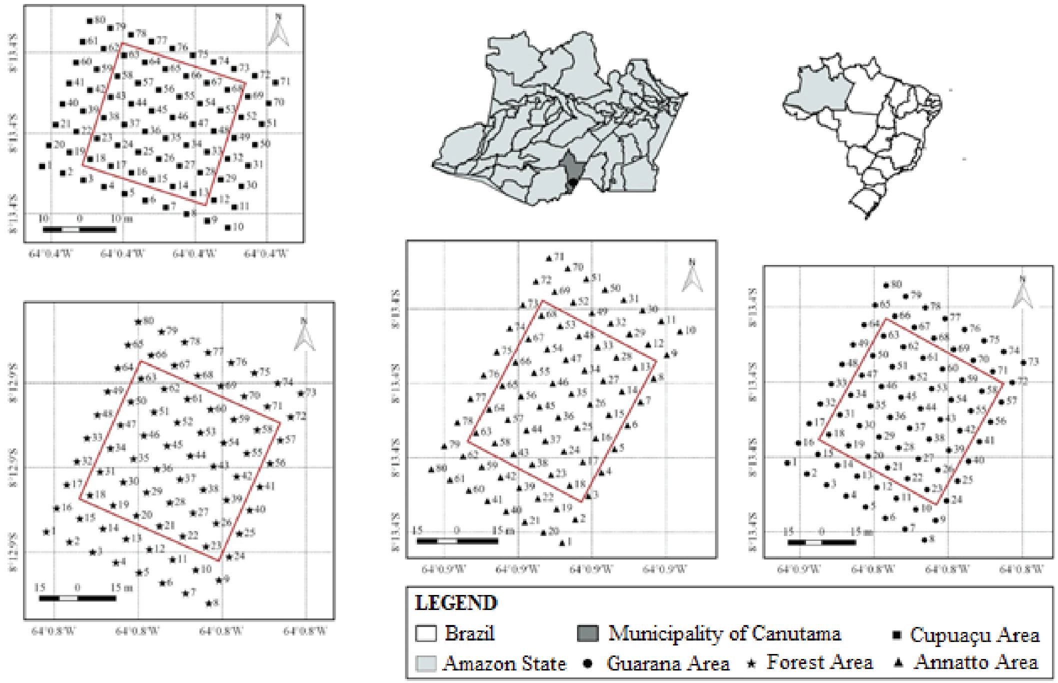

**Figure 2.** Representation of sampling grids and collection points in the study areas of the municipality of Canutama, Amazonas state.

block at 150 °C (30 minutes) and titrated with 0.25 mol $L^{-1}$ ferrous ammonium sulfate (Yoemans & Bremner, 1988).

The bulk density (Bd) was calculated by the ratio between the dry mass at 105 °C during 24 h of the soil sample from the soil core and the volume of the soil core (Embrapa, 2011). The soil organic carbon stock (SOC stock) was calculated by the following expression (Veldkamp, 1994) (Equation 1):

$$\text{SOC stock} = (Bd \times e \times OC)/10 \qquad (1)$$

where SOC stock is the soil organic carbon stock at a given depth (Mg $ha^{-1}$); OC is the organic carbon content at the sampled depth (g kg-1); Bd is the bulk density (kg $dm^{-3}$); and e is the thickness of the considered layer (cm).

After determining the soil attributes, the data were subjected to descriptive statistics and univariate and multivariate analyses, and the comparisons of the averages of the variables within each studied environment were analyzed by the Tukey test at the 5% significance level using the statistical software Statistica 7 (Statsoft, 2004). To complement the work, a geostatistical analysis was performed, which was used to identify the distribution and the spatial pattern of the variables studied, defining theoretical semivariogram models to verify the spatial dependence.

The geostatistical analysis was performed based on the experimental semivariogram, estimated by Equation 2:

$$\hat{y}(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} [Z\,(xi\,) - Z(xi + h)]^2 \qquad (2)$$

where ŷ (h) is the semivariance value for distance h; n(h) is the number of pairs involved in the semivariance calculation; Z(xi) is the value of attribute Z at position xi; and Z (xi + h) is the value of attribute Z separated by a distance h from position xi.

The semivariogram showed a pattern of behavior that was described by theoretical models. The choice for the theoretical model of the semivariogram was carried out with a lower residual error (SQR) and a higher coefficient of determination ($R^2$) and maximum correlation coefficient (r) of the cross-validation. The models used to adjust the semivariograms were spherical (Equation 3) and exponential (Equation 4):

$$\hat{y}(h) = C_0 + C_1\left[\frac{3}{2}\left(\frac{h}{a}\right) - \frac{1}{2}\left(\frac{h}{a}\right)^3\right], \quad if\ 0 < h < a \tag{3}$$

$$= C_0 + C_1, \quad if\ h \geq a$$

$$\hat{y}(h) = C_0 + C_1 = \left[1 - \exp\left(-3\frac{h}{a}\right)\right], \quad if\ 0 < h < d \tag{4}$$

where γˆ (h) is the coefficient of the theoretical model for the semivariogram, C0 is the nugget effect, C0 + C1 is the threshold, [(C0/(C0 + C1) × 100] is the degree of spatial dependence (DSD), a (m) represents the distance with which the attributes are correlated, according to an area with an estimated uniform radius, and d is the maximum distance at which the semivariogram was defined. The pure nugget effect (PNE) is the semivariance value for zero distance and represents the random variation component; the threshold is the value of the semivariance at which the curve stabilizes over a constant value; and the range is the distance from the origin to where the threshold reaches stable values, expressing the distance beyond which the samples are correlated. The semivariogram models for the attributes studied were estimated by GS+ software (Robertson, 2004). Based on the classification by Cambardella et al. (1994), the DSD of the variables was of the strong spatial dependence type when the ratio [(C0/(C0+C1)) × 100] ≤ 25%. It was moderate when [(C0/(C0+C1)) × 100] was between 26 and 75 and weak when [(C0/(C0+C1)) × 100] > 75%.

## Results and discussion

The summary of descriptive statistics of the organic carbon (OC), humin fraction (C–HU), humic acid fraction (C–FAH) and fulvic acid fraction (C–FAF) in the different land uses and for the 0.0-0.05 m and 0.05-0.10 m layers are shown in Table 2. The evaluated properties showed normality, and on average, these showed significance ($p<0.05$) as measured by the Kolmogorov–Smirnov test, with higher levels in areas under native forest and Cupuaçu in both layers, which was attributed to the greater contribution of residual plants to the soil (Alho et al., 2014; Aquino et al., 2014; Pantoja et al., 2019) than that in other land uses. Occupied with annatto and guarana crops, these areas were similar, with higher OC, C–HU, C–FAH and C–FAF contents in the 0.0-0.05 m layer.

Regarding chemical fractionation, there was a predominance of the humin fraction (C–HU), to the detriment of the humic acid fraction (C–FAH) and the fulvic acid fraction (C–FAF) (Table 2). A study by Santos et al. (2013) also reported higher amounts of C in the chemical fractions of OM among the different systems found in the C–HU fraction, corroborating the results of other investigations in Brazilian soils (Assis et al. 2006; Rossi et al., 2011). Furthermore, the levels found were similar to the findings by Araújo et al. (2004), who studied the land use and physical and chemical properties of Argissolo Vermelho Amarelo distrófico in the Western Amazon and reported higher carbon values in the C–HU fraction to the detriment of the C–FAF and C–FAH fractions.

Barreto et al. (2008), Pulronik et al. (2009) and Santos et al. (2013) reported higher levels of carbon related to C–HU, which signaled an advance in the transformation of soil organic matter into humus, thus favoring the formation of stable organomineral and/or clay-humic complexes, giving this fraction resistance to microbial degradation. In all areas, the C associated with the C–FAF and C–FAH fractions was the lowest, possibly due to the low proportion of organic residues in the subsoil. C–FAH represents the intermediate fraction in the stabilization process of humic compounds and is therefore a natural marker of the humification process and reflects soil use and management (Rangel & Silva, 2007).

**Table 2.** Descriptive statistics of soil organic carbon fractions in forest areas and agroecosystems in the southern region of Amazonas.

| Descriptive statistics | C-HUM | C-FAF | C-FAH | CO | COAM | COP | C-HUM | C-FAF | C-FAH | CO | COAM | COP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | --------------------g kg$^{-1}$-------------------- | | | | | | | | | | | |
| | ----------0,0–0,05 m---------- | | | | | | ----------0,05–0,10 m---------- | | | | | |
| | | | | | | Forest | | | | | | |
| Mean | 17,41a | 4,57a | 3,12a | 19,67b | 16,18a | 8,53a | 16,87a | 2,87b | 1,58b | 13,11c | 0,25a | 7,27a |
| Median | 17,41 | 4,44 | 3,12 | 20,22 | 16,18 | 8,58 | 16,76 | 2,87 | 1,57 | 13,32 | 0,25 | 7,43 |
| Minimum | 11,67 | 3,75 | 1,12 | 15,46 | 7,73 | 4,46 | 12,14 | 1,99 | 0,34 | 9,84 | 0,16 | 3,31 |
| Maximum | 22,56 | 5,75 | 4,82 | 23,13 | 25,61 | 13,89 | 22,85 | 4,01 | 2,79 | 17,16 | 0,32 | 12,00 |
| SD | 2,93 | 0,59 | 1,01 | 2,02 | 5,08 | 2,57 | 3,06 | 0,52 | 0,62 | 1,61 | 0,037 | 2,03 |
| Variance | 8,60 | 0,35 | 1,01 | 4,09 | 25,87 | 6,63 | 9,34 | 0,27 | 0,38 | 2,60 | 0,0014 | 4,14 |
| CV (%) | 16,84 | 12,89 | 32,32 | 10,28 | 31,42 | 30,19 | 18,12 | 18,28 | 38,98 | 12,30 | 15,17 | 27,99 |
| Skewness | -0,22 | 0,70 | -0,06 | -0,43 | 0,08 | 0,25 | 0,35 | 0,62 | 0,03 | -0,03 | -0,37 | 0,18 |
| Kurtosis | -0,81 | -0,62 | -0,62 | -0,65 | 2,06 | 2,18 | -0,55 | -0,04 | -0,20 | 0,70 | 2,84 | 3,08 |
| K-S | 0,12* | 0,19* | 0,11* | 0,14* | 0,87 | 0,74 | 0,12* | 0,19* | 0,12* | 0,19* | 0,47 | 0,80 |
| | | | | | | Cupuaçu | | | | | | |
| Mean | 14,23b | 2,92b | 3,57a | 24,35a | 13,45b | 7,14a | 11,30b | 3,27a | 2,95a | 22,55a | 0,52b | 2,80b |
| Median | 13,76 | 2,89 | 3,57 | 23,66 | 13,45 | 7,14 | 11,37 | 3,25 | 2,95 | 22,55 | 0,52 | 1,40 |
| Minimum | 3,06 | 2,27 | 1,54 | 15,18 | 5,17 | 2,48 | 6,16 | 2,16 | 1,59 | 17,24 | 0,32 | 0,76 |
| Maximum | 29,64 | 3,91 | 5,46 | 34,29 | 23,3 | 12,68 | 16,34 | 4,62 | 4,06 | 27,32 | 0,69 | 4,74 |
| SD | 6,95 | 0,41 | 0,96 | 4,53 | 5,30 | 3,29 | 2,39 | 0,59 | 0,59 | 2,85 | 0,08 | 1,18 |
| Variance | 48,29 | 0,16 | 0,93 | 20,50 | 28,12 | 10,88 | 5,70 | 0,35 | 0,34 | 8,11 | 0,007 | 1,41 |
| CV (%) | 48,85 | 13,88 | 26,96 | 18,60 | 39,41 | 46,19 | 21,12 | 18,03 | 19,86 | 12,63 | 16,78 | 42,38 |
| Skewness | 0,52 | 0,79 | -0,15 | 0,41 | 0,23 | 0,06 | -0,39 | 0,27 | -0,32 | -0,20 | -0,29 | -0,003 |
| Kurtosis | -0,36 | 0,82 | -0,01 | 0,50 | 1,87 | 1,72 | 0,11 | -0,30 | 0,11 | -0,49 | 2,62 | 2,04 |
| K-S | 0,15* | 0,14* | 0,08* | 0,17* | 0,38 | 0,71 | 0,13* | 0,13* | 0,11* | 0,16* | 0,77 | 0,99 |
| | | | | | | Guaraná | | | | | | |
| Mean | 14,97b | 2,71b | 2,98b | 13,36bc | 14,62c | 6,27a | 7,84c | 2,31b | 2,04a | 11,71c | 0,56b | 2,67b |
| Median | 14,38 | 2,71 | 2,98 | 13,36 | 14,62 | 6,27 | 7,71 | 2,26 | 1,98 | 11,29 | 0,56 | 2,67 |
| Minimum | 6,73 | 1,73 | 1,07 | 9,86 | 7,35 | 0,97 | 4,64 | 1,72 | 1,27 | 7,84 | 0,28 | 1,30 |
| Maximum | 25,05 | 3,90 | 4,62 | 18,42 | 23,07 | 10,38 | 11,24 | 3,12 | 3,06 | 15,80 | 0,81 | 4,09 |
| SD | 4,66 | 0,65 | 0,97 | 2,48 | 4,17 | 2,38 | 1,95 | 0,45 | 0,47 | 2,08 | 0,14 | 0,70 |
| Variance | 21,69 | 0,42 | 0,93 | 6,13 | 17,42 | 5,66 | 3,81 | 0,21 | 0,22 | 4,32 | 0,02 | 0,49 |
| CV (%) | 31,11 | 23,77 | 32,35 | 18,54 | 28,55 | 37,92 | 24,89 | 19,67 | 23,13 | 17,75 | 25,23 | 26,34 |
| Skewness | 0,51 | 0,32 | -0,05 | 0,43 | 0,12 | -0,05 | 0,24 | 0,38 | 0,52 | 0,23 | 0,028 | 0,37 |
| Kurtosis | -0,02 | -0,73 | -0,62 | -1,00 | 2,04 | 2,39 | -1,05 | -1,13 | -0,11 | -0,63 | 2,16 | 2,84 |
| K-S | 0,13* | 0,11* | 0,11* | 0,15* | 0,78 | 0,90 | 0,12* | 0,13* | 0,16* | 0,13* | 0,88 | 0,57 |
| | | | | | | Urucum | | | | | | |
| Mean | 16,85a | 1,92c | 2,67b | 16,13c | 14,58a | 7,66a | 10,83b | 2,08b | 1,19b | 16,07b | 0,32a | 3,44ab |
| Median | 16,77 | 1,94 | 2,67 | 16,17 | 14,58 | 7,66 | 10,90 | 2,08 | 1,10 | 16,07 | 0,32 | 3,44 |
| Minimum | 9,78 | 1,39 | 1,08 | 11,47 | 6,39 | 2,96 | 7,16 | 1,18 | 0,47 | 13,01 | 0,23 | 1,74 |
| Maximum | 29,34 | 2,55 | 4,70 | 19,98 | 22,73 | 13,70 | 13,36 | 2,92 | 2,05 | 19,51 | 0,44 | 5,28 |
| SD | 4,41 | 0,31 | 0,85 | 2,25 | 3,79 | 2,59 | 1,63 | 0,54 | 0,44 | 1,89 | 0,06 | 1,10 |
| Variance | 19,41 | 0,09 | 0,72 | 5,07 | 14,16 | 6,71 | 2,66 | 0,29 | 0,20 | 3,57 | 0,003 | 1,22 |
| CV (%) | 26,15 | 15,88 | 31,84 | 13,95 | 25,81 | 33,80 | 15,07 | 25,74 | 37,16 | 11,75 | 19,19 | 32,19 |
| Skewness | 1,09 | -0,09 | 0,39 | -0,10 | 0,31 | 0,31 | -0,27 | 0,02 | 0,47 | 0,02 | -0,02 | 0,21 |
| Kurtosis | 1,85 | -0,73 | 0,34 | -0,41 | 2,93 | 2,86 | -0,68 | -1,04 | -0,55 | -0,71 | 2,24 | 1,82 |
| K-S | 0,14* | 0,09* | 0,17* | 0,15* | 0,89 | 0,89 | 0,11* | 0,09* | 0,13* | 0,09* | 0,99 | 0,66 |

SD: standard deviation; CV: coefficient of variation (%); K-S: Kolmogorov-Smirnov normality test. * Significant at 5% probability; C-HUM: humin fraction C-FAF: fulvic acid fraction; C-FAH: humic acid fraction; CO: organic carbon; means followed by the same letter in the column do not differ by Tukey's test ($p<0.05$). COP: particulate organic carbon; COAM: organic carbon associated with minerals; COP: particulate organic carbon; SD: standard deviation.

The skewness coefficients were close to zero in all layers evaluated, with a symmetrical normal distribution and platykurtic-type kurtosis (Campos et al., 2013). Based on the classification established by Warrick and Nielsen (1980), the coefficient of variation (CV) of soil OC fractions was considered low (CV<12%) and medium (CV<60%) for all properties, while the area occupied with the Guaraná crop had mean variation for both layers. In native and Cupuaçu forests, the values ranged from 10.28% to 38.98% and 12.63% to 48.85%, respectively (Table 2).

The normal distribution of data is not a prerequisite for evaluating the spatial pattern of soil attributes (Gomes et al., 2017; Zhang et al., 2022). In addition, measures of central tendency were not dominated by outliers in the distribution, which for Cambardella et al. (1994) reinforced that the data were suitable for the application of geostatistics. In their research, Zhang et al. (2022) and Silva et al. (2020) argued that descriptive statistics based on CV% were not suitable for the study of spatial variability because they considered the general average, and geostatistical analysis was ideal because it is based on the local mean, avoiding erroneous conclusions and inadequate management.

Most variables showed a spatial dependence structure, with few exceptions in the evaluated layers (Table 3). The semivariogram models that best fit the study areas were spherical and exponential, similar to the findings of other studies (Carvalho et al., 2002; Oliveira et al., 2015; Gomes et al., 2018; Zhang et al., 2022). Except in the Cupuaçu area in the 0.05-0.10 m layer, the variability was described by a greater proportion of the exponential model, suggesting an abrupt spatial change (Isaaks & Srivastava, 1989). In turn, the Bd, OC and SOC stock for the 0.0-0.05 m layer had variability described by the spherical model independent of land use, thus suggesting a change in the behavior of these attributes (Silva et al., 2020). Some areas showed the pure nugget effect (PNE), indicative of unexplained variability, considering the sampling distance used (McBratney & Webster, 1986).

All attributes studied that showed spatial variability were classified as moderate and weak degrees of spatial dependence following the criteria by Cambardella et al. (1994). In the forest area, it was possible to identify that the DSD was classified as moderate and weak, with a change in GDE between layers for C-FAF and C–FAH, since the 0.0-0.05 m layer was of the weak and moderate type, while the 0.05-0.10 m layer was classified as moderate and weak. In the Cupuaçu area, the variables presented different GDEs between layers, in which they were mostly classified as weak in the most superficial layer and moderate in the second innermost layer (Table 3).

In the Guaraná area, most of the variables presented a weak DSD, with fluctuations between the layers (0.0-0.05 and 0.05-0.10) in the SOC stock (Figures 3 and 4). In the 0.0-0.05 m layer, the DSD was classified as strong and moderate in the 0.05-0.10 m layer. In the Annatto area, few variables showed similarities between layers, classified as weak DSDs at 0.0-0.05 m and moderate DSDs at 0.05-0.10 (Table 3). None of the four study areas had a strong DSD, attesting to the variability of the variables reflecting the different land uses (Oliveira et al., 2015; Zhang et al., 2022). The coefficient of determination ($R^2$) of the semivariograms revealed excellent adjustments in the modeling of the variables (Table 3), capable of explaining 0.45% to 1.00% of the spatial dependence of the OC and its fractions. Additionally, the C0 values were low, which, according to Zhu et al. (2018), reflects the spatial distribution being dependent on structural factors.

The range (a) indicates the limit distance between the correlated points; that is, the points located in an area with a radius similar to the range are more homogeneous, i.e., more similar to each other (Vieira, 2000; Cunha et al., 2018; Silva et al., 2020; Brito et al., 2021). This parameter allowed the evaluation of the spatial pattern, which was obtained using the ordinary kriging technique, and the OC and its fractionation are illustrated in Figures 3-10. In general, the variables had vari-

**Table 3.** Geostatistical parameters of organic carbon, carbon stock and fractions of organic carbon in forest and agroecosystems in the southern region of Amazonas.

| Parameters | Bd | CO | SOC stock | COP | COAM | C-HUM | C-FAF | C-FAH | Bd | CO | SOC stock | COP | COAM | C-HUM | C-FAF | C-FAH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ----------0,0–0,05 m---------- | | | | | | | | ----------0,05–0,10 m---------- | | | | | | | |
| | Guaraná | | | | | | | | | | | | | | | |
| Model | Sph. | Sph. | Sph. | Lin | Exp. | Lin | Lin | Esf. | Sph. | Exp. | Sph. | Lin | Exp. | Lin | Lin | Sph. |
| $C_0$ | 2,26E-03 | 0,38 | 0,87 | EPP | 0,76 | EPP | EPP | 0,10 | 5,94E-04 | 2,53 | 0,43 | EPP | 0,70 | EPP | EPP | 0,03 |
| $C_0+C_1$ | 0,01 | 5,92 | 1,27 | | 4,76 | | | 0,30 | 0,01 | 7,90 | 1,54 | | 4,94 | | | 0,25 |
| a (m) | 21,32 | 20,10 | 45,51 | | 28,20 | | | 32,90 | 26,54 | 83,64 | 29,70 | | 27,30 | | | 25,60 |
| $R^2$ | 0,81 | 0,51 | 0,57 | | 0,61 | | | 0,70 | 0,73 | 0,71 | 0,59 | | 0,75 | | | 0,92 |
| DSD % | 29,25 | 6,42 | 68,93 | | 15,96 | | | 33,37 | 10,86 | 32,06 | 27,87 | | 14,17 | | | 12,19 |
| | Urucum | | | | | | | | | | | | | | | |
| Model | Sph. | Sph. | Sph. | Sph. | Lin. | Sph. | Sph. | Sph. | Lin | Sph. | Sph. | Sph. | Sph. | Lin | Sph. | Lin |
| $C_0$ | 0,01 | 9,30 | 0,28 | 3,50 | EPP | 10,20 | 0,03 | 0,42 | EPP | 3,08 | 0,81 | 0,24 | 2,91 | EPP | 0,06 | EPP |
| $C_0+C_1$ | 0,01 | 31,92 | 4,52 | 8,16 | | 27,15 | 0,10 | 0,96 | | 5,88 | 1,68 | 1,49 | 5,87 | | 0,31 | |
| a (m) | 69,43 | 70,00 | 26,00 | 70,00 | | 75,66 | 38,54 | 70,00 | | 35,40 | 70,00 | 24,92 | 70,00 | | 34,14 | |
| $R^2$ | 0,93 | 0,77 | 0,81 | 0,874 | | 0,70 | 0,52 | 0,70 | | 0,54 | 0,74 | 0,62 | 0,76 | | 0,62 | |
| DSD % | 38,59 | 29,13 | 6,25 | 42,95 | | 37,57 | 27,74 | 44,22 | | 52,38 | 47,93 | 16,03 | 49,56 | | 20,76 | |
| | Cupuaçu | | | | | | | | | | | | | | | |
| Model | Exp. | Sph. | Sph. | Sph. | Sph. | Lin. | Sph. | Sph. | Exp. | Exp. | Exp. | Lin | Exp. | Exp. | Sph. | Sph. |
| $C_0$ | 0,00 | 24,60 | 2,97 | 0,64 | 8,48 | EPP | 0,05 | 0,31 | 0,00 | 0,90 | 0,68 | EPP | 1,18 | 3,15 | 0,22 | 0,03 |
| $C_0+C_1$ | 0,00 | 67,23 | 10,04 | 10,89 | 26,90 | | 0,20 | 1,21 | 0,01 | 10,80 | 2,46 | | 4,39 | 6,31 | 0,38 | 0,35 |
| a (m) | 26,96 | 14,64 | 16,47 | 25,54 | 24,62 | | 16,26 | 13,77 | 13,14 | 42,12 | 42,69 | | 20,11 | 122,40 | 12,64 | 14,06 |
| $R^2$ | 0,45 | 0,92 | 0,52 | 1,00 | 0,99 | | 0,99 | 0,51 | 1,00 | 0,74 | 0,73 | | 0,61 | 0,99 | 0,58 | 0,67 |
| DSD % | 39,53 | 36,59 | 29,58 | 5,90 | 31,52 | | 26,11 | 25,75 | 16,40 | 8,34 | 27,60 | | 26,87 | 49,90 | 58,07 | 8,01 |
| | Forest | | | | | | | | | | | | | | | |
| Model | Sph. | Sph. | Sph. | Lin. | Lin. | Sph. | Exp. | Sph. | Exp. | Exp. | Sph. | Exp. | Sph. | Sph. | Sph. | Exp. |
| $C_0$ | 7,61E-04 | 6,25 | 0,70 | EPP | EPP | 1,95 | 0,04 | 0,46 | 2,40E-03 | 7,47 | 0,12 | 1,50 | 0,79 | 2,93 | 0,05 | 0,11 |
| $C_0+C_1$ | 0,01 | 15,76 | 2,39 | | | 10,71 | 0,21 | 1,26 | 0,01 | 17,36 | 3,14 | 3,18 | 14,34 | 10,01 | 0,15 | 0,55 |
| a (m) | 18,42 | 33,90 | 44,74 | | | 23,91 | 20,55 | 2716 | 33,85 | 34,02 | 48,02 | 53,67 | 15,10 | 26,30 | 48,50 | 84,42 |
| $R^2$ | 0,67 | 0,66 | 0,57 | | | 0,53 | 0,95 | 0,76 | 43,85 | 0,83 | 0,80 | 0,88 | 0,84 | 0,72 | 0,57 | 0,77 |
| DSD % | 14,39 | 39,66 | 29,17 | | | 18,21 | 20,95 | 36,18 | 0,66 | 43,06 | 3,85 | 47,09 | 5,51 | 29,32 | 35,43 | 20,62 |

C-HUM: humin fraction C-FAF: fulvic acid fraction; C-FAH: humic acid fraction; TOC: organic carbon; Exp.: exponential; Sph: spherical, Lin: linear; C0: nugget effect; C0+C1: plateau; a: range (m); R²: coefficient of determination; DSD%: degree of spatial dependence; Bd: bulk density; OC: organic carbon; SOC stock: soil organic carbon stock; COP: particulate organic carbon; EPP: pure nugget effect; and COAM: organic carbon associated with minerals.

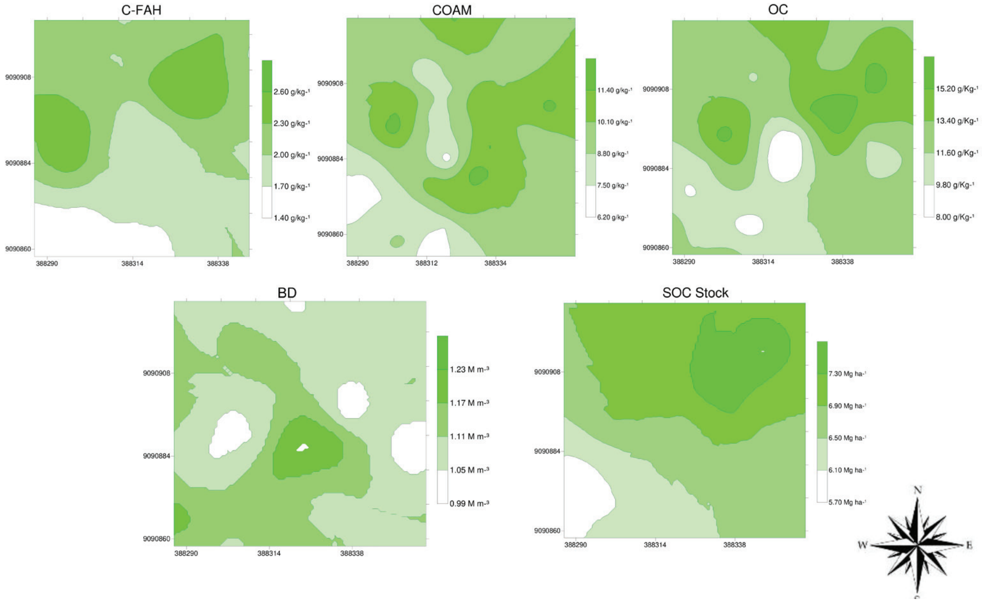

**Figure 3.** Kriging maps of soil attributes in an area under Guaraná cultivation, 0.0-0.05 m layer, in the southern region of Amazonas, Brazil.

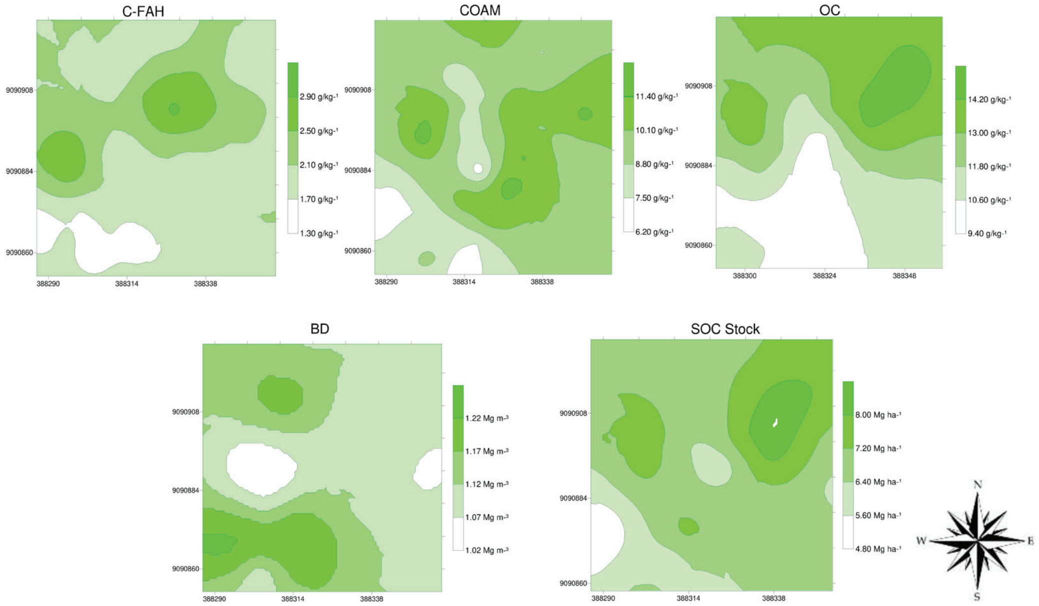

**Figure 4.** Kriging maps of soil attributes in an area under Guaraná cultivation, 0.05-0.10 m layer, southern Amazon region, Brazil.

ability at different scales, even when considering the same agricultural and forestry occupation of the areas. The different inputs of organic matter imposed by the particularities of the systems produced large amplitudes in the range values of the fractions C–HUM, C–FAF, C–FAH, OC, and organic carbon associated with silt and clay minerals (COAM) between the areas in the two evaluated layers.

The spatial pattern of COAM is normally less modified by land uses, especially in the short term (Bayer et al., 2004). In fact, in all areas, the spatial dependence of COAM was recorded in the 0.05-0.10 m layer (Figures 4, 6, 8 and 10). The textural gradient of the A horizon to B, common in the Argissolos class (Brito et al., 2022), favors the greater protection of OC due to the formation of organomineral complexes, favoring the formation of stable aggregates (Gomes et al., 2017). Considering that the soil texture was the same in all areas, the difference in the spatial pattern of COAM between the 0.0-0.05 m and 0.05-0.10 m layers was provided by the variation in the contribution of organic material, either shoot or root production. Over time, the roots decompose and become incorporated into the soil profile, which is a source of vertical variability.

The smooth spatial variability of the soil attributes, that is, more continuous changes, was noted in the areas of Guaraná and Annatto (Figures 3, 4, 5 and 6). This is indicated by the more sinuous behavior of the isolines, following a degrader in the south–north direction. In a cause–effect relationship, larger spatial spots related to higher OC contents were found to be consistent with the decay in Bd, corroborating the results of Gomes et al. (2018) and Zhang et al. (2022). For Vasconcelos et al. (2014), organic matter dampened compacting forces, preventing the reduction of soil volume, which explained the similar spatial patterns of the OC and SOC stock antagonistic to that of Bd. This behavior occurred for both evaluated layers, which reinforces the importance of adopting production systems that inject organic matter into the soil, contributing to reducing soil efflux $CO_2$ to the atmosphere, which is a challenge for modern agriculture based on the principles of environmental sustainability.

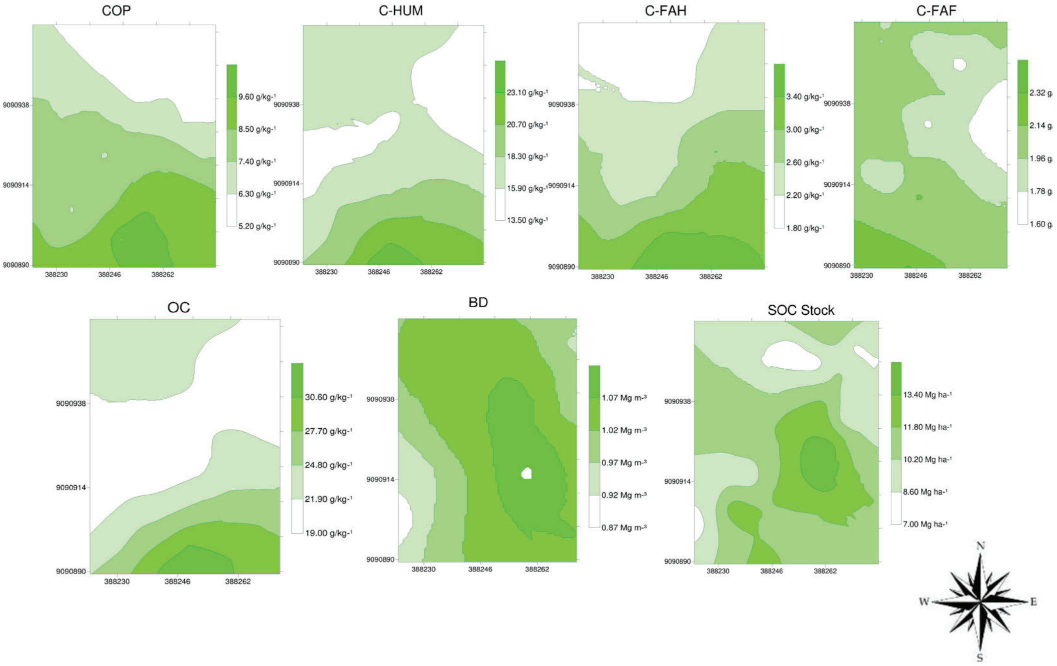

**Figure 5.** Kriging maps of soil attributes in an area under Urucum (annatto) cultivation, layer 0.0-0.05 m, southern Amazon region, Brazil.

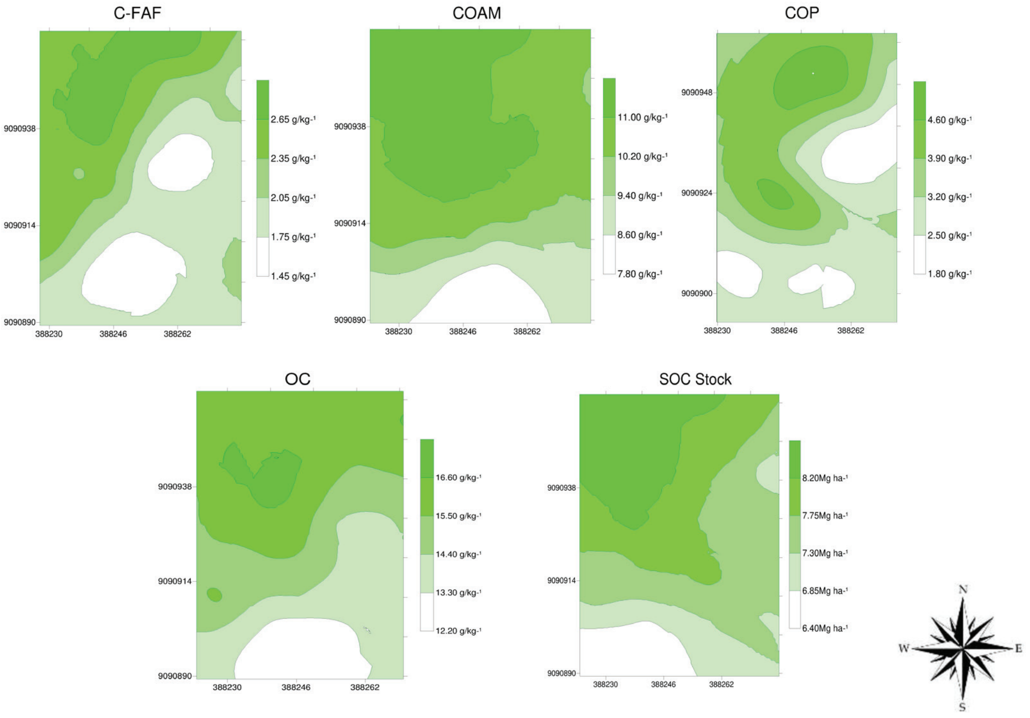

**Figure 6.** Kriging maps of soil attributes in an area under Urucum (annatto) cultivation, 0.05-0.10 m layer, southern Amazon region, Brazil.

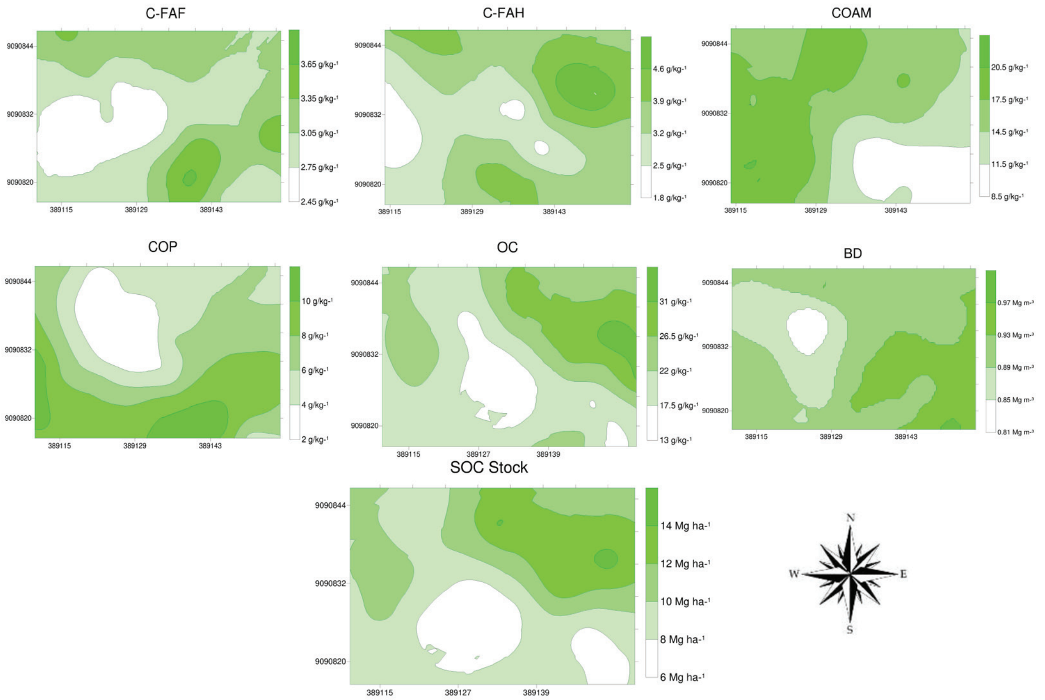

**Figure 7.** Kriging maps of soil attributes in an area under Cupuaçu cultivation, 0.0-0.05 m layer, southern Amazon region, Brazil.

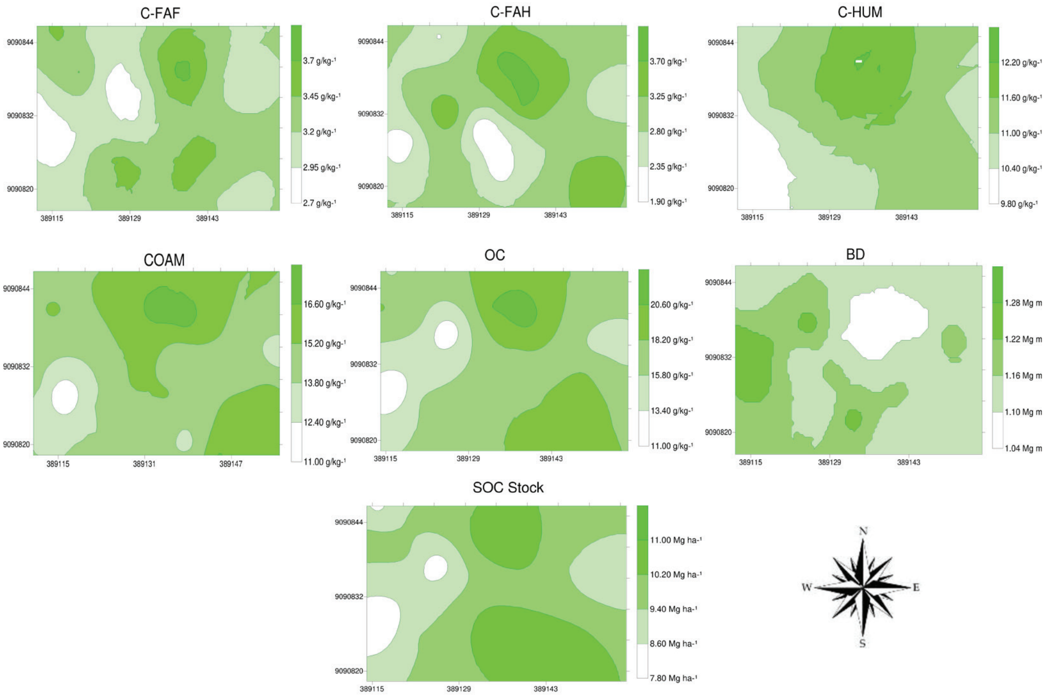

**Figure 8.** Kriging maps of soil attributes in an area under Cupuaçu cultivation, 0.05-0.10 m layer, southern Amazon region, Brazil.

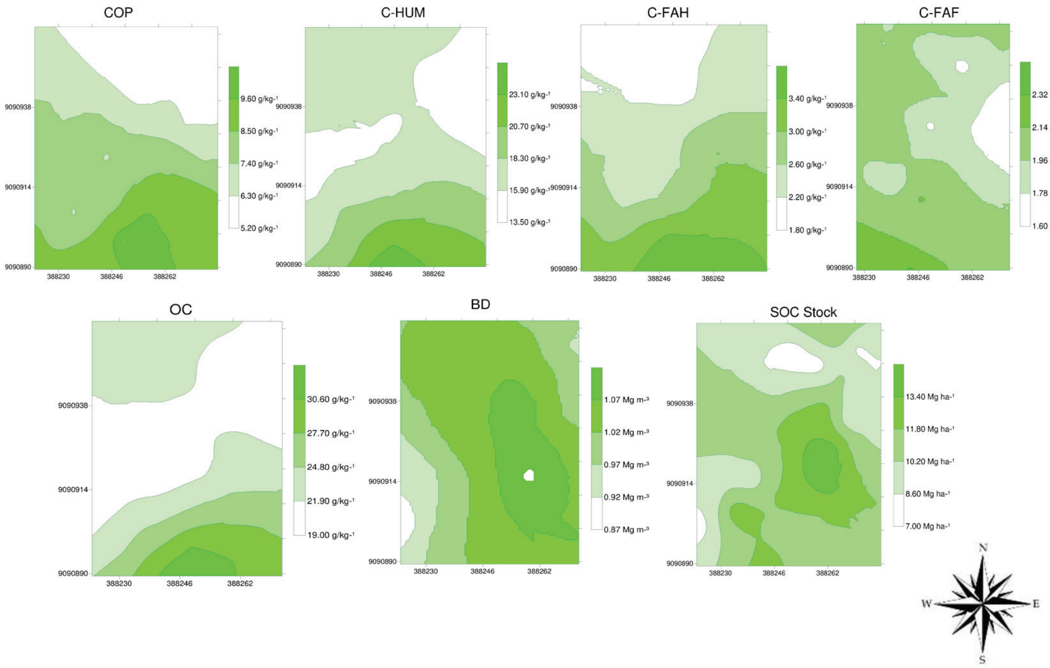

**Figure 9.** Kriging maps of soil attributes in an area under forest, 0.0-0.05 m layer, southern Amazon region, Brazil.

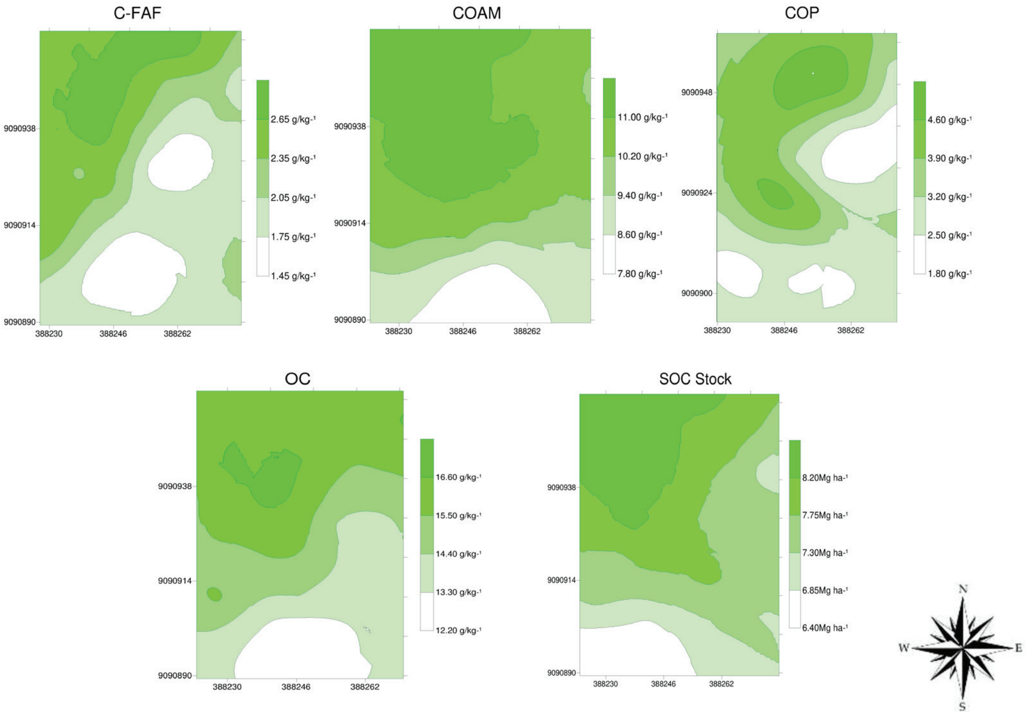

**Figure 10.** Kriging maps of soil attributes in an area under forest, 0.05-0.10 m layer, southern Amazon region, Brazil.

In short, with the help of these spatial maps of soil organic matter fractionation, it is possible to develop soil management and use strategies aimed at maintaining soil organic matter (Pajares et al., 2009; Gomes et al., 2018; Zhang et al., 2022), given that the mapping will enable the appropriate treatment for each compartment of the studied areas. In this way, the evaluation of soil carbon in the context of spatial variability will help in the adoption of agricultural production systems that best contribute to the increase and quality of soil organic matter, for example, no-tillage, minimum tillage and livestock, which are essential for the maintenance of the ecosystem and the multiple functions of the soil in the Amazonian environments.

## Conclusion

The C-HUM fraction showed the highest amount of 17.41 g kg$^{-1}$, in the forest area followed by the Cupuaçu area with 16.85 g kg$^{-1}$, thus showing the effect of resilience and recovery of this fraction in this anthropized environment.

Among the attributes analyzed, the C-FAH fraction had the greatest spatial distribution range, being greater than 84 m.

The conversion of natural ecosystems to agricultural systems affects the rates of addition and decomposition of soil organic matter. Changes in soil carbon stocks due to the use of different agricultural systems are determined by evaluating the free light fraction of soil organic matter. For the chemical fractions of organic matter, it was observed that there was a predominance of the humin fraction in relation to the humic acid, fulvic acid and organic carbon associated with minerals in the different land uses and soil layers analyzed. Geostatistical procedures proved to be important in determining the degree of carbon dependence and its fractionation in the context of spatial variability, which is useful in soil quality monitoring.

## Resumen

**J. I. Silva Praça, B. F. Enck, M. C. Costa Campos, M. G. Pereira, F. Gomes de Souza, B. Campos Mantovanelli, E. Gomes de Brito Filho, L. Santos Silva, y J. M. da Cunha. 2023. Variabilidad espacial de las fracciones de carbono orgánico del suelo en áreas de cultivo de especies amazónicas en la región sur del estado de Amazonas, Brasil. Int. J. Agric. Nat. Resour. 58-74.** El carbono orgánico (CO) del suelo es heterogéneo y sensible al manejo agrícola, por lo que el conocimiento de su variabilidad espacial puede mejorar el monitoreo de áreas bajo influencia antrópica, ya que el CO puede servir como un indicador sensible de los cambios en el medio ambiente. El objetivo de este estudio fue evaluar la variabilidad espacial de las fracciones de CO del suelo en áreas de cultivo con especies amazónicas en la región sur del estado de Amazonas. Se recolectaron un total de 256 puntos de datos georreferenciados en las capas de 0,0-0,05 m y 0,05-0,10 m en los siguientes sistemas agrícolas: áreas con cultivo de Guaraná, Annatto, Cupuaçu y bosque. Se analizó el contenido de OC y se realizó el fraccionamiento químico de la materia orgánica del suelo. Los resultados analíticos se evaluaron mediante análisis estadístico descriptivo y el patrón espacial se evaluó mediante análisis geoestadístico. La conversión de ecosistemas naturales a sistemas agrícolas afectó las tasas de adición y descomposición de la materia orgánica del suelo. Los cambios en las reservas de carbono orgánico del suelo (reservas de SOC) debido a los usos de diferentes sistemas agrícolas se determinaron mediante la evaluación de la fracción ligera libre de materia orgánica del suelo. Para las fracciones químicas de la materia orgánica hubo predominio de la fracción humina (C-HU) en relación a las fracciones de ácido húmico (C-FAH), ácido fúlvico (C-FAF) y OC asociado a minerales (COAM) en los diferentes usos del suelo y capas del suelo analizados. Los procedimientos geoestadísticos demostraron ser importantes para determinar el grado de dependencia del carbono y su fraccionamiento en el contexto de la variabilidad espacial, y esta información es útil en el monitoreo de la calidad del suelo.

**Palabras clave**: Atributos del suelo, bosque, fraccionamiento químico, geoestadística, mapeo.

## References

Alho, L. C., Campos, M. C. C., Silva, D. M. P., Mantovanelli, B. C. & Souza, Z. M. (2014). Variabilidade espacial de estabilidade de agregados e estoque de carbono em Cambissolo e Argissolo. *Pesquisa Agropecuária Tropical*, *44*, 254. https://doi.org/10.1590/S1983-40632014000300001

Aquino, R. E., Campos, M. C. C., Marques Júnior, J., Oliveira, I. A., Mantovanelli, B. C. & Soares, M. D. R. (2014). Geoestatística na avaliação dos atributos físicos em Latossolo sob floresta nativa e pastagem na região de Manicoré, AM. *Revista Brasileira Ciência do Solo, 38*, 406. http://dx.doi.org/10.1590/S0100-06832014000200004

Araújo, AE, Lani, J. L., Amaral, E. A. & Guerra, A. (2004). Uso da terra e propriedades físicas e químicas de Argissolo Amarelo Distrófico na Amazônia ocidental. *Revista Brasileira de Ciência do Solo, 28*, 315. https://doi.org/10.1590/S0100-06832004000200009

Araújo, E. A., Ker, J. C., Mendonça, E. S., Silva, I. R. & Oliveira, E. K. (2011). Impacto da conversão floresta-pastagem nos estoques e na dinâmica do carbono e substâncias húmicas do solo no bioma Amazônico. *Acta Amazonica, 41*(1), 103-114. https://doi.org/10.1590/S0044-59672011000100012

Assis, C. P., Jucksch, I., Mendonça, E. & Neves, J. C. L. (2006) Carbono e nitrogênio em agregados de Latossolo submetido a diferentes sistemas de uso e manejo. *Pesquisa Agropecuária Brasileira, 41*, 1541-1550. https://doi.org/10.1590/S0100-204X2006001000012

Barreto, A. C., Freire, M. B. G. S. F., Nacif, P. G. S., Araújo, Q. R., Freira, F. J. & Inácio, E. S. B. (2008). Fracionamento químico e físico do carbono orgânico total em um solo de mata submetido a diferentes usos. *Revista Brasileira de Ciência do Solo, 32*, 1471-1478. https://doi.org/10.1590/S0100-06832008000400011

Boy, J., Strey, S., Schönenberg, R., Strey, R., Weber-Santos, O., Nendel, C. & Guggenberger, G. (2018). Seeing the forest not for the carbon: why concentrating on land-use-induced carbon stock changes of soils in Brazil can be climate-unfriendly. *Regional Environmental Change, 18*(1), 63-75. https://doi.org/10.1007/s10113-016-1008-1

Cambardella, C. A., Moorman, T. B., Parkin, T. B., Karlen, D. L., Novak, J. M., Turco, R. F. & Konopka, A. E. (1994). Field-scale variability of soil properties in central Iowa soils. *Soil Science Society of America Journal, 58*(5), 1501-1511. https://doi.org/10.2136/sssaj1994.03615995005800050033x

Campos, M. C. C., Santos, L. A. C., Silva, D. M. P., Mantovanelli, B. C. & Soares, M. D. R. (2012). Caracterização física e química de terras pretas arqueológicas e de solos não antropogênicos na região de Manicoré, Amazonas. *Revista Agro@mbiente, 6*(2), 102-109. https://doi.org/10.18227/1982-8470ragro.v6i2.682

Campos, M. C. C., Soares, M. D. R., Santos, L. A. C., Oliveira, I. A. & Aquino, E. A. (2013). Spatial variability of physical attributes in Alfissol under agroforestry, Humaitá region, Amazonas state, Brazil. *Revista de Ciências Agrárias, 56*(2), 149-159 https://doi.org/10.4322/rca.2013.023

Carvalho, J. R. P., Silveira, P. M. & Vieira, S. R. (2002). Geoestatística na determinação da variabilidade espacial de características químicas do solo sob diferentes preparos. *Pesquisa Agropecuária Brasileira, 37*(8), 1151-1159. https://doi.org/10.1590/S0100-204X2002000800013

Cotrufo, M. F. & Lavallee, J. M. (2022). Soil organic matter formation, persistence, and functioning: a synthesis of current understanding to inform its conservation and regeneration. *Advances in Agronomy, 172*, 1-66. https://doi.org/10.1016/BS.AGRON.2021.11.002

Empresa Brasileira de Pesquisa Agropecuária – Embrapa. (2011) *Manual de métodos de análise de solo*. 2ª ed. Rio de Janeiro: Embrapa Solo. 230p.

Isaaks, E. H. & Srivastava, R. M. (1989). *An Introduction to Applied Geostatistics*. Oxford University Press, New York.

IUSS - Working Group WRB. (2015). *World reference base for soil resources 2014, update 2015: International soil classification system for naming soils and creating legends for soil maps*. Rome: Food and Agriculture Organization of the United Nations; 2015. (World Soil Resources Reports, 106).

Lehmann, J. & Kleber, M. (2015). The contentious nature of soil organic matter. *Nature, 528*, 60-68. https://doi.org/10.1038/nature16069

Li, Y., Li, Z., Cui, S., Liang, G. & Zhang, Q. (2021). Microbial-derived carbon components are critical for enhancing soil organic carbon in no-tillage croplands: a global perspective. *Soil and Tillage Research, 205*, 104758. https://doi.org/10.1016/j.still.2020.104758

Mcbratney, A. B. & Webster, R. (1986). Choosing functions for semi-variograms of soil properties and fitting them to sampling estimates. *European Journal of Soil Science, 37*(4), 617-639. https://doi.org/10.1111/j.1365-2389.1986.tb00392.x

Melo, N. C., Ribeiro, F., Costa, H. M. S., Souza, F. J. L., Sales, E. C. G., Melo, N. F. B. & Lima, M. C. (2021). Conservação do solo: um estudo de caso sobre o processo de ensino e aprendizagem no campus agrícola do Instituto Federal do Amapá. *Research, Society and Development, 10*(6), e22810615723. https://doi.org/10.33448/rsd-v10i6.15723

Oliveira, E. C. A. M., Peluzio, J. M., Oliveira Junior, W. P., Tsai, S. M., Navarrete, A. A. & Morais, P. B. (2015). Alterações dos atributos físico-químicos da camada superficial do solo em resposta à agricultura com soja na várzea do Tocantins. *Biota Amazônia, 5*(4), 56-62. http://dx.doi.org/10.18561/2179-5746/biotaamazonia.v5n4p56-62

Oliveira, N. A., Oliveira, N. A., Silva, K. R., Silva, L. J. A. & Mello, A. H. (2017). Atributos químicos de solo sob diferentes sistemas de uso e manejo no projeto de assentamento Veneza - São Domingos do Araguaia, PA. *Revista Agroecossistemas, 9*, 170-179. http://dx.doi.org/10.18542/ragros.v9i1.4781

Owuor, S. O., Butterbach-Bahl, K., Guzha, A. C., Jacobs, S., Merbold, L., Rufino, M. C. & Breuer, L. (2018). Conversion of natural forest results in a significant degradation of soil hydraulic properties in the highlands of Kenya. *Soil and Tillage Research, 176*, 36-44. https://doi.org/10.1016/j.still.2017.10.003

Paris, J. O., Gontijo, I., Partelli, F. L. & Facco, A. G. (2020) Variability and spatial correlation of soil micronutrients and organic matter with macadamia nut production. *Revista Brasileira de Engenharia Agrícola e Ambiental, 24*, 31-36. https://doi.org/10.1590/1807-1929/agriambi.v24n1p31-36

Rangel, O. J. P. & Silva, C. A. (2007). Estoques de carbono e nitrogênio e frações orgânicas de Latossolo submetido a diferentes sistemas de uso e manejo. *Revista Brasileira de Ciência do Solo, 31*, 1609-1623. https://doi.org/10.1590/S0100-06832007000600037

Rodrigues, M., Rabêlo, F. H. S., Castro, H. A., Roboredo, D., Carvalho, M. A. C. & Roque, C. G. (2017). Changes in chemical properties by use and management of an oxisol in the Amazon biome. *Rev. Caatinga, 30*(2), 278-286. https://doi.org/10.1590/1983-21252017v30n202rc

Rossi, C. Q., Pereira, M. G., Giacomo, S. G., Betta, M. & Polidoro, J. C. (2011). Frações húmicas da matéria orgânica do solo cultivado com soja sobre palhada de braquiária e sorgo. *Bragantia, 70*(3), 622-630. https://doi.org/10.1590/S0006-87052011000300018

Santos, D. C. D., Farias, M. D. O., Lima, C. L. R. D., Kunde, R. J., Pillon, C. N. & Flores, C. A.

(2013). Fracionamento químico e físico da matéria orgânica de um Argissolo Vermelho sob diferentes sistemas de uso. *Ciência Rural, 43*, 838-844. https://doi.org/10.1590/S0103-84782013005000037

Santos, H. G., Jacomine, P. K. T., Anjos, L. H. C., Oliveira, V. A., Lumberas, J. F., Coelho, M. R., Almeida, J. A., Araújo Filho, J. C., Oliveira, J. B. & Cunha, T. J. F. (2018). *Centro Nacional de Pesquisa de Solos*. Sistema Brasileiro de Classificação de Solos. Brasília, 356p.

Silva, L. S., Marques Júnior, J., Barrón, V., Gomes, R. P., Teixeira, D. D. B., Siquiera, D. S. & Vasconcelos, V. (2020). Spatial variability of iron oxides in soils from Brazilian sandstone and basalt. *CATENA, 185*, 104258. https://doi.org/10.1016/j.catena.2019.104258

Souza, F. G., Campos, M. C. C., Pinheiro, E. N., Lima, A. F. L., Brito Filho, E. G., Cunha, J. M., Santos, E. A. N. & Brito, W. B. M. (2020). Aggregate stability and carbon stocks in Forest conversion to different cropping systems in Southern Amazonas, Brazil. *Carbon Management, 11*, 81-96. https://doi.org/10.1080/17583004.2019.1694355

Statsoft Inc 7.0. (2004) *Statistica* (data analysis software system). USA.

Swift, R. S. (1996). *Organic matter characterization*. Methods of Soil Analysis Part 3 –Chemical Methods, p. 1011-1069.

Vieira, S. R. (2000). Geoestatística em estudos de variabilidade espacial do solo. In: NOVAIS, R. F. et al. (Eds). *Tópicos em ciência do solo*. Viçosa: Sociedade Brasileira de Ciência do Solo. 1-53.

Warrick, A. W. & Nielsen, D. R. (1980) Spatial variability of soil physical properties in the field. In: Hillel, D. (Ed.). *Application of soil physics*. New York: Academic Press.

Yeomans, J. C. & Bremner, J. M. (1988). A rapid and precise method for routine determination of organic carbon in soil. *Communications in Soil Science and Plant Analysis, 19*(13), 1467-1476. https://doi.org/10.1080/00103628809368027