Impact of Land Use On The Variability of Soil Attributes Within Distinct Amazonian Environments

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Impact of land use on the variability of soil attributes within distinct Amazonian environments

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ABSTRACT. Changes in soil attributes caused by the conversion of native forest for agricultural use in the Amazon region is an area of research because of current uncertainties regarding land use and occupation processes. These uncertainties are significant for tropical soils. Understanding changes in soil attributes is vital for developing strategies to mitigate greenhouse gas emissions in the Amazon region. The objective of this study was to investigate the impact of land use on soil attribute variability occurring in distinctly Amazonian environments. This study was conducted using five meshes in Southern Amazonas: Forest 1, cassava, sugarcane, Forest 2, and Archeological Dark Earth (ADE). Descriptive statistical, geostatistical, and multivariate analyses were performed on data obtained from local measurements of CO$_2$ emissions and data obtained from physical and chemical analysis of soil layers up to a depth of 20 cm. Most physical, chemical, and biological attributes of the soil were related to land use classifications. The similarity between cultivated and forested areas yielded no evidence of land degradation resulting from land use. Increasing certain physical attributes total porosity (PT), soil moisture (SM), and Macroporosity (Macro) yielded a greater increase in the CO$_2$ efflux for ADE and Amazon forest environments than for cultivated regions.

Keywords: Spatial variability; land use; dark archaeological earth; efflux of CO$_2$.

1 Introduction

Native forests are of fundamental importance for local biodiversity and the protection of soil and water (Shorupa 2003). Human activities are changing soil characteristics. Such changes are credited to several factors, such as agricultural exploitation, ranching, and forestry management (Cohen et al. 2007). Significant increases in the degradation of natural resources are being observed as a result of no or little consideration being given to soil management during aforementioned human activities (Lima et al. 2009; Rockstrom 2009).
In forest environments, the removal of cover vegetation (e.g., deforestation) may disrupt the natural state of the forest by modifying the chemical, physical, and biological attributes of the soil (Wendling et al. 2012). This disruption is especially significant for low-fertility soils such as those found in most of the Amazon region (Loureiro 2002; Cardoso et al. 2009). As a result, recent studies have reported increases in soil density (Cunha et al. 2018). Ranching increases these impacts. Additionally, nutrient leaching, increased CO$_2$ efflux, and an abrupt reduction of biological activity result from the scarcity of organic material input to soil. The loss of feedback in Amazonian environments is demonstrated by these soil quality indicators.

Some studies have adopted geostatistical methods (Montanari et al. 2012; Silva Júnior et al. 2012; Oliveira et al. 2013) and multivariate analysis (Freitas et al. 2012; Marques Júnior et al. 2014) to analyze data on quantify the impacts of soil use and land occupation. Geostatistics has been used to characterize patterns variability for physical (Oliveira et al. 2013), chemical (Aquino et al. 2014), mineralogical (Bahia et al. 2015), and biological attributes of soil (Bahia et al. 2014, 2015). Sample planning is usually defined using semivariogram ranges (Montanari et al. 2005, 2012). However, a few studies have compared the changing attributes of native and disturbed (human-occupied) soils. Such comparisons may fill an existing gap in the literature regarding the impact of disturbance and the subsequent homogenization of initially highly diverse soil.

Multivariate principal component analysis (PCA) is another potential tool for exploratory studies on soil and land use. By means of this statistic test, it is possible to investigate the physical, chemical, biological, and mineralogical soil attributes that are limiting for plant growth (Gomes et al. 2004; Silva et al. 2010; Cherubin et al. 2011; Nogara Neto et al. 2011; Santi et al. 2012; Bahia et al. 2014). The impact of soil use and land occupation upon these parameters can also be quantified by PCA. Thus, these indexes can be used as pseudo-indicators of soil changes from natural to anthropogenic environments. In this sense, the objective of this study was to evaluate the impact of land use on the variability of soil attributes in distinct Amazonian environments.
Material and methods

2.1 Characterization of the area and sampling plan

The study area is located in the regions of Manicoré (05° 48' 33" S and 61° 18' 01" W) and Humaitá (07° 30' 22" S and 63° 01' 15" W) within southern Amazonas, a state in Brazil. According to the Thornthwaite (1948) classification, the climate of these regions is tropical and rainy with a short dry season (Am). The average temperatures vary from 25 to 27 °C and annual rainfall levels range between 2250 and 2750 mm; the rainy season is from October to June (Brasil 1978). The geology of these areas is derived from Rondonian granites. The study area in Humaitá consists of ancient alluvial sediments that date to the Holocene (Brasil 1978). The soils are classified as Oxisol in Manicoré and as Inceptissol in Humaitá (Soil Survey Staff 2010).

Five meshes were used in this study; two were in natural environments and the others were classified as agricultural activity. Three areas—forest 1, cassava and sugarcane—were characterized by the same geomorphological, geological and pedological features. These areas had varied soil uses and were utilized in the municipality of Humaitá. One forest area (Forest 2) and an Archeological Dark Earth (ADE) are were chosen in Manicoré (Fig. 1). These systems were chosen as the most representative of the southern Amazon region. ADE is of particular importance in the region, highly variable in composition, and possibly associated with combustion of biomass in past geological ages (Neves et al. 2007). The distance between the cassava (Manihot esculenta), sugarcane (Saccharum officinarum), Forest 1 (Humaitá), and Forest 2 (ADE) environments resulted from our discovery of ADE fragments in Manicoré.
Fig. 1 Schematic representation of the experimental areas located in the south of Amazonas state and sample collection

The forest 1 area is located at 7º 28' 29" S and 63º 02' 07" W, and has average altitude of 63 m, where species of cocoa (*Theobroma cacao*), chestnut (*Bertholletia excelsa*), palm (*Arecaceae*), and andiroba (*Carapa guianensis*), among others are cultivated. Cassava crops have been cultivated for approximately five years at 7º 30' 24" S and 63º 04' 56" W. Finally, the sugarcane area (7º 54' 38" S and 63º 14' 27" W) has a mean altitude of 70 m and has been cultivated for about ten years (only with sugarcane) with periodic burns. The ADE area (07º 55' 02.1" S and 61º 31' 45.2" W) has an average altitude of 102 m and has been cultivated with corn (*Zea mays*) for approximately 120 days. Adjoining the ADE area is the forest 2 area (7º 54' 44.5" S and 61º 31' 44.7" W) with an average altitude of 140 m. This area is characterized by a fragment of Dense Tropical Forest (multiple forest species) consisting of trees varying from 20 to 50 meters in height. Five sample meshes with a regular spacing of 10 meters and 64 georeferenced points have been established in soil sampling. Each mesh
has dimensions of 70 x 70 m, totaling 0.49 hectares.

2.2 Analysis of soil attributes

Soil CO$_2$ emissions were recorded by a portable, automated system the LI-8100 (LI-COR Inc. USA). The LI-8100 system monitors CO$_2$ concentration inside its chamber via infrared spectroscopy (IRGA Infrared Gas Analyzer). The soil chamber has an internal volume of 854.2 cm$^3$ and a contact area of 83.7 cm$^2$. The LI-8100 was placed over polyvinyl chloride (PVC) collars previously inserted into the soil to a depth of 0.03 m. Soil temperature was monitored simultaneously with soil respiration, using a temperature sensor in the LI-8100 system. This sensor consists of a 0.2 m rod, which is inserted into the soil near the PVC collars. A Campbell® (Hydrosense TM, Campbell Scientific, Australia) time domain reflectometry (TDR) device recorded the soil moisture. For the study of spatial variability, measurements were made at the 64 points in each mesh. Measurements were taken from 7 to 10 am in the morning throughout January.

Particle size analysis was conducted on the disturbed samples following the methodology proposed by Embrapa (1997). These samples were collected at depths up to 0.20 m. Soil samples with a preserved structure were collected with volumetric rings up to 0.20 m in depth and were saturated gradually with water up to about 2/3 ring height to determine the total porosity (TP). The TP measurement was completed by the calculating the difference in mass between saturated and dried soil mass, subsequent to placing the sample in an oven at 105 °C for 24 h. Macroporosity (MP) was obtained by calculating the difference between the total and micro porosities. Bulk density (BD) was calculated by the ratio of the dry soil mass to the cylinder volume (Embrapa 1997).

The pH of the samples was potentiometrically determined using a 1:2.5 soil to water ratio (Embrapa 1997). Phosphorus (P) was determined using the ion-exchanged resin method (Raij et al. 1987). Total carbon was determined using the Walkley–Black method, modified by Yeomans and Bremner (1988). Organic matter content was estimated based on organic carbon content. The sum of bases (BS), cation exchange capacity (CEC), and base saturation (V%) where calculated using results
of chemical analysis.

2.3 Statistics and mean test

The data were subject to a variance analysis (ANOVA) and the means were compared by the Tukey test at a 5% probability level. This analysis was performed with the Minitab statistical software (Minitab 2000) and had the purpose to detect the possible differences among the studied attributes in varying environments.

Exploratory data analysis was performed by calculating the mean, median, minimum, maximum, and coefficients of variation. The coefficient of variation (CV) was calculated based on the criterion of Warrick and Nielsen (1980), who categorized the CV as low (< 12%), medium (from 12–24%) or high (> 24%).

2.4 Geostatistical analyses

We used Geostatistical analysis to characterize the spatial variability of our data. Under the theory of the intrinsic hypothesis, the experimental semivariogram was estimated by the following equation:

\[
\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left[Z(x_i) - Z(x_i + h)\right]^2
\]

(1)

in which \( \gamma(h) \) is the semi-variance value for distance \( h \); \( N(h) \) is number of pairs involved in the semi-variance calculation; \( Z(x_i) \) is the \( Z \) value of the \( Z \) attribute in the position \( x_i \); \( Z(x_i + h) \) is the value of attribute \( Z \) separated by a distance \( h \) from position \( x_i \).

The coefficients of the semivariogram theoretical model are adjusted a mathematical model to the calculated values of \( \gamma(h) \) (\( C_0 \), nugget effect, \( C_1 \), structural variance; \( C_0 + C_1 \), sill, and \( a \), range).

The nugget effect is the semi-variance value for non-zero distances smaller than the smallest distance between samples. It represents the random-variational component. The sill is the semi-variance value for which the curve stabilizes to a constant value. The range is the distance from the source to the sill, and is interpreted as the distance to which the samples start to be are uncorrelated (Trangmar et al. 1985).
To determine the significance of spatial dependence (SD) within the data, the semivariogram exam was utilized using GS+ software (Robertson 1998). Multiple models were utilized to calculate the same semivariogram for verification. The \( R^2 \) (coefficient of determination) criteria was employed to determine the most accurate model. The Cambardella et al. (1994) classification was adopted to analyze the correlation of soil attributes with spatial dependence; a strong spatial dependence is indicated by comparing the nugget effect, resulting from semivariograms, to the sill value. Nugget effects that are less than or equal to 25% of the sill indicate a strong spatial dependence, a nugget effect between 25% and 75% of the sill indicates moderate dependence, and a nugget greater than 75% is indicates marginal dependence.

2.5 Multivariate statistical analysis

The data were subjected to principal component analysis (PCA) with the objective of reducing the number of variables required to describe the variation in the attributes studied within the various environments. As a result, most of the variance in the data was assigned to the first and second principal components (PCs). The criteria used in the choice of PCs to be interpreted was the percentage of attribute variance explained by each.

For this purpose, the initial set of 13 variables is reduced to two new latent variables (CP1 and CP2). This greatly simplifies graphic illustration of the data, enabling two-dimensional figures (ordering of indices by principal components). The suitability of this analysis is verified by comparison of the transformed data to the data from the original variables; The main components contain eigenvalues superior to the unit and contain data that contribute significantly to the variance, while eigenvalues inferior to the unit do not contain data that contribute significantly to the variance. All multivariate statistical analyzes were processed in the software Statistica version 7.0 (Statsoft 2004).

3 Results and discussion

3.1 Descriptive statistics and mean test
Results regarding the attributes evaluated are presented in Table 1. CO2 emissions in the soil ($F_{CO2}$) did not reflect any biological attribute for forest 2 or ADE. In contrast, a few differences were observed in forest 1, cassava, and sugarcane crops. In forest 2, the $F_{CO2}$ value was 7.00 µmol m$^{-2}$ s$^{-1}$; for ADE, it was 7.59 µmol m$^{-2}$ s$^{-1}$. The mean values found in forest 2 were higher than those in data presented by Xu and Qi (2001), who found high CO2 emissions (4.7, 3.4 and 4.2 µmol m$^{-2}$ s$^{-1}$) in a study of forest soils. The highest $F_{CO2}$ values were found in forest areas, similar to the areas surrounding the ADE sites. The high $F_{CO2}$ values reflect biomass abundance, soil respiration, and the process of decomposing biological material, according to Oliveira (2017), Gomes et al. (2018) and Cunha et al. (2019).

Forest 1 yielded mean values lower than those for forest 2 and DAE, but greater than those for cassava and sugarcane crops. Soil moisture (SM) varied among all environments. Similarly, soil temperature (ST) varied between cassava and sugarcane. The same variation is shown between forest 1 and ADE. Studies indicate that temporal variations of soil CO2 emission might be attributable to water content and soil temperature changes (Kosugi et al. 2007; Ohashi and Gyokusen 2007). In general, spatial variations of soil respiration are commonly related to physical, chemical, mineralogical, and biological factors (Dilustro et al. 2005; Herbst et al. 2011; Panosso et al. 2011; Bahia et al. 2014, 2015).
| Var | FCO₂ | SM | ST | BD | Macro | TP | Clay | pH | OM | P | SB | CEC | BS |
|-----|------|----|----|----|-------|----|------|----|-----|---|----|-----|-----|----|
|     | (μmol m⁻² s⁻¹) | %  | °C | mg m⁻³ | m² m⁻³ | %  | g kg⁻¹ | dm⁻³ | mg dm⁻³ | mmol kg⁻¹ | %  |
| Mean | 3.86b | 31.01a | 24.10c | 1.31a | 3.16d | 33.87d | 549.09a | 3.77d | 20.57c | 8.18b | 11.93c | 561.03a | 2.15c |
| Median | 3.19 | 32.00 | 24.00 | 1.30 | 2.70 | 34.40 | 558.87 | 3.80 | 20.50 | 8.00 | 12.00 | 573.87 | 2.12 |
| CV | 59.61 | 12.31 | 6.70 | 7.21 | 52.26 | 9.20 | 11.93 | 1.53 | 15.48 | 18.96 | 16.54 | 11.75 | 18.63 |
| Min | 1.21 | 23.00 | 21.00 | 1.07 | 0.92 | 26.65 | 402.00 | 3.60 | 14.00 | 6.00 | 9.00 | 415.00 | 1.39 |
| Max | 17.19 | 37.00 | 27.00 | 1.58 | 9.28 | 39.02 | 680.00 | 3.90 | 30.00 | 13.00 | 18.00 | 693.00 | 3.13 |

Table 1: Descriptive statistics of physical, chemical, and biological soil attributes up to depths of 20 cm, measured in the varying environments of the southern-Amazonian region.

N= 64; Means followed by the same letter do not statistically differ significantly according to the Tukey’s test at 1% probability; Min = minimum; Max = maximum; CV = variation coefficient; FCO₂ = Soil CO₂ emission; ST = soil temperature; SM = soil moisture; BD = bulk density; TP = total porosity; Macro = macroporosity; OM = organic matter content; P = available phosphorus; SB = sum of bases; CEC = cation exchange capacity; BS= base saturation
The results indicated that the highest values for ST and soil SM observed in both forest 2 and ADE are correlated to higher $FCO_2$ emissions at these locations. Similarly, Cunha et al. (2019) observed positive correlations among $FCO_2$, ST and SM when measuring the spatial variability of soil $FCO_2$ in archeological, black soil areas containing different land uses. It is noteworthy that regardless of land use, a variation of 7-31% in SM is not restrictive to crop development and biological activity in the Amazonian Oxisols and Inceptisols (Gomes et al. 2019; Cunha et al. 2019).

Among the physical attributes evaluated, the bulk density (BD) in forest 2 indicated a statistically significant difference from ADE. Macroporosity (Macro) in forest 1 had the lowest value compared to the other areas evaluated; this may have occurred due to the high clay content in this soil, which favored the dominance of micropores.

The comparatively low Macro values for forest 1 does not imply an unfavorable physical condition; on the contrary, it may serve as a pseudo-indicator of the natural physical quality of this soil. Such information may aid in decision-making concerning agricultural activities in this area.

According to Roque et al. (2010), Macro values below 0.10 m$^3$ m$^{-3}$ (10% of the total existing pores) can be considered as limiting and indicate inadequate land use. Such conditions are not reflective of the current study conditions.

The highest values of total porosity (TP) were found in ADE. This observation has been documented in previous studies (Barros et al. 2016; Oliveira et al. 2018a, b). The authors attributed the high TP values in ADE to significant stable organic matter content in the soil (Cunha et al. 2019).

Additionally, the low clay contents in ADE implies the dominance of coarser soil fractions such as sand (Campos et al. 2012; Santos et al. 2013). In fact, Barros et al. (2016) stated that sandy soils (associated to ADE) exhibits better soil structure when compared to soils with higher clay content. This is because organic matter within soil acts as a natural cementing agent of the coarser fractions. This forms larger aggregates, and consequently increases total porosity.

Based on the results obtained, it was expected that $FCO_2$ would be greater in cassava and sugarcane areas as a result of intense soil mobilization during conventional agricultural activities (Lal
2007; Teixeira et al. 2013a). Turning the superficial soil layer and disaggregating soil exposes microbiota and accelerates OM deterioration, thereby increasing \( \text{CO}_2 \) emissions from the soil (Bicalho et al. 2014). This pattern was not observed in this study, where the soil \( F\text{CO}_2 \) in forests and ADE exceeded the efflux of \( \text{CO}_2 \) in agricultural areas. Cunha et al. (2018) found that agricultural exploitation of the Amazon is still widespread; therefore, it was noteworthy that factors such as biomass diversity and microbiota drive soil respiration, thus contributing to higher \( \text{CO}_2 \) effluxes in comparisons of the \( F\text{CO}_2 \) of forest and ADE soils.

The forest 2 area varies statistically from ADE in terms of soil pH. This parameter is usually low in anthropogenic environments, characterizing soils with high acidity; however, ADE displayed a pH of 6.27. OM, forest 1 and 2 displayed similar values. Regarding P values, forest 1 showed no difference in comparison to cassava and sugarcane areas. This was expected in Amazonian soils, which generally exhibit low P values in soil solutions. In contrast, ADE contained a high concentration value for this macronutrient, especially in comparison to forest 2. This difference is probably due to ADE organic origin (Santos et al. 2013).

The CEC was statistically different for all environments. Forest 1 had the highest CEC (561.03 mmol kg\(^{-1}\)), while sugarcane and cassava areas displayed lower values of 292.20 and 313.94 mmol kg\(^{-1}\), respectively. Forest 2 displayed a CEC of 83.86 mmol kg\(^{-1}\) and this parameter was 225.49 mmol kg\(^{-1}\) in the ADE area. CEC values are strongly influenced by the potential acidity of the soil and slightly influenced by bases (Campos et al. 2012).

While studying the conversion of eastern Amazon forest into Mombasa grass-grazing areas, Neves Neto et al. (2012) observed the strong influences of chemical and physical characteristics in Haplorthox Oxisol. Other studies have also demonstrated changes in soil attributes in forested areas that were converted into agricultural sites (Correa and Reichardt 1995; Muller et al. 2001; Salimon et al. 2007; Faria et al. 2010).

In this study, the CVs for \( F\text{CO}_2 \) were 46.47%, 31.79%, and 59.61% for forest 2, ADE, and forest 1, respectively. These CV values are high. Conversely, cassava and sugarcane areas displayed
CVs of 23.15% and 23.07 respectively; these are average (Warrick and Nielsen, 1980). Other studies have produced similar results (Schwendenmann et al. 2003; Epron et al. 2004; Konda et al. 2008). The SM had a high CV value in all environments except forest 1, which displayed an average CV value. As for St, the CV value obtained was low in all studied areas, indicating a low variability of ST therein (Table 1).

Regarding the CV variations in anthropogenic environments compared to forest 2, ADE, which has an anthropogenic heritage had a 47% reduction in variability for $F_{CO_2}$. In relation to soil physical properties, expressed by BD, Macro, TP and clay content, anthropization promoted an increase of 5 to 75% for variability. This variation can be related to the higher sensitivity of physical attributes when soil is subjected to intense use (such as agriculture). Such intense use promotes inversion of the soil surface layer and/or compaction. Both ADE and forest 1 environments presented the greatest CV for physical attributes (17 to 71%).

Interestingly, the highest CV variation was observed in chemical attributes comparing forest and anthropogenic environments. For pH values, the variation promoted by anthropization ranged between 2% and 213%. OM ranged from 72% to 128% and available P from 29% to 121%. The greatest variations occurred for SB, CEC, and V%, which varied from 31% to 1564%. Following the same trend found for physical attributes, the ADE and forest 1 environments showed the greatest variation. Chemical attributes are more sensitive to changes in environment; therefore, favoring the greatest variation of these attributes.

### 3.2 Geostatistical analysis

A pure nugget effect (PNE) was observed during the geostatistical analysis for $F_{CO_2}$ in forest 2 (Table 2). It was also observed for SM, pH, and V% in ADE; for SM, clay content, pH, OM, SB, and V% in forest 1; for clay content, CEC, and V% in cassava; and finally, $F_{CO_2}$ in sugarcane. This parameter indicates a random distribution—i.e., unexplainable variability or undetected variation due to measurement or sampling errors—and undetected micro-variations (Vieira et al. 2000; Oliveira et al. 2015). PNE may indicate that the utilized sample spacing is larger than necessary to detect spatial
dependence for a given attribute (Cambardella et al. 1994).

In general, the evaluated attributes presented a spatial dependency, which was quantitatively described by spherical and exponential models. This modeled is similar that performed in the studies of Gomes et al. (2017, 2018) and Cunha et al. (2018) which were also performed in ADE areas. Exponential models are capable of describing erratic phenomena on small scales, while spherical models describe properties with high-spatial continuity which are less erratic at small scales (Isaaks and Srivastava 1989). According to Trangmar et al. (1985) and Cambardella et al. (1994), these are the most common theoretical models used to express soil and plant attributes.

The degree of spatial dependence (DSD) was modeled according to Cambardella et al. (1994). Regarding biological attributes, $\text{FCO}_2$ presented a low DSD value consistent with that in Ishizuka et al. (2005). SM had a moderate DSD for forest 2 and a low DSD in the other studied areas. ST was moderate in both forest 2 and sugarcane areas but low in all other environments. Low DSD values were among the physical attributes of soil in forest 2. In other environments, DSD was moderate; clay content was the exception. DSD showed low spatial dependency in all environments.
Table 2 Models and physical, chemical, and biological parameters of soil estimated using semivariograms at depths up to 0.20 m in different environments in the southern Amazon region

| Variables | FCO₂ | SM | ST | BD | Macro | PT | Clay | pH | OM | P | SB | CEC | BS |
|-----------|------|----|----|----|-------|----|------|----|-----|---|----|-----|-----|
|           | μmol m⁻²s⁻¹ | %  | °C | mg m⁻³ | m² m⁻³ | %  | g kg⁻¹ | g dm⁻³ | g dm⁻³ | mmol kg⁻¹ | % |
| Model     |           |     |    |      |       |     |       |     |     |   |    |     |    |
| NE (C₀)   | 0.80     | -   | 0.55 | 0.06 | 1.21  | 3.51 | -     | -   | -   |   | 0.08 | -   | 93.70 |
| Sill (C₀+C₁) | 2.51     | -   | 2.66 | 0.08 | 2.50  | 8.50 | -     | -   | 2.47 | -  | 282.30 | -   |       |
| Reach (a) | 14.30    | -   | 15.30 | 45.50 | 61.18 | 67.90 | -     | -   | 64.64 | -  | 52.50 | -   |       |
| [C₀/(C₀+C₁)]x100 | 96.00 | -   | 79.00 | 27.00 | 50.00 | 58.00 | -     | -   | 96.00 | -  | 67.00 | -   |       |
| R²        | 0.71     | -   | 0.69 | 0.96 | 0.99  | 0.98 | -     | -   | 0.95 | -  | 0.96 | -   |       |
| Model     |           |     |    |      |       |     |       |     |     |   |    |     |    |
| NE (C₀)   | 0.10     | 0.82 | 0.62 | 0.00 | 4.20  | 2.78 | -     | 0.00 | 2.12 | 0.92 | 0.30 | -   |       |
| Sill (C₀+C₁) | 0.41     | 3.39 | 2.65 | 0.04 | 8.82  | 5.05 | -     | 0.00 | 22.62 | 0.91 | 1.79 | -   |       |
| Reach (a) | 14.20    | 14.10 | 17.70 | 66.94 | 65.40 | 37.63 | -     | 21.30 | 22.70 | 20.60 | 18.60 | -   |       |
| [C₀/(C₀+C₁)]x100 | 75.00 | 75.00 | 75.00 | 32.00 | 52.00 | 45.00 | -     | 80.00 | 90.00 | 97.00 | 82.00 | -   |       |
| R²        | 0.74     | 0.93 | 0.76 | 0.82 | 0.91  | 0.95 | -     | 0.83 | 0.91 | 0.91 | 0.76 | -   |       |
| Model     |           |     |    |      |       |     |       |     |     |   |    |     |    |
| NE (C₀)   | -        | 2.15 | 2.29 | 0.01 | 5.13  | 0.01 | 105.37 | 0.01 | 8.11 | 0.94 | 34.04 | 0.02 |       |
| Sill (C₀+C₁) | -        | 14.32 | 6.70 | 0.02 | 8.35  | 0.02 | 498.80 | 0.02 | 40.40 | 23.4 | 174.30 | 0.12 |       |
| Reach (a) | -        | 15.40 | 68.41 | 61.50 | 8.80  | 5.80 | 6.90  | 17.40 | 26.00 | 18.50 | 26.70 | 13.90 |       |
| [C₀/(C₀+C₁)]x100 | -        | 85.00 | 65.00 | 43.00 | 38.00 | 70.00 | 78.00 | 77.00 | 79.00 | 88.00 | 77.00 | 80.00 | 75.00 |
| R²        | -        | 0.74 | 0.98 | 0.95 | 0.76  | 0.83 | 0.97  | 0.77 | 0.81 | 0.97 | 0.81 | -   |       |
| Model     |           |     |    |      |       |     |       |     |     |   |    |     |    |
| NE (C₀)   | -        | 8.70 | 0.01 | 0.01 | 2.27  | 1.22 | 0.01  | 0.01 | 7.60 | 0.70 | 1.52 | 75.00 | 3.70 |
| Sill (C₀+C₁) | -        | 25.73 | 0.06 | 0.02 | 13.31 | 9.91 | 0.02  | 0.03 | 51.27 | 3.81 | 13.87 | 598.00 | 14.62 |
| Reach (a) | -        | 32.10 | 26.10 | 29.70 | 18.30 | 18.00 | 17.30 | 38.70 | 63.50 | 25.10 | 48.00 | 73.00 | 35.70 |
| [C₀/(C₀+C₁)]x100 | -        | 66.00 | 75.00 | 83.00 | 82.00 | 87.00 | 81.00 | 31.00 | 14.00 | 18.00 | 11.00 | 12.00 | 25.00 |
| R²        | -        | 0.92 | 0.96 | 0.73 | 0.66  | 0.94 | 0.97  | 0.98 | 0.98 | 0.59 | 0.96 | 0.98 | 0.76 |

FCO₂ = Soil CO₂ emission; Sh = soil moisture; St = soil temperature; BD = bulk density; PT = total porosity; Macro = macroporosity; OM = organic matter content; P = available phosphorus; SB = sum of bases; CEC = cation exchange capacity; BS = base saturation; C₀ = Nugget Effect; C₀+C₁ = Sill; DSD: degree of spatial dependence; R² = coefficient of determination; Exp = exponential; Sph = spherical; Gau = Gaussian; PNE = pure nugget effect
Regarding the chemical attributes, forest 2 presented a large CV value, with exceptions for pH and V%, which had a moderate CV, while the other environments presented large CV values. In general, the large CV of soil properties is given due to intrinsic factors, while a weak dependency is attributed to extrinsic factors (Cambardella et al. 1994). Therefore, a moderate or low CV might occur due to the soil homogenization among the varying systems and adopted management in the areas (Cavalcante et al. 2007; Gomes et al. 2017).

Based on the reach value, a parameter which indicates the distance required to observe a spatial correlation (Trangmar et al. 1985; Vieira et al. 2000), it was possible to assess the spatial distribution of the studies sites in each land use. The $F_{CO_2}$ values in forest 1 (14.30 m) and cassava (14.20 m) indicate a slightly similar spatial distribution with each other, however, with greater spatial discontinuity in relation to ADE (28.20 m). This behavior strengthens the hypothesis that land use affects CO$_2$ movement. Increasing the content of stable OM in ADE increases the homogeneity of the OC distribution (Goes et al. 2018) which increases the range of $F_{CO_2}$ and as consequence decreases spatial variability.

Regarding physical attributes, the reach values of forest 2 and sugarcane areas indicated a heterogeneous environment (from 5.80 to 18.30 m) demonstrated by the macro variables (PT and clay content). The opposite behavior was verified in ADE, forest 1, and cassava areas (19.80 to 67.90 m). Assuming the largest range of reach values, 29.70-66.94 m, BD was the physical soil attribute of lowest spatial variability within the studied areas, revealing the good soil structure promoted by soil use. In fact, crops usually provide large volumes of plant material, either in forests by recycling (Cunha et al. 2018), agricultural areas by plant waste generation and deposition (Oliveira et al. 2015), or in ADE by pedogenic processes (Santos et al. 2013).

Due to the observed spatial variability given by descriptive statistical (Table 1) and geostatistical (Table 2) parameters, it was not possible to evaluate the differences imposed by land use. This interpretation motivated by the lack of a structure of special dependency, i.e. PNE, for $F_{CO_2}$, SM, pH, clay content, OM, CEC and SM determined by type of land use, together with
observed high values of CV and DSD. Taking $FCO_2$ as an example, the lack of a spatial structure might be a reflect seasonal variations (Ohashi and Gyokusen 2007), month of analysis (Stoyan et al. 2000) and precipitation events (La Scala et al. 2000).

3.3 Multivariate statistical analysis

The multivariate structure contained in the original data set was evaluated in the “scree-plot” graph and in the principal components analysis (PCA). The “scree-plot” graph (Fig. 2) can be used to verify the importance and contribution of each variable to explain the total variance of the data set. This graph can be serve as a tool for decision-making about the quantity of components that should be retained for the application of the PCA, as well as in the verification of which attributes have the greatest potential to be used as pseudo-indicators of environmental changes, or for the characterization of different groups (Silva et al. 2019).

The two first principal components were responsible for 82.14% of the variance observed within in the evaluated environments. The variables with greater potential to be used as pseudo-indicators in different groups were SB, V%, pH, CEC, $FCO_2$, OM, and SM, which varied from 7.53 to 6.05% as shown in Figure 2. These values are related to the higher sensitivity of the attributes to changes occurring as a result of soil management in these environments.

**Fig. 2** Proportion of variation in the data set explained by the principal component analysis (PC) and contribution of each variable to the total variance by the "scree-plot" of physical, chemical and...
biological soil attributes at a depth of up to 0.20 m. Data obtained in various environments, within
the south Amazonian region

PCA was used to identify the ability of the variables to account for the variance observed. In
this study, the two first principal components (PC1 and PC2) were considered. The eigenvalues for
each was greater than 1 (Kaiser 1958), and together the two variables were responsible for 82.14%
of the variability of soil properties. In this case, these components explain at least 80% of the total
variance to be accounted in decision-making. PC1 explained 64.36% of the total variance, whilst
17.78% of this variance was explained by PC2. The eigenvalue for PC1 and PC2 were 8.36 and 2.31
respectively, reinforcing the choice of using these two components.

The biplot graphical representation, which expresses existing correlations among variables
with the principal components, defined four well-differentiated groups as shown in Figure 3. Linear
correlations within each soil attribute (presented in each variable) and its respective primary
component reveal the ability of the variable to quantitatively describe the soil attribute. Groups I and
III, formed by forests 1 and 2, represent the natural environmental, which are distinct from
environments are used for human activities.

**Fig. 3** Biplot graphical representation of the major components PC1 and PC2 resulting from the
principal component analysis of physical, chemical, and biological properties of soil at a depth up to
0.20 m, in different southern-Amazonian environments. F1 = forest 1; F2 = forest 2; C = cassava; S = sugarcane; ADE = archaeological dark earth

The variables BD (-0.865776) and clay (-0.826436) displayed correlations with PC1 and were responsible for the differentiation of group II, cassava, and sugarcane. This characteristic relates to the use of agricultural machinery used for soil preparation, fertilization, harvest. The use of agricultural machinery increases BD, within a given group, provided the soil management is the same. The clay content associated with groups II and III was high for these environments, particularly forest 1. The areas that formed group II are the most closely approximated by forest 1, due to the lower variability provided by soil management, which occurs in the agricultural cultivation of cassava and sugarcane.

In group IV, which presented correlations with both PC1 and PC2, the variables responsible for its differentiation were TP (0.867287), $FCO_2$ (-0.823351), pH (0.935219), V% (0.953819), OM (0.877744), SB (0.931631), and P (0.915063). This group (represented by ADE) was the most distinct from forest 2 and other anthropogenic environments. In this group the physical, chemical and biological properties where attributed to the pre-Columbian people who inhabited the Amazon for thousands of years, especially influencing the superficial soil layer (Santos et al. 2013). The high content of OM, Ca and P of ADE differentiate this group from other soils most commonly found in the Amazon, a hypothesis from many researchers is that this difference is a result of the food scraps of pre-Columbian populations, human and animal bones, and Ca-rich ceramic fragments (Lima et al. 2002; Campos et al. 2011; Barros et al. 2012; Santos et al. 2013; Aquino et al. 2016; Gomes et al. 2017, 2018, Cunha et al. 2018).

Given the forest soils as references of soil quality, the similarity of group II to group I and III support the statement that, for the conditions of the present study, there is no reason for concern in relation to soil degradation processes. This is an important finding for sustainable agricultural management which is recommended for the natural physical-chemical maintenance of Amazonian soils. Thus, the continuation of studies similar to the current study are necessary. If soil degradation
is a silent and slow process, this work is of importance of the Amazonas region, and consequently, the world ecosystem.

4 Conclusions

Physical-chemical and biological soil attributes generally presented a structure of spatial dependency that was coordinated by the type of land use.

The similarity among cultivated and forest areas indicated no evidence of land degradation imposed by land use under subsistence activities.

The influence of high content organic matter in the soil upon the efflux of CO$_2$ in ADE and forest areas is significant compared to that of cultivated sites; consequently, this variable is useful as an indicator of the preservation of Amazonian environments.

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Figure 1

Schematic representation of the experimental areas located in the south of Amazonas state and sample collection. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.
Figure 2

Proportion of variation in the data set explained by the principal component analysis (PC) and contribution of each variable to the total variance by the "scree-plot" of physical, chemical and biological soil attributes at a depth of up to 0.20 m. Data obtained in various environments, within the south Amazonian region.

Figure 3
Biplot graphical representation of the major components PC1 and PC2 resulting from the principal component analysis of physical, chemical, and biological properties of soil at a depth up to 0.20 m, in different southern-Amazonian environments. F1 = forest 1; F2 = forest 2; C = cassava; S = sugarcane; ADE = archaeological dark earth