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Research Article

Keywords: Spatial variability, land use, dark archaeological earth, efflux of CO₂

Posted Date: May 12th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-490140/v1>

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**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

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 CO₂ 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 CO₂ efflux for ADE and Amazon forest environments than for cultivated regions.

Keywords: Spatial variability; land use; dark archaeological earth; efflux of CO₂.

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).

28 In forest environments, the removal of cover vegetation (e.g., deforestation) may disrupt the
29 natural state of the forest by modifying the chemical, physical, and biological attributes of the soil
30 (Wendling et al. 2012). This disruption is especially significant for low-fertility soils such as those
31 found in most of the Amazon region (Loureiro 2002; Cardoso et al. 2009). As a result, recent studies
32 have reported increases in soil density (Cunha et al. 2018). Ranching increases these impacts.
33 Additionally, nutrient leaching, increased CO₂ efflux, and an abrupt reduction of biological activity
34 result from the scarcity of organic material input to soil. The loss of feedback in Amazonian
35 environments is demonstrated by these soil quality indicators.

36 Some studies have adopted geostatistical methods (Montanari et al. 2012; Silva Júnior et al.
37 2012; Oliveira et al. 2013) and multivariate analysis (Freitas et al. 2012; Marques Júnior et al. 2014)
38 to analyze data on quantify the impacts of soil use and land occupation. Geostatistics has been used
39 to characterize patterns variability for physical (Oliveira et al. 2013), chemical (Aquino et al. 2014),
40 mineralogical (Bahia et al. 2015), and biological attributes of soil (Bahia et al. 2014, 2015). Sample
41 planning is usually defined using semivariogram ranges (Montanari et al. 2005, 2012). However, a
42 few studies have compared the changing attributes of native and disturbed (human-occupied) soils.
43 Such comparisons may fill an existing gap in the literature regarding the impact of disturbance and
44 the subsequent homogenization of initially highly diverse soil.

45 Multivariate principal component analysis (PCA) is another potential tool for exploratory
46 studies on soil and land use. By means of this statistic test, it is possible to investigate the physical,
47 chemical, biological, and mineralogical soil attributes that are limiting for plant growth (Gomes et al.
48 2004; Silva et al. 2010; Cherubin et al. 2011; Nogara Neto et al. 2011; Santi et al. 2012; Bahia et al.
49 2014). The impact of soil use and land occupation upon these parameters can also be quantified by
50 PCA. Thus, these indexes can be used as pseudo-indicators of soil changes from natural to
51 anthropogenic environments. In this sense, the objective of this study was to evaluate the impact of
52 land use on the variability of soil attributes in distinct Amazonian environments.

53

54 **2 Material and methods**

55 **2.1 Characterization of the area and sampling plan**

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

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

74

75 **Fig. 1** Schematic representation of the experimental areas located in the south of Amazonas state and
 76 sample collection

77

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

89 has dimensions of 70 x 70 m, totaling 0.49 hectares.

90

91 **2.2 Analysis of soil attributes**

92 Soil CO₂ emissions were recorded by a portable, automated system the LI-8100 (LI-COR Inc.
93 USA). The LI-8100 system monitors CO₂ concentration inside its chamber via infrared spectroscopy
94 (IRGA Infrared Gas Analyzer). The soil chamber has an internal volume of 854.2 cm³ and a contact
95 area of 83.7 cm². The LI-8100 was placed over polyvinyl chloride (PVC) collars previously inserted
96 into the soil to a depth of 0.03 m. Soil temperature was monitored simultaneously with soil respiration,
97 using a temperature sensor in the LI-8100 system. This sensor consists of a 0.2 m rod, which is
98 inserted into the soil near the PVC collars. A Campbell® (Hydrosense TM, Campbell Scientific,
99 Australia) time domain reflectometry (TDR) device recorded the soil moisture. For the study of
100 spatial variability, measurements were made at the 64 points in each mesh. Measurements were taken
101 from 7 to 10 am in the morning throughout January.

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

110 The pH of the samples was potentiometrically determined using a 1:2.5 soil to water ratio
111 (Embrapa 1997). Phosphorus (P) was determined using the ion-exchanged resin method (Raij et al.
112 1987). Total carbon was determined using the Walkley–Black method, modified by Yeomans and
113 Bremner (1988). Organic matter content was estimated based on organic carbon content. The sum of
114 bases (BS), cation exchange capacity (CEC), and base saturation (V%) were calculated using results

115 of chemical analysis.

116 **2.3 Statistics and mean test**

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

121 Exploratory data analysis was performed by calculating the mean, median, minimum,
122 maximum, and coefficients of variation. The coefficient of variation (CV) was calculated based on
123 the criterion of Warrick and Nielsen (1980), who categorized the CV as low (< 12%), medium (from
124 12–24%) or high (> 24%).

125

126 **2.4 Geostatistical analyses**

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

$$130 \quad \hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \quad (1)$$

131 in which $\gamma(h)$ is the semi-variance value for distance h ; $N(h)$ is number of pairs involved in the semi-
132 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
133 attribute Z separated by a distance h from position x_i .

134 The coefficients of the semivariogram theoretical model are adjusted a mathematical model
135 to the calculated values of $\gamma(h)$ (C_0 , nugget effect, C_1 , structural variance; $C_0 + C_1$, sill, and a , range).
136 The nugget effect is the semi-variance value for non-zero distances smaller than the smallest distance
137 between samples. It represents the random-variational component. The sill is the semi-variance value
138 for which the curve stabilizes to a constant value. The range is the distance from the source to the sill,
139 and is interpreted as the distance to which the samples start to be are uncorrelated (Trangmar et al.
140 1985).

141 To determine the significance of spatial dependence (SD) within the data, the semivariogram
142 exam was utilized using GS+ software (Robertson 1998). Multiple models were utilized to calculate
143 the same semivariogram for verification. The R^2 (coefficient of determination) criteria was employed
144 to determine the most accurate model. The Cambardella et al. (1994) classification was adopted to
145 analyze the correlation of soil attributes with spatial dependence; a strong spatial dependence is
146 indicated by comparing the nugget effect, resulting from semivariograms, to the sill value. Nugget
147 effects that are less than or equal to 25% of the sill indicate a strong spatial dependence, a nugget
148 effect between 25% and 75% of the sill indicates moderate dependence, and a nugget greater than
149 75% is indicates marginal dependence.

150

151 **2.5 Multivariate statistical analysis**

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

157 For this purpose, the initial set of 13 variables is reduced to two new latent variables (CP1 and
158 CP2). This greatly simplifies graphic illustration of the data, enabling two-dimensional figures
159 (ordering of indices by principal components). The suitability of this analysis is verified by
160 comparison of the transformed data to the data from the original variables;. The main components
161 contain eigenvalues superior to the unit and contain data that contribute significantly to the variance,
162 while eigenvalues inferior to the unit do not contain data that contribute significantly to the variance.
163 All multivariate statistical analyzes were processed in the software *Statistica* version 7.0 (Statsoft
164 2004).

165

166 **3 Results and discussion**

167 **3.1 Descriptive statistics and mean test**

168 Results regarding the attributes evaluated are presented in Table 1. CO₂ emissions in the soil
169 (FCO₂) did not reflect any biological attribute for forest 2 or ADE. In contrast, a few differences were
170 observed in forest 1, cassava, and sugarcane crops. In forest 2, the FCO₂ value was 7.00 μmol m⁻² s⁻¹;
171 for ADE, it was 7.59 μmol m⁻² s⁻¹. The mean values found in forest 2 were higher than those in data
172 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
173 study of forest soils. The highest FCO₂ values were found in forest areas, similar to the areas
174 surrounding the ADE sites. The high FCO₂ values reflect biomass abundance, soil respiration, and
175 the process of decomposing biological material, according to Oliveira (2017), Gomes et al. (2018)
176 and Cunha et al. (2019).

177 Forest 1 yielded mean values lower than those for forest 2 and DAE, but greater than those
178 for cassava and sugarcane crops. Soil moisture (SM) varied among all environments. Similarly, soil
179 temperature (ST) varied between cassava and sugarcane. The same variation is shown between forest
180 1 and ADE. Studies indicate that temporal variations of soil CO₂ emission might be attributable to
181 water content and soil temperature changes (Kosugi et al. 2007; Ohashi and Gyokusen 2007). In
182 general, spatial variations of soil respiration are commonly related to physical, chemical,
183 mineralogical, and biological factors (Dilustro et al. 2005; Herbst et al. 2011; Panosso et al. 2011;
184 Bahia et al. 2014, 2015).

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

Var	<i>FCO₂</i>	SM	ST	BD	Macro	TP	Clay	pH	OM	P	SB	CEC	BS
	$\mu\text{mol m}^{-2} \text{s}^{-1}$	%	°C	mg m^{-3}	$\text{m}^3 \text{m}^{-3}$	%	g kg^{-1}		g dm^{-3}	mg dm^{-3}	mmol kg^{-1}		%
Forest 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
Cassava													
Mean	2.80c	7.17e	24.10c	1.15c	12.93b	40.42b	282.40c	3.91c	27.68b	6.03b	9.79c	292.20c	3.47c
Median	2.59	7.00	24.00	1.16	13.11	40.54	272.00	3.90	28.00	6.00	9.50	282.80	3.30
CV	23.12	25.88	6.70	6.28	26.20	6.12	20.75	1.57	17.30	15.62	17.84	20.01	29.92
Min	1.74	4.00	21.00	0.99	5.64	34.37	104.80	3.80	19.00	3.00	7.00	115.80	1.34
Max	4.88	13.00	27.00	1.36	22.65	45.43	662.90	4.10	40.00	8.00	18.00	671.90	9.50
Sugarcane													
Mean	2.88bc	13.53d	25.81b	1.26b	7.02c	36.16c	284.94c	4.42b	30.48b	6.35b	29.00b	313.94b	9.26b
Median	2.67	13.00	26.00	1.28	6.00	35.33	287.98	4.50	30.50	7.00	29.00	318.85	9.20
CV	23.07	27.49	8.56	6.71	59.02	9.01	9.99	3.39	20.51	24.64	24.63	9.37	24.83
Min	2.00	7.00	21.00	1.05	0.47	31.83	202.12	3.90	11.00	3.00	12.00	229.12	4.64
Max	4.35	22.00	29.00	1.50	21.93	50.22	347.68	4.70	47.00	10.00	51.00	373.68	17.25
Forest 2													
Mean	7.00a	17.50c	25.28b	1.30ab	21.43a	41.28b	327.94b	3.97c	18.65c	6.09b	8.94c	83.86e	11.10b
Median	5.96	16.50	25.28	1.31	21.55	41.23	324.92	3.90	20.50	5.50	7.05	93.95	8.38
CV	46.75	28.20	0.96	5.98	15.05	7.55	12.67	4.79	35.29	36.13	69.08	26.16	68.41
Min	2.58	9.00	24.73	1.10	12.80	33.94	233.60	3.70	6.00	2.00	3.30	39.50	5.38
Max	17.58	29.00	25.99	1.42	29.45	51.37	439.56	4.60	31.00	10.00	41.20	115.80	49.52
Dark Archaeological Earth (DAE)													
Mean	7.58a	21.03b	26.79a	0.88d	22.04a	50.47a	121.50d	6.27a	68.19a	309.40a	197.19a	225.49d	87.20a
Median	7.04	21.00	26.63	0.88	22.79	50.95	120.00	6.20	68.00	298.5	195.2	227.65	86.79
CV	31.79	24.90	2.53	9.40	37.82	12.76	35.01	4.71	19.86	27.93	14.80	12.30	4.11
Min	3.32	12.00	25.64	0.61	0.81	30.81	42.90	5.70	29.00	165.00	103.80	128.80	78.12
Max	16.02	37.00	28.94	1.04	47.52	75.68	250.30	7.10	94.00	547.00	252.60	274.40	93.66

187 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
188 = maximum; CV = variation coefficient; *FCO₂* = Soil CO₂ emission; ST = soil temperature; SM = soil moisture; BD = bulk density; Tp = total porosity;
189 Macro = macroporosity; OM = organic matter content; P = available phosphorus; SB = sum of bases; CEC = cation exchange capacity; BS= base
190 saturation

191 The results indicated that the highest values for ST and soil SM observed in both forest 2 and
192 ADE are correlated to higher FCO_2 emissions at these locations. Similarly, Cunha et al. (2019)
193 observed positive correlations among FCO_2 , ST and SM when measuring the spatial variability of
194 soil FCO_2 in archeological, black soil areas containing different land uses. It is noteworthy that
195 regardless of land use, a variation of 7-31% in SM is not restrictive to crop development and
196 biological activity in the Amazonian Oxisols and Inceptisols (Gomes et al. 2019; Cunha et al. 2019).

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

201 The comparatively low Macro values for forest 1 does not imply an unfavorable physical
202 condition; on the contrary, it may serve as a pseudo-indicator of the natural physical quality of this
203 soil. Such information may aid in decision-making concerning agricultural activities in this area.
204 According to Roque et al. (2010), Macro values below $0.10 \text{ m}^3 \text{ m}^{-3}$ (10% of the total existing pores)
205 can be considered as limiting and indicate inadequate land use. Such conditions are not reflective of
206 the current study conditions.

207 The highest values of total porosity (TP) were found in ADE. This observation has been
208 documented in previous studies (Barros et al. 2016; Oliveira et al. 2018a, b). The authors attributed
209 the high TP values in ADE to significant stable organic matter content in the soil (Cunha et al. 2019).
210 Additionally, the low clay contents in ADE implies the dominance of coarser soil fractions such as
211 sand (Campos et al. 2012; Santos et al. 2013). In fact, Barros et al. (2016) stated that sandy soils
212 (associated to ADE) exhibits better soil structure when compared to soils with higher clay content.
213 This is because organic matter within soil acts as a natural cementing agent of the coarser fractions.
214 This forms larger aggregates, and consequently increases total porosity.

215 Based on the results obtained, it was expected that FCO_2 would be greater in cassava and
216 sugarcane areas as a result of intense soil mobilization during conventional agricultural activities (Lal

217 2007; Teixeira et al. 2013a). Turning the superficial soil layer and disaggregating soil exposes
218 microbiota and accelerates OM deterioration, thereby increasing CO₂ emissions from the soil
219 (Bicalho et al. 2014). This pattern was not observed in this study, where the soil FCO₂ in forests and
220 ADE exceeded the efflux of CO₂ in agricultural areas. Cunha et al. (2018) found that agricultural
221 exploitation of the Amazon is still widespread; therefore, it was noteworthy that factors such as
222 biomass diversity and microbiota drive soil respiration, thus contributing to higher CO₂ effluxes in
223 comparisons of the FCO₂ of forest and ADE soils.

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

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

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

241 In this study, the CVs for FCO₂ were 46.47%, 31.79%, and 59.61% for forest 2, ADE, and
242 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 FCO_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 a 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 FCO_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, FCO_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

269 dependence for a given attribute (Cambardella et al. 1994).

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

277 The degree of spatial dependence (DSD) was modeled according to Cambardella et al. (1994).
278 Regarding biological attributes, FCO_2 presented a low DSD value consistent with that in Ishizuka et
279 al. (2005). SM had a moderate DSD for forest 2 and a low DSD in the other studied areas. ST was
280 moderate in both forest 2 and sugarcane areas but low in all other environments. Low DSD values
281 were among the physical attributes of soil in forest 2. In other environments, DSD was moderate; clay
282 content was the exception. DSD showed low spatial dependency in all environments.

283 **Table 2** Models and physical, chemical, and biological parameters of soil estimated using semivariograms at depths up to 0.20 m in different
 284 environments in the southern Amazon region

Variables	FCO ₂ μmol m ⁻² s ⁻¹	SM %	ST °C	BD mg m ⁻³	Macro m ³ m ⁻³	PT %	Clay g kg ⁻¹	pH	OM g dm ⁻³	P mg dm ⁻³	SB mmol kg ⁻¹	CEC	BS %
Forest 1													
Model	Sph	PNE	Exp	Sph	Exp	Sph	PNE	PNE	PNE	Sph	EPP	Sph	PNE
NE (C ₀)	0.80	-	0.55	0.06	1.21	3.51	-	-	-	0.08	-	93.70	-
Sill (C ₀ +C ₁)	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	-
[C ₀ /(C ₀ +C ₁)]x100	96.00	-	79.00	27.00	50.00	58.00	-	-	-	96.00	-	67.00	-
R ²	0.71	-	0.69	0.96	0.99	0.98	-	-	-	0.95	-	0.96	-
Cassava													
Model	Sph	Exp	Exp	Sph	Exp	Sph	PNE	Exp	Sph	Sph	Exp	PNE	PNE
NE (C ₀)	0.10	0.82	0.62	0.00	4.20	2.78	-	0.00	2.12	0.02	0.30	-	-
Sill (C ₀ +C ₁)	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	-	-
[C ₀ /(C ₀ +C ₁)]x100	75.00	75.00	76.00	32.00	52.00	45.00	-	80.00	90.00	97.00	82.00	-	-
R ²	0.74	0.93	0.76	0.82	0.91	0.95	-	0.83	0.91	0.91	0.76	-	-
Sugar cane													
Model	PNE	Sph	Gau	Sph	Exp	Sph	Sph	Sph	Exp	Sph	Sph	Exp	Sph
NE (C ₀)	-	2.15	2.29	0.01	5.13	0.01	105.37	0.01	8.11	0.26	0.01	34.04	0.02
Sill (C ₀ +C ₁)	-	14.32	6.70	0.02	8.35	0.02	498.80	0.02	40.40	2.34	0.07	174.30	0.12
Reach (a)	-	15.40	68.41	61.50	8.80	5.80	6.90	17.40	26.10	33.00	18.50	26.70	13.90
[C ₀ /(C ₀ +C ₁)]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
R ²	-	0.74	0.98	0.95	0.76	0.60	0.84	0.83	0.97	0.77	0.81	0.97	0.81
Forest 2													
Model	PNE	Exp	Exp	Sph	Exp	Sph	Exp	EsF	Sph	Sph	Exp	Sph	Exp
NE (C ₀)	-	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 (C ₀ +C ₁)	-	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
[C ₀ /(C ₀ +C ₁)]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
R ²	-	0.92	0.96	0.73	0.66	0.86	0.94	0.97	0.98	0.59	0.96	0.98	0.76
Archaeological dark earth (ADE)													
Model	Exp	PNE	Gau	Exp	Sph	Exp	Exp	PNE	Exp	Exp	Exp	Exp	PNE
NE (C ₀)	1.33	-	0.12	0.01	44.31	6.36	306.50	-	8.90	10.00	19.00	132.35	-
Sill (C ₀ +C ₁)	6.32	-	1.19	0.02	59.47	22.86	1612.00	-	183.70	5467.00	825.80	735.70	-
Reach (a)	28.20	-	65.00	58.02	30.68	23.70	19.80	-	33.00	21.30	22.50	22.50	-
[C ₀ /(C ₀ +C ₁)]x100	78.00	-	89.00	49.00	25.00	72.00	99.00	-	95.00	99.00	97.00	82.00	-
R ²	0.83	-	0.97	0.90	0.81	0.87	0.95	-	0.89	0.80	0.71	0.87	-

285 FCO₂ = Soil CO₂ emission; Sh = soil moisture; St = soil temperature; BD = bulk density; TP = total porosity; Macro = macroporosity; OM = organic
 286 matter content; P = available phosphorus; SB = sum of bases; CEC = cation exchange capacity; BS = base saturation; C₀ = Nugget Effect; C₀+C₁ = Sill;
 287 DSD: degree of spatial dependence; R² = coefficient of determination; Exp = exponential; Sph = spherical; Gau = Gaussian; PNE = pure nugget effect

288 Regarding the chemical attributes, forest 2 presented a large CV value, with exceptions for
289 pH and V%, which had a moderate CV, while the other environments presented large CV values. In
290 general, the large CV of soil properties is given due to intrinsic factors, while a weak dependency is
291 attributed to extrinsic factors (Cambardella et al. 1994). Therefore, a moderate or low CV might occur
292 due to the soil homogenization among the varying systems and adopted management in the areas
293 (Cavalcante et al. 2007; Gomes et al. 2017).

294 Based on the reach value, a parameter which indicates the distance required to observe a
295 spatial correlation (Trangmar et al. 1985; Vieira et al. 2000), it was possible to assess the spatial
296 distribution of the studies sites in each land use. The FCO_2 values in forest 1 (14.30 m) and cassava
297 (14.20 m) indicate a slightly similar spatial distribution with each other, however, with greater spatial
298 discontinuity in relation to ADE (28.20 m). This behavior strengthens the hypothesis that land use
299 affects CO_2 movement. Increasing the content of stable OM in ADE increases the homogeneity of
300 the OC distribution (Goes et al. 2018) which increases the range of FCO_2 and as consequence
301 decreases spatial variability.

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

310 Due to the observed spatial variability given by descriptive statistical (Table 1) and
311 geostatistical (Table 2) parameters, it was not possible to evaluate the differences imposed by land
312 use. This interpretation motivated by the lack of a structure of special dependency, i.e. PNE, for
313 FCO_2 , SM, pH, clay content, OM, CEC and SM determined by type of land use, together with

314 observed high values of CV and DSD. Taking FCO_2 as an example, the lack of a spatial structure
 315 might be a reflect seasonal variations (Ohashi and Gyokusen 2007), month of analysis (Stoyan et al.
 316 2000) and precipitation events (La Scala et al. 2000).

317
 318 **3.3 Multivariate statistical analysis**

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

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

331
 332 **Fig. 2** Proportion of variation in the data set explained by the principal component analysis (PC) and
 333 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 were 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

379 is a silent and slow process, this work is of importance of the Amazonas region, and consequently,
380 the world ecosystem.

381 **4 Conclusions**

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

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

386 The influence of high content organic matter in the soil upon the efflux of CO₂ in ADE and
387 forest areas is significant compared to that of cultivated sites; consequently, this variable is useful as
388 an indicator of the preservation of Amazonian environments.

389

390 **5 References**

- 391 Aquino RE., Marques Júnior J, Campos MCC, Oliveira IA, Bahia ASR, Santos LAC (2016)
392 Characteristics of color and iron oxides of clay fraction in archaeological dark earth in Apuí
393 county, southern Amazonas. *Geoderma* 262: 35-44. doi 10.1016/j.geoderma.2015.07.010
- 394 Aquino RE, Marques Júnior J, Campos MCC, Oliveira IA, Siqueira DS (2014) Distribuição espacial
395 de atributos químicos do solo em área de pastagem e floresta. *Pesqui Agropecu Trop* 44: 32-41.
396 doi 10.1590/S1983-40632014000100001
- 397 Bahia ASRS, Marques Júnior J, Panosso AR, Camargo LA, Siqueira DS, Teixeira DDB, La Scala N
398 (2015) Field-scale spatial correlation between contents of iron oxides and CO₂ emission in an
399 Oxisol cultivated with sugarcane. *Sci Agric* 72: 157-166. doi 10.1590/0103-9016-2014-0142
- 400 Bahia ASRS, Marques Júnior J, Panosso AR, Camargo LA, Siqueira DS, La Scala N (2014) Iron
401 oxides as proxies for characterizing anisotropy in soil CO₂ emission in sugarcane areas under
402 green harvest. *Agric Ecosyst Environ* 192: 152-162. doi 10.1016/j.agee.2014.04.017
- 403 Barros KRM, Lima HV, Canellas LP, Kern DC (2012) Fracionamento químico da matéria orgânica
404 e caracterização física de Terra Preta de Índio. *Rev Cienc Agrar* 55: 44-51. doi

405 10.4322/rca.2012.037

406 Brasil (1978) Ministério das Minas e Energia. Projeto Radambrasil, folha SB. 20. Purus, Rio de
 407 Janeiro

408 Cajazeira JP, Assis Júnior RN (2011) Variabilidade espacial das frações primárias e agregados de um
 409 Argissolo no Estado do Ceará. Rev Ciênc Agron 42: 258-267. [http://dx.doi.org/10.1590/S1806-](http://dx.doi.org/10.1590/S1806-66902011000200002)
 410 66902011000200002

411 Cambardella CA, Moorman TB, Novak JM, Parkin TB, Karlen DL, Turco RF, Konopka AE (1994)
 412 Field-scale variability of soil properties in Central Iowa. Soil Sci Soc Am J 58: 1501-1511. doi
 413 10.2136/sssaj1994.03615995005800050033x

414 Campos MCC, Ribeiro MR, Souza Júnior VS, Ribeiro Filho MR, Almeida MC (2012)
 415 Topossequência de solos na transição campos naturais-floresta na região de Humaitá, Amazonas.
 416 Acta Amazon 42: 387-398. doi 10.1590/S0044-59672012000300011

417 Campos MCC, Ribeiro MR, Souza Júnior VS, Ribeiro Filho MR, Souza RVCC, Almeida MCC
 418 (2011) Caracterização e Classificação de Terras Pretas Arqueológicas na região do Médio Rio
 419 Madeira. Bragantia 70: 18-27. doi 10.1590/S0006-87052011000300016

420 Cardoso EL, Silva MLN, Moreira FMS, Curi N (2009) Atributos biológicos indicadores da qualidade
 421 do solo em pastagem cultivada e nativa no Pantanal. Pesqui Agropec Bras 44: 631-637.

422 Cavalcante EGS, Alves MC, Souza ZM, Pereira GT (2007) Variabilidade espacial de atributos
 423 químicos do solo sob diferentes usos e manejos. Rev Bras Cienc Sol 31: 1329-1339. doi
 424 10.1590/S0100-06832007000600012

425 Carvalho MP, Takeda EY, Freddi OS (2003) Variabilidade espacial de atributos de um solo sob
 426 videira em Vitória Brasil (SP). Rev Bras Cienc Sol 27: 695-703. doi 10.1590/S0100-
 427 06832003000400014

428 Cherubin MR, Santi AL, Basso CJ, Eitelwein MT, Vian AL (2011) Caracterização e estratégias de
 429 manejo da variabilidade espacial dos atributos químicos do solo utilizando a análise dos
 430 componentes principais. Enciclop Biosf 7: 196-210.

431 Cohen JCP, Beltrão JC, Gandu AW, Silva RR (2007) Influência do desmatamento sobre o ciclo
 432 hidrológico na Amazônia. *Cienc Cult* 59: 36-39.

433 Correa JC, Reichardt K (1995) Efeito do tempo de uso das pastagens sobre as propriedades de um
 434 Latossolo amarelo da Amazônia central. *Pesqui Agropecu Bras* 30: 107-114.

435 Cunha TJF, Madari BE, Canellas LP, Ribeiro LP, Benites VM, Santos GA (2009) Soil organic matter
 436 and fertility of anthropogenic dark earths (Terra Preta de Índio) in the Brazilian Amazon basin.
 437 *Rev Bras Ciênc Sol* 33: 85-93. doi 10.1590/S0100-06832009000100009

438 Cunha JM, Campos MCC, Gaio DC, Souza ZM, Soares MDR, Silva DMP, Simões EL (2018) Spatial
 439 variability of soil respiration in Archaeological Dark Earth areas in the Amazon. *Catena* 162
 440 148–156. doi:10.1016/j.catena.2017.12.001.

441 Dilustro JJ, Collins B, Duncan L, Crawford C (2005) Moisture and soil texture effects on soil CO₂
 442 efflux components in southeastern mixed pine forests. *For Ecol Manage* 204: 87-97. doi
 443 10.1016/j.foreco.2004.09.001

444 Embrapa (1997) Empresa Brasileira de Pesquisa Agropecuária. Centro Nacional de Pesquisa de
 445 Solos. Manual de métodos de análise de solo. Embrapa, Rio de Janeiro

446 Epron D, Nouvellon Y, Rouspard O, Mouvondy W, Mabiala A, Saint-André L, Joffre R, Jourdan C,
 447 Bonnefond J, Berbigier P, Hamel O (2004) Spatial and temporal variations of soil respiration in
 448 a Eucalyptus plantation in Congo. *For Ecol Manage* 202: 149-160. doi
 449 10.1016/j.foreco.2004.07.019

450 Faria AFG, Santos AC, Santos TM, Batistella Filho F (2010) Influência do manejo do solo nas
 451 propriedades químicas e físicas em topossequência na bacia do Rio Araguaia, estado do
 452 Tocantins. *Rev Bras Ciênc Sol* 34: 517-524. doi 10.1590/S0100-06832010000200025

453 Freitas L, Casagrande JC, Oliveira IA, Aquino RE (2012) Análises multivariadas de atributos físicos
 454 em Latossolo Vermelho submetidos a diferentes manejos. *Enciclopédia Biosfera* 8: 126-139.

455 Gomes JBV, Curi N, Motta PEF, Ker JC, Marques JJGSM, Schulze DG (2004) Análise de
 456 componentes principais de atributos físicos, químicos e mineralógicos de solos do bioma cerrado.

457 Rev Bras Ciênc Sol 28: 137-153. doi 10.1590/S0100-06832004000100014

458 Gomes RP, Campos MCC, Soares MDR, Silva DMP, Cunha JM, Franciscon U, Silva LS, Oliveira
 459 IA, Brito WBM (2017) Variabilidade espacial de agregados e carbono orgânico sob três
 460 diferentes usos de terra preta de índio no sul do Amazonas. Biosci J 33: 1513-1522. doi
 461 10.14393/BJ-v33n6a2017-37142

462 Herbst M, Prolingheuer N, Graf A, Huisman JA, Weihermüller L, Vanderborght J, Vereecken H
 463 (2011) Multivariate conditional stochastic simulation of soil heterotrophic respiration at plot
 464 scale. Geoderma 160: 74-82. doi 10.1016/j.geoderma.2009.11.018

465 Isaaks EH, Srivastava RM (1989) An introduction to applied geostatistics. Oxford University Press,
 466 New York

467 Ishizuka S, Iswandi A, Nakajima Y, Yonemura S, Sudo S, Tsuruta H, Muriyarso D (2005) Spatial
 468 patterns of greenhouse gas emission in a tropical rainforest in Indonesia. Nutr Cycl Agroecosys
 469 71: 55-62. doi 10.1007/s10705-004-5284-7

470 Kaiser HF (1958) The varimax criterion for analytic rotation in factor analysis. Psychometrika 23:
 471 187-200. doi 10.1007/BF02289233

472 Konda R, Ohta S, Ishizuka S, Aria S, Ansori S, Tanaka N, Hardjono A (2008) Spatial structures of
 473 N₂O, CO₂, and CH₄ fluxes from Acacia mangium plantation soils during a relatively dry season
 474 in Indonesia. Soil Biol. Biochem 40: 3021-3030. doi 10.1016/j.soilbio.2008.08.022

475 Kosugi Y, Mitani T, Ltoh M, Noguchi S, Tani M, Matsuo N, Takanashi S, Ohkubo S, Nik AR (2007)
 476 Spatial and temporal variation in soil respiration in a Southeast Asian tropical rainforest. Agric
 477 For Meteorol 147: 35-47. doi 10.1016/j.agrformet.2007.06.005

478 La Scala N, Marques Júnior J, Pereira GT, Corá JE (2000) Short-term temporal changes in the spatial
 479 variability model of CO₂ emissions from a Brazilian bare soil. Soil Biol Biochem 32: 1459-1462.
 480 doi 10.1016/S0038-0717(00)00051-1

481 Lima JSS, Sattler MA, Passos RR, Oliveira PC, Souza GS (2009) Variabilidade espacial de atributos
 482 físicos de um Argissolo Vermelho- Amarelo sob pastagem e vegetação secundária em

483 regeneração natural. Eng Agríc 29: 185-195. doi 10.1590/S0100-69162009000200002

484 Lima HN, Schaefer CER, Mello JWV, Gilkes RJ, Ker JC (2002) Pedogenesis and pre-colombian land
 485 use of terra preta anthrosols (“Indian Black Earth”) of western Amazonia. Geoderma 110: 01-17.
 486 doi 10.1016/S0016-7061(02)00141-6

487 Loureiro VR (2002) Amazônia: uma história de perdas e danos, um futuro a (re)construir. Estud Av
 488 16: 107-121. doi 10.1590/S0103-40142002000200008

489 Marques Júnior J, Siqueira DS, Camargo LA, Teixeira DB, Barrón V, Torrent J (2014) Magnetic
 490 susceptibility and diffuse reflectance spectroscopy to characterize the spatial variability of soil
 491 properties in a Brazilian Haplustalf. Geoderma 219-220, 63-71. doi
 492 10.1016/j.geoderma.2013.12.007

493 Minitab Release 14.1, 2000. Statistical Software. US/ Canadá.

494 Montanari R, Marques Júnior J, Pereira GT, Souza ZM (2005) Forma da paisagem como critério para
 495 otimização amostral de Latossolos sob cultivo de cana-de-açúcar. Pesq Agropec Bras 40: 69-77.
 496 doi 10.1590/S0100-204X2005000100010

497 Montanari R, Siqueira DS, Marques Júnior J, Pereira GT, Souza GSA, Siqueira GM (2012) The use
 498 of scaled semivariograms to plan soil sampling in sugarcane fields. Precis Agric 13: 542-552.
 499 doi 10.1007/s11119-012-9265-6

500 Muller MML, Guimarães MF, Desjardins T, Martins PFS (2001) Degradação de pastagens na Região
 501 Amazônica: propriedades físicas do solo e crescimento de raízes. Pesq Agropec Bras 36: 1409-
 502 1418. doi 10.1590/S0100-204X2001001100012

503 Neves CMN, Silva MLN, Curi N, Cardoso EL, Macedo RLG, Ferreira MM, Souza FS (2007)
 504 Atributos indicadores da qualidade do solo em Sistemas Agrossilvipastoril no Noroeste do
 505 Estado de Minas Gerais. Sci For 74: 45-53.

506 Neves Neto DN, Santos AC, Silva Neto SP (2012) Atributos físicos e químicos do solo em
 507 ecossistema de capim-mombaça na Amazônia Oriental. Rev Cien Ag 55: 75-84. doi
 508 10.4322/rca.2012.041

509 Nogara Neto F, Roloff G, Dieckow J, Motta ACV (2011) Atributos de solo e cultura espacialmente
510 distribuídos relacionados ao rendimento do milho. *Rev Bras Ciênc Sol* 35: 1025-1036.

511 Oliveira IA, Campos MCC, Soares MDR, Aquino RE, Marques Júnior J, Nascimento EP (2013)
512 Variabilidade espacial de atributos físicos em um cambissolo háplico sob diferentes usos na
513 região sul do Amazonas. *Rev Bras Ciênc Sol* 37: 1103-1112. doi 10.1590/S0100-
514 06832013000400027

515 Ohashi M, Gyokusen K (2007) Temporal change in spatial variability of soil respiration on a slope
516 of Japanese cedar (*Cryptomeria japonica* D. Don) forest. *Soil Biol Biochem* 39: 1130-1138. doi
517 10.1016/j.soilbio.2006.12.021

518 Panosso AR, Marques Júnior J, Milori DMBP, Ferraudo AS, Barbieri DM, Pereira GT, La Scala N
519 (2011) Soil CO₂ emission and its relation to soil properties in sugarcane areas under Slash-and-
520 burn and Green harvest. *Soil Till Res* 111: 190–196. doi 10.1016/j.still.2010.10.002

521 Raij BV, Andrade JC, Cantarella H, Quaggio JA (1987) *Análise química para avaliação da fertilidade*
522 *de solos tropicais*. Instituto Agronômico, Campinas

523 Robertson GP (1998) *GS+ geostatistics for the environmental sciences: GS+ user's guide*. Gamma
524 Design Software, Plainwell

525 Rockstrom JA (2009) Safe operating space for humanity. *Nature* 461: 472-475.

526 Salimon CI, Wadt PGS, Melo AWF (2007) Dinâmica do carbono na conversão de florestas para
527 pastagens em Argissolos da Formação Geológica Solimões, no Sudoeste da Amazônia. *Rev Biol*
528 *Cien Terra* 7: 29-38.

529 Santi AL, Amado TJC, Cherubin MR, Martin TN, Pires JL, Flora LPD, Basso CJ (2012) Análise de
530 componentes principais de atributos químicos e físicos do solo limitantes à produtividade de
531 grãos. *Pesq Agropec Bras* 47: 1346-1357

532 Santos LAC, Campos MCC, Aquino RE, Bergamin AC, Silva DMP, Marques Júnior J, Franca ABC
533 (2013) Caracterização e gênese de terras pretas arqueológicas no sul do Estado do Amazonas.
534 *Rev Bras Ciênc Sol* 37: 825-836. doi 10.1590/S0100-06832013000400001

535 Schwendenmann L, Veldkamp E, Brenes T, O'brien JJ, Mackensen J (2003) Spatial and temporal
536 variation in soil CO₂ efflux in an old-growth neotropical rain forest, La Selva, Costa Rica.
537 Biogeochemistry 64: 111-128. doi 10.1023/A:1024941614919

538 Shorupa LA (2003) Áreas de preservação permanente e desenvolvimento sustentável. Embrapa Meio
539 Ambiente, Jaguariúna

540 Silva Júnior JF, Siqueira DS, Marques Júnior J, Pereira GT (2012) Classificação numérica e modelo
541 digital de elevação na caracterização espacial de atributos dos solos. Rev Bras Eng Agr Amb 16:
542 415-424 doi 10.1590/S1415-43662012000400012

543 Silva SA, Lima JSS, Xavier AC, Teixeira MM (2010) Variabilidade espacial de atributos químicos
544 de um Latossolo Vermelho-Amarelo húmico cultivado com café. Rev Bras Ciênc Sol 34: 15-22.
545 doi 10.1590/S0100-06832010000100002

546 Soil Survey Staff (2010) Keys to soil taxonomy. 11th ed. USDA-Natural Resources Conservation
547 Service, Washington

548 Statsoft Inc. Statistica (data analysis software system) version 7, 2004.

549 Stoyan H, de-Polli H, Böhm S, Robertson GP, Paul EA (2000) Spatial heterogeneity of soil respiration
550 and related properties at the plant scale. Plant Soil 222: 203-214. doi 10.1023/A:1004757405147

551 Thornthwaite CW (1948) An approach towards a rational classification of climate. Geogr Rev 38:
552 55-94. doi 10.2307/210739

553 Trangmar BB, Yost RS, Uehara G (1985) Application of geostatistics to spatial studies of soil
554 properties. Adv Agron 38: 54-94. doi 10.1016/S0065-2113(08)60673-2

555 Vieira SR, Dechen SCF, Siqueira GM, Dufranc G (2011) Variabilidade espacial de atributos físicos
556 e químicos relacionados com o estado de agregação de dois Latossolos cultivados no sistema de
557 semeadura direta. Bragantia 70: 185-195. doi 10.1590/S0006-87052011000100025

558 Warrick W, Nielsen DR (1980) Spatial variability of soil physical properties in the field. In: Hillel,
559 D. (Ed.). Applications of soil physics. Academic Press, New York; p. 319-344.

560 Wendling B, Vinhal-Freitas IC, Oliveira RC, Babata MM, Borges EN (2012) Densidade, agregação

561 e porosidade do solo em áreas de conversão do cerrado em floresta de pinus, pastagem e plantio
562 direto. Biosci J 28: 256-265.

563 Yeomans JC, Bremner JM (1988) A rapid and precise method for routine determination of organic
564 carbon in soil. Comm Soil Sci Plant Anal 19: 1467-1476. doi 10.1080/00103628809368027

565 Xu M, Qi Y (2001) Soil-surface CO₂ efflux and its spatial and temporal variations in a Young
566 ponderosa pine plantation in northern California. Glob Chang Biol 7: 667-677. doi
567 10.1046/j.1354-1013.2001.00435.x

Figures

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