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Temporal-spatial Analysis of Stocks of Carbon Acrisols and Different Land-use in Brazilian Amazon

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Abstract: The term *land-use* describes the different forms land is employed and occupied. In rural environments, an agroforestry system (AFS) is any land-use method that is a source of income and food to households and can help reduce anthropogenic carbon emissions to the soil caused by change in land-use. This study analyzed the spatial variability of organic carbon stocks (OCS) and organic carbon levels (OCL) in soils exposed to different use and cover practices in a rural settlement in the southern Amazon in Brazil. Images were digitally processed and a theme map was constructed. Then quadrats were defined and soil samples were collected. AFSs established for over 10 years (AFS19 and HG15) presented the highest soil OCS (21.02 mg C/ha and 18.86 mg C/ha) in the 0-10cm layer in the rainy season. The lowest soil OCS (2.58 mg C/ha) was recorded in migratory agriculture quadrats. AFSs established for longer periods induced an increase in soil OCS and the recuperation of the chemical attributes of soil.

Key words: change land-cover, stocks of carbon soil, agroforestry systems

1. Introduction

As one of the most abundant elements in nature, carbon is present in the oceanic, geologic, pedologic, biotic and atmospheric compartments. For example, in the pedologic compartment, inorganic carbon stocks are 938 Gt, while organic carbon (OC) level reaches 1,576 Gt. Approximately 50% of the total OC level, that is, 800 Gt, is confined as different physical and chemical species in the first 30 cm layer [1, 2].

The OC level in the 30 cm layer has its origins in plant and animal organic matter (OM) present in the topsoil, especially in the litterfall compartment. Litterfall is formed by dry leaves, bark, branches, flowers, fruits, and other plant and animal waste material [3]. According to numerous specialists, litterfall is both the main entryway and exit (through slash and burn practices) of carbon in the pedologic compartment in tropical regions [4, 5].

Several studies have concluded that the equatorial and tropical forests that emerged after the last ice age in the intertropical zone grew on slightly dystrophic soils with very low levels of exchangeable bases and high concentration of metals. Some of these micronutrients are essential to the forest ecosystem; others are non-essential. For this reason, the diversity of species and ecosystems, especially in the equatorial Amazon Forest, is associated with the efficiency of the cycling of nutrients released through the decomposition and mineralization of OC from the forest biomass, which becomes incorporated in the soil. Subsequently, these nutrients are absorbed by plants through biogeochemical processes [6].

The cycling of nutrients in the Amazon Forest ecosystem is interrupted by land-use change, in

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particular the clearcutting of trees. Besides affecting the bioavailability of nutrients, OM in soil changes organic carbon stocks (OCS) in the topsoil and lower layers. In this sense, OC is an efficient indicator of the effects of changes in land-use and cover on the spatial-temporal profile of the soil in the Brazilian Amazon [7].

In the past 140 years, the expansion of cattle farming based on deforestation in the Amazon has led to the emission of 121 Gt of carbon into the atmosphere as CO_2. This indicates that a given change in land-use and cover may eventually increase greenhouse gas (GHG) emissions, worsening the climate change scenario. The extensive changes in land-use and cover that occur due to the high deforestation rates in the Amazon have caused Brazil to be considered one of the main contributors of GHG [8].

In the effort to meet the target in GHG emissions established in the 2009 United Nations Climate Change Conference (CPO-15) in Copenhagen, Denmark, the Brazilian government recently started the Low Carbon Agriculture Program (LCAP). In addition to improving the income of households, the program also aims to motivate farmers to use sustainable agriculture techniques developed to reduce GHG emissions. The LCAP includes agricultural systems based on planting crops, cattle grazing and preservation of forest, through direct cultivation systems, agroforestry systems (AFSs), and others [9]

Agroforestry is a category of land use and cover based on the cultivation of tree and shrub species in association with agricultural crops in the same geographic space [10]. Depending on the complexity of the floristic structure, an AFS may play an important role in restraining deforestation by smallholders, since it represents a shift from migratory agriculture (MA, also called slash and burn practices) and extensive cattle grazing as carried out by Amazonian farmers [11].

To some extent, the presence of trees in AFSs is possibly the most evident feature shared with primary forests. Another similarity between AFSs and primary forests is the diversity of forest species and the continuous deposition of plant waste, which promotes the formation of litterfall. In turn, litterfall is a source of OM in soil, influencing the organic and inorganic attributes of this compartment [12, 13].

Adopted as a replacement for land-use categories such as agriculture, cattle breeding and bushland, AFSs can provide several environmental advantages, like soil and water conservation as well as the absorption or sequestration of GHG and storage of these gases as organic compounds in the soil. The conversion of GHG into organic compounds in soil may be the most important environmental support and regulation benefit of AFSs [14].

Research has demonstrated the increase of OCS and OCL in soils as a function of the time an AFS has been established [15, 16]. More specifically, A. M. P. Marin (2002) [17] reported that changes in chemical attributes of soil take time to occur, as long as 10 to 35 years in agricultural systems focused on conservation.

The underlying hypothesis of the present study was that the introduction of AFSs in the mid-1990s to replace MA in the rural settlement of Umari (RS-Umari), state of Amazonas, Brazil has increased soil OCL and OCS, compared with the values recorded in primary forest soil. The objective of this research was to analyze the spatial variability of soil OCS exposed to different land-use approaches in RS-Umari.

2. Material and Methods

2.1 Geoenvironmental Characterization of the Study Area

RS- Umari (64°40’ 14.4” to 64°10.1” W and 07°21” 16.5” to 07°18’ 06.4” S, Fig. 1) was established in 1996 by the Brazilian Agrarian Settlement and Land Reform Institute (INCRA) in the Middle Paciá River Basin. Covering 9,654 hectares, RS-Umari is home to 158 settler families [18] (Fig. 1).

With its riverhead in the Caititu Indigenous Reserve, the Paciá River flows through RS-Umari. The basin

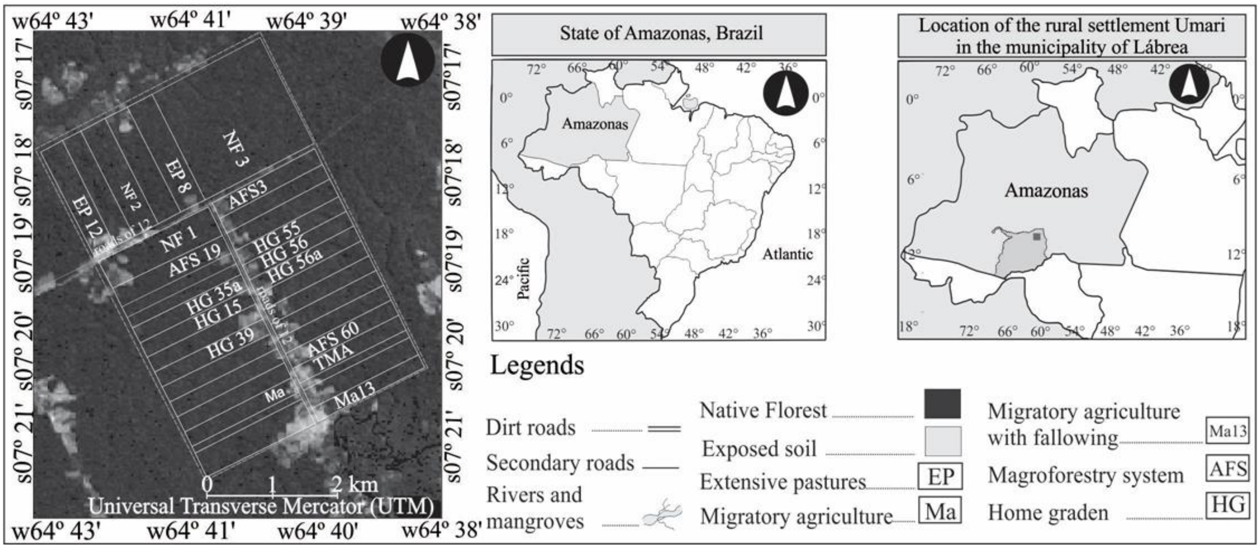

Fig. 1 Map showing the study area.

lies in the equatorial forest lowlands of the southern Amazon, where the climate is classified as wet equatorial. The dry season lasts three months (June to August) and the rainy season is between January and April, with April and October being transition periods [19]. Mean annual temperatures are between 24°C and 27°C.

Plant cover in RS-Umari is formed by two main vegetation systems, namely (i) the original vegetation, which includes open ombrophilous forests and open lowland forests and ombrophilous riparian terraced forests with palms; and (ii) cultivated vegetation such as pastures, plantations, orchards and other man-made cover systems. These systems occur on red and red-to-yellow clay-like, naturally dystrophic acrisols (%BS < 50%) [20].

2.2 Digital Processing of Images and Preparation of Theme Map

Based on pedologic data obtained from the natural resource survey *Projeto RADAMBRASIL* (datasheet SB.20 Purus), a land-use map was prepared for RS-Umari [21]. Three vector themes were layered on this map, namely drainage, road, and farming structure layers. Spatial information was clarified based on an elevation map using images (1:250,000) from the geomorphologic map of Brazil (Topodata). This elevation map was used to define the quadrats.

Land use and cover category were determined using 30 m RGB resolution (TM3 = red, TM4 = green, and TM5 = blue) images (233/65, Lábrea) taken by the satellite LANDSAT-5/TM. After image rectification, data were initially interpreted using a supervised classification method with the maximum likelihood algorithm. Four general land-use and cover classes were considered: (i) deforested, (ii) primary forest, (iii) pasture, and (iv) exposed soil. The information obtained was used to construct an exploratory theme map showing the approximate location of AFSs measuring at least 10,000 m^2 and the classes of land use (agriculture, pasture, and forest) observed. This map was used to define the quadrats for soil sample collection [22].

Based on the land-use and cover map, a 50 × 50 m quadrat was randomly defined in each AFS (N = 23) [23]. More specifically, 10 quadrats were defined inside AFSs, eight in cultivated areas with and without fallowing, two quadrats in pasture areas, and three control quadrats established in primary forest. Quadrats were outlined using PVC tubes and georeferenced by a global positioning system (GPS) device.

Three soil cores (0.25 m × 0.25 m × 0.20 m, L × W × H) were drilled in each quadrat. Collection sites were defined according to [24]. A total of 108 cores were collected from each quadrate from the 0-10 cm layer and 10-20 cm layer, 54 in the dry season and 54 in the rainy season. In total, therefore, 216 soil samples were obtained. A 500 g aliquot of soil was retrieved from each core to determine physicochemical parameters and OCS. Next, 100 g of each aliquot was weighed, clods were broken, and the material was sieved and homogenized in a sterilized tray to obtain a sample pool. All single and pooled samples were stored in identified plastic bags in a refrigerated environment for subsequent analyses in the laboratory.

2.3 Description of Experimental Units and Soil Sampling

Soil OCS according to land used for different purposes for various periods were analyzed in samples collected in 11 quadrats in areas that were not treated with agrochemicals or soil correction agents (except HG15): (i) primary forest (PF), (ii) migratory agriculture (MA), (iii) mechanized agriculture (TMA), (iv) extensive pasture (EP), (v) agroforestry system (AFS), and (vi) home gardens (HG). The land-use and cover records of the quadrats are shown in Table 1.

Table 1 Land-use and soil cover records of the quadrats in RS-Umari.

Land-use	Use and occupation record
Forest (F):	Primary Amazon vegetation; classified as open ombrophilous lowland forest characterized by palms; three areas in the reserve were selected (PF1, 300 hectares, and PF2 and PF3, 80 hectares each); there is no recent record of occasional or selective logging in the forest or use of agrochemicals to grow plants; for this reason, area PF1 was used as control.
Extensive pasture (EP8)	Pasture formed exclusively by *Brachiaria brizantha* cv. Marandu, established approximately eight years before, after primary vegetation was removed by slash and burn in 2007.
Extensive pasture (EP12):	Pasture formed by *Bachiaria brizantha* cv. Marandu after primary vegetation was removed by slash and burn in 2003; followed by reestablishment in 2010 after cutting, apparently with no burning of undesired woody species.
Temporary mechanized agriculture (TMA).	In the 2011 draught, the primary vegetation was removed by tractor followed by ploughing and harrowing. Afterward, ruts were open to spread crushed leaves of cassava (*M. esculenta*); in 2015 the area was left fallow.
Migratory agriculture (MA),	Primary vegetation was recently removed and burned; crushed cassava leaves (*Manihot esculenta* Crantz) were spread (first slash and burn cycle) after harvesting of cassava for flour production.
Migratory agriculture with fallowing (MAF13)	The primary vegetation was converted into a *M. esculenta* plantation, which was grown from 1997 to 2001; after the last harvest, the area was left fallow; 13 years after fallowing (in 2014), the secondary forest was removed and burned for the 2nd *M. esculenta* cultivation cycle.
Agroforestry system (AFS3):	In 2011 the forest was converted into an *M. esculenta* plantation, with which pineapple (*A. cosmosus*) was grown in alternate rows; when *M. esculenta* plants reached 1 m in height, tree species were planted (*B. excelsa*, *T. grandiflorum*,etc.) in the AFS.
Home garden (HG15)	The forest was converted into a *M. esculenta* plantation in 1999. In 2000 the first seedlings of tree species (*B. excelsa*, *T. grandiflorum*, *A. aculeatum*, *E. oleracea*,etc.) were planted to form the HG; before trees were planted, dolomite limestone was used to adjust soil pH.
AFS established for 19 years (ASF19)	Identical description as the previous AFS; the annual species used were *M. esculenta* and *Zea mays*, which were grown for two years; next, the species *T. grandiflorum*, *A. aculeatum*, *C. guianensis*,etc. were introduced.

In the spatial analyses, in addition to the quadrats described in Table 1, seven other home gardens (HG) situated in RSU were analyzed (named HG ≥ 10^{35}, HG ≥ 10^{35a}, HG ≥ 10^{39}, HG ≥ 10^{55a}, HG ≥ 10^{56a}, HG ≥ 10^{56}, and HG ≥ 10^{60}). Five MA areas were also included (MA^{61}, MA^{58}, MA^{33}, MA^{55} and $MA^{59)}$. All areas had undergone change and conversion of land use and cover similar to what was observed for AFS19, HG15 and TMA.

Soils were characterized for the presence of Al, Ca, Mg, K, and P. pH of samples was analyzed as pHw and KCl in a 1:2.5 soil to liquid ratio. Measurements were carried out using a benchtop pH meter. Apparent density (Das) was analyzed using the test tube method, and N levels were obtained by digestion and distillation using the Kjeldahl method [25].

2.4 Laboratory Procedures

Briefly, OM levels were measured using air-dried fine soil (ADFS) after combustion in a muffle furnace at 60ºC for 6 h. Also, OM levels were determined by weight difference. Grain size (sand, silt, and clay) was analyzed using the total dispersion method. The material originating from the washing of the pipette was collected in a 50 mL beaker and placed in a desiccator until evaporation of all water. Samples were left to rest upon reaching room temperature. Afterward, samples were weighed for clay determination (0.0001 g accuracy). The sand fraction (coarse and fine) was segregated by sieving (0.2 mm, #70), while the silt fraction was determined by weight difference [26].

Total OC levels were determined based on the oxidation of OM in 0.5 g of ADFS. The samples were acidified using $K_2Cr_2O_7$ 0.4 N. In order to ensure total oxidation of carbon, samples were heated in water over an induction burner and gently boiled for 5 min. OCS levels were calculated based on the volumes of Mohr's salt 0.1 N solution consumed in titration of samples using the equation C (g/kg) = (40 – volume used) × f × 0.6, where f = 40/the volume spent in titration of the blank [27].

Soil OCS were calculated for each treatment (land-use and cover) and the 0–10 cm and 10-20 cm layers according to the equation proposed by [28]:

OCS = (Total OC × Das × Th)/10

where: OCS = carbon stock (mg. ha).

Total OC = total organic carbon (g/kg).

Das = soil density (kg/cm^3);

Th = thickness of soil layer (cm)

2.5 Spatial and Conventional Statistical Analyses

The statistical design of physicochemical data and soil OCS values was totally random. These variables were analyzed in four steps.

The first was the organization of data using the main module of the TerraView 5.5.0 geographic information system to generate a geographic databank (MySQL server) and the *AR Umari AM* project. The study area was delineated using the Universal Transverse Mercator (UTM) conformal projection (UTM/zone 20) combined with the South American geodesic reference system Datum/SAD 69. The digital base map of RS-Umari was imported using the theme/view tool, and 15 information plans (IPs) in the format SHAPFILE (SHP) were defined in connection to the variables pHw, K, N, cation exchange capacity (CEC), base saturation (%BS), Al, total OC, OM, OCS, Ca+Mg, etc.). By default, each area (theme class = quadrat, or experimental unit) of the map was given an identification (ID) organized as a table of alphanumerical attributes having 23 rows, representing each experimental unit. Next, a column was added to the soil attributes described above for all IPs.

In the second step, physicochemical variables in the tables of each view/theme (IPs) were keyed in in the TerraView 5.5.0 geographic information system. Then, the global Moran's I (IM) and local Moran's I (LI) described by [29] were generated. Based on [30] and [31], interpretation criteria were defined for the local spatial correlation indices (SCI) for the variable soil *OCS*. Six classes of autocorrelation or spatial dependence were defined in the mapping of the geographic phenomena (Table 2).

In the view tree (PIs), the view studied and the soil variable table were selected. Then, the option *statistical analyses* of IM and LI (*P-value* ≤ 0.05) was selected on the menu bar. By default, after processing, seven new columns for IM and LI were added to the table of each PI.

The spatial representation of the LI (map of clusters of soil parameters) was carried out using the interpolation algorithm of the quantic function, calculation option for Das. These procedures enabled the generation of a set of tridimensional matrix cell maps for all parameters assessed.

Table 2 Criteria used to interpret the local Moran's I (LI) in the mapping of total OC level and soil attributes with different land-use/cover in RS-Umari [29-31].

Classes of SCI	Interpretation criteria
Perfect	Local indicators of spatial association (LISA) for total OC level> 0.745; significance level of the cartographic representation of the phenomenon (*lisamap*) of (1) *P-value* ≤ 0.05, (2) *P-value* ≤ 0.01, or (3) *P-value* ≤ 0.001. LI or LISA are generally surrounded by LI or LISAwith strong or moderate spatial correlation and confidence level ≤ 5%. This SCI with *P-value* ≤ 0.05 indicates very high spatial dependence of the variable in the space studied.
Strong	LISA for total OC level in the range 0.545 > SCI ≤ 0.745. Significance level of the cartographic representation of the phenomenon: (1) *P-value* ≤ 0.05, (2) *P-value* ≤ 0.01, with rare cases of *P-value* ≤ 0.001. LI or LISA surrounds areas of perfect SCI. It may be surrounded by LI or LISAvarying from moderate to minimal spatial correlation.In this class, SCI with *P-value* ≤ 0.05 indicates high spatial dependence of the variable in the space studied.
Moderate	LI or LISAfor total OC level in the range 0.174 > SCI ≤ 0.545 and significance of cartographic representation of the phenomenon (*lisamap*) of (1) *P-value* ≤ 0.05 or (2) *P-value* ≤ 0.01. LocalSCI of this class normally appears around areas of perfect and strong spatial correlation with *P-value* ≤ 0.05. This SCI (*P-value* ≤ 0.05) indicates average spatial dependence of the variable in the space studied.
Weak	LI or LISA for total OC level in the range 0.089 > SCI ≤ 0.174. It is rare to obtain levels of confidence of *lisasig* and *lisamap* below 5% (*P-value* ≤ 0.05). LI or LISA, when significant (*P-value* ≤ 0.05), appears around the area mapped, with very low spatial dependence.
Minimal	LI or LISA for total OC level in the range 0 > SCI ≤ 0.089. *P-value* ≥ 0.05 is common in *lisasig* and *lisamap*. When significant, this LI or LISA appears at the edge of the area mapped. SCI with *P-value* ≤ 0.05 indicates a trend towards spatial independence of the variable in the space studied.
Zero	LI or LISA for total OC level equal to zero(LI = 0) and *lisasig* = *P-value* = 0.00. Level of significance of cartographic representation of the phenomenon equal to zero (*lisamap* / or *P-value* = 0. 00). When LI or LISA for soil OCS reaches this value, the spatial dependence of the variable is totally absent in the study area.

In the third step, the tridimensional matrix cell maps were exported as GEOTIFF files to SIG/SPRING 5.2. These maps were used to construct the maps of concentrations of physical and chemical variables of the soil based on an on-screen analysis considering 255 tones. The darkest tone indicated the highest level of total OC. Five vector concentration classes (very low, low, medium, high, and very high) were defined in the theme data model.

3. Results and Discussion

The results of analysis of variance revealed no difference in soil texture across the different land use and cover parameters assessed, suggesting that the soils in these environments are the same (Fig. 2A and B). Also, the results indicated that physical attributes of soil do not change due to erosivity and erodibility a few years after the establishment of an AFS.

Mean P levels in AFSs recorded in the rainy season were two and four times higher than those observed in MA and PF, respectively. This means that AFSs, when well managed, are more efficient in cycling P compared with the other land use classes. On the other hand, mean Al levels differed significantly in AFSs compared with NF and the other systems studied (Fig. 2D).

CEC values were higher in HG15 and AFS19 (Fig. 2E). The CEC values observed in AFSs established for longer times may be associated with the role of the root system of tree and bush species, which improves soil physical structure and respiration, and the soil biota inhabiting the shallow horizons (as observed in HG15).

Soil Das values varied between minimums of 0.96 g/cm³ (0-10 cm layer) in the dry season and 0.97 g/cm³ (0-10cm layer) in the rainy season, and maximums of 1.23 g/cm³ (10-20 cm layer) in the rainy season in AFSs.

The statistical analysis showed there were no statistically significant differences between Das values across classes of land-use and cover studied.

OCL values were high in EP areas (EP8 and EP12), AFSs (AFS19 and HG15), and primary forest (PF). Values were intermediate in MA with 13-year fallowing (MAF13), and low in MA, TMA, and AFS03.

In the 0-10 cm layer in the rainy season, OCL values in TMA differed significantly from the ones observed for PF and AFSs implemented for longer periods.

Except for the values recorded in PF and AFS19 in the rainy season, OCL values in EP8 and EP12 were significantly higher than the values observed for the other land use and cover categories. The highest OCL value observed in EP12 in the dry season may be associated with the incorporation of plant waste material originating from the cutting of weeds with no burning of the material (Fig. 2F).

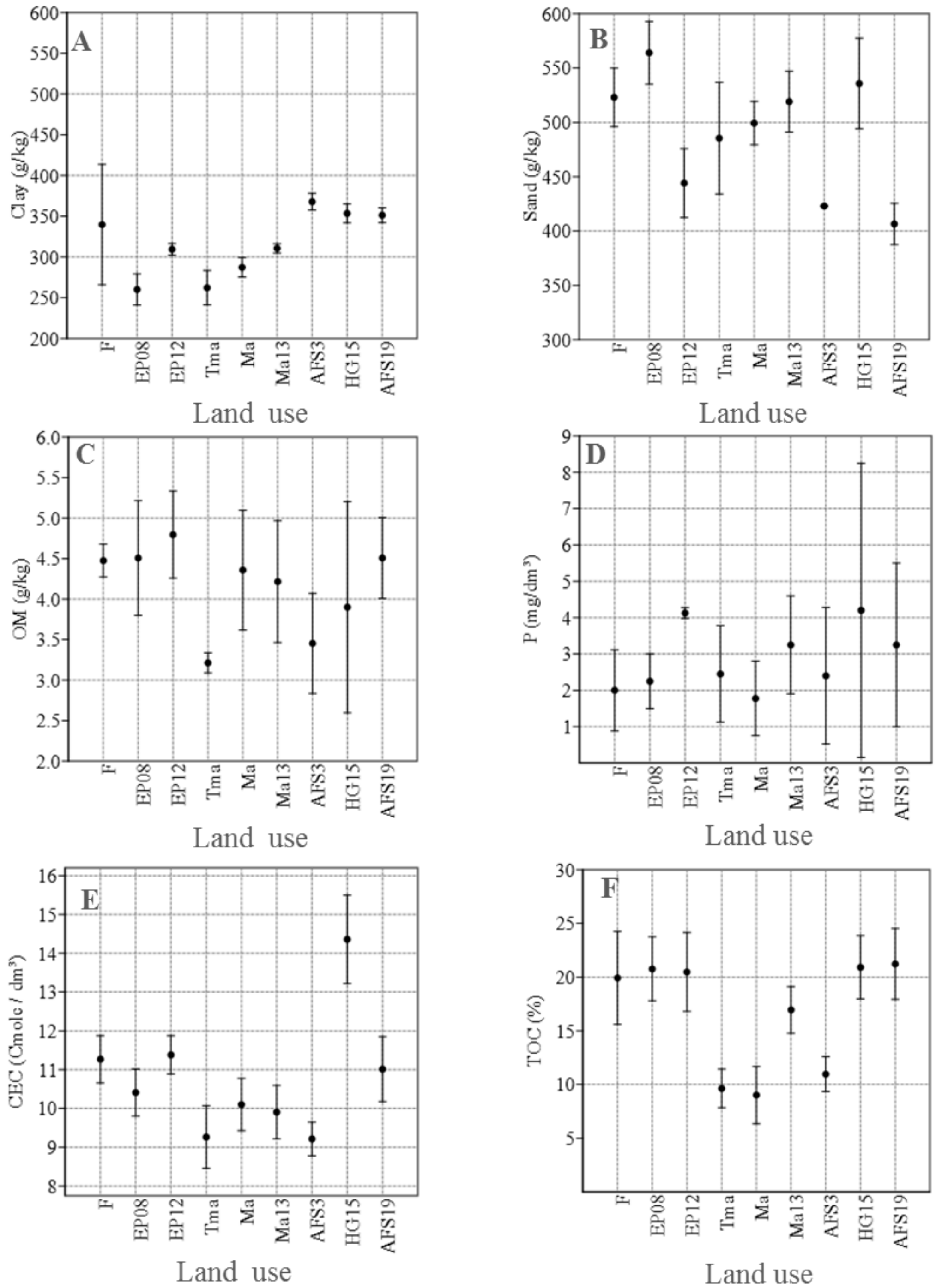

Fig. 2 Soil physical and chemical attributes in the 0-20 cm layer: (A) clay, (B) sand, (C) OM, (D) P, (E) CEC and (F) total OC level (TOC).

3.1 Spatial Analyses of Soil OCS

The results of Moran's global spatial correlation (IM) showed no spatial dependence between the soil OCS calculated for the land-use and cover categories (agroforestry system, agriculture, cattle grazing, and forest) and the land-use classes (MA, TMA, MAF13, AFS19, HG15, etc.), since Moran's global index was -0.03002 (minimal negative spatial correlation) and significance was 0.39 (P-value < 0.05). These findings mean that the hypothesis of absence of spatial correlation for OCS on a regional scale cannot be ruled out. On the other hand, total spatial interdependence is impossible, since IM was not zero.

The analysis of local spatial correlation (LI) revealed perfect positive direct spatial correlation with significance level below 5% for the soil OCS in HG ≥ 10^{56a} and HG ≥ 10^{35} in the 0-10 cm layer in both the rainy and dry seasons. This was also observed for soil OCS in the 0-20 cm layer of quadrats in PF and agroforestry systems AFS19, HG ≥ 10^{56},and HG ≥ 10^{35} established for over 10 years. All soil OCS presented confidence levels of 5% or below (Table 3).

Table 3 Spatial variability of soil OCS in the 0-20 cm layer in different land-use and cover category in RS-Umari.

System	Spatial geostatistics					
	OCS	*Wz*	*Li*	OCS	*Wz*	*Li*
	0-10 cm			0-20cm		
PF	18.31	6.140	-1.0531**	31.42	-10.73	-1.3620*
EP8	15.53	1.335	0.2650	25.85	-3.71	-0.4825
EP12	15.68	1.020	0.1890	29.63	3.76	0.6002
TMA	6.85	0.856	-0.0555	13.66	1.30	-0.0468
MA	2.58	0.599	0.0260	12.35	-0.972	-0.0252
MAF13	15.01	5.834	0.5206**	24.56	-9.00	-0.6267**
AFS3	8.78	3.515	0.1712	13.67	7.99	0.2878
HG15	21.02	-0.469	-0.1040	24.99	-1.46	-0.1811
AFS19	18.86	0.789	0.1638	26.31	5.43	0.7264*
AFS≥10^{55}	10.29	-2.407	-0.2160	16.21	-2.61	0.1457
HG≥10^{56}	11.66	0.430	0.0500	22.94	10.21	1.0998*
HG≥10^{56a}	13.48	0.430	0.7496*	19.11	4.22	0.3299
AFS≥10^{60}	11.89	-1.564	-0.1910	18.46	2.50	0.1828
HG≥10^{39}	17.24	-5.834	-1.3410	26.43	9.00	-1.1212
HG≥10^{35a}	11.78	-5.834	0.6990	20.55	2.46	0.2195
HG≥10^{35}	21.46	3.087	0.9720*	30.16	5.66	1.5789**

PF: primary forest, EP: pasture, TMA: mechanized agriculture, MA: migratory agriculture, MAF13: migratory agriculture with 13-year fallowing, AFS: agroforestry system established 3, 10, 15, and 19 years before, *Wz*: vectorial median. Local spatial correlation index (LI orSCI). Significant values of SCI or LI (**) P-value ≤ 0.001 and (*) P-value < 0.05.

SCI were higher for soil OCS in the 10-20 cm layer, mainly in quadrats in AFSs (Fig. 3B, C). Clay levels and the high Das of these samples influenced soil OCS in AFS03, HG15, and AFS19, thus affecting the levels of spatial dependence.

In MAF13, MA, and TMA, SCI were zero and weak, with significance level above 5% (except for MAF13, P-value = 0.001). These results indicate significant spatial independence of soils in the 0-10 cm and 10-20 cm layers in both the rainy and dry seasons. However, SCI for soil OCS in HG15, AFS ≥ 10^{60}, AFS ≥ 10^{39}, and HG ≥ 10^{35a} varied between moderate and perfect. The expectation concerning these systems was that confidence levels would be 5% or below, since floristic composition, soil type, topography, and distance between quadrats were similar to what is observed for lowland ombrophilous open forest with palms in the southern Amazon. This result may indicate that, in addition to the pedogenetic and bioclimatic characteristics, other variables affect the local spatial variability of soil OCS in the area studied.

The cluster maps (Fig. 3) generated using LI, quantic interpolation, and the TerraView 5.5.0 geographic information system allowed identifying the formation of two areas of specific characteristics concerning the distribution and variation of soil OCS in the 0-10 cm layer. The first area (A1) was formed by perfect SCI for soil OCS, in AFS $\geq 10^{56}$.

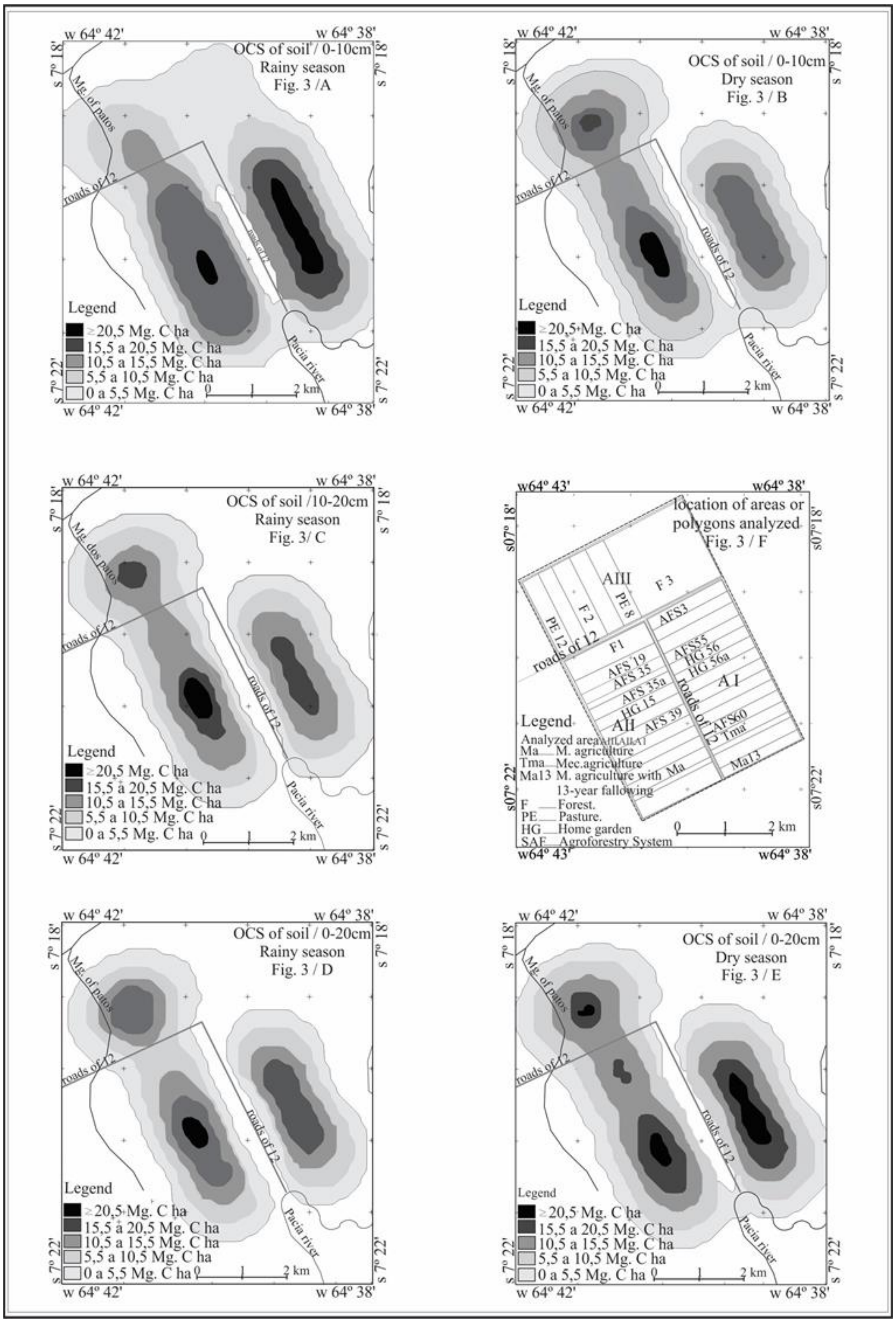

Fig. 3 Spatial variability of soil OCS in different land-use / cover in RS-Umari-AM.

This area is surrounded by parcels with SCI varying from moderate to perfect SCI for soil OCS, in the polygons defined by AFS ≥ 10^{55} and AFS10^{60}, but with significance level above 5%. At the edges of A1, soil OCS levels below average were observed in quadrats exposed to TMA and in AFSs established three years beforehand (Fig. 3A).

The second area (A2) is formed by clusters with perfect SCI for soil OCS in HG ≥ 10^{35}, but it is surrounded by SCI for soil OCS varying from moderate (EP8 and EP12) to minimal in MA. These clusters are formed by AFS19, HG15, AFS ≥ 10^{39} and HG ≥ 10^{35a}, whose SCI for soil OCS varied between perfect and weak (Fig. 3A), all with confidence level above 5%.

The weak spatial correlation associated with soil OCS observed in pastures (EP8 and EP12) and agricultural areas (MA, MAF13, and TMA) supports the hypothesis that the conversion of the primary forest to establish pasture for the extensive grazing of beef cattle and subsistence agriculture are net sources of CO_2 to the atmosphere. On the other hand, SCI for soil OCS calculated for primary forest and agroforestry systems established for 10 years or more in RS-Umari indicate these systems are potential carbon sinks.

The interpolation of the spatial correlation coefficients of soil OCS in the dry season in the 0-10 cm and 10-20 cm layers presented a similar spatial distribution pattern as that observed for the rainy season (Fig. 3B). However, total OC levels accumulated in the 0-20 cm layer had distinct spatial variability, with four land-use systems (areas or polygons) presenting spatial correlation between perfect and moderate. In A1, the local SCI was indirect moderate for soil OCS in AFS ≥ 10^{60} (LI = -0.1981 and *P*-value = 0.320 and direct moderate for soil OCS in HG ≥ 10^{56a} (LI = 0.5799 and *P*-value = 0.04).

In polygons A2 and A3, several classes of land-use presented indirect perfect negative SCI (PF, MAF13, and AFS39, with LI = -1.5025, LI = -1.1969, and LI = -1.1381, respectively) for the variable soil OCS, but the level of significance was zero. This indicates the strong spatial interdependence between soil OCS in these land-use category. In A2, AFS19 had moderate SCI for soil OCS, surrounded by agricultural low soil OCS systems (Fig. 3E).

3.2 Effect of Change in Land-Use and Cover on Soil OCS

The results obtained show that the changes in land use and cover in the southern Amazon, namely conversion and modification, alter the agricultural landscape, affecting the quality of the soil and the temporal-spatial distribution of soil OCS.

The change from primary forest to migratory agriculture with or without fallowing (MAF13 and MA), temporary mechanized agriculture (TMA), and extensive pasture (EP08 and EP12) for extensive beef cattle grazing significantly reduced OCL and soil OCS. Conversely, change in land-use from MA to AFSs (ASF15, HG ≥ 10^{35a}, HG ≥ 10^{35}, AFS19, and HG ≥ 10^{39}) induced an increase in P, K, OM, and total OC levels. The results also show that the retention or macronutrients, micronutrients and OC in soils may differ significantly in space and time when the change in land-use involves conversion and/or modification (Fig. 4). According to D. Foster et al. [32], the changes in land-use/cover affect the natural dynamic of nutrient flow and total OC levels, since this support service afforded by forest ecosystems can be influenced for up to 100 years after the change or conversion in a given agricultural setting.

Concerning the effective recovery time of the ecological roles of the soil, the soil of AFSs implemented for over 10 years in RS-Umari had a significant nutritional resilience, especially in HG15, HG ≥ 10^{35}, HG ≥ 10^{56a}, ASF19, and HG ≥ 10^{39}. Different behavior was observed in AFS3 (agroforestry system three years after the conversion from AM to AFS), whose physicochemical parameters behaved similarly to what was observed for MA and TMA; the exceptions were OCL, Das, and total N levels. These results confirm the findings published by W. R.

Santiago et al., A. C. S. Silva et al., and R. M. Cesar et al. [33-35]. Experiments carried out by A. M. P. Marin [36] in the tropical Atlantic Forest and by G. X. Rousseau et al. [37] in the Centro de Endemismo Biogeográfico de Belém (CEB, Amazônia Oriental) showed that changes in chemical soil variables in conservation agricultural systems do not take place in the short run. The authors reported that the time required for changes in chemical attributes of the soil to become perceptible may vary from one to three decades after the implementation of an AFS.

The high soil OCS in AFSs implemented for more than 10 years (HG $\geq 10^{35}$, HG $\geq 10^{56a}$, AFS19, and HG15) in RS-Umari suggests that plant cover formed by individuals of the family Sterculiaceae (*Theobroma grandiflorum* Schum, *Theobroma cacao L.*, etc.), Arecaceae (*Astrocaryum aculeatum* G. F. W. Meyer, *Bactris gasipaes* Kunth, *Euterpe oleracea* Mart), Meliaceae (*Carapa guianensis* Aubl.), and mainly Lecythidaceae (*Bertholletia excelsa* Humb) contribute increasing amounts of plant waste in the top soil layer in these AFSs, raising the levels of OM, which is the main source of soil OCS in the southern Amazon.

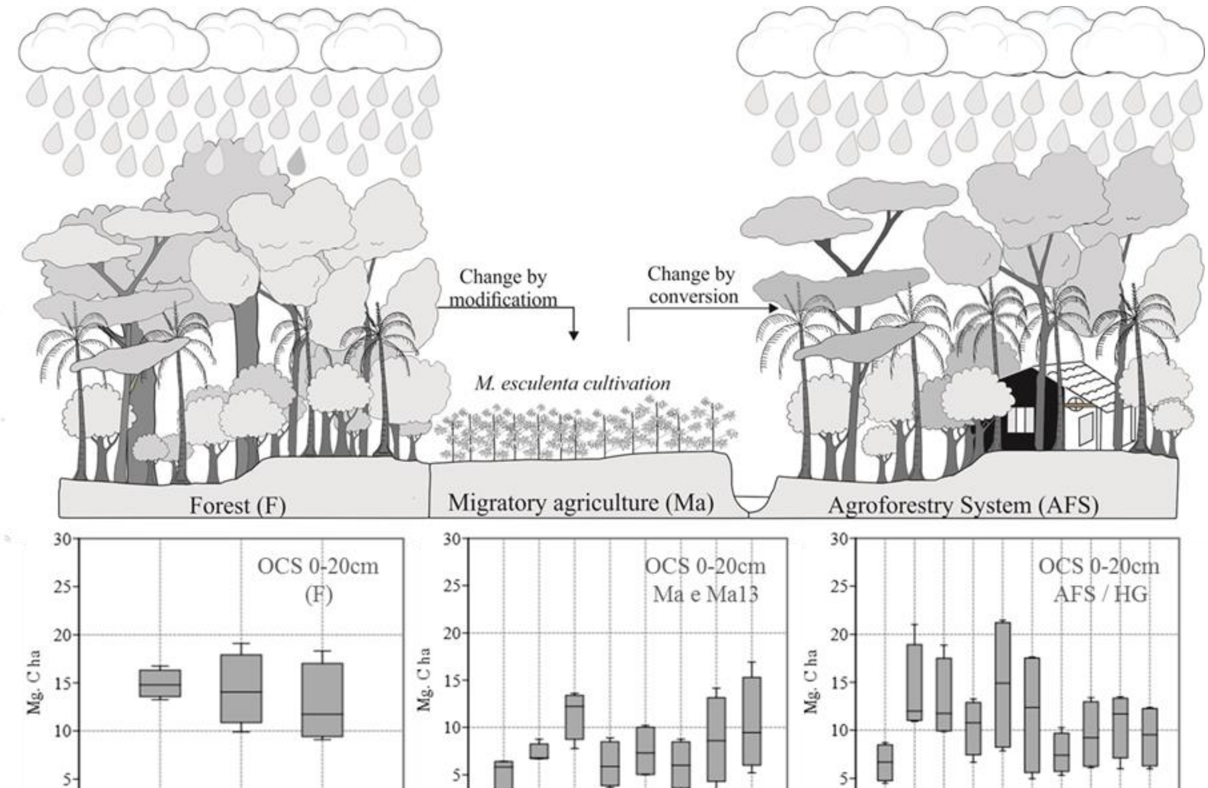

Fig. 4 Retention of soil OCS in a chronological sequence formed by PF, AM, and HG in RS-Umari.

3.3 Spatial Correlation Between Chemical Characteristics and Soil OCS in AFSs, Agriculture, Pasture, and Primary Forest

Perfect spatial correlation index, with significance below 5% (P-value ≤ 0.05) for soil OCS was recorded for quadrats in HG $\geq 10^{56a}$, HG $\geq 10^{35}$ (0-10 cm layer), PF, AFS19, HG $\geq 10^{56}$, and HG $\geq 10^{35}$ (0-20 cm layer) both in the rainy and dry seasons. These soil OCS values tended towards high spatial dependence indices, which is a result of the high soil OCS level in the 0-20 cm layer. According to M. Altieri (2012) [38], the presence of perennial woody species such as individuals of the family Lecythidaceae (*Bertholletia excelsa* Humb) promotes the recovery of the physical properties of soil, especially its structure. In addition, in due course tree species can promote an increase in OM levels, by decompacting the soil using their root systems. These plant species can also help recolonization of the soil by invertebrates of the biota.

The SCI for soil OCS in agricultural soils (MA, TMA, and MAF13) differed from the values observed for AFSs. In this category of land-use, a trend towards spatial independence was observed, since SCI varied from minimal to weak, with significance over 5%. The incorrect management of soil and the absence of perennial trees and woody bush species that promote the periodic recovery of OCL are two of the factors that explain the sharp drop in soil OCS, and therefore the low spatial correlation of soil OCS with agriculture and pasture land-uses.

In addition to total OC levels, other physicochemical attributes of the soil had perfect spatial correlation with significance level of 5% or below in AFSs established for 10 years or more in RS-Umari. Clay, P, and K levels as well as Das, CEC, base saturation (V%) directly influenced the spatial variability of soil OCS in AFSs and primary forest, which was used as reference environment (Fig. 5).

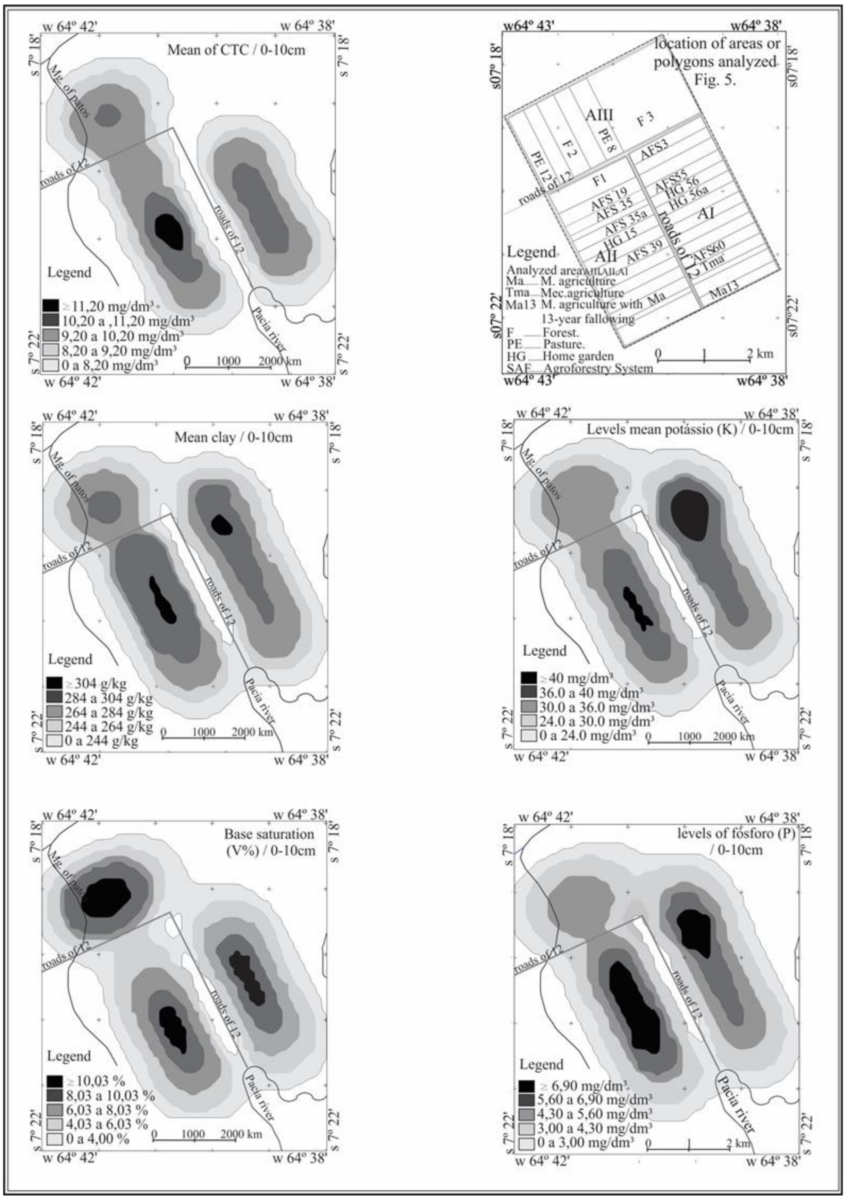

Fig. 5 Spatial variability maps for physicochemical attributes of the soil in the 0-10 cm layer in the rainy season.

These parameters had spatial correlation indices varying from moderate to minimal (P-value > 0.05) in extensive pastures, agriculture, and AFSs established for more than three years (AFS3).

The perfect spatial correlation of total OC levels and soil OCS in HG $\geq 10^{56a}$, HG$\geq 10^{35}$, and HG $\geq 10^{39}$ indicates the stronger influence of soil attributes like time, source material, relief, and physicochemical and biological processes.

On the other hand, minimal and weak spatial correlation indices for total OC levels and soil OCS in MA and TMA suggest a more intense influence of extrinsic factors in pedogenesis, as observed for soil management practices like change in land-use, application of ground limestone, and employment of agricultural machinery [39-41].

In other words, it is possible to say that AFSs favor pedogenesis and the sustainable use of soil within a few years, while MA with or without fallowing affects pedogenesis. The implementation of these systems has important pedologic and environmental implications concerning retention of total OC levels, and therefore the natural fertility of soil. These consequences may last for decades [42-44].

The results of the present study confirm the hypothesis that AFSs induce the increase of soil OCS 10 years after implementation, helping recover the physicochemical attributes of soil that was lost due to modification of the primary forest for migratory agriculture (slash and burn) and extensive cattle grazing. This dynamic is apparently faster in HG and AFSs in the southern Amazon, possibly due to the poor diversity of perennial woody tree species, and mainly the asymmetric spatial distribution of species adopted by farmers in the southern Amazon. This practice differs from the strict, methodic spacing methods prescribed by forest engineers and agronomists.

4. Conclusion

The different systems of land use and cover assessed influence the variation of OCL and soil OCS values. Modification of the forest to migratory agriculture caused pronounced loss of total OC levels and levels of P, K, and N. On the other hand, the conversion of agricultural land to AFSs helped recover OM levels and chemical attributes of the soil.

AFSs implemented for over 10 years enabled the generation of new, finer litterfall. The formation and maintenance of this compartment is explained by the fact that slash and burn methods or tillage are not carried out, inducing the recolonization of the soil by the natural microbiota. The soil microbiota promoted the increase of soil OCS, especially in HG $\geq 10^{35}$ and HG $\geq 10^{56a}$, which presented perfect spatial dependence and significance level that confirms the hypothesis tested.

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