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Land Use and Changes in Soil Morphology and Physical-Chemical Properties in Southern Amazon

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ABSTRACT: Many Amazonian farmers use the slash-and-burn method rather than fertilization for crop production. The aim of the present study was to evaluate changes in the morphological, physical, and chemical properties of naturally fertile Inceptisols after conversion from native forest to different uses in southern Amazonia, Brazil. Land covered by dense native forest (NF) was split into four areas of 1.0 ha each. Three areas were slashed and burned and then cultivated for 11 years with coffee (CO), secondary forest (SF), and pasture (PA). Four soil profiles were sampled in each treatment (four uses × four replicates). The mean value distribution of each physical and chemical analysis was determined for different depths, and standard error bars were placed to display significant differences among treatments. Results showed that morphology and physical properties were negatively affected after the establishment of PA and CO: a reduction in the thickness of the A horizon and in aggregate stability, a decrease in total porosity and macroporosity, and an increase in aggregate size and bulk density. Soil bulk density (SBD), geometric mean diameter of water-stable aggregates (GMD), and microporosity (SMi) were higher in soil under pasture as a consequence of more intense soil surface compaction. Native and secondary forests were the only treatments that showed granular structures in the A horizon. Significant differences between native forest and secondary forest were mainly found in the top soil layer for total porosity (STP) (NF>SF), macroporosity (SMa) (NF>SF), SBD (NF>SF) and GMD (SF>NF). Phosphorus contents in the A horizon increased from 6.2 to 21.5 mg kg^{-1} in PA and to 27.2 mg kg^{-1} in SF. Soil under coffee cultivation exhibited the lowest levels of Ca^{2+} and sum of bases in surface horizons. In all slash-and-burn areas there was a reduction in the C stock (Mg ha^{-1}) of the A horizon: native forest 6.3, secondary forest 4.5, pasture 3.3, and coffee 3.1.

Keywords: secondary forest, coffee, pasture, slash and burn, ash effect.

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INTRODUCTION

Several studies have been conducted in various biomes around the world to evaluate the effects of deforestation, afforestation, and agriculture on soil physical and chemical properties (Marques et al., 2010; Braz et al., 2013; Paix et al., 2013; Belay et al., 2015). The discussion on deforestation in the Amazon extrapolates national boundaries due to its global relevance. Crop systems in the Amazon have mostly been based on extensive cattle raising (pasture), coffee plantations, and secondary forest. In some areas, farmers intercrop annual agricultural species and secondary forest after slashing and burning forested areas. Such practice is based on indigenous agricultural system, which is characterized by long fallow periods after a short cultivation period of 1-3 years (Davidson et al., 2008; Comte et al., 2012; Reichert et al., 2016).

Burning of vegetation has been widely used as a deforestation practice, with significant impacts on physical (Scheffler et al., 2011; Comte et al., 2012; Cruz et al., 2014) and chemical (Moreira et al., 2009; Lindell et al., 2010) properties of different soil classes. Some physical effects can be highlighted: reduction in soil water infiltration rate after conversion of forest into pasture and into annual crops in Mato Grosso, Brazil (Scheffler et al., 2011); and increase in surface soil bulk density (SBD) of an Oxisol after conversion of forest into pasture in the Amazon region (Braz et al., 2013). In areas of the eastern Brazilian Amazon (Ultisol soil class), the surface layers in mulched plots showed significantly ($p<0.05$) greater water retention capacity than the surface layers in burned forest plots. Similarly, Ultisols and Oxisols under pastures showed increased SBD compared to the same soil classes under forested plots in the Amazon (Comte et al., 2012). Soil tillage after the slash-and-burn practice, as well as stump removal and plowing, can reduce compaction of upper soil layers and improve soil physical properties, but the effects are usually short term (Reichert et al., 2014), since soil reconsolidates quickly with the lack of or reduced effect of organic matter on soil structure and system equilibrium.

Soils in the Brazilian Amazon (Typic Hapludox soil class) have low fertility, low levels of available P, Ca^{2+}, and Mg^{2+}, and high acidity and Al^{3+} saturation (Braz et al., 2013). Chemical fragility in this environment is attributed to the soil parent material, with predominance of unconsolidated clayey sediments deposited in the Holocene period.

The consequences of slashing and burning of forests and of subsequent crop cultivation on soil chemical properties have been debated. This method of forest clearing leaves the soil susceptible to high nutrient losses as a result of volatilization, leaching, and erosion of ash, as found in an Ultisol from Africa (van Reuler and Janssen, 1993) and in different soil classes around the world (Juo and Manu, 1996). The decline in fertility of cultivated soils (Inceptisols, Ultisols, and Oxisols) when lime and fertilizers are not applied compared to native forest in the Amazon has been widely described in the literature (Patry et al., 2013). In contrast, some authors have observed an increase in exchangeable base (Ca^{2+}, Mg^{2+}, and K^{+}) contents and reduction in acidity in Ultisols and Oxisols in slash-and-burn areas in the Brazilian Amazon, even after a decade of cultivation (McGrath et al., 2001; Numata et al., 2007; Braz et al., 2013). A third result was that of Lindell et al. (2010), who did not find significant differences in soil fertility in the Inceptisols and Entisols in the Western Amazon Basin of Peru when they compared a forested area and plots under coffee plantation, pasture, and secondary forests after slashing and burning of native vegetation. These apparent contradictions can be attributed to specific experimental conditions, such as forest production before deforestation and the quantity of ash produced, the term of evaluation of fertility after slashing and burning, climatic conditions, soil classes, and soil slope (ash runoff), among others.

These seemingly contradictory data reinforce the need to expand studies in the vast Amazonia region, especially in the southwestern (meridional) part, because most studies have been conducted in the northern portion of the Amazon, where Typic Hapludox is widespread. The region of the present study (southwestern Amazon) is dominated by Inceptisol, with high natural levels of exchangeable bases (Ca^{2+}, Mg^{2+}, and K^{+}) and granite/gneiss as parent material (Orrutéa et al., 2012).

As a working hypothesis, a decrease in soil morphological, chemical, and physical quality is expected in all land use practices after slashing and burning the native forest. The aim of the present study was to evaluate the changes in the morphological, physical, and chemical properties of Inceptisols with high natural fertility after conversion of forested areas into different land uses in southwestern Amazonia (11 years of secondary forest, pasture, and coffee).

MATERIALS AND METHODS

Study area and soil sampling

The study was carried in the municipality of Cacoal (61° 22′ 44.9″ W and 11° 28′ 41.6″ S) in the state of Rondônia, Brazil. Local climate is tropical humid - Am, according to the Köppen classification system, with average rainfall from 1,400 to 2,300 mm yr^{-1} and average annual air temperature from 23 °C to 26 °C. The area has biotite granite/gneiss as parent material (Orrutéa et al., 2012), rolling relief, and average altitude of 188 m.

Original vegetation is characterized by dense submontane rain forest. The experimental area was placed under the main land uses of small, medium, and large farmers in the southern Amazon: 1) native forest (dense submontane rain forest); 2) slashing and burning of forest (once in the beginning) + pasture (*Brachiaria brizantha* Hochst Stapf. cv. Marandu) - in use for 11 years as pasture, without chemical fertilization. Addition of organic matter was limited to manure from the Nelore cattle breed in a free range system. Weed control with 2,4 D herbicide and mineral supplementation in troughs for cattle was used in the pasture area; 3) slashing and burning of forest (once in the beginning) + annual crops (without soil turnover and with manual planting) + secondary forest-rice/beans in the first year and corn/beans in the second year, followed by a fallow period for the next nine years. At no time was there any organic or chemical fertilization; 4) slashing and burning of forest (once in the beginning) + coffee (*Coffea canephora* Pierre ex A. Froehner) - intercropping system of rice/beans was used in the first year and corn/beans/squash in the following 7 years, without soil turnover and with manual planting. This area was used for 11 years without chemical fertilization, and addition of organic matter was limited to coffee husk, coming from the process of grain husking in the area itself. On average, 40 kg ha^{-1} yr^{-1} of coffee husk was applied to the soil [with average nutrient content (g kg^{-1}) of: C 529.5, N 14.7, P 1.7, K 36.6, Ca 8.1, Mg 1.2, S 1.4]. Herbicides (Oxyfluorfen, Glyphosate, Paraquat) and fungicides (copper sulfate and Epoxiconazole) were also applied.

The study was planned and set up 11 years before soil sampling, which occurred in 2008, allotting an area of approximately 1.0 ha side-by-side for each use.

A total of 16 soil profiles were dug, four soil profiles for each treatment (four uses × four replicates). Positioning of profiles in each treatment considered equal distances from each other, transversal location to the slope, and the same position in the landscape (similar position in the lower third of a convex slope). This care in establishing the soil profiles was to maintain pedological homogeneity among replicates and treatments. Morphological description and horizon sampling were performed according to recommendations of Santos et al. (2005). All 16 soil profiles showed a similar horizon sequence (A, AB, B1, 2B2, and 2BC) and were classified as *Cambissolo Háplico Tb Eutrófico típico* (Santos et al., 2013), corresponding to Eutrudept in the USA Soil Taxonomy (Soil Survey Staff, 2014).

Contents of Si, Al, Fe, and Mn oxides extracted by sulfuric acid digestion (1:1 dilution) (Donagema et al., 2011) were determined to check pedological uniformity in the soil profiles.

Soil samples (16 profiles × 5 horizons = 80 samples) were air dried and sieved in a 2 mm mesh to obtain fine air-dried soil (FADS) for analysis of fertility, degree of flocculation, and texture. To determine soil bulk density and porosity, samples were collected with Kopecky rings (undisturbed samples) in thin layers (0.05 m) to a depth of

0.20 m (16 profiles × 4 layers = 64 samples). Undisturbed samples from the A horizon (soil blocks of 0.20 m × 0.20 m × the thickness of the A horizon in each profile) were also collected to determine the geometric mean diameter of water-stable aggregates (GMD) (16 profiles × 1 horizon = 16 samples).

Fertility analysis

Samples of FADS were chemically analyzed to determine the following soil chemical properties (Donagema et al., 2011): pH in water (soil:solution ratio 1:2.5); non-exchangeable potential acidity (H) extracted with 0.5 mol L^{-1} calcium acetate at pH 7; Ca^{2+}, Mg^{2+}, and Al^{3+} extracted with 1 mol L^{-1} KCl; and P and K in 0.05 mol L^{-1} H_2SO_4 + 0.025 mol L^{-1} HCl (Mehlich-1). Organic carbon (OC) was determined with cold oxidant solution of concentrated H_2SO_4 and $Na_2Cr_2O_7$. Manganese, Cu^{2+}, Zn^{2+}, and Fe were extracted with 0.1 mol L^{-1} HCl.

The soil carbon stock (CS) of the A horizon was estimated using equation 1, taking the organic carbon content (OC, g kg^{-1}), soil bulk density (SBD, Mg m^{-3}), and depth of the A horizon (h, variable for each soil profile) into account.

$$CS = SBD \times h \times OC \qquad \text{Eq. 1}$$

Physical analysis

Physical analyses were performed according to Donagema et al. (2011): particle size analysis - pipette method using 0.2 mol L^{-1} NaOH as a dispersant; soil bulk density (SBD) - volumetric method (Kopecky ring); soil particle density (SPD) - method of volumetric flask filled with ethanol. Degree of flocculation (DF) was determined considering differences in the size of the soil fractions (Donagema et al., 2011). The DF was calculated according to equation 2:

$$DF = [(Total\ Clay - DC)/Total\ Clay] \times 100 \qquad \text{Eq. 2}$$

where *DC* is dispersive clay after shaking the soil sample in water (Donagema et al., 2011).

Soil porosity was determined in soil samples collected in a volumetric ring. Water in macropores (pores of diameter ≥0.05 mm) was withdrawn by applying a tension of 0.6 m of water column. Equations 3 and 4 were used to determine soil porosity (Donagema et al., 2011):

$$TSP = 100\ (a-b)/a \qquad \text{Eq. 3}$$

where *TSP* is total soil porosity (%); *a* is soil particle density (Mg m^{-3}); and *b* is soil bulk density (Mg m^{-3}).

$$SMi = (a-b)/c \qquad \text{Eq. 4}$$

where *SMi* is soil microporosity (%); *a* is weight of sample after applying a tension of 0.6 m of water column (g); *b* is weight of sample dried at 105 °C; and *c* is volume of Kopecky ring (m^3).

Soil macroporosity was estimated by the difference between total soil porosity and soil microporosity.

Geometric mean diameter of water-stable aggregates (GMD) was determined in air-dried undisturbed samples from the A horizon (soil blocks) using a vertical mechanical oscillator (Yoder) (Donagema et al., 2011). The percentages of the following classes of aggregates were obtained: 2.0-1.0; 1.0-0.5; 0.5-0.25; <0.25 mm. The aggregate size distribution (geometric mean diameter of water-stable aggregates - GMD) was calculated using equation 5:

$$GMD = 10^x \qquad \text{Eq. 5}$$

where $x = [\sum(n\log d)/\sum n]$; *n* is proportion of specific aggregate size (%); and *d* is average diameter of a specific aggregate class (mm).

Soil data

Four soil uses in four replicates (soil profiles) were tested. The mean value distribution of each physical and chemical analysis was determined at different depths, and standard error bars were placed to display significant differences among treatments. Qualitative morphological data were also used to evaluate the effects of different land uses on soil properties.

RESULTS

The selected profiles in four treatments (native forest, secondary forest, pasture, and coffee field) showed very similar morphology, highlighting the shallow B horizon and presence of a stone line (lithologic discontinuity), consisting of rock fragments. Soil structure under pasture and coffee exhibited significant changes, especially in the A horizon (Table 1). The structure changed from granular in native forest and secondary forests to subangular blocks. There was also a reduction in depth (Figure 1a) and

Table 1. Morphological properties of selected profiles and mean physical and chemical soil properties for four management systems in southern Amazonia, Brazil

Horizon[1]	Depth	Color	Structure[2]	Consistency[3]		Clay	Concentrated H_2SO_4		
							SiO_2	Al_2O_3	Fe_2O_3
	m					g kg^{-1}			
				Native Forest (slope 12 %)					
O	0.05-0.00								
A	0.00-0.12	5YR 4/2	G; S; VS; Sm	VF	SPl; Sy	259	56.7	64.8	59.4
AB	0.12-0.26	5YR 4/4	SA; M; Sm; Me	Fr	Pl; Sy	300	56.7	76.2	59.9
B1	0.26-0.40	5YR 4/6	SA; M; Sm; Me	Fr	Pl; Sy	322	72.3	98.1	66.0
2B2	0.75-1.19	5YR 5/8	SA; M; Sm	St	Pl; VSy	480	171.8	187.2	129.2
2BC	1.19-1.40$^+$	5YR 6/8	SA; W; La	St	Pl; Sy	397	186.6	141.7	123.3
				Secondary Forest (slope 11 %)					
A	0.00-0.07	2.5YR 4/4	G; M; Sm	VF	Pl; SSy	302	98.6	100.8	61.5
AB	0.07-0.17	2.5YR 4/6	SA; M; Sm	Fr	Pl; Sy	348	105.2	137.5	69.2
B1	0.17-0.30	2.5YR 4/6	SA; M; Sm	Fr	Pl; Sy	385	115.9	146.6	69.1
2B2	0.54-1.04	10R 5/6	SA; M; Me	St	Pl; VSy	504	202.2	201.5	88.7
2BC	1.04-1.40$^+$	2.5YR 5/8	SA; W; La	St	Pl; Sy	403	221.1	232.6	88.5
				Pasture (slope 12 %)					
A	0.00-0.06	5YR 4/4	SA; M; VS	Fr	Pl; SSy	295	102.7	83.3	60.3
AB	0.06-0.30	5YR 5/6	SA; M; Me; La	Fr	Pl; Sy	342	75.6	70.8	60.4
B1	0.30-0.50	5YR 5/8	SA; M; Sm; Me	Fr	Pl; Sy	410	101.9	118.7	64.0
2B2	0.92-1.12	5YR 6/8	SA; S; Sm; Me	St	Pl; VSy	475	161.9	162.8	84.7
2BC	1.12-1.40$^+$	2.5YR 5/8	SA; W; Me; La	St	Pl; SSy	357	161.1	141.7	87.3
				Coffee (slope 12 %)					
A	0.00-0.07	5YR 5/3	SA; M; VS	Fr	SPl; Sy	266	82.2	66.8	36.3
AB	0.07-0.28	5YR 5/4	SA; M; Me	St	Pl; Sy	302	87.9	78.6	40.0
B1	0.28-0.43	5YR 5/6	SA; M; Sm; Me	St	Pl; Sy	329	104.4	91.4	46.1
2B2	0.64-1.32	2.5YR 5/8	SA; M; Me; La	St	Pl; VSy	458	148.8	182.3	60.3
2BC	1.32-1.40$^+$	2.5YR 5/8	SA; W; Me; La	St	SPl; Sy	337	145.5	179.3	61.5

(1) Occurrence of stone line (lithologic discontinuity) in all profiles, composed of 30-50 % angular and sub-angular rock fragments (mostly from 0.02 to 0.20 m) at the following depths: native forest - 0.40 to 0.75 m; secondary forest - 0.30 to 0.54 m; pasture - 0.50 to 0.92 m; coffee - 0.43 to 0.64 m. In this layer, soil samples were not collected for physical and chemical analysis. (2) Structure: type (G - granular, SA - subangular blocks); degree of development (S - strong, M - moderate, W - weak); and size (VS - very small, Sm - small, Me - medium, La - large). (3) wet consistency (VF - very friable, Fr - friable, St - steady); plasticity (Pl - plastic, NPl - non plastic, SPl - slightly plastic); and stickiness (VSy - very sticky, Sy – sticky, NSy – not sticky, SSy - slightly sticky).

increases in the value and chroma (color components) of the A horizon in soils under secondary forest, pasture, and coffee compared to native forest, which serves as a reference (Table1). The organic O horizon, consisting of plant residues over the soil, was found only in native forest.

The pH values in all soil profiles were neutral or slightly acidic, and in cultivated areas and secondary forest, the pH values were higher than in native forest (Figure 2a). The pH increase under pasture in relation to native forest was significant at a greater depth (B1 horizon).

Exchangeable Ca (Figure 2b) and sum of bases (SB = Ca^{2+} + Mg^{2+} + K^{+}) (Figure 2c), even under natural conditions (the A horizon of native forest), were considered high: maximum values of 6.4 and 8.4 $cmol_c$ kg^{-1}, respectively. Exchangeable Ca levels were higher in secondary forest and pasture than in native forest up to the AB horizon. Soil under coffee cultivation had the lowest levels of Ca^{2+} and SB in surface horizons.

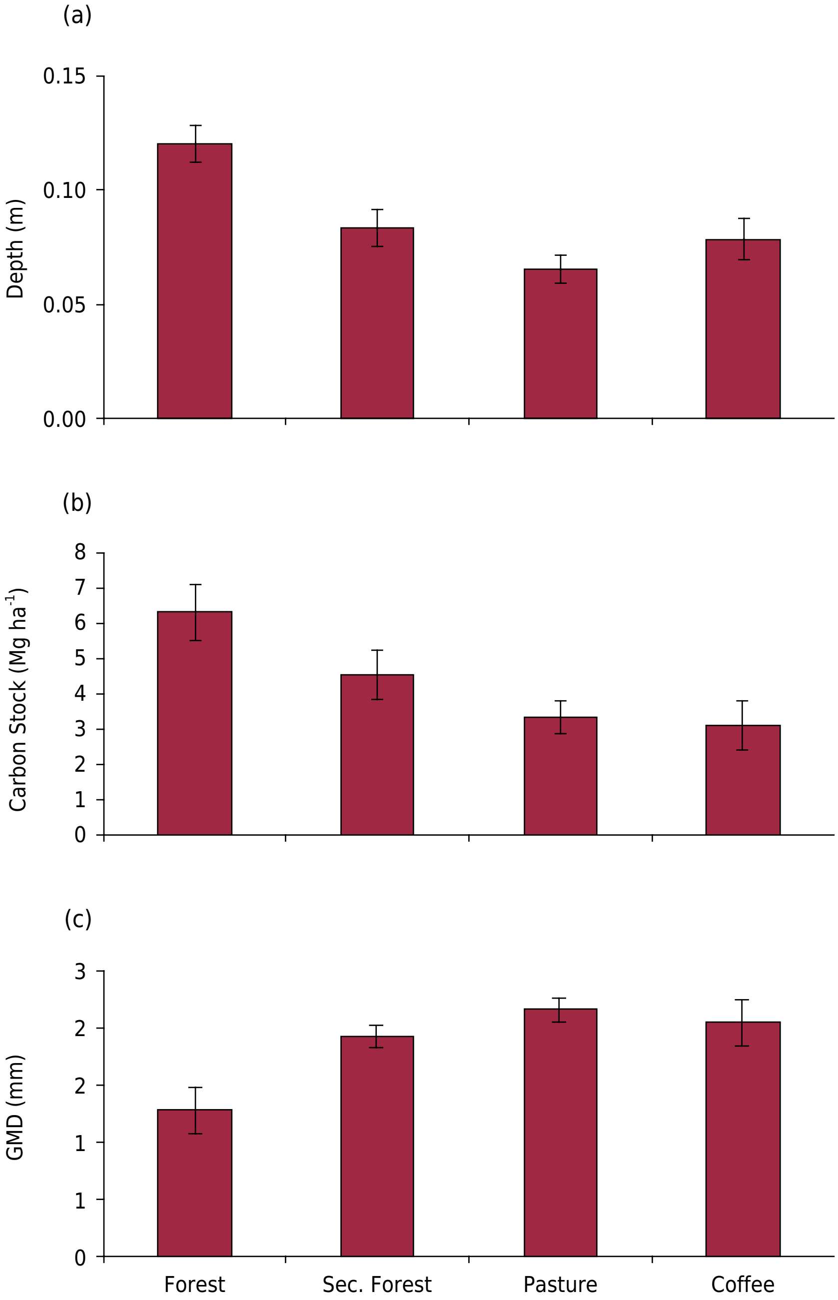
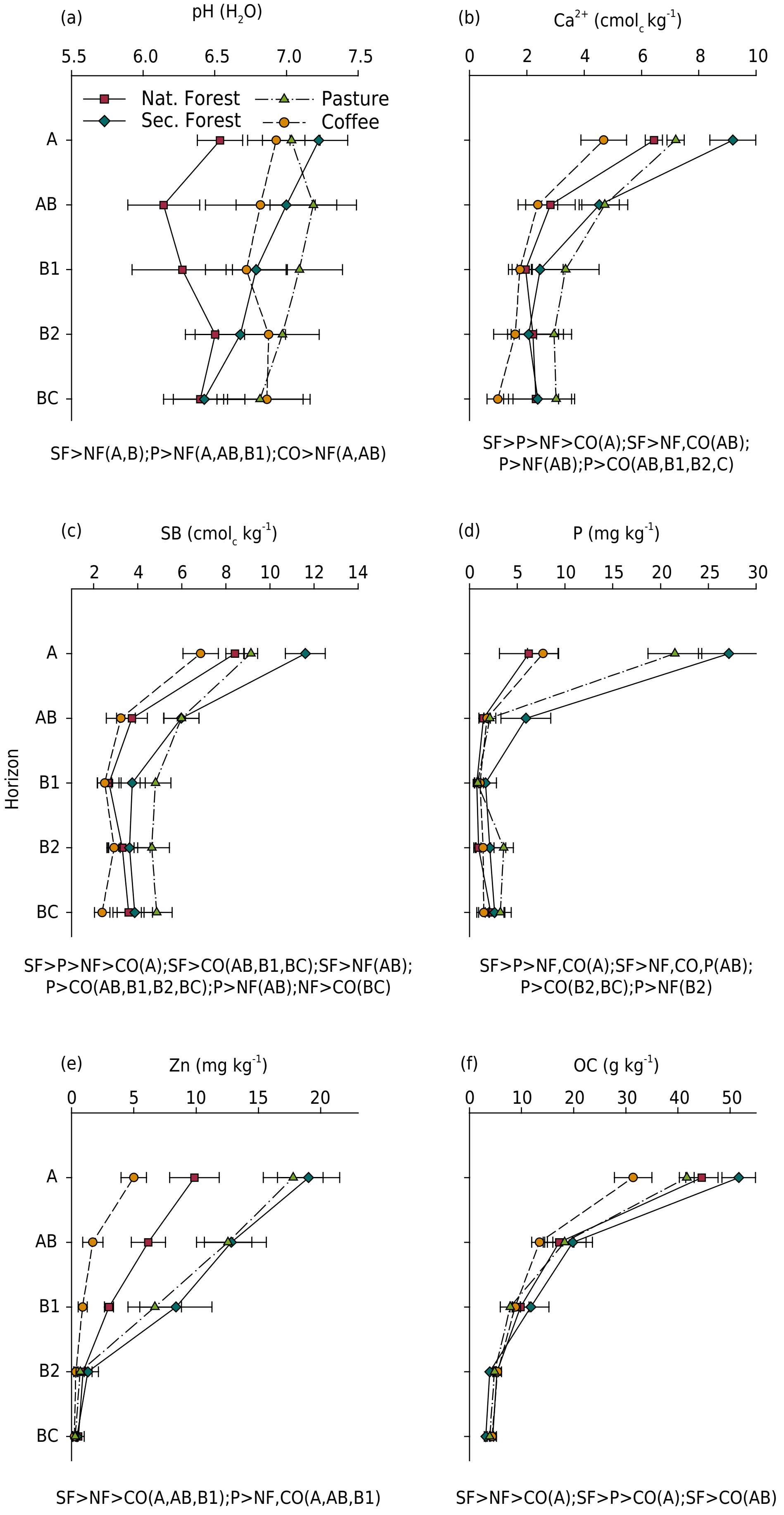


Figure 1. Depth (a), carbon stock (b), and geometric mean diameter of water-stable aggregates - GMD (c) of the A horizon of soils subjected to different management systems in southern Amazonia, Brazil. Standard deviation is represented inside the bars.



SF>NF(A,B);P>NF(A,AB,B1);CO>NF(A,AB)

SF>P>NF>CO(A);SF>NF,CO(AB);
P>NF(AB);P>CO(AB,B1,B2,C)

SF>P>NF>CO(A);SF>CO(AB,B1,BC);SF>NF(AB);
P>CO(AB,B1,B2,BC);P>NF(AB);NF>CO(BC)

SF>P>NF,CO(A);SF>NF,CO,P(AB);
P>CO(B2,BC);P>NF(B2)

SF>NF>CO(A,AB,B1);P>NF,CO(A,AB,B1)

SF>NF>CO(A);SF>P>CO(A);SF>CO(AB)

Figure 2. Chemical properties of soils subjected to different management systems in southern Amazonia, Brazil. SB: sum of bases ($Ca^{2+} + Mg^{2+} + K^{+} + Na^{+}$); OC: organic carbon. Significant differences are highlighted on the line above each figure. Standard deviation is represented in horizontal lines.

Enhancement of P availability was expressive even after 11 years of soil use (Figure 2d): in the A horizon it increased more than three times, from 6.2 mg kg^{-1} in native forest to 21.5 mg kg^{-1} in pasture and to 27.2 mg kg^{-1} in secondary forest. In soil under coffee cultivation, the P contents returned to native forest levels.

The Zn contents naturally available in the A horizon of native forest (9.9 mg kg^{-1}) (Figure 2e) were high for humid tropical conditions. Secondary forest and pasture had higher Zn contents in relation to native forest up to the B1 horizon. Coffee cultivation promoted a significant reduction in Zn levels in relation to soil under native forest.

Organic carbon (OC) contents in the A horizon decreased in the following order: SF>NF>CO and SF>P>CO (Figure 2f). However, the C stock is significantly higher in the A horizon of native forest in relation to all other uses (Figure 1b) (Mg ha^{-1}), when considering the combined effect of soil use on depth of the A horizon (Figure 1a) and the OC content (Figure 2f): native forest 6.3, secondary forest 4.5, pasture 3.3, and coffee 3.1. The differences between carbon stock in secondary forest and other slash-and-burn areas were not significant at $p<0.05$.

Cultivated soils also showed significant physical changes. Soil under native forest exhibited higher total porosity (STP) in relation to the other soils, specifically for the 0.025 and 0.075 m layers, and higher in relation to the soil under secondary forest in the 1.75 m layer. The secondary forest had superior total porosity in relation to the coffee crop in the 0.075 m layer. Macroporosity (SMa) was higher for soil under native forest in relation to all soils in the 0.025 and 0.075 m layers, and coffee cultivation was higher (0.16 m^3 m^{-3}) than soil under pasture in the 1.25 m layer (0.10 m^3 m^{-3}) (Figure 3b). Microporosity (SMi) (Figure 3c) and soil bulk density (SBD) (Figure 3d) were superior in soil under pasture as a consequence of higher surface compaction. Coffee cultivation had a higher value for SBD (1.47 Mg m^{-3}) compared to secondary and native forest uses (1.27 and 1.01 Mg m^{-3}, respectively) in the 0.075 m layer. The geometric mean diameter of water-stable aggregates (GMD) of native forest was higher than secondary forest (Figures 1c).

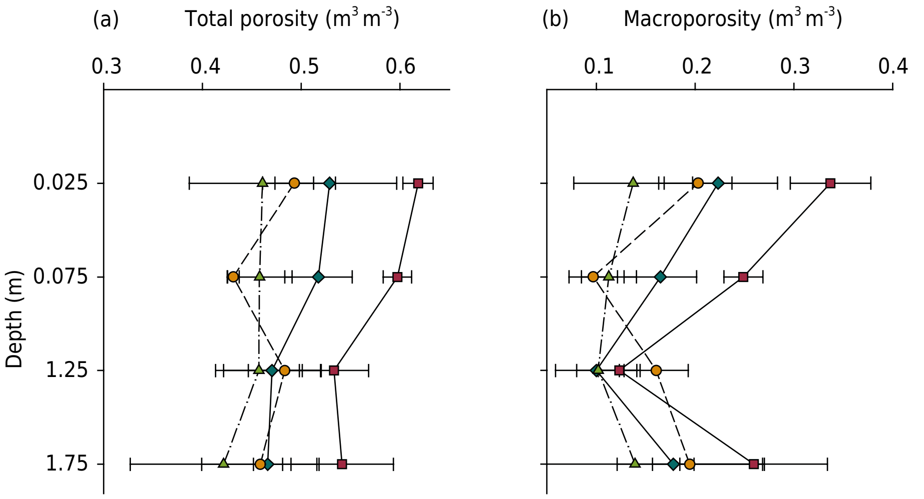
Besides the size and shape of structures, another important parameter is the degree of flocculation (DF) (Figure 3e). Soil under native forest had the highest DF values in the surface layer (A horizon). There was a systematic increase in DF values with the depth of layers for all soil uses.

DISCUSSION

Soil fertility

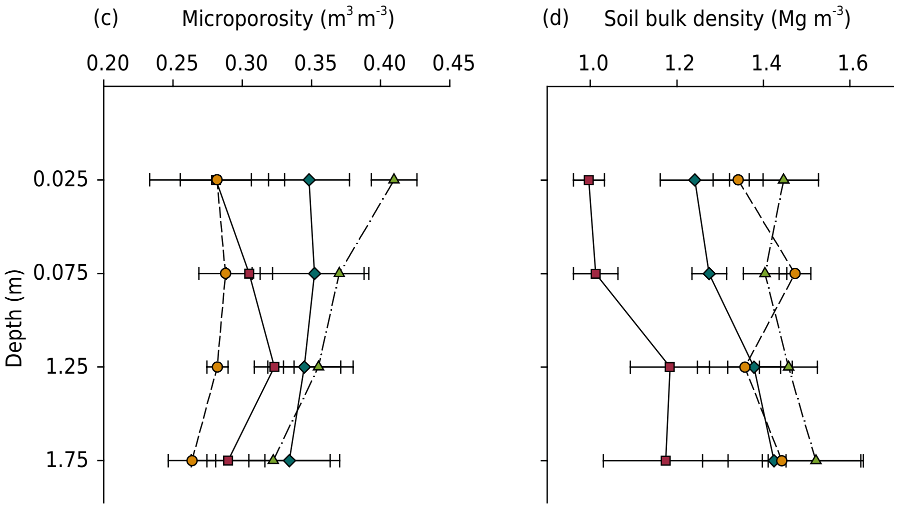
The high values of pH (Figure 2a) and Ca^{2+} concentration (Figure 2b) in soil under native forest were attributed to local associations of granite/gneiss with limestone (Orrutéa et al., 2012) and the low degree of development of Inceptisol. Another important factor in maintaining high levels of sum of bases in forest soils is nutrient cycling (Bedel et al., 2016). The elevation of pH up to the AB horizon of soils in plots that have undergone slashing and burning of vegetation could be attributed to ash input and leaching of bases through these horizons. Even 15 years after slashing and burning of forest, an increase in pH from 4.1 to 6.3 was found under pastures within the 0.0-0.2 m soil layer (Braz et al., 2013).

High Ca^{2+} contents are not common in soils of the Brazilian Amazon, especially in the northern region, where Typic Hapludox predominates (Comte et al., 2012). Exchangeable Ca^{2+} contents in soils under natural vegetation in this area are less than 1.4 $cmol_c$ kg^{-1} (typically less than 0.5 $cmol_c$ kg^{-1}) (McGrath et al., 2001; Braz et al., 2013). In these environments, with considerable poverty of nutrients in the source material (usually sediments of the Barreiras Group), nutrient cycling is even more important to maintain minimum levels of bases available for plants (McGrath et al., 2001).



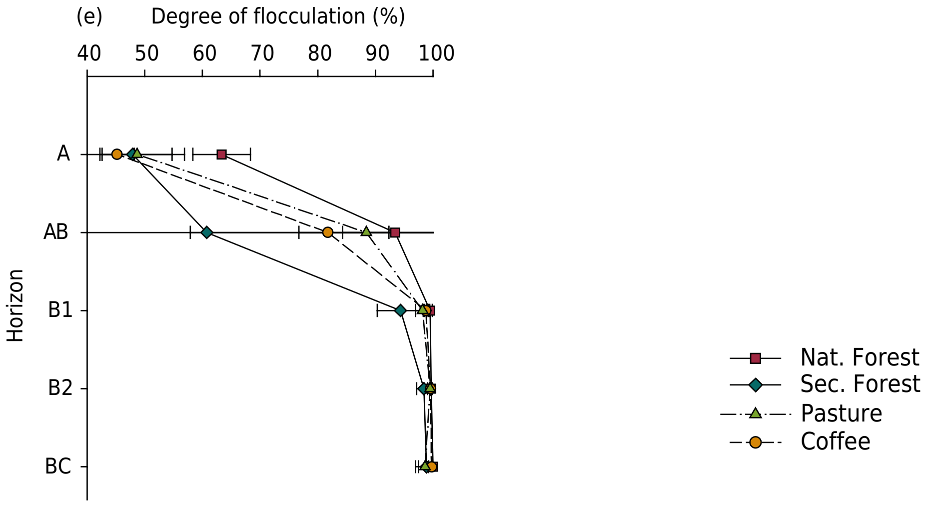
NF>SF,CO,P (0.025, 0.075); SF>CO (0.075); NF>SF (1.75)

NF>SF,CO,P (0.025, 0.075); CO>P (1.25)



P>SF,CO,NF (0.025); SF>NF (0.025); P>NF,CO (0.075); SF>CO (0.075, 1.75); P,SF,NF>CO (1.25)

P>SF>NF (0.025); CO>NF (0.025); CO>SF>NF (0.075); P>NF (0.075); P,SF>NF (1.25, 1.75)



NF>P, SF,CO (A)

Figure 3. Physical properties of soils subjected to different management systems in southern Amazonia, Brazil. Significant differences are highlighted on the line above each figure. Standard deviation is represented in horizontal lines.

Eleven years after burning, there was still a positive residual effect of ash on Ca^{2+} availability in secondary forest and pasture; both also showed higher levels of SB. However, the increase in available Ca^{2+} in our study was lower than that observed by McGrath et al. (2001) and Braz et al. (2013), who found a more than ten-fold increase when forest was converted into agricultural land more than a decade after slashing and burning of vegetation. Fifteen years after conversion to pasture, Ca^{2+} increased from 0.2 to 2.5 $cmol_c\ kg^{-1}$ in the 0.00-0.20 m soil layer at low fertility sites in the state of Pará, Brazil (Braz et al., 2013). These authors also reported an increase in Ca^{2+} contents after burning of vegetation from nutrient uptake by crops and subsequent plant decomposition. Several authors have studied more weathered soils (Ultisols and/or Oxisols) in the Amazon (McGrath et al., 2001; Comte et al., 2012; Braz et al., 2013; Viana et al., 2014).

In a study under conditions similar to this one (western Brazilian Amazon, Inceptisol, and high concentrations of natural bases), $Ca^{2+} + Mg^{2+}$ contents were greater in agroforestry, agricultural crop use, and secondary forestry than in primary rainforest (Moreira et al., 2009). Studies considering Inceptisols with higher natural soil fertility are not very common in the Amazon.

Data from these studies are apparently contrary to the nutrient depletion model (Juo and Manu, 1996), which holds that a significant portion of mineral nutrients released from burning of vegetation may be lost by erosion and runoff and leaching (i.e., K, Mg, Ca, nitrate, and sulfate) and some nutrients may be volatilized (van Reuler and Janssen, 1993). Another portion of plant nutrients will be removed in harvested crops. Thus, the total mineral nutrient stock in the whole ecosystem gradually declines during subsequent fallow and cropping cycles. The concept of nutrient stocks is broader because it also considers nutrients temporarily immobilized in forest growth. In this regard, chemical loss from the system after burning of vegetation is unquestionable. However, when analyzing only the nutrient content in the soil after burning, the levels rise so expressively that there has apparently been an improvement in the chemical environment (Table 1) (McGrath et al., 2001; Moreira et al., 2009; Braz et al., 2013). The time of depletion of soil nutrients is thought to be dependent on several factors, such as climatic conditions; morphological, chemical, and physical soil properties; inadequate management of soils; and the nature of individual nutrients. Proper soil conservation practices are one effective manner of maintaining the levels of nutrients in the soil for a longer time.

Lower Ca^{2+} and SB contents in soils under coffee cultivation (Figures 2b and 2c) are attributed to the low level of technology employed without adequate replenishment of nutrients exported in harvests and to the intercropping system used in the first eight years. This high level of export of bases exceeded the increase in nutrients through the ash. Exchangeable Ca and SB levels in soil under coffee cultivation are even lower than in soil under native forest.

It is plausible that the medium level of P available in soils under native forest (Figure 2d) and the presence of a primary mineral source of this nutrient at the study site (Orrutéa et al., 2012) supplied enough P to native vegetation. High P uptake in abundant forest vegetation might become available through slashing and burning of this vegetation. Managed soils probably had both lower precipitation and adsorption of P and provided high P recovery. Precipitation of P with exchangeable Al did not occur, since soil pH was above 5.5 (Figure 2a). The A horizon had the highest P levels due to its OC content and ash deposition. Higher P levels in secondary forest up to the AB horizon is a consequence of fewer years of land use, an increase in P recycling efficiency, and low nutrient export by crops. After slashing and burning, soil texture also influences P availability. In sandy soils, the P will be more available because specific adsorption in Fe and Al oxides is less significant. In the present study, the soils were classified as medium and clayey texture soils (Table 1).

Significant increases in P contents have also been found in cropping and grazing systems six years after slashing and burning of vegetation (Comte et al., 2012). Phosphorus contents within the 0.0 to 0.2 m soil layer increased from 2.5 to 3.8 mg kg^{-1} after 11 years of pasture, declining to 3.0 mg kg^{-1} after 13 years, and finally reaching 2.7 mg kg^{-1} 15 years after slashing and burning of forest (Braz et al., 2013). However, Moreira et al. (2009) did not find differences in P contents between native forest and four land use systems (pasture, agroforestry, agricultural use, and secondary forest) in the upper Solimões river region, in the western Amazon.

The increase in Zn availability in soils under pasture and secondary forest, especially below the A horizon (Figure 2e), was not expected. Zinc content in granite is commonly low and this nutrient is more associated with Fe minerals from mafic rocks. Zinc mobility in soils is low mainly at pH values close to neutrality (Figure 2a). This indicates that a large amount of Zn was added by the slash-and-burn process. An increase in Zn availability observed in soil under pasture could explain the good pasture productivity 11 years after burning of vegetation in the study area. The distribution of Zn within the soil profile was similar to the distribution of the other cations analyzed (SB). Except for soil under coffee cultivation, which had greater nutrient export, the addition of ash from burning of vegetation resulted in a significant increase in Zn concentration from the topsoil to the B1 horizon.

The lower stock of soil OC in the A horizon of cultivated soils compared to native forest (Figure 1b) was consistent with previous studies. The soil surface (A horizon) is most susceptible to land use change caused by clear cutting and agricultural or grazing use (Ceddia et al., 2015). In forest/pasture chronosequence research in the Amazon, a reduction was also observed in the C stock in the 0.0-0.2 m soil layer in the first five years after conversion from forest (Cerri et al., 2007). A study reviewing the effects of land use in the Amazon concluded that OC content is maintained in pasture areas, especially in well-managed areas, and it also showed a predominance of lower OC contents in Oxisols and Ultisols under agricultural uses and secondary forest (McGrath et al., 2001). In contrast, there was an increase in the C stock in soils under pasture for 8 years (6.2 Mg ha^{-1}) and 13 years (2.3 Mg ha^{-1}) (Braz et al., 2013). However, there was a decrease in the soil OC stock in a 15-year-old pasture (0.49 Mg ha^{-1}) in relation to soil under a forested area. Pasture in our study area was adequately managed and had a good soil cover and vigorous plant growth (field observations), but soil OC content and the C stock in the area were lower than in soils under native and secondary forests (Figures 1b and 2f). The reduced thickness of the A horizon in soils under the slash-and-burn process, especially in pasture (Figure 1a), negatively affected the result of soil OC.

The C stock in native forest soils would be even more expressive considering the immobilization of C in the organic O horizon, with an average thickness of 0.05 m in the four native forest profiles (Table 1). Despite the lower nutrient content in native forest soil (Figure 2), the expressive potential of nutrient reserves temporarily fixed in the O horizon and in native forest biomass must also be considered.

Soil morphology and physical analysis

In pasture, in addition to intense machine traffic in the early years after slashing and burning of vegetation, cattle treading for 11 years of the experiment resulted in a clear reduction in soil physical qualities: lower SMa and STP and higher SBD and SMi.

Pressure from animal hooves have kneaded the soil and promoted the coalescence of smaller structural units. Such aggregations can be identified in the higher value of GMD in soil under pasture (Figure 1c). Combined with rolling relief and the relatively high slope of pasture areas (12 % - Table 1), these physical degradation conditions favor water runoff and soil erosion (smaller depth of the A horizon in pasture - Figure 1a).

The effect of cattle trampling was more deleterious to soil physical properties in the Northern Amazon, as SBD values in the surface layer (0.0-0.025 m) under pastures exceeded the 1.40 Mg m^{-3} value, which is considered the limit for good development of the pasture root system in medium-texture soils (Braz et al., 2013). Compaction of surface layers of Typic

Hapludox is favored by its higher kaolinite content in the clay fraction. Unconsolidated clay sediments that gave rise to most soils in the Amazon in Brazil are essentially kaolinitic, with very little occurrence of Fe and Al oxides (Benedetti et al., 2011). This abundance of kaolinite in Typic Hapludox favors face-to-face arrangement of this phyllosilicate, formation of blocky structures, and soil compaction (Giarolla et al., 2003). The SBD value for the surface layer of Eutric Inceptisol under native forest in the present study (granite/gneiss as parent material) was only 0.99 Mg m^{-3} (Figure 3d). The SBD value presented in Braz et al. (2013) was 1.4 Mg m^{-3} for a Typic Hapludox under native forest. These data show that deforested soils in the northern Amazon region require care to avoid physical depletion. In the eastern Brazilian Amazon, Comte et al. (2012) found a significant increase in SBD for Kandiudults six years after conversion of forest into pasture (1.21 and 1.33 Mg m^{-3}).

The lowest SBD value for native forest was obtained in the 0.0-0.025 m soil layer (Figure 3d), due to higher OC content and biological activity (fauna and roots) in this section of soil, which favored greater structuring and an increase in SMa and STP.

The better physical quality of soil under coffee cultivation compared to soil under pasture (Figure 3) was also positively influenced by the addition of coffee bean husk and intense leaf drop during manual coffee harvest. In the secondary forest area, machinery was only used to slash the forest in the early years of conversion since cultivation of rice, beans, and corn in the first two years was performed manually in the area, without soil tillage. In the present study, over the next nine years, forest regeneration promoted a favorable environment for resilience of soil physical properties.

Native and secondary forests were the only treatments that showed granular structures in the A horizon (Table 1). However, very small structures in morphological analysis (Table 1) were observed only in native forest, which resulted in the smallest value of GMD in the A horizon (Figure 1c). Very small granular structures are associated with high hydraulic conductivity and SMa, which ease root growth (VandenBygaart et al., 1999).

Degree of flocculation (DF) (Figure 3e) is influenced by all parameters that affect the thickness of the diffuse double layer (Fontes et al., 2001), especially the content and mineralogy of the clay fraction, content and quality of organic matter, pH, and type and quantity of exchangeable soil cations. The higher content of organic matter in the A horizon promote an increase in negative charges within aggregates, which induces repulsion among particles, hinders flocculation, and results in clay dispersion (lower DF in the soil surface - Figure 3e).

Ashes increase soil pH (Figure 2a) and negative charges inside the aggregates and reduce DF in the soil surface of managed areas (Figure 3e). A study on the mineralogy of the same soil samples used in the present study found that the mineralogical composition of the clay fraction was rather homogeneous, with predominance of kaolinite, followed by hematite, goethite, mica, and 2:1 secondary minerals (Orrutéa et al., 2012).

The literature indicates that kaolinite and Fe oxides have pH dependent charges. The formation of negative charges on the surface of these minerals is directly proportional to the increase in pH (Fontes et al., 2001). However, the physical destruction of aggregates and an increase in DF resulting from the machinery used for soil tillage in areas of secondary forest, pasture, and coffee fields should also be considered. Aggregate instability, surface crust formation, and lack of good soil pedality were observed within thin sections in the conventional tillage system compared to no-tillage sites (VandenBygaart et al., 1999).

CONCLUSIONS

In the cropping systems in the southern Amazon region, morphological and physical quality decreased 11 years after the slash-and-burn process in forest. Conversion to pasture resulted in the highest physical damage. The secondary forest system showed more sustainable use, with good resilience after nine years of fallow.

A significant increase in pH and nutrient contents were observed in soil under pasture and secondary forest, even though the native forest soil is naturally rich in nutrients. In the coffee field, the intense soil nutrient export in harvests supplanted the residual effects of ash. The lowest levels of Ca^{2+} and SB in surface horizons were observed in this crop.

In all slash-and-burn study areas, there was a reduction in the carbon stock in the A horizon. This scenario worsens if the carbon stock of the O horizon of forested soil is taken into account.

To minimize decline in soil quality, coffee cultivation is best among the practices commonly used by farmers in the southern Amazon. To ensure maintenance of soil fertility in this management system, the farmer should restore the exported nutrients by means of fertilization.

REFERENCES

Bedel L, Poszwa A, van der Heijden G, Legout A, Aquilina L, Ranger J. Unexpected calcium sources in deep soil layers in low-fertility forest soils identified by strontium isotopes (Lorraine plateau, eastern France). Geoderma. 2016;264:103-16. https://doi.org/10.1016/j.geoderma.2015.09.020

Belay KT, Van Rompaey A, Poesen J, Van Bruyssel S, Deckers J, Amare K. Spatial analysis of land cover changes in eastern Tigray (Ethiopia) from 1965 to 2007: are there signs of a forest transition? Land Degrad Develop. 2015;26:680-9. https://doi.org/10.1002/ldr.2275

Benedetti UG, Vale Júnior JF, Schaefer CEGR, Melo VF, Uchôa SCP. Gênese, química e mineralogia de solos derivados de sedimentos pliopleistocênicos e de rochas vulcânicas básicas em Roraima, Norte Amazônico. Rev Bras Cienc Solo. 2011;35:299-312. https://doi.org/10.1590/S0100-06832011000200002

Braz AMS, Fernandes AR, Alleoni LRF. Soil attributes after the conversion from forest to pasture in Amazon. Land Degrad Develop. 2013;24:33-8. https://doi.org/10.1002/ldr.1100

Ceddia MB, Villela ALO, Pinheiro EFM, Wendroth O. Spatial variability of soil carbon stock in the Urucu river basin, Central Amazon-Brazil. Sci Total Environ. 2015;526:58-69. https://doi.org/10.1016/j.scitotenv.2015.03.121

Cerri CEP, Easter M, Paustian K, Killian K, Coleman K, Bernoux M, Falloon P, Powlson DS, Batjes N, Milne E, Cerri CC. Simulating SOC changes in 11 land use change chronosequences from the Brazilian Amazon with RothC and Century models. Agric Ecosyst Environ. 2007;122:46-57. https://doi.org/10.1016/j.agee.2007.01.007

Comte I, Davidson R, Lucotte M, Carvalho CJR, Oliveira FA, Silva BP, Rousseau GX. Physicochemical properties of soils in the Brazilian Amazon following fire-free land preparation and slash-and-burn practices. Agric Ecosyst Environ. 2012;156:108-15. https://doi.org/10.1016/j.agee.2012.05.004

Cruz DLS, Vale Júnior JF, Cruz PLS, Cruz ABS, Nascimento PPRR. Atributos físico-hídricos de um Argissolo Amarelo sob floresta e savana naturais convertidas para pastagem em Roraima. Rev Bras Cienc Solo. 2014;38:307-14. https://doi.org/10.1590/S0100-06832014000100031

Davidson EA, Sá TDA, Carvalho CJR, Figueiredo RO, Kato MSA, Kato OR, Ishida FY. An integrated greenhouse gas assessment of an alternative to slash-and-burn agriculture in eastern Amazonia. Global Change Biol. 2008;14:998-1007. https://doi.org/10.1111/j.1365-2486.2008.01542.x

Donagema GK, Campos DVB, Calderano SB, Teixeira WG, Viana JHM, organizadores. Manual de métodos de análise do solo. 2a ed. rev. Rio de Janeiro: Embrapa Solos; 2011.

Fontes MPF, Camargo OA, Sposito G. Eletroquímica das partículas coloidais e sua relação com a mineralogia de solos altamente intemperizados. Sci Agric. 2001;58:627-46. https://doi.org/10.1590/S0103-90162001000300029

Giarolla NFB, Silva AP, Imhoff S, Dexter AR. Contribution of natural soil compaction on hardsetting behavior. Geoderma. 2003;113:95-108. https://doi.org/10.1016/S0016-7061(02)00333-6

Juo ASR, Manu A. Chemical dynamics in slash-and-burn agriculture. Agric Ecosyst Environ. 1996;58:49-60. https://doi.org/10.1016/0167-8809(95)00656-7

Lindell L, Åström M, Öberg T. Land-use versus natural controls on soil fertility in the Subandean Amazon, Peru. Sci Total Environ. 2010;408:965-75. https://doi.org/10.1016/j.scitotenv.2009.10.039

Marques JDO, Teixeira WG, Reis AM, Cruz Junior OF, Batista SM, Afonso MACB. Atributos químicos, físico-hídricos e mineralogia da fração argila em solos do Baixo Amazonas: Serra de Parintins. Acta Amaz. 2010;40:1-12. https://doi.org/10.1590/S0044-59672010000100001

Mcgrath DA, Smith CK, Gholz HL, Oliveira FA. Effects of land-use change on soil nutrient dynamics in Amazônia. Ecosystems. 2001;4:625-45. https://doi.org/10.1007/s10021-001-0033-0

Moreira FMS, Nóbrega RSA, Jesus EC, Ferreira DF, Pérez DV. Differentiation in the fertility of Inceptisols as related to land use in the upper Solimões river region, western Amazon. Sci Total Environ. 2009;408:349-55. https://doi.org/10.1016/j.scitotenv.2009.09.007

Numata I, Chadwick OA, Roberts DA, Schimel JP, Sampaio FF, Leonidas FC, Soares JV. Temporal nutrient variation in soil and vegetation of post-forest pastures as a function of soil order, pasture age, and management, Rondônia, Brazil. Agric Ecosyst Environ. 2007;118:159-72. https://doi.org/10.1016/j.agee.2006.05.019

Orrutéa AG, Melo VF, Motta ACV, Lima VC. Mineralogia e reserva de K de Cambissolos submetidos a diferentes manejos após derrubada e queima da floresta na Amazônia Meridional. Acta Amaz. 2012;42:461-70. https://doi.org/10.1590/S0044-59672012000400003

Paix MJ, Lanhai L, Xi C, Ahmed S, Varenyam A. Soil degradation and altered flood risk as a consequence of deforestation. Land Degrad Dev. 2013;24:478-85. https://doi.org/10.1002/ldr.1147

Patry C, Davidson R, Lucotte M, Béliveau A. Impact of forested fallows on fertility and mercury content in soils of the Tapajós River region, Brazilian Amazon. Sci Total Environ. 2013;458-460:228-37. https://doi.org/10.1016/j.scitotenv.2013.04.037

Reichert JM, Bervald CMP, Rodrigues MF, Kato OR, Reinert DJ. Mechanized land preparation in eastern Amazon in fire-free forest-based fallow systems as alternatives to slash-and-burn practices: hydraulic and mechanical soil properties. Agric Ecosyst Environ. 2014;192:47-60. https://doi.org/10.1016/j.agee.2014.03.046

Reichert JM, Rodrigues MF, Bervald CMP, Kato OR. Fire-free fallow management by mechanized chopping of biomass for sustainable agriculture in eastern Amazon: effects on soil compactness, porosity, and water retention and availability. Land Degrad Dev. 2016;27:1403-12. https://doi.org/10.1002/ldr.2395

Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Oliveira JB, Coelho MR, Lumbreras JF, Cunha TJF. Sistema brasileiro de classificação de solos. 3a ed. Rio de Janeiro: Embrapa Solos; 2013.

Santos RD, Lemos RC, Santos HG, Ker JC, Anjos LHC, editores. Manual de descrição e coleta de solo no campo. 5a ed. Viçosa, MG: Sociedade Brasileira de Ciência do Solo; 2005.

Scheffler R, Neill C, Krusche AV, Elsenbeer H. Soil hydraulic response to land-use change associated with the recent soybean expansion at the Amazon agricultural frontier. Agric Ecosyst Environ. 2011;144:281-9. https://doi.org/10.1016/j.agee.2011.08.016

Soil Survey Staff. Keys to soil taxonomy. 12th ed. Washington, DC: United States Department of Agriculture, Natural Resources Conservation Service; 2014.

van Reuler H, Janssen BH. Nutrient fluxes in the shifting cultivation system of south-west Cote d'Ivoire - I. Dry matter production, nutrient contents and nutrient release after slash and burn for two fallow vegetations. Plant Soil. 1993;154:169-77. https://doi.org/10.1007/BF00012522

VandenBygaart AJ, Protz R, Tomlin AD, Miller JJ. Tillage system effects on near-surface soil morphology: observations from the landscape to micro-scale in silt loam soils of southwestern Ontario. Soil Till Res. 1999;51:139-49. https://doi.org/10.1016/S0167-1987(99)00050-1

Viana RM, Ferraz JBS, Neves Jr AF, Vieira G, Pereira BFF. Soil quality indicators for different restoration stages on Amazon rainforest. Soil Till Res. 2014;140:1-7. https://doi.org/10.1016/j.still.2014.01.005