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Artigos

Amazon plinthosols: carbon stocks and physical properties under different land uses

Estoques de carbono e propriedades físicas de plintossolos em diferentes usos do solo na Amazônia

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ABSTRACT

The population growth and the climate changes impose challenges to society, especially regarding food supply and the maintenance of desirable soil conditions. Besides, it is necessary to reduce greenhouse gas emissions. Hence, there is a necessity of studies addressing the understanding of soil conditions under different land uses, as soils can become carbon pools or sources depending on management practices. This study was conducted in soil profiles of Amazon Plinthosols under different land uses: undisturbed forests, cattle ranching pastures, and mixed crops. Soil density and carbon fraction were assessed at four depths (0-5, 5-10, 10-20, and 20-40 cm), while particle size and mineralogy were examined at 0-20 and 20-40 cm. Soils under undisturbed forests presented lower densities and higher carbon fractions when compared to other land uses. These soils also presented the highest carbon stock; however, the Tukey test indicated no significant differences. Soil densities were lower in forest environments. Cattle ranching pastures presented higher carbon stocks when compared to mixed crops (at age 10 years). Our results indicated that proper soil management practices are needed to maintain the soil productive capacity after converting forested areas for other uses. Plinthosols, due to its textural and mineralogical characteristics, presented high amounts of quartz, demonstrating how sensitive these environments are to changes in the landscape due to deforestation and how unstable the maintenance of carbon stocks is because of such conditions. This study provides useful information to the understanding of the carbon stock in Amazon Plinthosols. It may be helpful to improve the Brazilian Inventory of Anthropogenic Emissions and Removals of Greenhouse Gases and to understand the impacts of land-use change.

Keywords: Land-use change; Soil density; Carbon fraction; Carbon stock

RESUMO

O crescimento populacional e as questões climáticas impõem desafios à sociedade, principalmente no que diz respeito ao abastecimento de alimentos e à manutenção de condições desejáveis do solo. Além disso, há uma evidente necessidade de reduzir as emissões de gases de efeito estufa, notadamente àquelas causadas por mudanças no uso do solo. Portanto, há necessidade de estudos que abordem o entendimento das condições do solo sob os diferentes usos do solo, uma vez que esses podem se tornar fontes de carbono dependendo das práticas de manejo. Este estudo foi conduzido em perfis de Plintossolos Amazônicos sob: florestas primárias, pastagens para pecuária e plantios mistos de restauração florestal. A densidade e o teor de carbono foram avaliados em quatro profundidades (0-5, 5-10, 10-20 e 20-40 cm), enquanto as propriedades físicas foram examinadas nas profundidades de 0-20 e 20-40 cm. Solos sob florestas primárias apresentaram as menores densidades e os maiores teores de carbono quando comparados a outros usos da terra. Esses solos também apresentaram o maior estoque de carbono. Entretanto, não foi observada diferença significativa pelo teste de Tukey para ambas variáveis. As pastagens apresentaram maiores estoques de carbono quando comparados aos plantios mistos (aos 10 anos). Nossos resultados indicaram que práticas de manejo adequadas são necessárias para a manutenção da capacidade produtiva do solo após a conversão de florestas para outros usos. Os Plintossolos, por suas características texturais e mineralógicas, apresentaram elevados teores de quartzo, notadamente nas camadas superficiais, demonstrando quão sensíveis às mudanças na paisagem. O estoque de carbono no solo é, portanto, sensível às mudanças na sua cobertura. Este estudo fornece informações úteis para o entendimento do estoque de carbono em Plintossolos na Amazônia Brasileira, bem como para aprimorar as estimativas realizadas no Inventário Nacional de Emissões de Gases de Efeito Estufa.

Palavras chaves: Mudança no uso do solo; Densidade do solo; Teor de carbono; Estoque de carbono

1 INTRODUCTION

The world currently faces two closely related challenges: population growth and climate change (IPCC, 2013). As the population grows, the higher the demand for natural resources availability is (SAATH; FACHINELLO, 2018)..

Soils are the primary resource for food production. Hence, maintaining soil quality is crucial in securing food availability for future generations. However, as the world population grows, soil degradation increases. Thousands of hectares of arable land are lost annually due to inadequate soil management. Moreover, the rise of temperatures, caused by climate changes, promotes growth gaps in several crops (ABRAMOVAY, 2010; MARQUES *et al*., 2017) and increases greenhouse gas emissions (GHG). Thus, the current soil management practices imply higher amounts of carbon emitted to the atmosphere, contributing to a failure in reaching the Intergovernmental Panel on Climate Change (IPCC) goals to maintain the global warming rate below 1.5 ºC until 2100 (ROGELJ *et al*., 2016).

It is estimated that tropical soils store 2.5 times more carbon than the vegetation (BARROS; FERNANDES, 2016). Despite this, upper layers of soil (0-20 cm), the ones more susceptible to land preparation, account for the most significant carbon stock part. Indeed, agricultural uses were responsible for 21% of anthropogenic GHG emissions in 2010 (TUBIELLO *et al.*, 2015). The maintenance of carbon stocks in soils depends, in particular, on management practices (ARYAL *et al.*, 2018). However, related studies indicated that land-use change to agricultural uses promote significant soil structure changes, generally worsening soil conditions and increasing GHG emission (COSTA *et al.*, 2009; BARROS; FEARNSIDE, 2016).

The Food and Agriculture Organization of the United Nations (FAO) estimates that the global population will reach circa 9.3 billion by 2050 and about 70% will live in urban areas (FAO, 2013). Thus, to meet the food demand, it is expected that food production increase by 60%. The United Nations (2009) reports that more than 120 million hectares of land will be needed to meet this demand for food.

In this scenario, Latin America and Sub-Saharan Africa emerge as they encompass approximately 90% of the world's agricultural land (FAO, 2013). Inevitably, tropical forests such as the Brazilian Amazon will face tremendous pressure regarding land-use change issues (BROADBENT *et al.*, 2008). It is estimated that the conversion of forest areas into agricultural uses accounts for 60% of the world's deforestation (DE JONG *et al.*, 2010). The main drivers of deforestation in the Amazon are illegal logging, cattle farming, and road building (FAO, 2017), and deforested area reached ca. 16% of the total area, corresponding to circa 55 million ha (INPE, 2018).

However, land-use change in developing countries has been a significant issue. Usually, cattle ranching pastures are severely degraded. There is ca. 200 million ha of degraded pastures in Latin America (GAITÁN *et al.*, 2016). In Brazil, cattle ranching pastures encompass ca. 171 million ha (SAATH; FACHINELLO, 2018), and in the southwestern Amazon, 40% of pastures are degraded.

Plinthosols extends in ca. 60 million ha worldwide, and it is the most common soil in the wet tropics. These soils are common in the Brazilian Amazon basin (GARCIA *et al.*, 2013). Thus, it is crucial to understand carbon cycling and the impact of different land uses in Plinthosols, especially in the Brazilian Amazon. There is, however, a lack of studies addressing this particular question. The proper understanding of Plinthosols is crucial for developing management practices to reduce environmental issues and avoid loss of forested areas.

This study aimed to assess the carbon stock and physical properties of Amazon Plinthosols under different land uses: undisturbed forests, cattle ranching pastures, and mixed crops.

2 MATERIALS AND METHODS

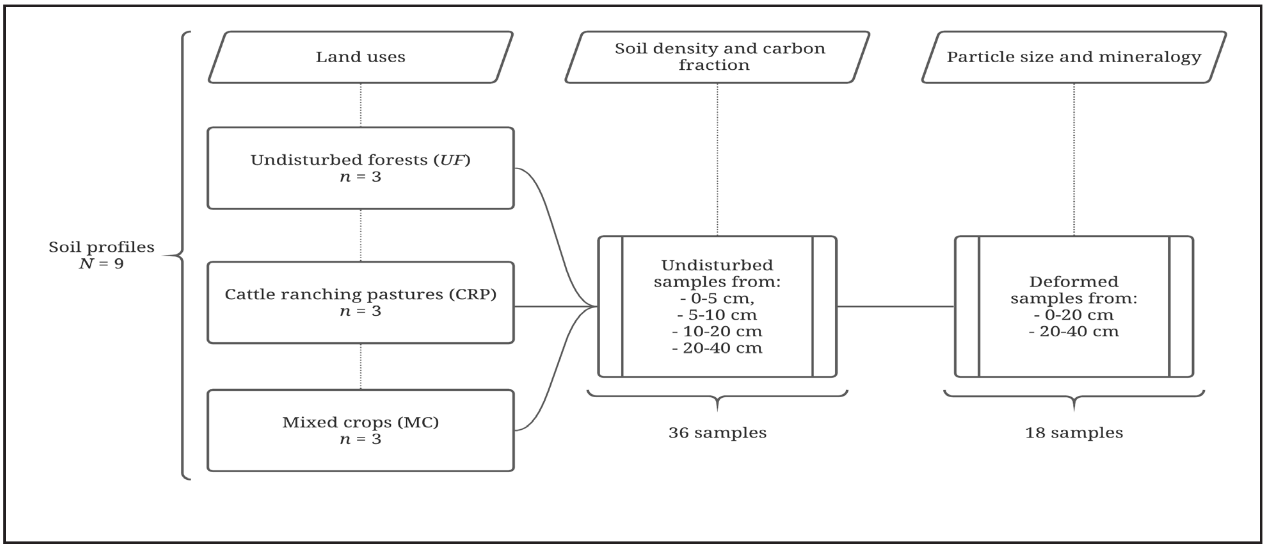
Data derived from Plinthosols samples collected in forests, pastures, and mixed crops in Itapuã do Oeste municipality, Rondônia state. Soil samples were collected around the Jamari National Forest (encompassed by the Tropical Amazon rainforest).

The climate zone is Aw (tropical savannah with dry winter) (ALVARES *et al.*, 2013). The mean annual temperature ranges from 24°C to 26°C, and the rainfall varies from 2,400 to 2,600 mm.

2.1 Soil sampling

Density, carbon fraction, particle size, and mineralogy were examined in nine soil profiles. Additionally, we assessed the carbon stock in these soil profiles (Figure 1). A total of 36 undisturbed samples were collected from four different depths (0-5, 5-10, 10-20, and 20-40 cm) to determine density and carbon fraction. Deformed samples assessed particle size and mineralogy from 0-20 and 20-40 cm depth, totaling 18 samples. The sampling was carried out in relatively flat relief environments (COSTA *et al.*, 2009), observing their use history. Soil samples from undisturbed forests (UF) were collected inside the Jamari National Forest, while samples from cattle ranching pastures (CRP) and mixed crops (MC) came from small-farm properties that use a family agriculture system.

Figure 1 – Diagram of sampling for soil density, carbon fraction, particle size and mineralogy



Source: Authors (2020)

Undisturbed forest areas (PF) were selected by performing a spatiotemporal analysis from satellite images and scenes from 1984 to the present day. The soil profiles form cattle ranching pastures (CRP) were established in family farming properties, in which CRP was established for at least ten years with signal grass (*Urolchoa brizantha* Hochst ex A. Rich R. Webster), synonymy of *Brachiaria brizantha*. None CRP has ever been limed or fertilized and the management practice is the extensive cattle ranching. Mixed crops (MC) consisted of young stands of forest restoration planted in January 2011. Mixed crops were planted in the vicinity of CRP areas, replacing them as a form of environmental regularization. The planting was conducted using drills for individual cots and spacing of 4 x 3 meters.

2.2 Soil density and carbon fraction

The 36 undisturbed soil samples were collected using volumetric rings of 100 cm^3. Subsequently, they were oven-dried at 65°C until they reached constant weight for mass determination. The soil density was obtained by dividing the mass (m) by the ring volume (v).

A portion of each sample was fractioned and sieved using a Mesh nº. 18 (1 mm). The carbon fraction ($gC.g^{-1}$) was determined by the dry combustion method in a Leco C-144 analyzer (MAAS *et al.*, 2020).

The soil carbon stock ($MgC.ha^{-1}$) was estimated by multiplying the dry matter of each layer by the carbon fraction using the following Equation (1):

$$SCS_i = \rho_i\ (e_i.10000)\ (CF_i / 100) \qquad (1)$$

where: SCS_i = soil carbon stock of the soil layer *i* ($Mg.ha^{-1}$); ρ = density of the soil layer *i* ($g.cm^{-3}$); e = thickness of the soil layer *i* (m); CF = carbon fraction of the soil layer *i* ($gC.g^{-1}$).

The results of density, carbon fraction, and carbon stocks were evaluated by performing standard deviation analyses. The Tukey test compared the measurements at a 95% probability level.

2.3 Granulometry

The granulometric analysis was conducted to determine the proportion of each fraction of clay (< 0.002 mm), silt (0.002-0.5 mm), and sand (0.05-2.0 mm). A shaker table was used for the sand separation (DOURADO *et al.*, 2012), while the laser diffraction method (CILAS 1064 laser particle size analyzer) for clay and silt fractions.

The 18 deformed soil samples were sieved using standard series of overlapped sieves (opening diameters: 5, 10, 20, 40, 60, 100, and 150 meshes). After sieving, each sample was oven-dried to determine the weight of each fraction.

2.4 Mineralogy

The qualitative analyses of minerals and mineral clay were performed using total pressed powder and X-ray diffraction.

The mineral quantification of sand fractions was performed by using a binocular lens. To determine the mineral content in the sand fraction, properties such as color, brightness, cleavage, magnetism, trace, hardness, and transparency were observed by a binocular loupe.

3 RESULTS AND DISCUSSIONS

The soil density was always lower in undisturbed forests (UF) when compared to cattle ranching pastures (CRP) and mixed crops (MC). However, the Tukey test indicated no significant differences, regardless of the soil layer (Table 1). CRP and MC presented higher density values, as Bernoux *et al.* (1998) found in their study. This fact can be explained due to livestock impacts (current activity in CRP) (*e.g.* COSTA *et al.*, 2009). We also noticed that livestock impact persisted within the soil for at least 11 years after the mixed crop (MC), corroborating with Lenci *et al.* (2018).

Several studies have confirmed livestock impacts on soil compaction and have shown that animal trampling is a compression vector. Despite the increase in densities after the forest replacement in other environments, soils under CRP had the lowest standard deviation at all depths.

An increased density impacts other soil properties by reducing aeration, water infiltration, and increased soil resistance to root penetration, especially in clayey soils; once such soils are more prone to compaction and restrictive to root growth than sandy soils (DEXTER, 2004; GALLAGE; UCHIMURA, 2010). Consequently, there is a decrease in productivity because, in addition to natural fertility, the productivity depends on a suitable porous system in the layers where the roots develop. Together with the decrease in such spaces, there is less circulation of nutrient solution, greater difficulty of root growth, and less access to nutrients by roots (SHAH *et al.*, 2017).

The carbon fraction ranged from 0.024 gC.g^{-1} in UF at 0-5 cm to 0.005 gC.g^{-1} in MC at 20-40 cm. We noticed that the higher the soil depth is, the lower the carbon fraction is, regardless of land use. The Tukey test evidenced this relationship, as the means differed depending on the soil layer (Table 1). These results reinforce the findings from Kato *et al.* (2010).

Table 1 – Descriptive statistics for soil density, carbon fraction, and carbon stock in Amazon Plinthosols under different land uses

Soil layer	**0-5 cm**	**5-10 cm**	**10-20 cm**	**20-40 cm**
Soil density (g.cm^{-3})				
Undisturbed forests (UF)	1.125±0.114 (a)	1.229±0.094 (a)	1.284±0.120 (a)	1.196±0.131 (a)
Cattle ranching pastures (CRP)	1.337±0.039 (a)	1.366±0.076 (a)	1.382±0.038 (a)	1.268±0.051 (a)
Mixed crops (MC)	1.240±0.185 (a)	1.390±0.162 (a)	1.439±0.180 (a)	1.355±0.208 (a)
Carbon fraction (gC.g^{-1})				
Undisturbed forests (UF)	0.024±0.006 (a)	0.020±0.006 (ab)	0.016±0.005 (ab)	0.009±0.001 (b)
Cattle ranching pastures (CRP)	0.022±0.009 (a)	0.017±0.008 (ab)	0.013±0.004 (ab)	0.008±0.001 (b)
Mixed crops (MC)	0.024±0.010 (a)	0.015±0.001 (ab)	0.009±0.001 (ab)	0.005±0.000 (b)
Carbon stock (MgC.ha^{-1})				
Undisturbed forests (UF)	13.29±2.09 (a)	12.43 ±2.76 (a)	20.88 ± 5.12 (a)	20.63 ±1.17 (a)
Cattle ranching pastures (CRP)	14.63±5.85 (a)	11.59±4.55(a)	18.67±5.37 (a)	21.22±2.09 (a)
Mixed crops (MC)	14.34±4.47 (a)	10.07±1.36 (a)	12.36 ±1.47 (b)	14.78±2.264 (b)

Source: Authors (2020)

Soils under undisturbed forests (UF) presented the highest carbon fraction, regardless of depth. However, for the 0-5 cm layer, we noticed a similar value for MC (0.024 gC.g^{-1}) compared to UF (0.024 gC.g^{-1}).This fact can be attributed to litter production, which incorporates nutrients to the soil. The persistency of undisturbed forests suggests a higher accumulation and decomposition of litter, contributing to higher carbon fraction at 5-10 cm (Table 1). Salimon *et al.* (2007) reported similar values for carbon fraction in forests and cattle ranching pastures in the southwestern Amazon after ten years.

Table 1 displays the means and standard deviations of carbon stocks for different land uses in Amazon Plinthosols. The soil carbon stock from 0-40 cm ranged from 67.233 $MgC.ha^{-1}$ (UF) to 51.551 $MgC.ha^{-1}$ (MC). These values are within 18.52-82.31 $MgC.ha^{-1}$ found for different crops in Petric Plinthosols (*e.g.*, GATTO *et al.*, 2010). The two first soil layers (0-5 and 5-10 cm) presented lower carbon stocks for all land uses, and this may be explained because of the lower thickness of these layers.

Although no explicit differences were noticed between UF and CRP, regardless of soil depth, we noticed that MC always showed lower values (Table 1), differing in the last two layers (10-20 and 20-40 cm). Considering the soil thickness of 0-20 cm, UF presented the higher carbon stock (46.60 $MgC.ha^{-1}$), followed by CRP (44.89 $MgC.ha^{-1}$), and MC (36.77 $MgC.ha^{-1}$). This layer in forests (0-20 cm) corresponds to 69.31% of the 0-40 cm layer total stock.

By comparing the soil carbon stock in UF and CRP, the differences were irrelevant for the layers 0-20 and 20-40 cm: 3.79% and 1.68%, respectively. However, when comparing these carbon stock values for UF and MC, we noticed that the variations were 26.74% and 40.19%. The layer 0-20 cm in CRP and MC represents 67.91% and 71.33% of the total stocks in the layer 0-40 cm. Bernoux *et al.* (2006) verified values for the layer 0-30 cm corresponding to 44% and 66% of the total stock up to 1-m depth, demonstrating the importance of the upper horizon of Amazon soils for agricultural purposes. Due to its low natural fertility characteristics, high acidity, and sandy texture, colloids in organic matter of the upper layers are the primary source of nutrition for cultivars.

Therefore, management practices in tropical soils should be emphasized since they are responsible for better structuring and stabilizing soil aggregates. Effective management practices avoid erosion, immobilization, and release of nutrients, offering cation exchange sites and carbon storage sites.

The fast cycling and incorporation of carbon into subsurface horizons by grassroots can explain the variation in carbon volume and the differences between CRP and MC. This fact is not observed with the roots of MC tree species (PULROLNIK, 2009).

To obtain an approximate idea of emissions from land-use change by converting forest into cattle ranching pastures, Cerri *et al.* (2007) projected a carbon loss in Amazonian soils of approximately 7% for the 0-20 cm layer between 2000 and 2030. Fearnside and Barbosa (1998) carried out a more conservative estimation of carbon emissions stored in soils and reported 5.6% values at the same layer. Thus, it is equivalent to state that, based on the mean values for this soil area (UF = 46.60 $MgC.ha^{-1}$), Rondônia state, which has six million hectares with pastures, would have contributed to the emission of 15,659,280 $MgC.ha^{-1}$.

These values may be higher if we consider that this estimate is a simple projection using the data obtained in this work. Plinthosols, although representative, are not common in the Amazon. Latosols and Argisols are common and may contain more expressive clay contents and, consequently, higher carbon stocks. Cerri *et al.* (1991) studied the impacts of converting forests into pastures on a very clayey Yellow Oxisol, estimated better initial losses after three years (24.31%) in a forest area converted into pasture.

Despite this difference, MCs areas presented the second-highest average at the layer 0-5 cm: 14.34 $MgC.ha^{-1}$. The CRP had the highest value (14.63 $MgC.ha^{-1}$), and the UF had the lowest value among the measured systems (13.29 $MgC.ha^{-1}$) (Table 1). There was an average increase of 10.08% in CRP areas concerning UF areas at the layer 0-5 cm. However, the MC areas presented the highest gradient variation between the stocks at the layers 0-5 to 5-10 cm, with a variation of 42.35%, while UF and CRP presented 6.96% and 26.25%, respectively.

Soils with CRP presented significant values for carbon stocks, but the standard deviations indicate a significant heterogeneity of stocks probably due to different forms of management. This environment presented the highest standard deviation for all the layers between 0 and 20 cm, followed by MC areas at the layer 0-5 cm, and UF at the layers 5-10 and 10-20 cm. For the layer between 20 and 40 cm, MCs highest standard deviation was found, followed by CRP and UF.

The relationship between increases in densities and layers may explain the higher carbon stocks in soils with pastures. Studies such as Desjardins *et al.* (2004) have reached similar conclusions regarding the contributions of carbon stocks in pastures in the Amazon.

There is an association between carbon stock and clay proportion. The sample UF3, containing 92.78 (0-20 cm) and 89.79% (20-40 cm) of clay, presented the highest stock among all samples in this environment, which is up to 53.52% higher than the point UF2, which had the lowest stock among the sites sampled in the forest. This behavior was also noticed in cattle ranching pastures. The point CRP1 had the highest stock at the 0-40 cm layer: 80.67 $MgC.ha^{-1}$ of carbon. At this site, clay contents reached 69.90% at 20-40 cm (Table 2). Among all studied environments, at the layer 20-40 cm, the point CRP1 presented the highest individual stock: 23.25 $MgC.ha^{-1}$ of carbon. Inverse results were measured at the point CRP2, which presented the lowest clay concentration. The point CRP2 presented a carbon stock at the layer 0-40 cm: 48.63 $MgC.ha^{-1}$. That is, it is 65.89% lower than CRP1. By comparing the points, there is a difference of 45.32% with clay contents.

Table 2 – Particle size distribution at the layers 0-20 and 20-40 cm in Amazon Plinthosols under different land uses

Soil layer	**0-20 cm**			**20-40 cm**		
Particle size proportion (%)	**Sand**	**Silt + Clay**	**SE**	**Sand**	**Silt + Clay**	**SE**
Undisturbed forests (UF)	28.34	71.66	±18.99	22.20	77.80	± 10.90
Cattle ranching pastures (CRP)	47.82	52.18	± 14.99	38.00	62.00	± 12.07
Mixed crops (MC)	48.56	51.44	± 20.53	42.60	57.40	± 19.94

Source: Authors (2020)

The relations between carbon and clay contents are due to the more remarkable ability of clay to conserve organic matter (TRUMBORE; CAMARGO, 2009). These relations are less prominent in the upper portions of the soil (0-20 cm) because of the influence of root systems and contributions from litter production. Therefore, even in environments where sand values were high concerning silt + clay, there were points with higher levels and carbon stocks, as can be observed, especially in mixed crop sites.

Minerals are dominant in the sand and clay fractions. In the sand fraction, quartz minerals were dominant because of relative enrichment due to their remarkable weathering stability. These results indicate that only the most stable minerals remain in the environment because of the intense weathering (PIRES et al., 2009). The only minerals in clay fractions were gibbsite and kaolinite. Their compositions are rich in aluminum, contributing to an increase in the toxicity and acidity of those soils.

The aluminum content is closely related to the amount of organic matter in the soil. The presence of aluminum ions decreases as the organic matter increases (RONQUIM, 2010), which is another factor to consider regarding acceptable management practices for arable soils in Amazon to decrease the acidity and toxicity caused by aluminum.

Table 3 displays the mineralogy pattern for Plinthsols profiles under different land uses. Although all soil profiles presented elevated concentrations of quartz (from 83.33 to 98.66% at 0-20 cm, and from 72.00 to 98.00% at 20-40 cm), soil profiles under UF presented the lowest values (0-20 cm: 88.11%; 20-40 cm: 80.55%). Cattle ranching pastures and mixed crops presented mean values ranging from 93.33% (CRP at 20-40 cm) to 95.67% (MC at 0-20 cm).

Table 3 – Soil mineralogy in sand fraction of Amazon Plinthosols under different land uses

Mineralogy (%)	**Depth (cm)**	**Quartz**	**Oxide/ Iron hydroxide**	**Opaque**	**Zircon**	**Lytic fragments**	**Ilmenite**
Undisturbed forests (UF)	0-20	88.11	10.67	-	-	-	<1
	20-40	80.55	18.24	-	-	-	1.82
Cattle ranching pastures (CRP)	0-20	94.77	5.34	-	TR	-	1.67
	20-40	93.33	7.33	-	-	-	1.78
Mixed crops (MC)	0-20	95.45	3.67	-	TR	-	2.11
	20-40	95.67	7.00	-	-	-	2.00

Source: Authors (2020)

The particle size and mineralogical composition demonstrate how sensitive these environments are to changes in the landscape due to deforestation, and how unstable the maintenance of carbon stocks is due to such conditions. Sandy soils tend to present more pronounced carbon loss when compared to clayey ones. The lower aggregation may justify this among particles, higher leaching, and higher exposure of aggregates to oxidation (OLIVEIRA *et al.*, 2015), which triggers fast erosive processes (BASTOS *et al.*, 2014). Resulting in a negative cycle of events that disrupt the carbon stored in the soil and its emission.

4 CONCLUSIONS

There were no significant differences in soil carbon stocks between undisturbed forests and cattle ranching pastures. Soils under mixed crops (at age 10 years) presented lower carbon stocks (23.32% lower than in undisturbed forests).

The layer 0-20 cm contains 69.31%, 67.91%, and 71.33% of the carbon stored at the 0-40 cm in undisturbed forests, cattle ranching pastures, and mixed crops.

The land-use change from forested areas onto other land uses led to an increase in soil density.

The carbon fraction decreases as the soil depth increases, regardless of the land use.

Plinthosol, due to its textural and mineralogical characteristics, should be the focus of differentiated management practices that provide the maintenance of productive conditions after the replacement of the forest for other use systems.

Plinthosols are widely distributed across the Amazon. They constitute large environments occupied by human activities in the region. Understanding carbon stocks can guide the best ways to manage them and, thus, guide biodiversity conservation policies and avoid greenhouse gase missions that further aggravate climate change context.

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