Carbon and nitrogen stock of Acrisols and Nitisols in South Bahia, Brazil

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A B S T R A C T

This study evaluated if the effect of secondary forest (SF) conversion into pasture (PAS) or rubber tree plantation (RT) and cacao + erythrina AFS into cacao + rubber tree AFS (C + RT) on the C and N storage in soils and aggregate-size fractions could be compensated by a high amount of organic residues deposited over the years by rubber tree plantation and agroforestry systems (above and belowground) and a high amount of belowground residues deposited by pasture. Soil samples were collected from six layers (0–10, 10–20, 20–40, 40–60, 60–80 and 80–100 cm) and separated by wet-sieving into three fraction-size classes (2000–250; 250–53 μm and < 53 μm) in soils under RT, PAS and SF sites (Argisols) and C + RT and C + E AFSs (Nitosols). The C and N were determined by dry combustion. The average soil organic carbon (SOC) stock in Acrisols was 207 Mg ha⁻¹ up to 100 cm depth, and 72 Mg ha⁻¹ was stored at the first 30 cm depth; while the average SOC stock in Nitosols was 224 Mg ha⁻¹ up to 100 cm, and 116 Mg ha⁻¹ at 30 cm depth. As expected, C and N stock in soils and in the different soil aggregate-size fractions revealed that the dissimilarity between sites was strongly influenced by soil order. There was high dissimilarity between the sites in Nitosols and those in Yellow Argisols, and the dissimilarity between the land use systems only occurred in the Yellow Argisol. The conversion effect of cacao + erythrina AFS into cacao + rubber tree AFS was restricted to the surface soil and did not promote dissimilarity among the AFSs regarding the C and N storage in the whole soil and aggregate size-fractions. Adopting no tillage and tree-based systems (such as the rubber tree plantation) would compensate the negative conversion effect in the amount of organic matter and promote C and N storage mostly in the soil aggregate size-fractions. The effect of land-use conversions was more evident in the aggregates than in the whole soil, regardless of the soil order. The conversions in both soil orders induced macroaggregate turnover and increased the yield of new free microaggregates.

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1. Introduction

Climate change is a prominent sign of human-driven changes to the global environment and requires concentrated action to mitigate greenhouse gas emissions and reduce global warming. The Conference of the Parties to the United Nations Framework Convention on Climate Change in Paris (November 30 to December 11, 2015) produced the Paris Climate Agreement, a settlement to reduce climate change, limiting global warming to <2 degrees Celsius (°C) and to pursue efforts to limit the increase to 1.5 °C. As a result of this Conference, an initiative called 4 per mil (4‰) was launched, an average sequestration rate to offset emissions of 0.6 t of C per hectare per year, with an aspiration to increase global soil organic matter stocks by 4 per 1000 (or 0.4%) per year as compensation for the global emissions of greenhouse gases by anthropogenic sources (Minasny et al., 2017; Ademe, 2015; Steffen et al., 2011). Soils are considered an asset in strategies for mitigating climate change and there also exists the technical potential of agriculture to mitigate CO₂ (5.5–6.0 Mt CO₂-Eq. yr⁻¹) whose C sequestration in soil is responsible for almost 89%, and therefore agriculture practices certainly can and should be part of the solution to climate change (Minasny et al., 2017; Ademe, 2015; Steffen et al., 2011; Smith et al., 2007).

Brazil’s nationally determined contribution (NDC) includes a reduction of its greenhouse gas emissions by 37% by 2025, with a further target of a 43% reduction by 2030 (both compared to 2005 levels). The actions required to implement the mitigation contribution outlined in the NDC are to restore 15 million hectares of degraded pastures, as well as implement an integrated crop livestock-forest system in 5 million hectares; to achieve zero illegal deforestation in the Amazon by

Therefore, it is imperative to adopt sustainable soil management techniques, which are so widely studied by soil science yet very little implemented in large-scale production systems. Agroforestry systems and forestry systems are sustainable land-use systems which may play an important role in storing carbon aboveground and belowground through continuous deposition of plant residues, and also can be a strategy to restore degraded lands (Nair et al., 2010).

Cacao (Theobroma cacao L.) AFS, with around 711,850 ha planted in Brazil, are a combination of cacao trees with non-woody species (Musa paradisiaca, Manihot esculenta, etc.) and woody species (Erythrina, Gliricidia sepium, Hevea brasiliensis), whether in the form of secondary forest (cabruto) or under homogeneous forest. These systems offer evidence of compatibility and complementarity of different species, and at the same time demonstrate the sustainability of multi-layered production systems (Müller and Gama-Rodrigues, 2012; Nair et al., 2009). (The next paragraph was removed) Cacao AFS may play an important role in the sequestration of soil organic carbon (SOC) and total soil N (TSN) through continuous deposition of plant residue. The large amounts of leaf litter, roots and woody material from shade species as well as cacao represent a substantial addition of C into these systems, most of which is stored in the soil both on the surface and in depth after decomposition (Monroe et al., 2016; Fontes et al., 2014; Albrecht and Kandji, 2003). The average C content stored in soil (0–50 cm) in cacao AFSs is approximately 83 Mg ha$^{-1}$ (Fontes et al., 2014) and in the range of 100–300 Mg ha$^{-1}$ to 1 m depth (Monroe et al., 2016; Mattos, 2016; Gama-Rodrigues et al., 2010). Articles regarding TSN in depth are scarce, especially in soils under AFSs. Gelay et al. (2014) found TSN stock around 3 Mg ha$^{-1}$ in AFSs with Faidherbia albida and around 4 Mg ha$^{-1}$ in silvopasture systems also with Faidherbia albida up to 30 cm depth. Kassa et al. (2017) found TSN stock up to 60 cm depth in the range of 36 to 45 Mg ha$^{-1}$ in soils under different AFSs. (The next paragraph was removed).

In Brazil, reforestation with rubber tree has spread all over the country with a planted area of around 170 thousand ha (Associação Brasileira de Produtores de Florestas Plantadas – ABRAF, 2013; Wauters et al., 2008). Some studies have shown the potential of soil organic C (SOC) stock in rubber tree plantations in Brazil (55.2 to 105.5 Mg ha$^{-1}$ at depth 0–60 cm) (Maggiotto et al., 2014; Wauters et al., 2008). However, the SOC stock may be higher than 200 Mg ha$^{-1}$ in agroforestry or forestry systems up to 100 cm depth (Vicente et al., 2016; Monroe et al., 2016; Salgado et al., in press).

In addition, studies on cacao-producing areas in the south of Bahia, Brazil, showing the effect of secondary forest conversion to pasture, rubber tree plantations or agroforestry systems are scarce, and the few which have been carried out show that changes in SOC stock can increase, decrease or not even alter the accumulated values. For example, Monroe et al. (2016) showed that the conversion of secondary forest to 4-year-old cacao and rubber AFS were the most efficient in accumulating SOC in the top 20 cm of the soil, and the conversion of secondary forest to cacao AFS older than 20 years were similar to the natural forest regarding the accumulation of SOC along the soil profile. In turn, Mattos et al. (in press) showed that after the conversion of secondary forest into pasture the SOC stock was similar in both systems. On the other hand, they also showed that the conversion of secondary forest into a rubber tree plantation increased the SOC stock, and the conversion of secondary forest into agroforestry systems (rubber tree and açai AFS and rubber tree and cacao AFS) decreased the SOC stock up to 100 cm. Therefore, one general question remains unclear: Could the effect of secondary forest conversion into pasture or rubber tree plantation and cacao + erythrina AFS conversion into cacao + rubber tree AFS on the C and N storage in soils and aggregate-size fractions be compensated by a high amount of organic residues deposited over the years by rubber tree plantation and agroforestry systems (above and belowground) and a high amount of belowground residues deposited by pasture?

Another important issue related to soil C sequestration is the organic matter stored in subsurface horizons, as it represents high proportions of C of around 46% to 63% which is stored in the first meter of soils worldwide, mainly in tree-based production systems (Vicente et al., 2016; Ademe, 2015; Rumpel and Kögel-Knabner, 2011). The distribution of TSN within the soil profile showed a similar pattern of organic soil C, i.e. it reduces from the surface towards the subsoil and reaches stability in deeper soil horizons (Song et al., 2016). Hence, the relevance of studying C and N stock up to 1-meter-deep in these soils is categorical.

There is consensus in the literature regarding a link between SOC stock in agroforestry and forestry systems and soil aggregation due to the continuous addition of plant residues coupled with the absence of tillage. The formation of aggregates in natural and/or no tillage systems is due to plant residue decomposition, which forms coarse intra-aggregate particulate organic matter, later transformed by microorganism action into fine intra-aggregate particulate organic matter (fine iPOM). This process happens inside soil macroaggregates. This fine iPOM becomes embedded in clay minerals and in microbial compounds over time, consequently forming microaggregates within macroaggregates. Gama-Rodrigues et al. (2011 and 2010) suggest that no-till and the continuous supply of organic matter through cacao AFSs favor aggregation, and therefore macroaggregation would be the main mechanism of C stabilization in these soils.

Considering the above, the objective of the present study was to evaluate the carbon and nitrogen stocks in soils and in the different soil aggregate-size fractions up to 1 m between different land-use systems in two soil orders in the south of Bahia, Brazil.

2. Materials and methods

2.1. Characterization of the study area

Soil samples were collected from sites located in the municipality of Una, (15°16’ 11” S, 39° 4’ 10” W) and in the Cocoa Research Center (CEPEC/CEPLAC) in the municipality of Ilhéus (14°47’ 50” S and 39°2’ 8” W). All the sites are located in the southern region of the state of Bahia. The region’s climate is Af according to the Köppen classification, and the mean annual rainfall is around 1647 mm, with mean annual temperature around 24.3 °C.

Prior to the installation of the production systems, the original vegetation cover was secondary forest, which was felled, dismantled with a track tractor and then plowed and harrowed. The study was composed of five different land use systems, namely: (1) cacao (Theobroma cacao L.) + rubber tree (Hevea brasiliensis Muell. Arg.) AFS, 12 years of age, cacao row spacing was in four rows of 2 × 2.5 m. Lines L1 and L4 were planted at a distance of 2.5 m from the hevea hedgerows. Double hevea hedgerows at a density of 7 × 4 × 3 m, without inorganic fertilization since 2006; (2) cacao + erythrina (Erythrina glauca Lour.) AFS, 35 years of age, erythrina spacing of 25 × 25 m, distributed in a quincunx that totaled 32 trees per hectare, while cacao tree spacing was 3 × 3 m, without inorganic fertilization since 1990; (3) rubber tree plantation, 35 years of age, spacing 7 × 3 m, without fertilization since 1982, and presence of grass as cover; (4) unfertilized pasture formed by Brachiaria decumbens, 30 years of age; (5) an Atlantic Forest fragment as secondary forest.

The soils of the rubber tree plantation, pasture and secondary forest (SF) sites are classified as Dystricho Yellow Argisols (Ultisols) and Eutrophic Haplic Nitosols (Alfisols) for the sites of cacao + rubber tree and cacao + erythrina AFSs. In the Nitosols there were no secondary forest or pasture sites next to the AFS sites. In this case, we consider the cacao + erythrina AFS as the reference system, since it is the oldest system and was widely adopted in the region. Erythrina has currently been
replaced by rubber trees due to its economic value and rapid growth (Monroe et al., 2016).

2.2. Soil sampling

Four uniform (in terms of soil homogeneity, slope, historical land-use, and tree age) fixed plots (30 × 30 m) were delimited in the central part of each land use system and separated by at least 100 m. Trenches (1 × 1 × 1.5 m) were opened between plant rows in each plot, and soil was collected at six depths (0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm). The soil samples from each depth were air-dried and passed through a 2 mm sieve, then particle size analysis was performed by the pipette method, and the volumetric ring method was used to determine soil density (Table 1) (Embrapa, Embrapa Solos, 2017). Soil organic carbon (SOC) and total soil nitrogen (TSN) was determined by dry combustion in an automated elemental analyzer system (CHNS/O analyzer), while the bulk density of each soil depth was used to calculate the amount of SOC and TSN stored at 1 m depth and expressed as Mg ha⁻¹. The SOC (and TSN) stock was subsequently corrected according to the thickness of each soil layer, considering the secondary forest (for Argisols) and cacao + erythrina AFS (for Nitosols) soil layers as the reference thickness. This correction is recommended due to the influence of the soil layer in calculating SOC/TSN stock, which was done according to the following formula:

\[ D_{\text{ads/sub}} = \left( \frac{M_{\text{ref}} - M_{\text{stat}}}{B_0} \right) \times 100 \]

In which: \( D_{\text{ads/sub}} \) = depth to be added or subtracted in the stock calculation (cm); \( M_{\text{ref}} \) = soil mass at the reference soil depth (Mg ha⁻¹); \( M_{\text{stat}} \) = soil mass at the treatment soil depth (Mg ha⁻¹); and \( B_0 \) = soil bulk density (g/cm³).

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Particle size fractions and bulk density of soil at 100 cm below soil surface in the Southern Bahia, Brazil.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>Natural forest</td>
</tr>
<tr>
<td>(cm)</td>
<td>particle size fraction (%) and bulk density (g cm⁻³)</td>
</tr>
<tr>
<td>0–10</td>
<td>Sand 88.95, 93.26, 85.31</td>
</tr>
<tr>
<td>10–20</td>
<td>Silt 82.61, 93.01, 80.18</td>
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<tr>
<td>10–30</td>
<td>Sand 74.10, 87.98, 73.95</td>
</tr>
<tr>
<td>10–40</td>
<td>Silt 25.51, 32.34, 35.52</td>
</tr>
<tr>
<td>10–50</td>
<td>Sand 85.43, 90.28, 86.43</td>
</tr>
<tr>
<td>10–60</td>
<td>Silt 35.53, 40.34, 45.51</td>
</tr>
<tr>
<td>10–70</td>
<td>Sand 80.18, 85.31, 88.95</td>
</tr>
<tr>
<td>10–80</td>
<td>Silt 34.35, 39.52, 44.35</td>
</tr>
<tr>
<td>10–90</td>
<td>Sand 73.33, 78.53, 83.73</td>
</tr>
<tr>
<td>10–100</td>
<td>Silt 33.33, 38.52, 43.33</td>
</tr>
</tbody>
</table>

2.3. Fraction-size separation

The procedure consisted in weighing 100 g dry soil, passed through a 2000 μm sieve and submerged in a 500-ml beaker of deionized water for about five minutes before placing it on top of a 250-μm sieve. The sieving was done manually, moving the sieve up and down about 3 cm, 50 times, for 2 min. The entire fraction remaining at the top of the 250-μm sieve was collected in hard plastic pans. The fraction that went through the sieve (~250 μm) was then passed through a 53-μm sieve, which separated this material into two new fractions by the same previous sieving procedure. Three aggregate size classes were obtained: macroaggregates (2000–250 μm), microaggregates (250–53 μm), and the silt + clay fraction (~53 μm). All fractions were dried in a forced-circulation air oven at 60 °C for 72 h, and the weight percentages of each fraction were subsequently calculated (Elliot, 1986; Gama-Rodrigues et al., 2010). The overall average recovery mass percentage of soil fractions after the wet-sieving procedure was about 98% of the initial soil mass.

The SOC and TSN in aggregate size classes was also determined by dry combustion in an automated elemental analyzer system (CHNS/O analyzer). The C and N storage in aggregate size classes was calculated by multiplying the C concentration (or N concentration) (g/kg soil in aggregate size) with soil bulk density of depth interval (kg/m⁻³) and the weight percentage of the fraction.

2.4. Statistical analyzes

Data were tested for normality by the Kolmogorov-Smirnov and Lilliefors methods to evaluate the normal distribution of the analyzed variables, as well as homoscedasticity and normal distribution residues. Thus, the data that did not present normality were transformed by the equations arcsen(Xi/100) and log. The data were subjected to principal component analysis (PCA) to evaluate the degree of dissimilarity between the assessed sites considering the soil orders. PCA enabled clustering the sites evaluated in diagrams which consider the data set correlation quality between the variables, and between the variables and principal components (axis X and Y). The arrows with narrow angles are strongly correlated, while arrows that are perpendicular show no correlation (Viana et al., 2018; Aleixo et al., 2017; Fontes et al., 2014; Gomes et al., 2004).

3. Results

3.1. Soil organic C (SOC) and total soil N (TSN) stocks in depth

In the Argisols, the SOC stored in pasture and in the rubber plantation was approximately 11% and 15% lower than in secondary forest, respectively. The average SOC stock in the rubber tree plantation was almost 5% lower than pasture (Fig. 1). The TSN stock in the pasture was only 2% higher than in the secondary forest; in turn, the TSN stock in the rubber tree plantation was approximately 70% lower than in the secondary forest and in the pasture (Fig. 2). In the Nitosols, the difference in SOC stock between the AFSs was approximately 4%, and the greatest value was in the cacao + erythrina AFS. The TSN stock was 46% higher in the cacao + rubber AFS up to 100 cm of depth (Figs. 1 and 2).

The secondary forest and the rubber tree plantation showed an increase in the SOC stock up to 40 cm depth and the pasture up to the first 60 cm. There was a decrease along the profile from these depths. The cacao + erythrina AFS stood out from the cacao + rubber tree AFS, accumulating around 50% more SOC in the first 20 cm of soil.
The C stock decreased along the soil profile below this depth in both AFSs. Regarding TSN stock, the secondary forest, pasture and the AFSs presented values almost two times higher below 20 cm than in the greater depths. On the other hand, the rubber tree plantation presented similar TSN values accumulated along the soil profile (Figs. 3 and 4).

3.2. Depth-wise distribution of soil size fractions and their SOC and TSN

In the Argisols, the macro-size fraction was predominant in all depths, followed by micro-size fraction and silt + clay fraction in all land-uses. On the other hand, Nitosols under the AFSs (which presented higher clay content) presented the smallest amounts of macro-size fraction and the greatest amount of silt + clay fraction along the soil profile. In general, the amount of macro-size fraction decreased and the micro-size fraction increased along the soil profile in all land-use systems. The silt + clay fraction also increased along the soil profile, but only in the Argisol order. The amount of microaggregates was higher in the pasture and in the rubber tree plantation, while the amount of macroaggregates was higher in SF. The amount of macroaggregates and silt + clay fraction varied little between AFSs, but the amount of microaggregates...
C stock in the macro-size fraction of soil under the pasture up to 100 cm depth was approximately 50% lower than the secondary forest and the rubber tree plantation. Equally, the difference in C stock up to 20 cm between the AFSs in the macro-size fraction was 50%, with the highest values in the cacao + erythrina AFS. In relation to the micro-size fraction, C stock in the secondary forest and pasture were 40 and 24% lower, respectively, than the rubber tree plantation up to 100 cm depth. On the other hand, the AFSs presented very similar amounts of C stock in the micro-size fraction. The C stock in the pasture in the silt + clay fraction from 20 cm was approximately 30% higher than in the secondary forest and in the rubber tree plantation. Meanwhile, the difference among AFSs was approximately 10%. It is worth noting that AFSs presented larger C stocks in the silt + clay fraction (Fig. 6).

The N stock in macro-size fraction up to 100 cm of depth in the rubber tree plantation was almost two-times larger when compared to the secondary forest and pasture; and the difference between them in the AFSs (Nitosols) was around 30%. The rubber tree plantation kept the largest N stock in the micro-size fraction up to 100 cm, which was practically twice greater than the value observed for the pasture and 75% greater than the secondary forest. The AFSs were quite similar to each other in terms of TSN stock in the micro-size fraction. The TSN stock of the silt + clay fraction was practically the same in the secondary forest, pasture and rubber plantation, as well as between the AFSs (Fig. 7).

3.3. Principal components analysis

The C and N storage in the soil and in the different soil aggregates are associated with two main components (PC1 explained 61.86% and PC2 explained 18.70%) (Fig. 8), and the ordination diagram shows the Nitosols on the left side and the Argisols on the right side of the diagram. The pasture and the secondary forest are located on the right side of the lower quadrant and formed two different groups, while cacao + erythrina AFS (located in the upper quadrant) and cacao + rubber tree AFS (located in the lower quadrant) are located on the left side of the diagram and formed one group. The rubber tree plantation is located.
on the right side of the upper quadrant and represents another group (Fig. 8). The variables which are more closely associated with PC1 and thus more discriminant in forming the heterogeneous groups (load >0.70) are C and N from different soil-size fractions, while SOC and TSN stock are associated with PC2 (Fig. 8).

4. Discussion

As expected, C and N stock in soils and in the different soil aggregate-size fractions revealed that the dissimilarity between sites was strongly influenced by soil order. There was high dissimilarity between the sites in Nitosols and those in Yellow Argisols, and the dissimilarity between the land use systems only occurred in the Yellow Argisol (Fig. 8). Our results reinforce previous studies which show that the conversion of secondary forest into pasture and/or forest systems or between agroforestry systems can provide changes in SOC and TSN stock, increasing or decreasing it, or not even alter the accumulated values (Rittl et al., 2017; Guo and Gifford, 2002; Cerri et al., 2004). For example, Vicente et al. (2016) observed that the conversion of secondary forest into rubber tree plantation increased SOC stock by 46 Mg ha\(^{-1}\) up to 100 cm. Rubber tree plantations can act as a carbon sink by sequestering carbon in biomass and in soils. According to Wauters et al. (2008), the SOC stock (0–60 cm) in a 14-year-old rubber tree plantation was 153 Mg C ha\(^{-1}\). Although these conversions did not result in a significant decrease in SOC stock, we should not neglect the importance of forests in accumulating organic matter, and therefore in C sequestration within the soil-plant-atmosphere system, as well as the possibility of CO\(_2\) emission to the atmosphere during the conversion process of secondary forest into pasture and/or forest system, mainly in the first years after the conversion. In the present study we cannot affirm whether or not there was a reduction in SOC and TSN stock in the first years after the conversion, but we observed that both pasture and rubber tree plantation stored equivalent amounts of SOC to the secondary forest after 30 years. The reduction in the TSN stock with the introduction of the rubber tree plantation up to 100 cm is noticeable. Some articles in the literature reinforce the results of the present study that the conversion of secondary
forest into rubber plantation reduces TSN stock (De Blécourt et al., 2013; Yang et al., 2004). In the Nitosols, the PCA showed that there was no dissimilarity among the AFSs, probably because the conversion effect was restricted to the surface soil (Fig. 8). As such, 12 years of conversion could not have been enough to produce larger changes in SOC stock along the profile, as occurred for the conversions in the Argisols. There was also an increase of almost two-fold in the TSN stock up to 100 cm after 12 years of erythrina replacement by the rubber tree in the AFS (Figs. 1 and 2). Most studies have shown that the use of leguminous plants increases the TSN stock due to their inherent ability to fix the atmospheric nitrogen by the association with symbiotic bacteria (Jia et al., 2012; Sharrow and Ismail, 2004). In turn, other studies have shown that rubber-based agroforestry systems increase both SOC and TSN stock (Chen et al., 2017; Fox et al., 2014). In the present study, the cacao + erythrina AFS at the age of 35 years is characterized as a mature system that presents a stable and slow growth rate, and consequently low accumulation of vegetal residues and reduced root cycling. These factors contribute to the N transformation in plant residues occurring more slowly and gradually.

On the other hand, younger agroforestry systems and/or forest plantations present a high growth rate and high rates of organic matter accumulation, root cycling and exudate production by trees. Therefore, they may present high accumulation rates of C and N in soil, often accumulating higher or similar amounts to the secondary forest rates (Kassa et al., 2017). Monroe et al. (2016) investigated soils under different cacao AFS in southern Bahia and observed that 4-year-old cacao + rubber tree AFS had a higher C stock up to 100 cm depth than the older cacao AFS (above 20 years of age).

Both soil classes under similar edaphic conditions and land use systems with significant input of organic residues showed similar results: the average SOC stock in Acrisols was 207 Mg ha\(^{-1}\) up to 100 cm depth, and 72 Mg ha\(^{-1}\) was stored at the first 30 cm depth; while the average SOC stock in Nitosols was 224 Mg ha\(^{-1}\) up to 100 cm, and 116 Mg ha\(^{-1}\) at 30 cm depth. However, these same soils classes showed a reduction in the average of SOC stock under different climatic conditions and land use systems with low input of plant residues. For example, while Santana et al. (2019) found SOC stock of around 80 Mg ha\(^{-1}\) up to 100 cm under pasture and agriculture, Zanatta et al. (2007) found

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**Fig. 7.** Depthwise distribution of N stocks in different soil size fractions under natural forest, pastured, rubber tree plantation on Argisols and different cacao AFS on Nitosols in the Southern of Bahia, Brazil. Vertical bars represent ± standard error. SF: secondary forest; PAS: pasture; RT: rubber tree plantation; C + RT: cacao and rubber tree agroforestry system; C + E: cacao and erythrina agroforestry system.
approximately 60 Mg ha$^{-1}$ for grassland in Acrisol at 30 cm depth. Batjes (2005) found 61 and 103 Mg ha$^{-1}$ of SOC stock in Nitosols at 30 cm and up to 100 cm depth, respectively. These results emphasize the relevance of high input of organic residues (above and below-ground) from forestry and agroforestry systems on the enhancement of carbon content in these soils.

The macro-size soil fraction was predominant in the secondary forest, pasture and the rubber tree plantation at all depths. This larger fraction decreased while the silt + clay fraction increased with depth. In contrast, the silt + clay fraction in soils under the AFSs was superior to the aggregate classes. Tonucci et al. (2011) and Gama-Rodrigues et al. (2010) also found similar results for the macro-size fraction; however, these authors did not find any variation of the silt + clay fraction along the soil profile. The silt + clay fraction is closely related to soil particle size, and therefore directly influenced by the percentage of clay content of each soil, and which explains the higher amount of silt + clay fraction in the soils under AFSs (Table 1). The macro-size fraction decreased and the micro-size fraction increased with all the conversions up to 1 m in the Argisols and up to 20 cm in the Nitosols (Fig. 5). Additionally, the conversion to rubber tree plantation kept the C levels similar to the secondary forest, while the conversion of secondary forest into pasture reduced the C stock in the macro-size fraction (Fig. 6). These results suggest the initial C loss for pasture establishment might have been considerably higher than that for the rubber tree plantation. First, this result was due to inadequate pasture management, meaning the reduction in vegetable biomass caused by continuous grazing without restoring vegetal biomass by soil fertilization, thereby compromising the C accumulation in the macro-size fraction. Second, this reduction in plant biomass due to the lack of fertilization may have affected the microbial activity in the soil under pasture, which means the lower plant material input reduced substrate availability for microorganisms, in turn favoring C mineralization bound to the macro-size fraction. Moreover, the tree-based systems (such as the rubber tree plantation) would compensate the negative conversion effect in the amount of C in both soil and macroaggregates through continuous deposition of plant residues.

On the other hand, those conversions increased C stock in the micro-size fraction along the soil profile. In relation to N, the conversion of secondary forest to pasture did not change N stock in the macro-size fraction, while it increased in the micro-size fraction, and almost did not change in the silt + clay fraction up to 1 m. However, N in the rubber tree plantation increased twice its value in relation to the secondary forest in the macro and micro-size fractions, while the N stock in the silt + clay fraction was similar to the other systems along the soil profile (Figs. 6 and 7).

In the Argisols, the conversion of forest to rubber tree plantation was more efficient in keeping C and N in the macro-size fraction up to 1 m. The macro-size fraction is generally the fraction which most stocks C and N, mainly in systems with high plant residue inputs (Lenka and Lal, 2013) such as rubber tree plantations. Macroaggregates are formed around fresh residues because they are a source of C and N for microbial activity and for the production of microbial-derived binding agents such as fungal hyphae, fine roots, hyphae (particularly vesicular-arbuscular mycorrhizal hyphae) and microbial products, which can persist for months or years, depending on soil management (Six and Paustian, 2014).

The dissimilarity between the land use systems shown by the PCA in the Argisols suggests that soil tillage during the conversion of forest to pasture and also the conversion of forest into rubber tree plantation promoted a breakdown of the macroaggregates, and consequently the release of free microaggregates and C and N mineralization which were protected in the larger fraction (Six et al., 2004). Thus, the highest C and N values in the micro-size fraction of soils under pasture and the rubber tree plantation suggest that the increases in macroaggregate turnover induced by tillage after these conversions yields fewer new microaggregates and an incorporation of new C and N into free microaggregates over time, since there was no more soil disturbance. However, the 12-year replacement of shading trees in the Nitosols was not enough to enable incorporation of new C and N into the free microaggregates. In addition, the conversion of cacao + erythrina AFS into cacao + rubber tree AFS reduced almost half of the C and N stock in the macro-size fraction up to 20 cm. These results suggest that soil
disturbance induces a loss of C-rich macroaggregates and a gain in C-depleted microaggregates (Six et al., 2000).

5. Conclusions

Adopting no tillage and tree-based systems (such as the rubber tree plantation) would compensate the negative conversion effect in the amount of organic matter and promote C and N storage mostly in the soil aggregate size-fractions. The effect of land-use conversions was more evident in the aggregates than in the whole soil, regardless of the soil order. The conversions in both soil orders induced macroaggregate turnover and increased the yield of new free microaggregates. However, only the forest conversion into pasture and the forest conversion into rubber tree plantation enabled incorporating and consequently physically protecting new C and N into the micro-size fraction.

The conversion effect of cacao + erythrina AFS into cacao + rubber tree AFS was restricted to the surface soil and did not promote dissimilarity among the AFSs regarding the C and N storage in the whole soil and aggregate size-fractions. Additionally, 12 years of conversion was not enough to promote new C and N incorporation into the new free microaggregates yield after the macroaggregate turnover induced by tillage during this conversion.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at: https://doi.org/10.1016/j.geoder.2019.e00218. These data include the Google maps of the most important areas described in this article.

References