SOIL ORGANIC MATTER POOLS IN A TROPICAL SAVANNA UNDER AGROFORESTRY SYSTEM IN NORTHEASTERN BRAZIL[1]

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RESUMO – This study aimed at quantifying total organic carbon stocks and its pools in Acrisol under agroforestry systems with six (AFS6) and thirteen years old (AFS13), slash-and-burn agriculture (SBA) and savanna native forest (SNF) in northeastern Brazil. Soil samples were collected at 0-0.05 m, 0.05-0.10 m, 0.10-0.20 m and 0.20-0.40 m depths in the dry and rainy seasons to evaluate total organic carbon (TOC) stocks and labile carbon (LC), fulvic acid fraction (C-FAF), humic acid fraction (C-HAF), humin (C-HF) and microbial biomass carbon (Cmic) contents. Additionally, carbon management index (CMI) was determined. Higher TOC stocks (97.7 and 81.8 Mg ha^{-1} for the 0-0.40 m depth in the dry and rainy seasons, respectively) and LC, humic substances and Cmic contents were observed in the AFS13 in all the depths. CMI also was higher in the AFS13 (0-0. 05 m: 158 and 86; 0.05-0.10 m: 171 and 67, respectively for the dry and rainy seasons) especially when compared to the SBA (0-0.05 m: 5.6 and 5.4; 0.05-0.10 m: 5.3 and 5.8, respectively for dry and rainy seasons). The agroforestry systems increased soil quality through the conservation of organic matter and can be considered an excellent strategy to assurance sustainability in tropical soil of Northeastern Brazil

Palavras-chave: Soil quality; Microbial biomass; Carbon management index.

FRAÇÕES DA MATÉRIA ORGÂNICA DO SOLO NO CERRADO SOB SISTEMA AGROFLORESTAL NO NORDESTE DO BRASIL

ABSTRACT – Este estudo teve como objetivo quantificar os estoques de carbono orgânico total e de suas frações em um argissolo sob sistemas agroflorestais com 6 (SAF6) e 13 anos de idade (SAF13), agricultura de corte-e-queima (ACQ) e floresta nativa de Cerrado (FNC) no Nordeste do Brasil. As amostras de solo foram coletadas nas estações seca e chuvosa, nas camadas de 0-0,05 m; 0,05-0,10 m; 0,10-0,20 m; e 0,20-0,40 m, para avaliar os estoques de carbono orgânico total (COT) e os teores de carbono lábil (CL), fração ácido fúlvico (C-FAF), fração ácido húmico (C-FAH) e humina (C-FH) e carbono da biomassa microbiana (Cmic). Além disso, o índice de manejo de carbono (IMC) foi determinado. Maiores estoques de COT (97,7 e 81,8 Mg ha^{-1} para 0-0,40 m de profundidade, nas estações seca e chuvosa, respectivamente) e teores de CL, substâncias húmicas e Cmic foram observados no SAF13 em todas as camadas. O IMC também foi maior no SAF13 (0-0,5 m: 158 e 86, 0,05-0,10 m: 171 e 67, respectivamente, nas estações seca e chuvosa), especialmente quando comparado com ACQ (0-0,05 m: 5,6 e 5,4; 0,05 -0,10 m: 5,3 e 5,8, respectivamente, nas estações seca e chuvosa). Os sistemas agroflorestais aumentam a qualidade do solo por meio da conservação da matéria orgânica e podem ser considerados como excelente estratégia para a garantia da sustentabilidade em solo tropical do Nordeste brasileiro.

Palavras-chave: Qualidade do solo; Biomassa microbiana; Índice de manejo de carbono.

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1. INTRODUCTION

Land degradation can be considered as a result of natural or anthropogenic factors in terms of the loss of actual or potential productivity or utility; it is the decline in soil quality or reduction in its productivity (IMOKE et al., 2010). In Northeastern Brazil, loss of soil quality have been caused by overcutting of vegetation, shifting cultivation and intensive tillage, which reduces residue input and consequently soil organic matter (SOM) content (SAMPAIO et al., 1993; BIRD et al., 2007; LUCENA et al., 2007).

Therefore, there is a need to develop sustainable agricultural systems that maintain soil biological processes and are less dependent on external inputs (i.e. fertilizers and herbicides) and mechanical cultivation to reduce negative impacts on the environment and conserved soils (MOONEN; BÀRBERI, 2008;). Agroforestry systems (AFS), which consist of growing trees, crops and sometimes animals in interacting combination, create land-use systems structurally and functionally more complex with greater efficiency of resource (nutrients, light and water) capture and utilization than traditional land management (FAVERO et al., 2008; NAIR et al., 2008; SILVA et al., 2011; LIMA et al., 2011).

AFS are effective at improving and conserving soil quality by continuous deposition of plant biomass and turnover of leaf litter. This provides continuous stream of organic material to the soil, especially because of the long roots of the forest component that go deep into the soil (ALBRECHT; KANDJI, 2003), increasing soil organic matter (SOM) stocks and the C sequestration potential (KIRBY; POTVIN, 2007; NAIR et al., 2009; HERGOUALC'H et al., 2012). When AFS are implanted immediately after slash and burn agriculture, 35% of the original forest C stock can be regained in short term (SÁNCHEZ, 2000; OELBERMANN et al., 2004).

SOM and its pools (labile, slow and recalcitrant), which differ from each other in biochemical composition, biological stability and C turnover rates, are considered one of the most used soil quality indicators due to its high sensibility to the land use changes, mainly in tropical areas (MAIA; XAVIER, 2008; LAIK et al., 2009; LEITE et al., 2010). Soil microbial biomass (SMB), the living component of SOM, is considered the most labile C pool with turnover time of few days to months, with links to soil nutrient and energy dynamics, including mediating the transfer between SOM fractions (HAYNES, 2008; SAHA; MANDAL, 2009; ALLEN et al., 2011).

AFS generally enhance organic matter accumulation in soils through the inclusion of different crops and permanent vegetation cover, which would be expected to increase the soil microbial biomass (ARAÚJO et al., 2012). TANGJANG et al. (2009), in soils under AFS in long-term, observed that the soil microbial biomass was significantly affected by the AFS. Both the amount of microbial biomass carbon and the enzymatic activities were greater in soils under AFS than in conventional systems. According to the authors, the greater microbial biomass reflected the response of the increased input of organic matter to the soil under the AFS.

The humified SOM (fulvic acids, humic acids and humin) represents the stable C pool (SPACCINI et al., 2006) and it is more recalcitrant, abundant and chemically active than labile pool (JANDL et al., 2007), due the high stability and complex structure it interacts with clay and metallic cations, contributing therefore, to persistence in soils (SPOSITO, 2008; THENG; YUAN, 2008) as well as nutrient flows through ecological systems and C emissions to the atmosphere (LAL, 2006**)**. Additionally, it can be efficient marker of soil history (it suffers influences of soil formation factors like time, origin material, climate, relief and anthropomorphic action) assuming a key role (especially humic acids) as indicators of SOM quality, since during the humification process (organic residues stabilization), the humified fraction is the one that undergoes the largest structural change (CANELLAS et al., 2004; MARTINS et al., 2009; PESSOA et al., 2012). Therefore, changes in ûeld management practices, such as AFS, can alter the chemical properties of soil humic substances (MORAES et al., 2011; GUIMARAES et al., 2013)

Several studies have been published in Brazil linking soil properties and AFS although most of them are concentrated in the Amazon region and featured to the soil chemical and physical attributes (SCHROTH et al., 2002; BARROS et al., 2004; BARRETO et al., 2006; PEREIRA et al., 2008; PINHO et al., 2012) with few focusing SOM pools dynamic (MAIA at al., 2007; MORAES et al., 2011; ZAIA et al., 2012). Therefore, our objective was to evaluate the influence of AFS, established in long-term, on SOM pools in a tropical soil from Northeast Brazil.

2. MATERIALS AND METHODS

2.1. Study area

The study was conducted out at Esperantina (03º 54’ 07’’ S and 42º 14’ 02’’ W, 59 m), Piaui State, Northeastern Brazil. The climate is tropical humid, with mean precipitation of 1.300 mm yr^{-1} with rainfall from January to May and annual mean temperature of 30 °C, with minimum and maximum temperatures of 26 °C and 34 °C, respectively. The soil is a Typic Hapludult (Argissolo Vermelho-Amarelo, Brazilian Soil Classification) showing the following chemical and physical characteristics at 0–0.20 m depth: pH (H_2O) 4.9; Al^{3+} 0.6 cmolc/dm^3; Ca^{2+} 2.6 cmolc/dm^3; Mg^{2+} 1.7 cmolc/dm^3; P 4 mg/dm^3; K 58 mg/dm^3; SOM 14 g/kg. Coarse sand, fine sand, silt, and clay were 80, 60, 160, and 700 g/kg, respectively. Soil bulk density was 1.1Mg/m^3.

Four land-use systems, under the same type of soil, were selected: soil under thirteen years of AFS (AFS13) (03º38’13,7"/42º07’59.6"); soil under six years of AFS (AFS6) (03º38’16,0"/42º08’25.8"); conventional farming under slash and burn agriculture (SBA) (03º37’41,4"/42º07’42.9"); native forest under tropical savanna (SNF) (03º37’40,7"/42º07’43.6"). The size of each site is 0.25 ha. The main species included in these systems are: AFS13 - *Zea mays, Curcubita pepo, Phaseolus lunatus, Manihot esculenta Crantz, Ipomoea Lam, Gossypium herbaceum* associated with *Malpighia glabra, Carica papaya, Psidium guajava, Musa paradisiaca, Anacardium occidentale, Mangifera indica, Annona squamosa, Talisia esculenta, Ricinus communis, Bixa orellana, Sesamum indicum, Tabebuia* sp, *Attalea speciosa Mart. ex Spreng., Astromiun fraxinifolium Schott, Enterolobium* sp, *Hymenaea* sp, *Myracrodruon urundeuva Allemão, Combretum* sp and *Mimosa* sp*;* AFS6 - *Zea mays and Manihot esculenta associated with Carica papaya, Anacardium occidentale (predominant), Citrullus vulgaris, Cucumis anguria* and *Musa paradisiaca, Myracrodruon urundeuva Allemão, Astromiun fraxinifolium, Combretum* sp *and Mimosa* sp*;* SBA - *Oryza barthii* and *Zea mays*; SNF Savanna (predominant) and caatinga (tropical dry forest) especies. The net annual organic inputs (pruning from trees, goat manure, weeding, crop residues and herbaceous biomass) in this systems are 4.1, 3.7, 2.1 and 3.1 Mg ha^{-1} in the AFS13, AFS6, SBA and SNF, respectively.

The AFS13 and AFS6 were withdrawal of all conventional practices (slash and burn practices and subsequently, maize or rice planted in monoculture) and are managed since 1997 and 2004, respectively, in the ecological management with introduction of fruit trees and natural regeneration of native plants. In these areas, goat manure (Soil organic carbon: 277 g dm^{-3}; soil organic matter: 502 g dm^{-3}; water: 97 g kg^{-1}; nitrogen: 9,7 g kg^{-1}; phosphorous: 2,1 g kg^{-1}; potassium: 23 g kg^{-1}; calcium: 19 cmolC dm^{-3}; magnesium: 15,2 cmolC dm^{-3}; carbon and nitrogen ratio: 26:1) (40 m^3 ha^{-1}) and organic waste generated by the farmers were periodically added to the soil.

SBA is characterized by slash and burn of primary forest or secondary vegetation and subsequently cultivation of monoculture of maize or rice for one season. After the harvest, land is left to fallow for approximately 8 years. In this study, the last burning occurred on August 2009 and maize crop was planted. SNF is an area under native tropical savanna (Brazilian “Cerrado”) vegetation.

2.2. Soil sampling and analyses

Soil sampling was carried out on September 2009 (dry season) and April 2010 (rainy season). Each site was divided into four plots (replicates) and ten subsamples were collected in each plot (50 x 50 m) at 0-0.05, 0.05-0.10, 0.10-0.20 and 0.20-0.40 m depth, to form a composite sample per depth. The field-moist samples were sieved (2-mm mesh) and a 300-g aliquot of each sample was separated, placed in plastic bags and stored in refrigerator at 4-8 ºC for later determination of soil microbial biomass (SMB). The remaining soil samples were air-dried.

Soil samples were ground and passed through a 0.21-mm sieve to determine total organic carbon (TOC) by wet combustion using a mixture of potassium dichromate and sulfuric acid under heating (YEOMANS; BREMNER, 1988). The values of soil bulk density determined by the core method (SNF: 0-0.5 m = 0.97 kg m^{-3}; 0.05-0.10 m = 1.15 kg m^{-3}; 0.10-0.20m = 1.21 kg m^{-3}; 0.20-0.40 m = 1.25 kg m^{-3}; AFS13: 0-0.05 m = 1.61 kg m^{-3}; 0.05-0.10 m = 1.62 kg m^{-3}; 0.10-0.20 m = 1.63 kg m^{-3}; 0.20-0.40 m = 1.63 kg m^{-3}; AFS6: 0-0.05 m = 1.46 kg m^{-3}; 0.05-0.10 m = 1.42 kg m^{-3}; 0.10-0.20 m = 1.47 kg m^{-3}; 0.20-0.40 m = 1.61 kg m^{-3}; SBA: 0-0.05 m = 1.59 kg m^{-3}; 0.05-0.10 m = 1.55 kg m^{-3}; 0.10-0.20 m = 1.56 kg m^{-3}; 0.20-0.40 m = 1.31 kg m^{-3}) were used to compute TOC stocks on a unit area basis to all depths.

The labile organic carbon (LC) was quantiûed by wet oxidation with $KMnO_4$ (33 mol/L) as described by Blair et al. (1995) and modiûed for tropical soils by Shang and Tiessen (1997). The non-labile carbon (CNL) equivalent to non-oxidized C by $KMnO_4$ was calculated by difference (CNL = TOC”CL). Based on the difference between the TOC-savanna forest (reference) and TOC-cultivated systems, a Carbon Pool Index was created (CPI) and calculated as: CPI = TOC cultivated/TOC savanna forest. According to changes in the proportion of C_L (i.e. $L = C_L / C_{NL}$) in the soil, a Lability Index (LI) was calculated as: LI = L cultivated/L reference. These two indexes were used to calculate the Carbon Management Index (CMI) obtained by the following expression: CMI = CPIxLIx100 (BLAIR et al., 1995). Extraction and fractionation of soil humic substances (humic acids, fulvic acids and humin) were carried out by using the method recommended by the International Humic Substances Society (IHSS), as described by Swift (1996).

The carbon content of fulvic acid (C-FAF), humic acid (C-HAF) and humin (C-HF) fractions was measured by the dichromate oxidation method (Yeomans and Bremner 1988). The ratios of C-HAF by C-FAF and the alkali soluble fractions (C-FAF + C-HAF = AE) by H (AE/C-HF) were calculated to characterize the humified fraction of SOM (Benites et al. 2003). Additionally, to estimate the proportion of humified organic matter in relation to TOC content, the humification index (HI) proposed by Canellas and Santos (2005) was calculated using the following formula: HI = (C-FAF + C-HAF + C-HF) / COTx100.

The soil microbial biomass carbon (MBC) was estimated by the irradiation-extraction method using microwave (ISLAM; WEIL 1998) and 0.5 mol L^{-1} of K_2SO_4 as extractant and its content determined by wet combustion (Yeomans and Bremner 1988). The conversion factor (Kc) used to convert C for MBC was 0.38 (SPARLING; WEST, 1988). The MBC/TOC ratio or microbial quotient (q_{mic}) was calculated to indicate C inputs and the change of organic substrates for MBC.

The Sensitivity Index (SI) was used to compare the magnitude of changes in different C pools relative to a stable reference soil, here the soil under native forest. SI was computed for the 0-0.20 m, using the following formula, according to Banger et al. (2010):

SI = C fraction in soil a given treatment – C fraction in control soil/C fraction in control soil * 100

2.3. Statistical analyses

The study was carried out in a completely randomized design with 4 replicates. Analyses of variance (ANOVA) and the t-test were used to check for significant differences between the areas studied. When a significant F value was detected, the means were compared by the Tukey test ($P < 0.05$). All the statistical analyses were performed with the SPSS (version 15.0) software package.

3. RESULTS

Higher TOC stocks were observed in the soil under AFS13 in the 0-0.05 (19.2 Mg ha^{-1} and 18.4 Mg ha^{-1}), 0-0.05-0.10 (16.3 and 17.7 Mg ha^{-1}), 0.10-0.20 (25.9 and 33.0 Mg ha^{-1}) and 0.20-0.40 m depths (36.3 and 58.8 Mg ha^{-1}) for dry and rainy season, respectively (Table 1). On the other hand, SBA showed lowest TOC stocks, which ranged from 6.1 (0.05-0.10 m) to 15.7 Mg ha^{-1} (0-0.05 m) for dry season and from 2.02 (0.20-0.40 m) to 3.6 Mg ha^{-1} (0.10-0.20 m) for the rainy season. Considering 0-0.40 m depth, TOC stocks were higher in the rainy season compared to dry season for the SNF (81.7 x 63.7 Mg ha^{-1}); AFS13 (128.0 x 97.7 Mg ha^{-1}) and AFS6 (60.9 x 57.1 Mg ha^{-1}), differently from that observed in the SBA system (12.5 x 37.5 Mg ha^{-1}). Moreover, TOC stocks in the AFS13 were 62, 41, 35% and 90, 53 and 36% greater than in the SBA, AFS6 and SNF systems, for the dry and rainy seasons, respectively.

Highest LC contents were observed in the dry season in the AFS13 at 0-0.05 m (3.6 g kg^{-1}; 15.4 % TOC) and at 0.05-0.10 m (2.8 g kg^{-1}; 14.1 % TOC) and in the SNF at 0.10-0.20 m (1.1 g kg^{-1}; 7.2 % TOC) and at 0.20-0.40 m (0.79 g kg^{-1}; 6.4 % TOC) depths. Regarding the rainy season, SNF and AFS13 showed the highest values at 0-0.05 m depth (3.6 g kg-1; 16.6% TOC and 3.2 g kg^{-1}; 13.9% TOC, respectively). At 0.05-0.10 m (1.8 g kg^{-1}; 18% TOC), 0.10-0.20 (1.6 g kg^{-1}; 10.5% TOC) and 0.20-0.40 m (1.4 g kg^{-1}; 11.3% TOC) depths, highest LC contents were verified in the SNF followed by AFS13 (Table 5). For the dry season, NCL showed the same trend that LC with the highest values observed in the AFS13 in the 0-0.05 (20.0 g kg^{-1}) and 0.05-0.10 m (17.2 g kg^{-1}) as well as at 0.10-0.20 (15.4 g kg^{-1}) and 0.20-0.40 m (10.9 g kg^{-1}) depths, although in this case, the values have been similar to the SNF system. AFS13 showed highest values for the CPI and LI ranging from

Table 1 – Total organic carbon (TOC) stocks under different land use system in a tropical soil of Northeastern Brazil.
Tabela 1 – *Estoques de carbono orgânico total (COT) sob diferentes sistemas de uso da terra em um solo tropical do Nordeste do Brasil.*

Land use system	TOC Stocks (Mg ha^{-1}) *							
	Dry	rainy	dry	rainy	dry	rainy	dry	rainy
	0-0.05m		0.05-0.10m		0.10-0.20m		0.20-0.40m	
SNF	8.90 d	10.43b	5.72 c	11.23b	18.43 b	21.21 b	30.72 bc	38.92 b
AFS13	19.21 a	18.44a	16.30 a	17.71a	25.95 a	33.08 a	36.31 ab	58.81 a
AFS6	11.41 cd	14.15ab	8.21bc	7.82 c	11.26 cd	12.85 c	26.26 c	26.11 c
SBA	15.7 2b	3.52 c	6.14c	3.37d	8.23 d	3.60d	7.45 d	2.02 d

Means followed by same letter in column do not differ by Tukey test at 5% probability. SNF: savanna native forest; AFS6: agroforestry system with six years of adoption; AFS13: agroforestry system with thirteen years of adoption and SBA: slash and burn agriculture with six years of continuous cultivation of monocultures annual cycle.
Médias seguidas da mesma letra dentro de cada camada de solo não diferem entre si, pelo teste de Tukey a 5% de probabilidade. (FNC): floresta nativa de Cerrado; (SAF6): sistema agroflorestal com 6 anos de adoção; (SAF13): sistema agroflorestal com 13 anos de adoção; e (ACQ): agricultura de corte e queima com 6 anos de cultivo contínuo com monoculturas de ciclo anual.

0.91 (0.20-0.20-0.40 m) to 2.02 (0.10-0.20 m) and from 1.06 (0.0-0.05 m) to 1.30 (0.10-0.20 m), respectively to the dry and rainy seasons. Similarly, CMI values were observed in the AFS13 and compared to that under SBA, the differences were 96, 96, 94 and 93% (dry) and, 93, 91, 87 and 86% (rainy) at 0-0.05, 0.05-0.10, 0.10-0.20 and 0.20-0.40 m, respectively (Table 2).

For the dry season, C-FAF contents were similar in the SNF, AFS13 and SBA systems which were higher than AFS6 at 0-0.05 m depth. On the other hand, from 0.05 to 0.40 m, the AFS6 showed highest values, although at 0.10-0.20 and 0.20-0.40 m, they have been equal to those observed in native forest (Table 3). For the rainy season, highest values were verified in the AFS13 and AFS6 (2.6 and 2.3 g kg^{-1}, respectively) at 0-0.05 m. C-HAF contents were higher than C-FAF, especially for rainy season, ranging from 0.15 g kg^{-1} (SBA, 0.20-0.40 m) to 5.35 g kg^{-1} (AFS6, 0.10-0.20 m). In terms of systems, for the dry season, C-HAF contents were higher in the SBA and AFS13 and in the AFS6 and SBA at 0-0.05 m and 0.05-0.10 m, respectively. However, from 0.10 to 0.40 m the highest values were observed in the AFS13. For the rainy season, AFS6 and AFS13 showed higher C-HAF content than SBA and SNF systems at all the depths (Table 6). The largest difference between agroforestry and other systems was verified at 0.10-0.20 and 0.20-0.40 m, which represented 88% (AFS6 x SBA) and 96% (AFS13 x SBA), respectively. AFS13 showed higher values for C-HF at 0-0.05 m (15.9 g kg^{-1}), 0.05-0.10 (15.1 g kg^{-1}) and 0.10-0.20 m (9.4 g kg^{-1}) which was similar to the SNF (9.0 g kg^{-1}), for the dry season. On the other hand, for the rainy season, highest values were observed in the SNF followed by AFS13 up to 0-0.10 m. From 0.10 to 0.40 m, AFS13 showed highest C-HF contents (Table 6). C-HF showed higher values in all depths compared to C-FAF and C-HAF. In the AFS13, C-HF contents represented from 56.6% (0.10-0.20 m) to 75.0% (0.05-0.10 m) for the dry period and from 50.5% (0.20-0.40 m) to 69% (0.10-0.20 m) for the rainy period regarding TOC contents. For the dry period, AFS13 promoted higher degree of humification in soil organic matter, with the highest HI observed from 0.05 m depth, although they have been similar to those verified in the SNF system at 0.10-0.20 m depth. Highest HI in the AFS13 also observed for the rainy period at 0.05-0.10 m (85.2), 0.10-0.20 (85.2, equal to AFS6) and 0.20-0.40 m (87.8) (Table 3).

C_{mic} was higher in the SNF in all depths for the dry season, ranging from 137 mg kg^{-1} (0-0.05 m) to 58 mg kg^{-1} (0.20-0.40 m). Also, in both seasons, AFS13 showed highest values of C_{mic} than AFS6 and SBA, which showed the lowest values (Table 7). Highest values of the q_{mic} were observed in SNF (7.36 and 8.62%) followed by AFS13 (3.83 and 2.65%), at 0-0.05 and 0.05-0.10 m depths, respectively, for the dry season. On the other hand, for the rainy season, the highest values were observed in SBA system especially at 0-0.05 (7.2%), 0.10-0.20 (1.90%) and 0.20-0.40 m (2.03%) (Table 4)

For the dry period, sensitivity of TOC ranged from -31.59 (SBA) to 59.91% (AFS13) and MBC and LC ranged from -90.12 (SBA) to -32.16% (AFS13) and from -94.17 (SBA) to 65.15% (AFS13), respectively (Figure 1). For the rainy season, the SI of TOC ranged from -81.27(SBA) to 20.53% (AFS13), MBC ranged from -44.09 (SBA) to 20.53% (AFS13) and LC from -95.98 (SBA) to -38.39% (AFS13).

Table 2 – Total organic carbon (TOC), labile carbon (LC) and non-labile carbon (CNL) contents, carbon pool index (CPI), carbon lability (L), lability index (LI) and carbon management index (CMI) under different land use systems in a tropical soil of Northeastern Brazil.

Tabela 2 *– Teores de carbono orgânico total (COT), carbono lábil (CL) e carbono não lábil (CNL), índice de compartimento de carbono (CPI), labilidade (L), índice de labilidade de carbono I(L) e índice de manejo de carbono (IMC) sob diferentes sistemas de uso da terra em um solo tropical do Nordeste do Brasil.*

Land use system	TOC		LC (g kg $^{-1}$)		NLC		CPI		L		LI		CMI	
	dry	rainy	dry	rainy	dry	rainy	dry	rainy	dry	rainy	dry	rainy	dry	rainy
							0-0.05m							
SNF	18.53 bc	21.56 a	2.39 b	3.60 a	16.01 cd	14.94 c	-	-	0,1493	0,2410	-	-	100.00	100.00
AFS13	23.86 a	22.91 a	3.68 a	3.23 a	20.03 a	20.62 a	1.29 a	1.06 a	0,1837 a	0.1957 a	1,2307 a	0.8120 a	158.47 a	86.29 a
AFS6	15.74 c	19.35 b	0.21 c	0.51 b	15.48 d	15.23 bc	0.85 b	0.90 a	0.0394 b	0.0639 b	0.2540 b	0.2654 b	38.47 b	33.87 b
SBA	16.75 bc	4.40 c	0.15 d	0.09 c	16.14 bc	4.20 d	0.90 b	0.20 b	0.0093 c	0.0644 b	0.0623 c	0.2674 b	5.63 c	5.46 c
							0.05-0.10m							
SNF	10.01 b	19.63 b	0.70 b	1.78 a	9.19 cd	17.22 b	-	-	0,0762	0,1034	-	-	100.00	100.00
AFS13	20.20 a	21.89 ab	2.86 a	0.59 b	17.26 a	19.60 ab	2.02 a	1.19 a	0.0647 a	0.0581 b	0.8495 a	0.5624 a	171.42 a	67.18 a
AFS6	11.58 b	11.10 c	0.28 c	0.35c	11.12 bc	10.23 c	1.16 b	0.57 b	0.0252 b	0.0635 a	0.3306 b	0.6147 b	33.24 b	23.73 b
SBA	7.94 c	4.28 d	0.04 d	0.06 d	7.82 d	3.98 d	0.79 c	0.22 c	0.0051 c	0.0276 c	0.0672 c	0.2567 c	5.33 c	5.83 c
							0.10-0.20m							
SNF	15.27 a	17.55 b	1.10 a	1.60 a	13.95 b	13.66 b	-	-	0,0789	0,1171	-	-	100.00	100.00
AFS13	15.90 a	20.30 a	0.38 bc	0.48 b	15.44 ab	19.42 a	1.04 a	1.30 a	0.0699 a	0.0509 a	0.8862 a	0.4346 a	92.28 a	56.91 a
AFS6	7.65 b	8.75 c	0.24 c	0.12 c	7.01 c	8.33 c	0.50 b	0.50 b	0.0342 b	0.0252 b	0.4342 b	0.2152 b	21.75 b	21.63 b
SBA	5.28 c	2.32 d	0.05 d	0.13 c	5.13 d	2.04 d	0.38 c	0.13 c	0.0097 c	0.0237 b	0.1236 c	0.2441 b	4.69 c	7.19 c
							0.20-0.40m							
SNF	12.30 ab	15.56 b	0.79 a	1.43 a	10.41 b	13.97 b	-	-	0.0759	0,1024	-	-	100.00	100.00
AFS13	11.16 b	18.05 a	0.14 c	0.39 b	10.95 ab	16.70 a	0.91 a	1.22 a	0.0813 a	0.0461 a	1.0710 a	0.4504 a	97.18 a	55.03 a
AFS6	8.14 c	8.12 c	0.27 b	0.11 d	7.95 c	7.93 c	0.66 b	0.52 b	0.0340 b	0.0189 b	0.4475 b	0.1848 b	29.62 b	24.64 b
SBA	2.34 d	0.93 d	0.05 d	0.23 c	2.04 d	0.58 d	0.19 c	0.11 c	0.0245 c	0.0186 b	0.3230 c	0.1332 c	6.14 c	7.16 c

Means followed by same letter within each soil layer do not differ by Tukey test at 5% probability. (SNF): savanna native forest; (AFS6) agroforestry system with six years of adoption; (AFS13) agroforestry system with thirteen years of adoption and (SBA) slash and burn agriculture with six years of continuous cultivation with monocultures of annual cycle.
Médias seguidas da mesma letra dentro de cada camada de solo não diferem entre si, pelo teste de Tukey a 5% de probabilidade. (FNC): floresta nativa de Cerrado; (SAF6): sistema agroflorestal com 6 anos de adoção; (SAF13): sistema agroflorestal com 13 anos de adoção; e (ACQ): agricultura de corte e queima com 6 anos de cultivo contínuo com monoculturas de ciclo anual.

Table 3 – Soil carbon contents in the fulvic acid (C-FAF), humic acid (C-HAF), humin (C-HF) fractions, alkaline extract (AE), alkaline extract: humin ratio (AE / C-HF) and humification index (HI) under different land use systems in a tropical soil of Northeastern Brazil.
Tabela 3 – *Teores de carbono nas frações ácido fúlvico (C-FAF), ácidos húmicos (C-FAH), humina (C-FH), extrato alcalino (EA), relação extrato alcalino humina (EA/C-FH) e índice de humificação (IH), sob diferentes sistemas de uso da terra em um solo tropical do Nordeste do Brasil.*

Land use system	C-FAF		C-HAF (g kg $^{-1}$)		C-HF		AE		AE/C-HF		HI%	
	dry	rainy	dry	rainy	dry	rainy	dry	rainy	dry	rainy	dry	rainy
0-0.05m												
SNF	2.43 b	1.51 b	3.31cd	2.82b	10.72 b	15.02ab	3.65 d	3.92 c	0.34 c	0.26 c	91.20 b	91.90ab
AFS13	3.01ab	2.62 a	4.62b	1.83c	15.93 a	14.24 b	7.32 b	4.43 bc	0.46 b	0.32 bc	93.69 ab	86.36 b
AFS6	1.12c	2.31 a	2.91d	4.33a	9.8 8 c	5.02c	4.12 c	6.34 a	0.42 b	1.09 a	87.6 0 c	66.26 c
SBA	2.92b	0.61 c	5.01ab	0.84d	10.61b	1.45d	7.97ab	1.42 d	0.75 a	1.06 a	83.62 c	66.19 c
0.05-0.10m												
SNF	0.93 c	0.62 c	1.21c	2.91c	7.46c	12.12 b	2.31 d	3.65 b	0.31 b	0.31 c	85.14 b	79.81 bc
AFS13	2.54b	0.84bc	1.42c	4.12b	15.15a	13.85 ab	3.87 c	5.32 a	0.25 c	0.38 c	94.06 a	85.23 a
AFS6	4.71a	1.10ab	3.63ab	4.45ab	7.52bc	3.40c	8.21 a	5.67 a	0.98 a	1.71 a	83.65 b	70.02 c
SBA	1.01c	0.91b	3.21b	0.77d	4.62d	1.91d	4.22 b	1.78 c	0.91 a	0.97 b	78.61 c	78.98 bc
0.10-0.20m												
SNF	2.92b	1.01ab	2.21b	4.02b	9.42a	9.13 b	5.22 a	5.23 a	0.55 c	0.57 cd	92.95 a	80.34 c
AFS13	0.33c	0.52 c	4.93a	2.35c	9.01a	14.06 a	5.43 a	5.34 a	0.60 bc	0.49 d	91.87 a	85.23 b
AFS6	3.12ab	0.80 b	1.41cd	5.34a	2.13b	1.75 c	4.72 b	4.65 b	1.63 a	2.47 a	86.78 b	87.32 ab
SBA	0.51c	0.41c	0.83d	0.61d	3.3 c	0.92 d	1.37 c	1.23 c	0.54 c	1.42 b	86.33 b	80.21c
0.20-0.40m												
SNF	1.43 b	0.91 b	2.81b	3.90bc	6.24a	7.91b	4.23 a	4.87 b	0.69 c	0.61 d	84.32 c	81.61 b
AFS13	0.22c	1.82ab	3.72a	4.91a	6.52a	9.12a	4.12 a	6. 88 a	0.63 c	0.74 cd	92.21 a	87.89 a
AFS6	1.51ab	0.5 3c	2.53 b	3.13c	3.12b	1.15c	3.37 b	3.54 c	1.06 ab	3.17 a	86.21 bc	61.48 d
SBA	0.42c	0.11 d	0.51c	0.15 d	1.25c	0.22d	1.13 c	0.27 d	0.98 b	1.46 b	85.11 b	73.45 c

Means followed by same letter within each soil layer do not differ by Tukey test at 5% probability. (SNF): savanna native forest; (AFS6) agroforestry system with six years of adoption; (AFS13) agroforestry system with thirteen years of adoption and (SBA) slash and burn agriculture with six years of continuous cultivation with monocultures of annual cycle.
Médias seguidas da mesma letra dentro de cada camada de solo não diferem entre si, pelo teste de Tukey a 5% de probabilidade. (FNC): floresta nativa de Cerrado; (SAF6): sistema agroflorestal com 6 anos de adoção; (SAF13): sistema agroflorestal com 13 anos de adoção; e (ACQ): agricultura de corte e queima com 6 anos de cultivo contínuo com monoculturas de ciclo anual.

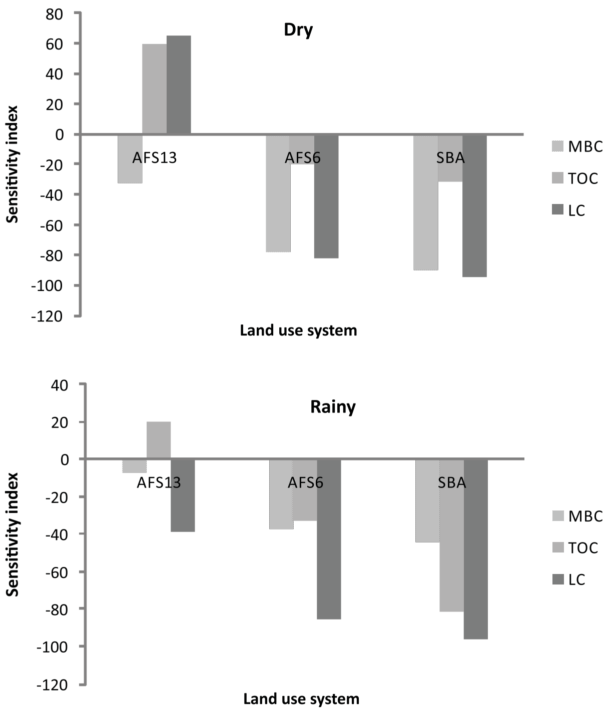

Figure 1 – Sensitivity index in different carbon fractions under different land use systems in a tropical soil of Northeastern Brazil at dry and rainy periods; (AFS6) agroforestry system with six years of adoption; (AFS13) agroforestry system with thirteen years of adoption and (SBA) slash and burn agriculture with six years of continuous cultivation with monocultures of annual cycle; (MBC) soil microbial biomass carbon; (TOC) total organic carbon; and (LC) labil carbon.

***Figura 1** – Índice de sensibilidade em diferentes frações de carbono sob diferentes sistemas de manejo em um solo tropical do Nordeste do Brasil nos períodos seco e chuvoso. (SAF6) sistema agroflorestal com seis anos de adoção; (SAF13) sistema agroflorestal com 13 anos de adoção; (ACQ) agricultura de corte e queima com 6 anos de cultivo contínuo com monoculturas de ciclo anual; (CBM) carbono da biomassa microbiana do solo; (COT) carbono orgânico total; e (CL) carbono lábil.*

4. DISCUSSION

Higher TOC stocks observed in the soil AFS13 compared to AFS6 and especially to SBA in both seasons can be related to the higher plant residue input and organic waste plus animal manure applied. As reported by Oelbermann et al. (2006), the already partially decomposed organic material in the manure, which contains higher proportion of chemically recalcitrant organic compounds compared to residues from senescent crops in the conventional system (SBA), can cause such differences. Additionally, the highest amount of tree roots present in the AFS13 can add large amounts of C because they are more ligniûed (woodier) than the foliage pruning and have C in more stable compounds. Hence, roots may supply more stable C to the soil as observed by Makumba et al. (2007) studying the effect of agroforestry practice on C sequestration and CO2-C efflux in a gliricidia-maize intercropping system. Lenka et al. (2012) and Pinho et al. (2012) have suggested that AFSs, especially with the insertion of trees, have higher potential to build up and sequester C in soils because of the increased rates of organic matter addition and retention. However, according to Derpsch (2008), clear increases in soil organic matter only appear 5-10 years after the adoption, as verified in the AFS13 system. Our results were similar to those observed by Maia et al. (2007), who reported in the semi arid region of Brazil studying a Luvisol under agroforestry TOC stocks ranging from 44 (intensive cropping) to 73 Mg ha^{-1} (native forest), at 0-0.40 m depth in the semi arid region of Brazil.

AFS13 and SNF showed higher labile carbon contents than SBA for both seasons. Several authors have reported that land management systems that encourage more frequent additions of organic material to the soil can increase C in the labile fraction (BLAIR et al., 1995; CHAN et al., 2001; NAIR et al., 2009) which is stimulated by soil macro- and mesofaunal activities (YOUKHANA and IDOL 2011). Similarly, Barreto et al. (2008) studying in Latosol and Cambisol, in Bahia, Brazil, verified that cacao agroforestry system also offered higher C levels in the labile pool (oxidized under 6 mol $L^{-1}H_2SO_4$) and that represented 52-55%, of the TOC, which means much less than those observed in our study (AFS13: 2.1 - 15 %) for both seasons. This result can indicate that organic carbon under AFS and also in the other systems can have more stability due to the interaction between clay minerals (in our study, high clay content) and organic matter such as humic substances (BRADY; WEIL, 2008). Also, as verified by Tirloni et al. (2012) studying a Oxisol under crop rotation systems in crop-livestock integration, lability was strongly reduced in the deeper soil layers, in all systems, since the surface layer is the most influenced by soil management, with respect to the input of organic material, especially where a minimal soil disturbance is expected.

Higher CPI values in AFS13 reflect the high potential in restoring the original soil organic C stocks. The CMI has been suggested as a useful indicator for monitoring the organic matter and soil quality status because it incorporates the TOC, CL and NLC of the management systems and reference (CONTEH et al., 1998; LEITE et al., 2010). On the other hand, CMI should be considered only as a soil quality indicator and not as general soil quality index, because several other aspects associated to the soil capacity of functioning must also be considered when assessing soil quality as reported by De Bona et al (2006). In our study, the higher CMI (above 100) observed in AFS13 may indicate a greater conservation of soil quality, due to a minor disturbance and a high crop residue input, as also observed by Maia et al. (2007) in the Brazilian semi arid region. Moreover, AFS6 showed higher CMI than SBA, although almost half of those obtained in the AFS13, which can be related to the short term input residue of the system as established by Loss et al. (2011) in the organic production systems.

In general, it was observed that less intensive treatments (AFS and SNF) led to the highest carbon humic fractions contents reinforcing the assumption that minimizing soil mobilization and stabilizing edaphoclimatic conditions favor the establishment of more stable chemical interactions among the humic substances and the soil mineral fraction (STEVENSON, 1994; CHAN et al., 2002; MAIA et al., 2007). This result is essential to the soil quality since the humic substance is considered the most stable pool of soil organic matter and represents the main reservoir of soil organic matter. On the other hand, although humic substances are more recalcitrant than the other binding agents, their chemical recalcitrance does not account for the persistence in soil if not their occlusion in the aggregates. Once the aggregates are broken down by cultivation, such as SBA system, the HS are exposed to microbial attack and degraded, decreasing their contents (BONGIOVANNI; LOBARTINI, 2006).

Highest C-HAF contents compared to the C-FAF can be related to the synthesis process through formation of more complex structures from a structural rearrangement of less condensed molecules, such as fulvic acid fraction or the degradation process of the FAF, which is more easily used as energy source by soil microorganisms (STEVENSON, 1994; MORAES et al., 2011). However, C-HF was the most abundant fraction in all systems, which can be explained by the fact that the organic material deposited in the soil is less degraded, due to its high chemical recalcitrant (STEVENSON, 1994; FONTANA et al., 2005). Similar result was verified by Cunha et al. (2007) studying humic substances from the 0-20 cm layer of Amazonian dark earth soils (Terra Preta do Índio) under forest and agricultural use.

Highest HI were observed in the AFS13 (above 85%) compared with other systems and occurred especially at 0.10-0.20 m and 0.20-0.40 m depths corroborating with the proportionally lower labile carbon contents. According to the Bausenwein et al. (2008), a higher degree of humiûcation apparently stimulates a richer community, which might have higher diversity in decomposition capabilities, or alternatively, the higher complexity in organic molecules caused by higher richness of metabolic pathways.

Soil microbial biomass carbon is influenced by quantity and diversity of fresh organic residues as found in the native forest (VALLEJO et al., 2010). In AFS13, several factors may have influenced the increased MBC, such as better microclimate for the soil microorganisms (BELSKY et al., 1989) or different plant residues, organic matter, vegetation and plant species composition added in AFS system (TANGJANG et al., 2009). In addition, long-term input of diverse plant residues in AFS13 influenced MBC as reported by Pereira et al. (2008), who found highest values of MBC in AFS than in native forest and conventional farming. Chander et al. (1998), in soils under a 12-year-old AFS, observed that soil microbial biomass was significantly long-term affected by the AFS. Both the amount of microbial biomass carbon and the enzymatic activities were greater in soils under AFS than in conventional systems. According to the same authors, the greater microbial biomass reflected the response of the increased input of organic matter to the soil under the AFS.

The q_{mic} is an indicator of the availability of carbon to microorganisms, input of organic matter to soil, conversion efficiency to microbial biomass and stabilization of carbon in soil (SPARLING, 1992). The results from SNF and AFS13 suggest that the diversity and quality of C sources promoted increases in q_{mic}. Therefore, soil microbial biomass improved its capacity to use the C sources and increases the pool of nutrients. Anderson and Domsch (1990) showed that the higher

q_{mic} in their crop rotation plots as compared to monoculture systems was a result of a higher efficiency of organic matter utilization for microbial growth, which they attributed to a more organic matter input. On the other hand, the highest values of q_{mic} found in SBA for the rainy season occurred probably due to soil moisture that influenced MBC associated with a low TOC, thus increasing q_{mic}. The sensitivity of the LC was greater than the sensitivity of the MBC which was greater than TOC in both seasons. The dynamic nature of labile fractions can provide early changes in soil organic matter status due to management practices as also reported by Banger et al (2010).

5. CONCLUSIONS

Higher values of labile carbon, microbial biomass and humic substances were observed in the agroforestry system with thirteen years of adoption which can indicate a greater stability of the labile and stable pools, essential to increase soil organic matter stocks in tropical soil.

Agroforestry system increased soil quality through the conservation of organic matter and can be considered an excellent strategy to assurance sustainability in tropical soil of Northeastern Brazil.

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