

Quantity and quality of soil organic matter as a sustainability index under different land uses in Eastern Amazon

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ABSTRACT: Soil organic matter (SOM), which influences chemical, physical and biological soil attributes, is the main form of C found in the soil which can also be used as a soil sustainability index. The aim of this study was to use the quantity and quality of SOM as an indicator to determine the sustainability of different land uses (native vegetation, secondary vegetation, fruit orchards, horticultural areas, degraded pasture, improved pasture, and fields with annual crops) in the eastern Amazon. Improved pasture had higher soil C stock than the other land uses and was similar to the native vegetation, and also presented the highest quantity of C in a stable form in the soil (fraction < 53 µm). According to the C management index, improved pasture is the most similar in use to native vegetation. Changes in land use reduced the soil microbial C content, although the more conservationist systems (fruit orchards, secondary vegetation, and improved pasture) had contents similar to those of the native vegetation. The highest soil microbial quotients were found in fruit orchards and horticultural areas. Well-managed pastures were effective in accumulating C as stable forms in the soil, which demonstrates the sustainability of this land use in the region studied.

Keywords: C stocks, changes in land use, physical fractionation, carbon management index, microbial biomass

Introduction

Soil organic matter (SOM) is the main form of C found in the soil (Brady and Weil, 2008) and can influence chemical, physical and biological soil attributes, be a source of C and energy for microorganisms and affect greenhouse gas emissions (Batjes and Sombroek, 1997). SOM is a mixture of molecules from plants, animals and microorganisms (Simpson et al., 2002) with different compositions, levels of availability, and functions in the environment (Carter, 2001).

Physical disturbance of the soil breaks the dynamic equilibrium of the soil causing emission of CO₂ into the atmosphere (Paustian et al., 2000). In the Amazon in Brazil, deforestation makes way for the establishment of pastures and recently, grazing areas have been replaced by corn and soybean fields (Frazão et al., 2010; Lammel et al., 2015). This can reduce the C in the 0-20 cm soil layer by 10 %, while changing from agriculture to pasture the soil C content may increase by 26 % (Don, 2011), and achieve a level similar to the native areas (Frazão et al., 2010; Maia et al., 2009). SOM is an important indicator of soil quality and agricultural sustainability, since management practices can cause it to undergo rapid change (Mielnickuk, 2008). Such change can be evaluated using the total soil C content, its chemical and physical fractions or by a combination of these factors (Blair et al., 1997). However, minor changes in total C content are hard to detect (Blair et al., 1995). Labile C, resulting from soil oxidation with K₂Cr₂O₇ at different acidity levels or by physical fractionation of SOM, as well as the microbial biomass can be used as indicators of sustainability for agricultural systems (Araújo and Melo, 2010; Dieckow et al., 2005; Chan et al., 2001).

Blair et al. (1995) proposed the use of labile C in soil to calculate the C management index (CMI), which is a measure of the relative sustainability of different systems or land uses in comparison to a reference area, generally a native one (Blair et al., 1997). More conservationist systems and pastures show higher CMI than conventional systems (Schiavo et al., 2011; Silva et al., 2011).

The aim of this study was to use the quality and quantity of SOM as an indicator to determine the sustainability of different land uses in the eastern Amazon.

Materials and Methods

The study was conducted in rural areas of the municipality of São Luís, in the eastern Amazon in Brazil (geographic coordinates on Table 1). The climate is tropical, hot, and humid, with an average temperature of 32 °C and annual rainfall of 2,326 mm. The rainy season is from Jan to July and the dry season from Aug to Dec. We evaluated areas under different land uses located in the same watershed drainage basin, in a Haplic Ferralsol (FAO-WRB). Land uses evaluated were native vegetation (forest); secondary vegetation (capoeira); improved pasture (represented by a cut and carry grass field); degraded pasture; fruit orchards; horticultural areas; and fields with annual crops (Table 1). The native vegetation represents the original vegetation of that area and was used as the reference site for all comparisons.

Soils samples were collected in Dec 2011. A 300 m-long transect was allocated in each land use. Five points were equidistantly distributed along the transect. At each point along the transect we collected two disturbed soil samples at three layers (0-10 cm, 10-20 cm,

Table 1 – Coordinates and historical land use of the areas evaluated in São Luís.

Land use	Coordinates	Elevation m	Age / Fertilization	Historical land-use
Native vegetation	02°36'20.8" S 44°16'23.6" O	24	-	Preserved area. Same use over the years.
Secondary vegetation	02°36'25.8" S 44°15'58.7" O	43	20 years No fertilization	Deforested in the 1970s for implementation of fruit growing area. It has been fallow for 20 years, since the eradication of the orchard.
Degraded pasture	02°37'3.1" S 44°16'29.5" O	26	35 years No fertilization	Converted from native vegetation into pasture. The forage specie is <i>Brachiaria brizantha</i> cv. Marandu. There is a high level of weed infestation and many points of uncovered soil.
Improved pasture	02°36'51.0" S 44°16'17.4" O	34	10 years 140 kg ha ⁻¹ of N after forage cut and 160 kg ha ⁻¹ of P ₂ O ₅ + 160 kg ha ⁻¹ of K ₂ O on time per year	Converted from "native vegetation" into pasture at the same time as "degraded pasture." For 10 years it has been conducted as a cut and carry grass field with <i>Pennisetum purpureum</i> (the animals are not allowed to graze in this area. Consequently, forage has been cut and is to be supplied to the animals in another place). Thus, native vegetation, degraded pasture and improved pasture form a chronosequence of land use. The forage is irrigated and cut three times per year.
Annual crops	02°36'46.0" S 44°16'26.2" O	45	41 years Fertilization according crop demand	This area was deforested in 1970 and since then has been used for alternative crops such as corn, cowpea beans, rice and cassava, all under conventional tillage. These crops are cultivated in the rainy season (Jan to July) and, after the harvest, the area is left fallow during the dry period of the year (Aug to Dec).
Fruit trees	02°36'26.0" S 44°16'25.9" O	20	31 years Fertilization with manure	This area was deforested in the early 1980s for coffee cultivation. In the same decade, coffee was replaced by fruit trees. At the time of sampling the species growing in the area were coconut, banana, and citrus. The area receives sprinkler irrigation during the dry period of the year.
Horticulture	02°36'27.3" S 44°15'59.0" O	43	41 years Fertilization with manure	Deforested in 1970s for the deployment of fruit trees. The area was kept fallow for 10 years (secondary vegetation) and then it was converted into horticulture. The area is irrigated in the dry season of the year and receives frequent additions of organic amendments. Thus, there is another chronosequence of land uses: native vegetation, fruit trees, secondary vegetation, and horticulture.

and 20-30 cm). The two samples from the same layer were mixed together to form one composite sample per point per layer. These samples were used for chemical and granulometric characterization (Table 2), total C and N, labile C, microbial C determinations and for the physical fractionation of SOM. A soil trench was opened at the midpoint of each transect and two undisturbed samples were collected for soil density determination.

C and N contents were determined by dry combustion. C and N stocks (Mg ha⁻¹) were calculated by multiplying the content (%) of each element in each soil layer, the width of the soil layer (cm), and the soil layer density (g cm⁻³). C and N stocks in the deepest layer were corrected by equivalent soil mass (Ellert and Bettany, 1995) using the native vegetation as reference. C and N stocks in the 0-30 cm layer were obtained by the summing the stocks in the 0-10 cm, 10-20 cm and 20-30 cm layers.

Labile C concentrations were determined by oxidation with KMnO₄ (333 mmol L⁻¹) + 12 N H₂SO₄, according to Chan et al. (2001). Non-labile C was obtained by subtracting labile C from total C (dry combustion).

To physically fractionate SOM, 20 g of air-dried soil and 70 mL of water were dispersed for 15 min in an ultrasonic apparatus working at 70 % power (500 W), providing approximately 13 J of energy to samples. SOM fractions were separated by wet sieving (Christensen, 1992) into two size classes: 53 to 2000 µm (subdivided into organic fraction and mineral fraction by water flotation); and < 53 µm. Fractions were dried in a circulating air oven (45 °C), weighed, and ground in a porcelain mortar. C contents in the fractions were determined by dry combustion. The total soil C stored in each fraction (g kg⁻¹ of soil) was calculated from the mass (g fraction kg⁻¹ of soil) and the C content in each fraction (g C kg⁻¹ of fraction).

CMI was calculated as follows: CMI = C Pool Index (CPI) × Lability Index (LI) × 100. In this calculation, CPI = C pool in the sample (g kg⁻¹) / C pool in the reference (g kg⁻¹); LI = lability in the sample (L_s) / lability in the reference (L_{ref}); L = content of labile C / content of non-labile C (Blair et al., 1995). CMI was calculated in two different ways: (i) considering labile C as the fraction oxidized by slightly acidic K₂Cr₂O₇ (Chan et

Table 2 – Granulometric and chemical characterization of soils under different land uses in São Luís, MA, Brazil (mean ± standard error of the mean) (n = 5).

Soil layer	Sand	Silt	Clay	pH (water)	P	K	Na	Ca	Mg	Al	H+Al
cm	g kg ⁻¹				mg dm ⁻³	cmol _c dm ⁻³					
Native vegetation											
0-10	884.6 ± 11.7	34.4 ± 5.2	81.0 ± 9.4	4.5 ± 0.03	5.3 ± 1.7	0.06 ± 0.017	0.06 ± 0.010	0.5 ± 0.1	0.8 ± 0.08	1.6 ± 0.04	13.1 ± 1.2
10-20	862.2 ± 19.9	32.0 ± 2.3	105.8 ± 21.6	4.6 ± 0.04	5.5 ± 3.4	0.03 ± 0.004	0.04 ± 0.004	0.4 ± 0.1	0.7 ± 0.07	1.6 ± 0.1	11.3 ± 1.7
20-30	861.0 ± 12.9	28.8 ± 4.8	110.6 ± 15.1	4.7 ± 0.04	5.3 ± 3.1	0.02 ± 0.004	0.04 ± 0.004	0.3 ± 0.1	0.8 ± 0.1	1.3 ± 0.1	9.7 ± 0.8
Secondary vegetation											
0-10	834.8 ± 6.3	28.6 ± 1.0 b	136.2 ± 6.0	4.4 ± 0.04	6.2 ± 1.0	0.06 ± 0.007	0.03 ± 0.002	0.5 ± 0.1	0.8 ± 0.2	1.3 ± 0.1	10.6 ± 0.8
10-20	832.0 ± 10.1	32.0 ± 2.9	136.0 ± 10.0	4.4 ± 0.02	5.2 ± 1.9	0.03 ± 0.002	0.03 ± 0.002	0.5 ± 0.1	0.6 ± 0.2	1.2 ± 0.02	8.1 ± 0.9
20-30	815.8 ± 14.6	38.2 ± 1.0	146.2 ± 14.7	4.5 ± 0.05	2.8 ± 0.5	0.03 ± 0.002	0.02 ± 0.005	0.4 ± 0.1	0.6 ± 0.1	1.3 ± 0.1	8.5 ± 1.2
Fruit trees											
0-10	912.4 ± 5.2	27.4 ± 2.7	60.0 ± 6.1	4.9 ± 0.1	11.0 ± 2.1	0.09 ± 0.01	0.05 ± 0.01	0.9 ± 0.1	1.0 ± 0.2	0.5 ± 0.02	5.9 ± 0.7
10-20	906.4 ± 4.7	28.2 ± 2.5	65.4 ± 6.1	4.9 ± 0.1	4.2 ± 0.7	0.04 ± 0.005	0.03 ± 0.007	0.9 ± 0.1	0.8 ± 0.2	0.7 ± 0.1	6.7 ± 1.0
20-30	890.8 ± 7.1	23.8 ± 1.6	85.6 ± 6.3	4.9 ± 0.1	2.6 ± 0.2	0.03 ± 0.003	0.03 ± 0.004	0.7 ± 0.1	1.0 ± 0.2	0.8 ± 0.1	6.8 ± 0.4
Horticulture											
0-10	833.8 ± 9.6	32.4 ± 3.1	133.4 ± 9.5	5.5 ± 0.1	61.2 ± 21.9	0.10 ± 0.04	0.05 ± 0.01	0.8 ± 0.2	0.6 ± 0.2	0.5 ± 0.1	6.1 ± 0.6
10-20	808.4 ± 8.9	33.6 ± 3.1	158.4 ± 9.2	5.4 ± 0.1	43.2 ± 18.6	0.04 ± 0.01	0.03 ± 0.01	1.8 ± 0.5	1.2 ± 0.2	0.1 ± 0.02	6.8 ± 1.0
20-30	791.6 ± 13.0 b	36.6 ± 2.5	171.8 ± 14.8	5.3 ± 0.2	24.2 ± 8.5	0.03 ± 0.005	0.03 ± 0.008	1.0 ± 0.3	0.9 ± 0.3	0.5 ± 0.2	9.0 ± 0.4
Degraded Pasture											
0-10	866.2 ± 6.7	27.8 ± 4.5	105.8 ± 9.4	4.9 ± 0.07	4.5 ± 1.1	0.03 ± 0.003	0.02	0.8 ± 0.2	0.7 ± 0.3	0.7 ± 0.1	8.4 ± 0.8
10-20	852.4 ± 8.7	32.0 ± 5.3	115.8 ± 12.5	4.7 ± 0.05	1.8 ± 0.2	0.02 ± 0.002	0.01 ± 0.002	0.6 ± 0.1	0.4 ± 0.1	0.9 ± 0.1	8.7 ± 1.0
20-30	826.6 ± 6.9	30.2 ± 4.4	143.4 ± 10.7	4.6 ± 0.03	4.3 ± 1.7	0.01 ± 0.002	0.01 ± 0.002	0.4 ± 0.1	0.6 ± 0.1	1.1 ± 0.1	9.9 ± 0.8
Improved pasture											
0-10	803.6 ± 25.4	35.2 ± 1.5	161.0 ± 25.7	5.2 ± 0.1	12.6 ± 5.1	0.07 ± 0.006	0.03 ± 0.002	2.1 ± 0.2	1.3 ± 0.05	0.2 ± 0.02	7.3 ± 1.2
10-20	817.4 ± 17.1	31.2 ± 2.8	152.0 ± 15.8	5.3 ± 0.1	12.7 ± 4.4	0.04 ± 0.004	0.02 ± 0.002	2.0 ± 0.05	1.2 ± 0.1	0.2 ± 0.05	7.5 ± 0.6
20-30	810.6 ± 13.1	28.4 ± 4.7	161.0 ± 16.9	5.3 ± 0.1	6.2 ± 1.4	0.03 ± 0.005	0.01 ± 0.002	1.3 ± 0.1	1.3 ± 0.1	0.4 ± 0.1	7.5 ± 0.7
Annual crops											
0-10	827.0 ± 4.8	27.2 ± 5.1	145.8 ± 5.2	5.2 ± 0.1	10.7 ± 3.2	0.07 ± 0.008	0.02 ± 0.002	1.2 ± 0.1	0.9 ± 0.2	0.2 ± 0.02	9.5 ± 0.7
10-20	793.4 ± 5.9 b	26.0 ± 2.9	181.0 ± 4.8	5.2 ± 0.1	9.4 ± 2.7	0.06 ± 0.01	0.02 ± 0.002	1.2 ± 0.1	0.9 ± 0.1	0.1 ± 0.02	8.3 ± 0.9
20-30	775.2 ± 4.7 b	28.6 ± 2.0	195.8 ± 4.9	5.3 ± 0.1	11.4 ± 5.0	0.06 ± 0.02	0.02 ± 0.004	1.2 ± 0.2	0.9 ± 0.2	0.2 ± 0.03	7.4 ± 0.8

al., 2001); and (ii) considering labile C as the SOM fraction with size between 53 and 2000 µm (Dieckow et al., 2005; Vieira et al., 2007).

The carbon content of the microbial biomass was determined by the fumigation-extraction method, using 0.38 as the correction factor (Vance et al., 1987). Soil microbial quotient (qMIC) was also calculated according to Anderson and Domsch (1989).

The normal distribution of the data was evaluated by the Shapiro-Wilk test. As normality was not confirmed and the independence assumption was not satisfied, data were subjected to the non-parametric analysis of Kruskal-Wallis and the means were compared by the Bonferroni (Dunn) test. Linear Pearson correlation coefficients (R²) were also calculated for the evaluated parameters. Statistical analyses were carried out using the SAS 9.0 software package.

Results

The C stock in improved pasture (0-30 cm) was higher than in any other anthropic use (50.37 ± 6.39 Mg ha⁻¹) and similar to that in native vegetation (42.63 ±

5.10 Mg ha⁻¹) (Table 3). Improved pasture also showed the highest N stock in the 0-30 cm layer (3.33 ± 0.27 Mg ha⁻¹). Accumulated C and N stocks in the 0-30 cm layer were similar to those in the areas under secondary vegetation, fruit orchards, horticulture, degraded pasture and annual crops.

Native vegetation and improved pasture had the highest C contents in the fraction greater than 53 µm, reflecting the constant addition of litter in these uses (Table 4 and Figure 1). This fraction contained 19 % of the total C in native vegetation and 11 % in the other areas (mean of the other land uses evaluated). In all land uses the fraction < 53 µm contained most of the soil C: approximately 74 % in native vegetation and 83 % in other uses (Figure 1). In improved pasture, the organic fraction between 53 and 2000 µm contained 12 % of the total C and the fraction < 53 µm contained 83 % of the total C.

The greatest contents of labile C (by physical fractionation) were observed in native vegetation and improved pasture, followed by fruit orchards, while the highest non-labile C contents occurred in the improved pasture, followed by native vegetation and secondary

Table 3 – C content, bulk density and C stock in the 0-10 cm, 10-20 cm and 20-30 cm layers and C stocks accumulated in the first 30 cm of depth in soils under different land uses in São Luís, MA, Brazil (mean \pm standard error of the mean). In each land use, lowercase letters compare means on the columns. Means followed by the same letter in the column do not differ as per the Bonferroni test ($\alpha = 0.05$).

Soil layer cm	C content		N content		C/N Ratio	Bulk density		C stock		N stock	
	%					g cm ⁻³		Mg ha ⁻¹			
Native vegetation											
0-10	1.22 \pm 0.13 a	0.07 \pm 0.02 a	18.43 \pm 1.13 a	1.23 \pm 0.09 c	15.01 \pm 1.60 a	0.82 \pm 0.29 Aa					
10-20	1.04 \pm 0.20 a	0.06 \pm 0.02 a	18.78 \pm 2.62 a	1.40 \pm 0.07 b	14.56 \pm 2.78 a	0.77 \pm 0.36 Aa					
20-30	0.87 \pm 0.09 a	0.05 \pm 0.02 a	18.24 \pm 1.48 a	1.50 \pm 0.02 a	13.06 \pm 1.30 a	0.72 \pm 0.24 Aa					
Accumulated stocks of elements (Mg ha ⁻¹)					42.63 \pm 5.10	2.31 \pm 0.18					
Secondary vegetation											
0-10	0.85 \pm 0.06 a	0.06 \pm 0.01 a	14.72 \pm 0.54 a	1.40 \pm 0.01 b	11.83 \pm 0.84 a	0.80 \pm 0.14 a					
10-20	0.66 \pm 0.08 a	0.04 \pm 0.01 b	15.20 \pm 1.06 a	1.37 \pm 0.07 c	9.09 \pm 1.15 a	0.59 \pm 0.18 b					
20-30	0.68 \pm 0.08 a	0.04 \pm 0.01 b	16.37 \pm 0.89 a	1.52 \pm 0.05 a	10.22 \pm 1.31 a	0.62 \pm 0.19 ab					
Accumulated stocks of elements (Mg ha ⁻¹)					31.14 \pm 2.56	2.01 \pm 0.11					
Fruit trees											
0-10	0.85 \pm 0.06 a	0.05 \pm 0.01 a	15.89 \pm 1.05 a	1.25 \pm 0.17 c	10.54 \pm 0.71 ab	0.66 \pm 0.13 ab					
10-20	0.78 \pm 0.05 a	0.05 \pm 0.01 a	15.12 \pm 1.09 b	1.55 \pm 0.004 b	12.04 \pm 0.79 a	0.80 \pm 0.19 a					
20-30	0.62 \pm 0.04 b	0.04 \pm 0.01 b	15.79 \pm 0.96 ab	1.59 \pm 0.006 a	9.31 \pm 0.66 b	0.59 \pm 0.10 b					
Accumulated stocks of elements (Mg ha ⁻¹)					31.89 \pm 1.92	2.05 \pm 0.09					
Horticulture											
0-10	0.82 \pm 0.14 a	0.06 \pm 0.04 a	13.43 \pm 1.18 b	1.48 \pm 0.02 b	12.15 \pm 2.02 a	0.92 \pm 0.48 a					
10-20	0.65 \pm 0.05 a	0.04 \pm 0.01 a	14.80 \pm 2.26 ab	1.53 \pm 0.01 a	10.05 \pm 0.77 a	0.69 \pm 0.22 a					
20-30	0.67 \pm 0.11 a	0.04 \pm 0.02 a	15.45 \pm 0.54 a	1.48 \pm 0.08 b	9.98 \pm 1.59 a	0.65 \pm 0.28 a					
Accumulated stocks of elements (Mg ha ⁻¹)					32.19 \pm 3.65	2.26 \pm 0.21					
Degraded pasture											
0-10	0.72 \pm 0.02 a	0.04 a	18.31 \pm 1.06 a	1.56 \pm 0.03 b	11.27 \pm 0.40 a	0.61 \pm 0.03 a					
10-20	0.64 \pm 0.03 ab	0.04 \pm 0.01 a	16.04 \pm 0.75 a	1.57 \pm 0.02 a	9.99 \pm 0.45 ab	0.62 \pm 0.08 a					
20-30	0.63 \pm 0.02 b	0.04 \pm 0.01 a	16.93 \pm 1.07 a	1.45 \pm 0.002 c	9.34 \pm 0.40 b	0.55 \pm 0.05 b					
Accumulated stocks of elements (Mg ha ⁻¹)					30.60 \pm 1.03	1.78 \pm 0.03					
Improved pasture											
0-10	1.35 \pm 0.17 a	0.09 \pm 0.04 a	14.86 \pm 1.92 a	1.45 \pm 0.05 c	19.61 \pm 2.42 a	1.35 \pm 0.55 a					
10-20	1.14 \pm 0.16 ab	0.07 \pm 0.02 ab	15.21 \pm 1.32 a	1.51 \pm 0.01 b	17.16 \pm 2.45 ab	1.12 \pm 0.39 a					
20-30	0.91 \pm 0.14 b	0.06 \pm 0.03 b	15.67 \pm 1.16 a	1.61 \pm 0.02 a	13.60 \pm 2.09 b	0.86 \pm 0.32 a					
Accumulated stocks of elements (Mg ha ⁻¹)					50.37 \pm 6.39	3.33 \pm 0.27					
Annual crops											
0-10	0.87 \pm 0.05 a	0.06 \pm 0.01 a	14.89 \pm 0.68 a	1.40 \pm 0.04 c	12.14 \pm 0.66 a	0.82 \pm 0.13 a					
10-20	0.75 \pm 0.06 a	0.05 \pm 0.02 a	15.59 \pm 0.94 a	1.44 \pm 0.09 b	10.83 \pm 0.83 a	0.70 \pm 0.19 a					
20-30	0.53 \pm 0.03 b	0.03 \pm 0.01 b	15.87 \pm 0.92 a	1.46 \pm 0.04 a	7.95 \pm 0.52 b	0.50 \pm 0.10 b					
Accumulated stocks of elements (Mg ha ⁻¹)					30.92 \pm 1.55	2.02 \pm 0.08					

vegetation. In all areas, the CMI calculated by physical fractionation was lower than the reference area value. Improved pasture had the highest CMI in disturbed areas (57.2), followed by fruit orchards (47.5).

The highest values for labile and non-labile C obtained by oxidation with $K_2Cr_2O_7$ were observed in the improved pasture (Table 5). CMIs in horticultural (97.1) and secondary vegetation (86.2) were close to the reference zone. Using this method, the CMI in improved pasture was 24 % higher than that in native vegetation (Table 5).

Oxidation with $K_2Cr_2O_7$ resulted in higher CMI values when compared to those obtained when using the physical fractionation method (Figure 2). CMI calculated by physical fractionation showed improved pas-

ture was the use which gave the result closest to native vegetation, while CMI calculated by $K_2Cr_2O_7$ oxidation surpassed native vegetation. Labile C obtained by oxidation was positively and moderately correlated to the labile C content obtained by physical fractionation ($R^2 = 0.40$; $p = 0.02$). However, a stronger correlation was observed between the labile C determined by oxidation and the non-labile C determined by physical fractionation ($R^2 = 0.69$; $p < 0.01$).

The C content of the microbial biomass ranged from 0.056 to 0.181 g kg⁻¹ of soil (Table 6). The highest values occurred in orchards and the lowest in annual crops and degraded pasture. The soil microbial quotient ranged from less than 1 % in improved pasture to 3 % at the fruit tree site.

Table 4 – Total carbon content, Carbon Pool Index (CPI), contents of labile and non-labile C, L (lability), lability index (LI) and carbon management index (CMI) in the 0-10 cm layer (mean \pm standard error of mean) obtained from the physical fractionation of organic matter in soils under different land uses in São Luís, MA, Brazil. Means followed by the same letter in the column do not differ by the Bonferroni test ($\alpha = 0.05$).

Land use	Total C content	CPI ^b	Labile C ^c		L ^e	LI ^f	CMI ^g
	g kg ⁻¹		g kg ⁻¹				
Native vegetation ^a	12.88 \pm 3.33 a	1.00	3.42 \pm 2.41 a	9.45 \pm 2.21 ab	0.36	1.00	100.0
Secondary vegetation	8.70 \pm 1.77 b	0.67	1.45 \pm 0.24 bc	7.25 \pm 1.65 bc	0.20	0.56	37.5
Fruit trees	8.46 \pm 1.59 b	0.66	1.73 \pm 0.86 ab	6.73 \pm 0.93 cd	0.26	0.72	47.5
Horticulture	7.99 \pm 2.95 bc	0.62	1.48 \pm 0.67 bc	6.51 \pm 2.31 cd	0.23	0.64	39.7
Degraded pasture	6.93 \pm 1.07 c	0.54	1.12 \pm 0.41 c	5.80 \pm 0.69 d	0.19	0.53	28.6
Improved pasture	13.44 \pm 3.92 a	1.04	2.21 \pm 0.38 a	11.23 \pm 4.08 a	0.20	0.55	57.2
Annual crops	8.11 \pm 1.31 bc	0.63	1.21 \pm 0.42 bc	6.90 \pm 0.96 c	0.17	0.47	29.6

^aReference area for the calculations of CPI, LI and CMI; ^bCPI = C pool in treatment/C pool in the reference area; ^clabile C = C in labile fractions with size between 53 and 2000 μ m; ^dnon-labile C = C in the labile fraction with size lower than 53 μ m; ^eLability (L) = Labile C content in the treatment / non-labile C content in the treatment; ^fLability Index (LI) = lability in the treatment / lability in the reference area; ^gCarbon Management Index (CMI) = CPI \times LI \times 100.

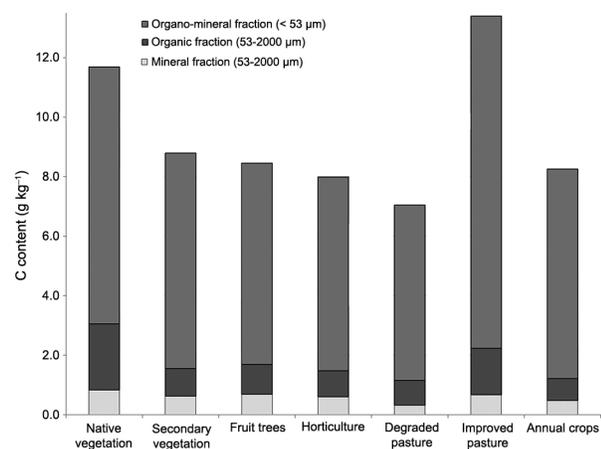


Figure 1 – C content (g kg⁻¹ soil) in physical fractions of soil organic matter (0-10 cm) obtained by wet sieving in areas under different land uses in São Luís, MA, Brazil.

Discussion

Native vegetation contains about 42.6 Mg ha⁻¹ of C in the first 30 cm (Table 3). In Amazonian soils, the first 30 cm contains 52 % of C stored in the first meter (Batjes and Dijkshoorn, 1999). Therefore, the native vegetation area in this study should have had approximately 82 Mg ha⁻¹ of C in the first meter. The C stock of the first meter of soil in São Luís has been shown to vary between 95 and 115 Mg ha⁻¹ (Batjes and Dijkshoorn, 1999), but our results indicated lower levels.

Considering the first 30 cm of soil, with the exception of improved pasture, soil C stocks were lower than in the native vegetation. Tillage operations, common after the conversion of native vegetation into other uses, can cause a sizeable loss of soil C (Silva-Olaya et al., 2013). In tropical regions, the conversion of native vegetation into pasture results in the loss of 12 % of soil organic C, mainly due to overgrazing, high export of biomass, and the lack of replenishment of nutrients

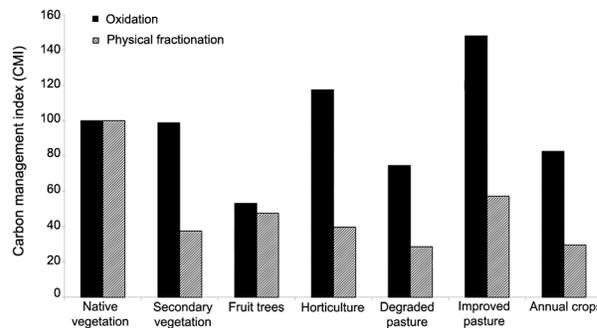


Figure 2 – Comparison between carbon management indexes (CMIs) calculated from C values obtained by oxidation of C with K₂Cr₂O₇, and by physical fractionation of soil organic matter, in 0-10 cm layer, in areas under different land uses in São Luís, MA, Brazil.

(Don, 2011), typical characteristics of poorly managed pastures that will most likely become degraded.

In the Amazon region, degraded pastures can lose about 0.28 Mg ha⁻¹ yr⁻¹ of C, while well-managed pastures with appropriate grazing intensity can have soil C stocks similar to those in soils under native forest (Maia et al., 2009). In this study, degraded pasture lost approximately 0.34 Mg ha⁻¹ yr⁻¹ of C, while well-managed pasture had a soil C stock similar to that for soil under native vegetation. However, taking into account that the improved pasture was established after the pasture was allowed to reach a degraded state, this land use accumulated 1.98 Mg ha⁻¹ yr⁻¹ of C and 0.15 Mg ha⁻¹ yr⁻¹ of N. These observations confirm the results of Carvalho et al. (2010), working with different land uses in Brazil, and state that it is soil management which determines whether the conversion from native vegetation to other uses will be a source or a drain of carbon. These authors also observed that non-degraded pastures can accumulate 0.46 g ha⁻¹ yr⁻¹ of C in the soil. In the Amazon region, C sequestration in well-managed pastures can reach 0.61 Mg ha⁻¹ yr⁻¹ due to the influence of the forage root system (Maia et al., 2009; Don, 2011), since nitrogen fertilization (common in

Table 5 – Total carbon content (g kg^{-1}), carbon pool index (CPI), levels of labile and non-labile carbon (g kg^{-1}), L (lability), lability index (LI) and carbon management index (CMI) in the layer 0-10 cm (mean \pm standard error of the mean) obtained by oxidation of C with $\text{K}_2\text{Cr}_2\text{O}_7$ in soils under different land uses in São Luís, MA, Brazil. Means followed by equal letters in the column do not differ by Bonferroni test ($\alpha = 0.05$).

Land use	Total C content	CPI ^b	Labile C	Non-labile	L ^c	LI ^d	CMI ^e
	g kg^{-1}		g kg^{-1}				
Native vegetation ^a	12.21 \pm 1.30 a	1.00	5.74 \pm 1.47 ab	6.47 \pm 1.30 ab	0.89	1.00	100.00
Secondary vegetation	8.47 \pm 0.60 b	0.69	4.46 \pm 0.58 ab	4.01 \pm 0.28 ab	1.11	1.25	86.2
Fruit trees	8.46 \pm 0.57 b	0.69	3.42 \pm 0.52 b	5.04 \pm 0.51 ab	0.68	0.76	52.4
Horticulture	8.19 \pm 1.36 b	0.67	4.62 \pm 0.37 ab	3.57 \pm 1.10 b	1.29	1.45	97.1
Degraded pasture	7.24 \pm 0.26 b	0.59	3.25 \pm 0.37 b	4.00 \pm 0.22 b	0.81	0.91	53.7
Improved pasture	13.49 \pm 1.67 a	1.10	6.77 \pm 0.83 a	6.73 \pm 1.07 a	1.01	1.13	124.3
Annual crops	8.66 \pm 0.47 b	0.71	4.13 \pm 0.91 b	4.53 \pm 0.63 ab	0.91	1.02	72.4

^aReference area for calculations of CPI, LI and CMI; ^bC pool in treatment/C pool in the reference area; ^cLability (L) = Labile C content in the treatment / non-labile C content in the treatment; ^dLability Index (LI) = lability in the treatment / lability in the reference area; ^eCarbon Management Index (CMI) = CPI \times LI \times 100.

Table 6 – Land uses and levels of microbial C biomass, organic C (mean \pm standard error of the mean) and microbial quotient in the 0-10 cm layer in São Luís, MA, Brazil. Means followed by the same letter in the column do not differ (Bonferroni test, $\alpha = 0.05$).

Land use	Microbial C	Organic C	Microbial quotient (%) (microbial C / organic C)
	g kg^{-1} soil		
Native vegetation	0.147 \pm 0.026 b	10.90 \pm 0.64 a	1.35 \pm 0.25
Secondary vegetation	0.094 \pm 0.017 c	8.25 \pm 0.36 b	1.14 \pm 0.21
Fruit trees	0.181 \pm 0.016 a	5.90 \pm 0.32 c	3.07 \pm 0.32
Horticulture	0.154 \pm 0.010 ab	7.78 \pm 0.52 b	1.98 \pm 0.18
Degraded pasture	0.042 \pm 0.067 e	5.37 \pm 0.25 c	0.78 \pm 1.25
Improved pasture	0.066 \pm 0.007 cd	12.40 \pm 0.62 a	0.53 \pm 0.06
Annual crops	0.056 \pm 0.005 de	7.92 \pm 0.39 b	0.71 \pm 0.07

well-managed pastures) stimulates forage biomass production and leads to the recovery of C in the soil (Sodhi et al., 2009; Vieira et al., 2007). In the improved pasture in this study, which is used as "a cut and carry grass field", cutting may have stimulated the increase of root density more than grazing (Cunha et al., 2010). Thus, cutting, irrigation and fertilization may explain why the improved pasture showed a higher C accumulation rate than the well-managed pastures studied by Maia et al. (2009).

The organic fraction between 53 and 2000 μm ranged from 9 % (annual crops) to 19 % (native vegetation) of the total C. This fraction consists of recently added material, in the early stages of decomposition, with a short residence time in the soil (Christensen, 2001). Our results confirm that this fraction can undergo rapid change as a result of soil management practices, as observed by Tisdall and Oades (1982), better reflecting such change in the total soil C content, as noted by Christensen (1992). In all land uses, the amount of C in the organic fraction between 53 and 2000 μm was lower than in the native vegetation (Figure 1). The conversion of native vegetation into degraded pasture reduced the C in this

fraction by 38 % ($0.04 \text{ g kg}^{-1} \text{ yr}^{-1}$), but the improvement of pasture led to the recovery of C in this fraction ($0.07 \text{ g kg}^{-1} \text{ yr}^{-1}$). Even though this fraction has been rapidly lost due to the change in land use, it was quickly recovered after improved pasture was introduced.

Changing the land use from native vegetation to fruit orchards reduced the C content in the fraction 53-2000 μm to about 45 % of the original content (approximately $0.04 \text{ g kg}^{-1} \text{ yr}^{-1}$). When the fruit orchard was converted to secondary vegetation, C content was reduced to 42 % (loss rate $0.004 \text{ g kg}^{-1} \text{ yr}^{-1}$), while subsequent horticultural use reduced it to 40 % of the original content (loss rate $0.0045 \text{ g kg}^{-1} \text{ yr}^{-1}$). In this case, soil C losses due to soil tillage may have been minimized by the frequent addition of organic compounds in orchards and horticultural areas.

In the fraction $< 53 \mu\text{m}$ the percentage ranged from 74 % to 85 % of total C (Figure 1). This fraction usually makes up 30-70 % of total C in tropical soils and contains the primary organomineral complexes with high residence time in the soil, which are physically protected against decomposition due to stable bonds formed with soil minerals (Christensen, 2001). Even though native vegetation had the lowest percentage of the total soil C content in this fraction, this land use has the second largest absolute amount of C in the fraction $< 53 \mu\text{m}$. However, since the native vegetation had the largest absolute C content in the organic fraction between 53 and 2000 μm , this fraction has a greater relative importance than in other areas, reducing the percentage of the total C stored in the fraction $< 53 \mu\text{m}$.

In anthropic uses, C content in the $< 53 \mu\text{m}$ fraction was between 70 % and 85 % of that in the native vegetation. The exception was improved pasture, where there was an increase of 29 % ($0.53 \text{ g kg}^{-1} \text{ yr}^{-1}$ of C) in the C content in this fraction after the conversion from degraded pasture. This area is subject to frequent irrigation and fertilization with a regular input of crop residues, but there is no tillage, and the temperature is constant throughout the year, which may have supported microbial activity (Brady and Weil, 2008) and thus

the transformation of particulate SOM into smaller and more stable complexes (Christensen, 2001).

Because of this, improved pasture also had CPI and CMI values similar to or greater than the native vegetation, and should be considered sustainable as it is maintaining C in the system (Blair et al., 1995). Therefore, our results indicate well-managed pastures in this region, with adequate nutritional and water management, can increase the amount of C stored in the soil, confirming previous results (Moraes et al., 2002; Silva Junior et al., 2009; Maia et al., 2010), and can also improve the C quality in the system.

The chemical method for the determination of labile C resulted in higher CMI values than the physical SOM fractionation (Figure 2). Physical fractionation separates the organic material not bound to minerals, while chemical fractionation with $K_2Cr_2O_7$ can also attack the organic fraction weakly bound to minerals, overestimating the amount of labile C and consequently the CMI (Vieira et al., 2007). This explains why the correlation between the labile C by oxidation and the non-labile C obtained by physical fractionation was stronger than the correlation obtained where labile C had been acquired by physical fractionation. As indicated by Vieira et al. (2007), the CMI calculated from the light SOM fraction is more accurate than CMI calculated by oxidation with $K_2Cr_2O_7$.

Microbial C content in the soil under native vegetation (147 mg kg^{-1}) was similar to that observed by Frazão et al. (2010) in another sandy soil from the Amazon in Brazil ($101.4 \text{ mg C kg}^{-1}$ soil). Soils under native vegetation usually have greater C contents than soils from agricultural areas due to the continuous and diversified supply of organic matter, which is responsible for the structure and development of the microbial community (Frazão et al., 2010; Lammel et al., 2015).

In this study, irrigation and the input of organic fertilizers resulted in high levels of microbial C in fruit orchards and horticultural sites (Table 6), with irrigation minimizing the effect of the dry season on soil microbial biomass. According to Lou et al. (2011), areas receiving manure have high soil microbial biomass.

The lowest microbial quotients were observed in annual crops and pastures. This indicates that microbial biomass is under stress, possibly due to the quality and/or quantity of available crop residues. The addition of low-quality waste (higher C/N ratio) is responsible for the weak relationship between microbial C and total organic C, i.e. soil microbial quotient (Deng et al., 2016). The forage C/N ratio in improved pasture was 39 and in degraded pastures it was 30, which may have limited microbial growth and explains the observed microbial quotient.

Converting native vegetation into agricultural areas or pastures reduced the amount of C immobilized by microorganisms. However, cultivation systems with large inputs of organic material and irrigation, with low- or no-tillage had microbial C contents similar to the native vegetation. This alone is not enough to indicate that these land uses are superior to native vegetation,

because this performance is due to management practices, the use of external C sources, and its implementation in a relatively small area. Its sustainability must be evaluated in the long term and obviously other variables should be taken into account.

In addition to encouraging C accumulation in soil, well-managed pastures can be productive for up to 35 years (Cerri et al., 2007) and the recovery of degraded areas improves water quality, plant biomass production and reduces the amount of CO_2 emissions into the atmosphere (Lal, 2008). This also has environmental and economic benefits as the capacity for animal stock and greater meat production in that area will be higher. Therefore, the recovery or restoration of grasslands in the Amazon region is a sustainable strategy for increasing soil C stocks. Such practices should be encouraged and disseminated, and will contribute to reduce the pressure for deforestation in areas covered with native vegetation, especially in the Amazon region.

Conclusions

In the region under evaluation, the conversion of native vegetation to other land uses reduced the C stored in the soil. However, well-managed pastures have the potential to accumulate C in the soil in larger amounts than in native areas. Furthermore, the quality of soil C accumulated in these pastures is better than in degraded pastures or in agricultural areas. Therefore, refurbishment and renovation of pastures in this region are viable alternatives for increasing the capacity for animal stock and promoting accumulation of C in the soil. Such programs should be continually encouraged by government policies in order to reduce the pressure for deforestation of native forests.

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