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Soil Organic Matter Quality in *Jatropha* spp. Plantations in Different Edaphoclimatic Conditions

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ABSTRACT: The substitution of native vegetation by agricultural ecosystems can change the quantity and quality of soil organic matter (SOM), and the intensity of these changes depends on the soil type, climate, and land use. The objective of this study was to evaluate the quality of organic matter in chronosequences of *Jatropha* cultivation in contrasting soil and climatic conditions. Soil samples were evaluated at depths of 0.00-0.10, 0.20-0.30, and 0.80-1.00 m in chronosequences located in Planaltina, Distrito Federal (*Cerrado*-Pasture-*Jatropha*), Dourados, Mato Grosso do Sul (Atlantic Forest-Corn-*Jatropha*), and Araripina, Pernambuco (*Caatinga-Jatropha*). To assess SOM quality, we determined C contents in the SOM fractions, C stocks, the carbon management index (CMI), the SOM humification index (H_{LIF}), and the C and N concentrations in the microbial biomass. The conversion of native vegetation to agropastoral systems changed the composition of SOM in the biomes evaluated, especially in the surface layers. The CMI and the C and N contents in the microbial biomass were the most responsive to land use changes in all the biomes studied. The pasture improved SOM quality by increasing the CMI (116) and the C content by 8, 21, and 6 % in the organic, mineral, and organomineral fractions, respectively, while maintaining the SOM humification index and the C and N contents in the microbial biomass in the 0-0.10 m layer. The lowest values of C in the SOM fractions, the CMI (52), and C microbial biomass (136 mg kg^{-1}) were observed for annual crops. *Jatropha* cultivation increased C contents in the SOM fractions, C stocks, the CMI, and C and N in the microbial biomass with an increase in cultivation time, which demonstrates the potential of this long-term system for improving SOM quality.

Keywords: land use change, soil carbon fractionation, carbon management index, laser-induced fluorescence spectroscopy, microbial biomass.

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INTRODUCTION

The most recent report prepared by the Intergovernmental Panel on Climate Change (IPCC) emphasizes that the greenhouse gas (GHG) emissions from anthropic actions, including farming, are now the main causes of climate changes (Stavi and Lal, 2013; IPCC, 2014). Among the mitigation measures, the report indicates better treatment of emissions and increased participation of biofuels in the energy mix, while not impairing food safety or reduction of poverty.

Among the oilseed plants available for biodiesel production, various species of the *Jatropha* genus are promising due to their high oil production per unit of growing area and adaptability to marginal and degraded areas that are unsuitable for food, thus not competing with food crops (Wani et al., 2012). On the other hand, most of these species are considered exotic and are not yet completely domesticated (Pandey et al., 2012).

The use of biodiesel produced from oilseed plants such as *Jatropha* spp. can bring important benefits by substituting fossil fuels, which attenuates the exacerbated accumulation of greenhouse gases in the atmosphere. It is estimated that reduction in GHG emissions by replacing fossil fuels with biodiesel (i.e., offsetting) ranges from 30 to 60 % (Souza et al., 2015).

Additionally, because they are perennial plants, *Jatropha* spp. can be used to preserve soil as well as accumulate C in the soil (Srivastava et al., 2014). In this latter respect, several studies have shown that growing crops for production of renewable energy also has potential for accumulating C in the soil by incorporation of substantial amounts of plant residues (La Scala Junior et al., 2012; Srivastava et al., 2014; Souza et al., 2015).

Alterations in soil organic matter (SOM) content can be measured by changes in the concentration of total C in the soil and its chemical and physical fractions. However, the use of total C content is of limited value since small changes are hard to detect (Blair et al., 1995). This makes it important to evaluate the C concentrations in the soil compartments to verify the ability of *Jatropha* spp. cultivation in improving the quality of SOM.

Various methods can be used to assess the quality of SOM. The C associated with microbial biomass accounts for 2 to 4 % of the total organic C in the soil, but because it is an active fraction of SOM, it is more sensitive than the levels of total organic C for ascertaining changes caused by soil use or management practices (Gama-Rodrigues and Gama-Rodrigues, 2008).

Techniques involving physical fractionation of soil samples can be useful to evaluate alterations in the SOM compartments, especially in short time frames (Rossi et al., 2012). These techniques are also considered to be less destructive, and the results obtained are directly related to the structure and function of the organic matter *in situ* (Ladd et al., 1993). Additionally, by measurement of the light SOM fraction (labile C), obtained in physical fractionation, it is possible to calculate the carbon management index (CMI), which is a measure of the relative sustainability of different systems and can be used to compare the changes that occur in the concentrations of labile and total C as a result of farming practices (Vieira et al., 2007).

Another method that can be used to evaluate the quality of SOM is laser-induced fluorescence spectroscopy (Milori et al., 2006), which allows determination of the humification of the soil in samples without pretreatment. According to these authors, light in the blue wavelength region (465 nm) mainly excites structures whose concentration increases during the humification process, such as functional groups with unsaturated bonds in rigid conjugated systems (conjugated and/or substituted aromatic rings, quinones, etc.) (Favoretto et al., 2008). Therefore, the fluorescence signal emitted is proportional to the degree of humification of the SOM.

The hypothesis of this study was that the cultivation of *Jatropha* spp. improves the quality of the SOM in relation to previous soil uses and that this improvement increases with time. Therefore, we evaluated alterations in the quality of soil organic matter by quantifying the concentrations of C in the physical SOM fractions, the C stocks, the C management index, the degree of humification of C and the concentrations of C and N in the microbial biomass in chronosequences of *Jatropha* spp. cultivation under different edaphoclimatic conditions.

MATERIALS AND METHODS

Characterization of the studied areas

The study was carried out in three chronosequences in locations with different soil uses and contrasting edaphoclimatic conditions: Planaltina (Distrito Federal), Dourados (Mato Grosso do Sul), and Araripina (Pernambuco). These locations were chosen as representative of the conditions under which *Jatropha* spp. is typically cultivated in Brazil.

In Planaltina, the study was carried out in the experimental field of *Embrapa Cerrados*, at 15° 35' S and 47° 42' W and average altitude of 1,200 m above sea level. The rainy season lasts from October through April, with annual rainfall of 1,400 to 1,600 mm, 80 % of which falls between November and April. The average temperature is 21 °C, and remains relatively stable for most of the year. The soil is classified as a typical *Latossolo Vermelho Distrófico típico* according to the Brazilian Soil Classification System (Santos et al., 2013), and as a Rhodic Hapludox by the Soil Taxonomy system (Soil Survey Staff, 2014), with a predominantly clayey texture.

The soil samples in Planaltina came from a chronosequence composed of four areas cultivated with *Jatropha* spp., first planted 1 (J1), 2 (J2), 3 (J3), and 4 years (J4) beforehand in areas formerly occupied by pastures. Additionally, two adjacent areas were evaluated, with soils having the same textural class, one cultivated with forage grasses for about 30 years and the other with native vegetation (*Cerrado*, Brazilian tropical savanna, used as reference), for a total of six areas.

The second study location was situated in the experimental field of *Embrapa Agropecuária Oeste*, with geographic coordinates of 22° 14' S and 54° 49' W and average altitude of 452 m, in the municipality of Dourados. The climate in the region is classified as humid mesothermal (Cwa according to the Köppen scale), with hot and wet summers and dry winters. The average annual rainfall is 1,500 mm and average annual temperature is 22 °C. The soil is also classified as a *Latossolo Vermelho Distroférrico típico* according to the Brazilian Soil Classification System (Santos et al., 2013), and as a Rhodic Hapludox by the Soil Taxonomy system (Soil Survey Staff, 2014), with a predominantly clayey texture.

In Dourados, samples were obtained from a chronosequence composed of three areas cultivated with *Jatropha* spp., that were initially planted 3 (J3), 5 (J5), and 7 years (J7) before, as well as in an area formerly occupied by annual cropping (corn) with conventional preparation for over 30 years and an area with native vegetation (Atlantic Forest, used as a reference), for a total of five areas.

The final location studied was in Araripina, in the experimental field of the Pernambuco Agronomic Institute, located at 07° 27' S and 40° 24' W at an altitude of 831 m. The climate is tropical semiarid, with the rainy season lasting from November to April, average annual precipitation of 750 mm, and average temperature of 24 °C. The soil is classified as a *Latossolo Amarelo Distrófico típico* according to the Brazilian Soil Classification System (Santos et al., 2013), and as Xanthic Hapludox by the Soil Taxonomy system (Soil Survey Staff, 2014), with sandy-clay-loam texture. The chronosequence sampled was composed of two areas cultivated with *Jatropha* spp., first planted 4 (J4) and 6 years (J6) beforehand, and one with native vegetation (*Caatinga*, xeric shrubland, used a as reference), for a total of three areas.

In each of the areas, soil samples were collected in five trenches at depths of 0.00-0.10, 0.10-0.20, 0.20-0.30, 0.30-0.40, 0.40-0.60, 0.60-0.80 and 0.80-1.00 m. However, only the samples taken from the depths of 0.00-0.10 (surface layer), 0.20-0.30 (intermediate layer), and 0.80-1.00 m (deep layer) were used to evaluate the alterations in the quality of organic matter. The choice of those layers was based on the differences in the C stocks among them, as well as the different responses to changes in soil use.

After collection, the soil samples were air dried, homogenized, sifted through a 2 mm sieve and subjected to the sequence of analyses. The chemical and physical properties of the areas evaluated in Planaltina-DF, Dourados-MS, and Araripina-PE are shown in table 1.

Fractionation of soil organic matter

Soil samples from depths of 0.00-0.10, 0.20-0.30, and 0.80-1.00 m were used for physical fractionation of the soil organic matter (SOM), with five replications. The fractions were separated by the particle size method described by Cambardella and Elliott (1992). This involved mixing 20 g samples in 70 mL of distilled water in 100 mL glass flasks. Then the suspensions were subjected to dispersion by ultrasound for 15 min at the 70 % power setting, supplying energy of 130 J mL^{-1}.

After sonication, the samples were passed through a set of two sieves, one with openings of 75 µm (200 mesh) and the other with 53 µm (270 mesh). The fractions that remained in the 200 mesh sieve were separated into an organic fraction (OF 75-2,000 µm) and a mineral fraction 1 (MF1 75-2,000 µm) by flotation in water. In turn, the fractions that passed through the 200 mesh sieve were separated in the 270 mesh sieve into a mineral fraction 2 (MF2 53-75 µm), which was retained in the sieve, and an organomineral fraction (OMF <53 µm), which passed through the sieve. The MF1 and MF2 fractions together composed the mineral fraction (MF 53-2,000 µm).

At the end of physical fractionation, the following fractions were obtained: OF 75-2,000 µm; MF 53-2,000 µm; and OMF <53 µm. The recovery of initial mass after fractionation was higher than 95 %, indicating there were no significant losses in mass of the samples from the process.

The fractions were identified and placed in an oven at 45 °C for complete drying. Then the samples were weighed and ground. The concentrations of C in the fractions were determined by the dry combustion method (Nelson and Sommers, 1982) in an elemental analyzer. Based on the masses of each fraction (g of fraction kg^{-1} of soil) and C concentration (g of C kg^{-1} of fraction), the quantities of C of the fractions were calculated, expressed as g kg^{-1} of soil. Additionally, the total levels of organic C were determined for all the soil samples used in the physical fractionation of the SOM.

Carbon Management Index (CMI)

The CMI was calculated from the values of labile carbon (LC) and total organic carbon (TOC), expressed as stock (Mg ha^{-1}). The LC refers to the light fraction of the SOM, with particle size between 75 and 2,000 µm, obtained in the physical fractionation (Vieira et al., 2007), whereas the non-labile carbon (NLC) was determined by the difference (NLC = TOC - LC). The stocks of total carbon (CS), labile C (LCS), and non-labile C (NLCS) were calculated by multiplying the concentration obtained in percent by the soil density (Mg dm^{-3}) and thickness of the layer (m).

The lability (L) of the C, both in the reference and cultivated areas, was obtained by dividing LCS by NLCS. Based on these changes in the proportion of LCS (L = LCS/NLCS) in the soil, the lability index (LI) was determined as: $LI = L_{cultivated}/L_{reference}$. Also, based on the changes in the CS values between a reference system and corresponding cultivated system, the carbon pool index (CPI) was obtained, calculated as: $CPI = CS_{cultivated}/CS_{reference}$.

Finally, these two indices were used to calculate the CMI, according to the following expression: CMI = CPI × LI × 100, as proposed by Blair et al. (1995).

Table 1. Chemical and physical properties in soils with different uses in Planaltina-DF, Dourados-MS, and Araripina-PE, Brazil

Area[(1)]	pH($CaCl_2$)	CECe[(2)]	CECt[(3)]	V[(4)]	P[(5)]	S[(6)]	BD[(7)]	Clay[(8)]
		$mmol_c\ dm^{-3}$		%	mg dm^{-3}		Mg m^{-3}	g kg^{-1}
				0.00-0.10 m				
Planaltina								
Cerrado	4.0	17.7	96.3	3.3	3.9	1.5	1.09	515
Pasture	4.8	22.4	67.6	31.8	3.8	2.3	1.18	568
J1	5.4	50.1	76.9	64.8	4.5	5.9	1.10	575
J2	5.3	49.7	75.8	65.2	4.5	4.5	1.09	588
J3	5.3	63.1	89.7	69.0	7.5	2.6	1.10	567
J4	5.2	43.8	78.9	53.9	6.6	4.4	1.19	598
Dourados								
Atlantic Forest	5.3	112.1	157.0	70.7	16.2	8.5	0.89	699
Annual crops	4.6	46.0	108.7	39.3	48.4	17.0	1.22	623
J3	4.4	43.9	132.5	28.7	28.0	22.9	1.15	654
J5	4.5	53.1	130.9	38.8	42.8	15.8	1.06	650
J7	5.0	65.6	111.3	58.1	39.7	8.6	1.21	606
Araripina								
Caatinga	3.9	11.9	39.1	19.2	2.0	10.2	1.33	202
J4	4.8	22.9	37.1	51.4	10.4	18.0	1.28	204
J6	4.2	13.6	38.3	27.3	8.0	22.5	1.33	236
				0.20-0.30 m				
Planaltina								
Cerrado	4.1	10.8	70.8	2.4	2.8	0.5	1.10	556
Pasture	4.5	11.3	62.7	14.4	2.9	12.0	1.14	602
J1	4.7	15.4	57.9	25.1	2.9	16.5	1.13	604
J2	4.7	19.5	58.0	32.0	2.9	17.7	1.13	598
J3	4.6	21.5	63.6	32.1	3.7	8.4	1.17	589
J4	4.5	11.7	57.3	18.0	4.2	13.9	1.14	607
Dourados								
Atlantic Forest	4.9	49.3	98.7	48.5	9.2	7.9	1.07	718
Annual crops	4.5	26.7	78.7	27.7	10.4	84.0	1.09	652
J3	4.5	31.2	100.2	25.5	4.5	59.5	1.10	691
J5	4.5	37.2	98.6	32.8	6.3	70.5	1.19	684
J7	4.8	39.2	85.9	42.9	7.3	30.6	1.23	625
Araripina								
Caatinga	3.8	8.0	26.8	10.5	1.0	4.8	1.43	206
J4	4.1	9.5	27.5	21.6	2.3	8.9	1.38	209
J6	3.7	7.1	32.2	9.6	2.8	16.8	1.43	208
				0.80-1.00 m				
Planaltina								
Cerrado	4.2	4.0	47.3	3.1	2.2	1.3	0.94	570
Pasture	4.4	4.1	41.1	7.3	2.2	11.0	0.92	612
J1	4.7	3.8	33.9	8.2	2.1	4.0	0.88	635
J2	4.7	4.0	34.6	8.8	1.7	3.4	0.87	614
J3	4.4	3.1	37.9	5.5	2.2	4.4	0.98	609
J4	4.4	5.8	38.6	12.2	2.9	7.4	0.88	633
Dourados								
Atlantic Forest	4.8	21.7	61.5	33.8	6.6	4.4	1.04	771
Annual crops	4.2	14.3	68.7	6.7	6.6	2.9	1.12	652
J3	4.2	23.0	94.0	7.8	1.8	2.	0.94	727
J5	4.1	30.7	106.7	7.5	2.3	4.5	0.86	740
J7	4.5	9.4	52.3	15.2	3.2	5.2	1.07	654
Araripina								
Caatinga	4.0	11.0	32.0	12.3	1.0	35.8	1.37	388
J4	4.0	11.0	30.6	13.3	1.5	68.0	1.23	430
J6	3.9	8.3	32.8	9.0	1.7	37.5	1.37	381

[(1)] The areas evaluated refer to cultivation with *Jatropha* spp. over 1 (J1), 2 (J2), 3 (J3), 4 (J4), 5 (J5), 6 (J6), and 7 (J7) years, pasture, annual crops, and native vegetation (*Cerrado*, Atlantic Forest, and *Caatinga*). [(2)] Effective cation exchange capacity (CECe = BS+Al). [(3)] Total cation exchange capacity at pH 7.0 [CECt = BS + (H+Al)]. [(4)] Base saturation [V = (BS × 100)/T]. [(5)] Phosphorus was extracted by the resin ion exchange method and quantified by calorimetry (Raij et al., 2001). [(6)] Sulfur was extracted with 0.01 mol L^{-1} monocalcium phosphate and quantified by turbidimetry (Raij et al., 2001). [(7)] Soil bulk density was determined by the volumetric ring method (Claessen, 1997). [(8)] Clay content was determined by the Bouyoucos densimetry method (Grossman and Reinsch, 2002).

Laser-Induced Fluorescence spectroscopy (LIF)

Laser-Induced Fluorescence spectroscopy (LIF) is a soil analysis technique that has proven to be efficient in analyzing SOM in whole soil samples, providing fast and clear results under conditions near to natural ones (Milori et al., 2006). The technique consists of exciting functional groups of SOM with a laser with emission in the ultraviolet-blue region, resulting in fluorescence of functional groups of organic matter related to the humification process. This fluorescence occurs in the visible region, with a peak at approximately 510 nm.

Measurements were performed in soil samples from three layers (0.00-0.10, 0.20-0.30, and 0.80-1.00 m) in the different study areas. The humification index by the LIF method (H_{LIF}) was obtained by the ratio between the area under the fluorescence emission spectrum and the total carbon content (g kg^{-1}) present in the sample (Milori et al., 2006).

Microbial biomass

The levels of C and N in the microbial biomass were determined in the soil samples collected in the surface layer (0.00-0.10 m) by the extraction-fumigation method described by Vance et al. (1987), which consists of comparing samples fumigated with chloroform and control samples (not fumigated). Chloroform kills and ruptures the microbial cells, but does not affect the non-living organic matter.

For extraction, the fumigated and non-fumigated samples were placed in 250 mL Erlenmeyer flasks, into which 100 mL of a 0.5 mol L^{-1} solution of potassium sulfate was added. Then each flask was stirred for 30 min and the extracts were centrifuged at 1,200 rpm. The extracts were then removed from the centrifuge tubes with a 50 mL syringe and passed through a 120 mesh (0.125 mm) polyester filter. In this step, an aliquot of extract was separated for determination of C and another for determination of N.

The organic C content was measured by the wet oxidation-redox titration method (Walkley and Black, 1934). Microbial C was obtained by the difference between the levels of organic C in the fumigated and non-fumigated samples, multiplied by the correction factor related to extraction efficiency of 0.38 (Vance et al., 1987).

The N content of the microbial biomass was quantified by the N-ninhydrin method (Joergensen and Brookes, 1990). Ninhydrin is a compound that, when decarboxylated, reacts with substances of the α-amino group, produced by microbial cells, forming a violet-colored complex whose shade of coloration is proportional to the concentration of N present in the extract. Microbial N was obtained by the difference between the organic N contents of the fumigated and non-fumigated samples, multiplied by the correction factor related to extraction efficiency of 3.1.

Statistical analysis

The results of the contents of total C and OF 75-2,000 µm, MF 53-2,000 µm, and OMF <53 µm fractions obtained in fractionation of the soil organic matter, the humification index (H_{LIF}), the levels of C and N, and the C/N ratio of the microbial biomass underwent comparative analysis in accordance with the different soil uses in Planaltina, Dourados, and Araripina. For that purpose, the results were subjected to analysis of variance, considering a completely randomized experimental design, with five replications, and the difference in means was evaluated by the Tukey test (α=0.05), applying the SAS 9.3 statistical program.

RESULTS AND DISCUSSION

Carbon in the granulometric fractions of soil organic matter

The organomineral fraction (OMF), with particle size smaller than 53 µm, contained higher concentrations of C than the other fractions evaluated, irrespective of the area and depth analyzed (Figure 1). This fraction contained an average of 79, 92, and 85 %

total C content in the areas of Planaltina, Dourados, and Araripina, respectively, for the surface layer (0.00-0.10 m).

As depth increased, so did the relative contribution of OMF to the TOC. In the deepest layer (0.80-1.00 m), these contributions were 83, 95, and 92 % in Planaltina, Dourados, and Araripina, respectively. In general, the clay fraction contained most of the total C, with a high degree of decomposition and longer residence time (von Lutzow et al., 2008).

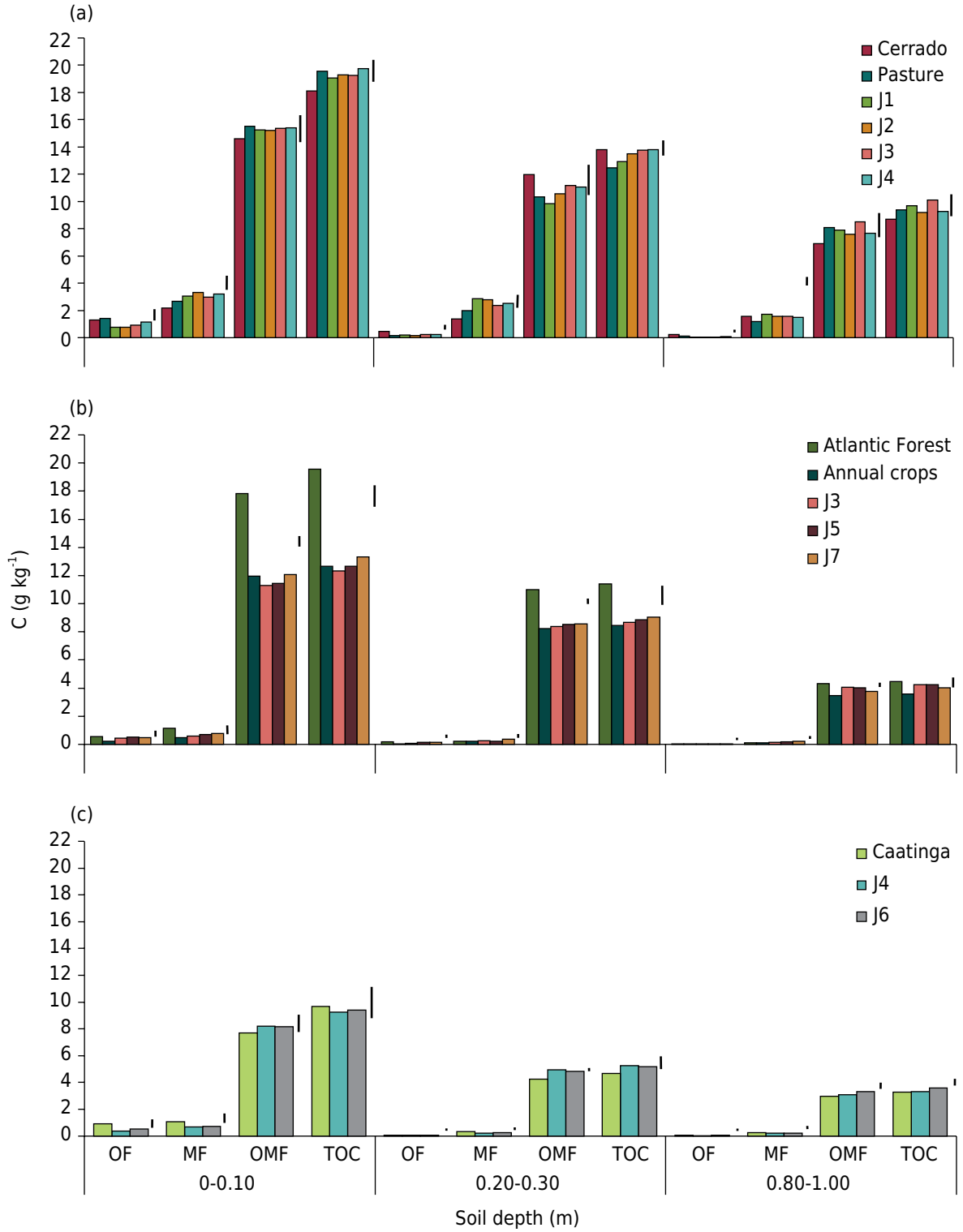

Figure 1. Concentrations of total organic carbon (TOC) and the organic fraction (OF), mineral fraction (MF), and organomineral fraction (OMF) of soil organic matter under different uses at depths of 0.00-0.10, 0.20-0.30, and 0.80-1.00 m in Planaltina-DF (a), Dourados-MS (b), and Araripina-PE (c), Brazil. The areas evaluated correspond to cultivation with *Jatropha* spp. over 1 (J1), 2 (J2), 3 (J3), 4 (J4), 5 (J5), 6 (J6), and 7 (J7) years, pasture, annual crops, and areas with native vegetation (*Cerrado*, Atlantic Forest, and *Caatinga*). Vertical lines represent a significant minimum difference by the Tukey test ($\alpha<0.05$) between soil uses at the same depth and the same fraction or soil.

The mineral fraction (MF), with particle size between 53 and 2,000 µm, basically composed of sand (coarse, medium, and fine), represented approximately 15.5 and 8 % of the TOC in Planaltina, Dourados, and Araripina, respectively, in the surface layer. Bayer et al. (2006), investigating an Acrisol with sandy-loamy texture, observed that the total C reservoirs in this fraction were lower than 10 %.

The higher levels of the MF observed in the samples from Planaltina were probably due to the method of separating the organic and mineral fractions in this study, which consisted of separation by flotation in water, unlike the traditional densimetric method of physical fractionation of SOM, in which liquids with higher density than water are used, permitting better separation of these fractions (Deon, 2013). Therefore, a portion of the organic fraction was left behind in the mineral fraction, enriching it with C and causing overestimation of the contents of the MF in the areas evaluated in Planaltina.

The organic fraction (OF), with particle size between 75 and 2,000 µm, corresponds to the micro-organic, particulate, or free light fraction of material. It is basically composed of plant residues in the initial decomposition stages, roots, and fungal hyphae (Cambardella and Elliot, 1992). In the three areas studied, this fraction accounted for approximately 6, 3, and 7 % of the TOC in Planaltina, Dourados, and Araripina, respectively, in the surface layer, with reduction in its quantity as depth increased. These variations in the quantity of the organic fraction in the soil profile are expected since this fraction is highly dependent on the input of C by plant residues and variation in the quantity of these residues in accordance with different cultivation systems.

In Planaltina, the labile fractions of the SOM (OF and MF) were more responsive to the change in soil use, with the highest values of C associated with these fractions occurring in the pasture areas, especially in the surface layer. In the soil under pasture for more than 30 years, increases of 8, 21, and 6 % were observed in the levels of C in the OF, MF, and OMF, respectively, in the surface layer. In comparison with the values obtained in the *Cerrado* areas, the same tendency regarding TOC was observed.

Comparing areas in pasture for more than 17 years with native vegetation (Amazon Forest), Lisboa et al. (2009) observed increases in C levels in all fractions, as well as alterations in C distribution among the fractions. In turn, Heid et al. (2009) reported reductions of 30.6 and 15.7 % of the C in the OF and OMF, respectively, in a pasture area in relation to the values observed in native forest in the 0.00-0.20 m layer of a *Latossolo Vermelho Distrófico*.

At the beginning of cultivation of *Jatropha* spp. in Planaltina, the concentration of C in the OF decreased by 45 % in the surface layer (0.00-0.10 m) in relation to the area with annual crops, but four years of this cultivation led to recovery of 26 % of the C in the OF. Ogunwole et al. (2008), studying the impact of growing *Jatropha curcas* on the quality of a degraded Entisol in India, found alterations in the levels of C and N and also in the soil structure. The authors attributed the improvement in soil quality to the fact that *Jatropha curcas* is a perennial and deciduous plant, which assures larger input of plant matter in the soil.

In Dourados, unlike in Planaltina, all the fractions were affected by the soil use, with the lowest values being observed in the area under annual cropping (corn) in all the fractions and depths. The shift from Atlantic Forest to annual cropping reduced the C by averages of 80, 34, and 25 % in the OF, MF, and OMF, respectively. In turn, the change from annual cultivation to *Jatropha* spp. maintained the levels of C of the OMF and increased the C associated with the other fractions, especially in the surface layer (0.00-0.10 m). However, the cultivation of *Jatropha* spp. for seven years was not sufficient to bring the levels of C up to those observed in the area with native vegetation.

The lower values measured in the area with annual cropping indicate that the conventional management used in the area reduces the input of plant residues and increases the exposure of the SOM to decomposition by microorganisms. Hartman et al. (2014), investigating the quantity of C in the soil in two long-term experiments involving two

farming practices (no-till and conventional) and crop rotation, observed a reduction of 45.7 g kg^{-1} in the content of TOC in a *Latossolo Vermelho Distrófico* in Ponta Grossa, Paraná, and 37 % of this decrease was C in the particulate fraction, indicating a clear reduction of C associated with minerals.

In Araripina, there was no statistical difference ($p<0.05$) among the concentrations of C in accordance with the different soil uses for the three SOM fractions and the depths analyzed, although the OF showed the greatest variations as a result of soil use. It can thus be inferred that although the time intervals and uses of the areas were different, the input of plant matter in the soil was similar. On average, the C values associated with the SOM fractions ranged from 0.61 to 0.05 g kg^{-1} in the OF, from 0.82 to 0.23 g kg^{-1} in the MF, and from 8.01 to 3.13 g kg^{-1} in the OMF among the depths. The average contributions to the TOC of the OF, MF, and OMF were 6, 9, and 85 %, respectively, in the surface layer.

Soil carbon stock and carbon management index (CMI)

In Planaltina, in the surface layer (0.00-0.10 m), the C stock in the pasture was 17 % higher than in the area with native vegetation (Table 2). Several researchers have reported that the conversion of *Cerrado* (savanna) to pasture increases the quantity of C in the soil (Corazza et al., 1999; Lardy et al., 2002; Carvalho et al., 2010).

Among the areas cultivated with *Jatropha* spp. in Planaltina, the highest C stocks were observed in the area under this cultivation for 4 years (J4), reaching 23.49 Mg ha^{-1} in the surface layer (Table 2), greater than the C stocks in the pasture and Cerrado areas. In the intermediate layer (0.20-0.30 m), as of two years of *Jatropha* spp. cultivation, the C stocks already surpassed those in the pasture and *Cerrado* areas.

In Dourados, the conversion from native vegetation to annual cropping (corn) with conventional soil preparation for 30 years reduced the C stocks by 11.2 and 24.3 % in the surface (0.00-0.10 m) and intermediate (0.20-0.30 m) layers, respectively (Table 2). Annual cropping, with intense soil turnover, causes a reduction in the C stock accumulated in the soil profile, as observed by Corazza et al. (1999) and La Scala Junior et al. (2012).

In the areas cultivated with *Jatropha* spp. in Dourados, there was a tendency for the C stocks to increase in accordance with cultivation time. The area with the longest *Jatropha* spp. cultivation (J7) reached C stocks of 16.13 and 11.13 Mg ha^{-1} in the surface and intermediate layers, respectively, exceeding the C stock in the annually cropped area (Table 2).

The different soil uses (*Caatinga*, *Jatropha* for 4 and 6 years) in Araripina rendered similar C stocks for the two depths evaluated (Table 2). The average C stock values in these areas were 12.4 and 6.6 Mg ha^{-1} for the surface and intermediate layers, respectively.

There is little information in the literature on the influence of cultivating *Jatropha* spp. on soil quality, especially the accumulation of C. Changes in C stocks in areas cultivated with *Jatropha* spp. range from losses of 34 to 50 Mg ha^{-1} of C when shifting from *Caatinga* and *Cerrado* native vegetation to *Jatropha* spp., respectively, to gains of 10 to 15 Mg ha^{-1} of C when changing to *Jatropha* spp. from agropastoral systems (Bailis and Baka, 2010; Bailis and McCarthy, 2011).

Evaluating the impact of converting from native vegetation to cultivation of *Jatropha curcas* in semiarid regions of Brazil and India, Bailis and McCarthy (2011) found losses of up to 54 % in C stocks in the cultivated areas analyzed in Brazil in the 0.00-0.30 m layer. However, the authors stressed that despite being adjacent to the cultivated area, the area with native vegetation (*Caatinga*) used as reference for the study in Brazil had different soil texture values than the area planted to *J. curcas*, making validation of the chronosequence difficult. In contrast, Wani et al. (2012) found increases of up to 19 % in the C stocks in seven degraded areas in India in the 0.00-0.15 m layer, with maximum annual rainfall of 800 mm.

In general, the results of this study show that the cultivation of *Jatropha* spp. maintained the C stocks in the soil, irrespective of the previous soil use (pasture, annual cropping, or native vegetation), with a tendency to increase the C stocks in accordance with the time of *Jatropha* spp. cultivation.

Table 2. Stocks of soil carbon (CS), labile carbon (LCS), and non-labile carbon (NLCS), carbon pool index (CPI), lability (L), lability index (LI), and carbon management index (CMI) at depths of 0.00-0.10 and 0.20-0.30 m in soils with different uses in Planaltina-DF, Dourados-MS, and Araripina-PE, Brazil

Area[1]	CS	LCS	NLCS	CPI[3]	L[4]	LI[5]	CMI[6]
	Mg ha^{-1}						
				0.00-0.10 m			
Planaltina							
Cerrado[2]	19.73	1.43	18.30	1.00	0.08	1.00	100
Pasture	23.09	1.66	21.43	1.17	0.08	0.99	116
J1	20.98	0.85	20.13	1.06	0.04	0.54	57
J2	21.04	0.83	20.21	1.07	0.04	0.53	56
J3	21.19	1.00	20.19	1.17	0.05	0.64	68
J4	23.49	1.35	22.14	1.19	0.06	0.78	93
Dourados							
Atlantic Forest[2]	17.40	0.49	16.91	1.00	0.03	1.00	100
Annual crops	15.45	0.25	15.20	0.89	0.02	0.58	52
J3	14.19	0.52	13.67	0.82	0.04	1.31	107
J5	13.42	0.55	12.87	0.77	0.04	1.49	115
J7	16.13	0.60	15.53	0.93	0.04	1.34	124
Araripina							
Caatinga[2]	12.87	1.24	11.63	1.00	0.11	1.00	100
J4	11.83	0.49	11.34	0.92	0.04	0.40	37
J6	12.53	0.70	11.83	0.97	0.06	0.55	54
				0.20-0.30 m			
Planaltina							
Cerrado[2]	15.20	0.50	14.70	1.00	0.03	1.00	100
Pasture	14.23	0.18	14.05	0.94	0.01	0.38	35
J1	14.59	0.23	14.36	0.96	0.02	0.48	46
J2	15.26	0.18	15.06	1.00	0.01	0.36	36
J3	16.12	0.27	15.85	1.06	0.02	0.49	52
J4	15.74	0.25	15.49	1.04	0.02	0.47	48
Dourados							
Atlantic forest[2]	12.19	0.20	11.99	1.00	0.02	1.00	100
Annual crops	9.23	0.02	9.21	0.76	0.00	0.11	8
J3	9.54	0.06	9.48	0.78	0.01	0.38	29
J5	10.56	0.15	10.41	0.87	0.01	0.88	76
J7	11.13	0.15	10.96	0.91	0.02	0.93	85
Araripina							
Caatinga[2]	6.38	0.11	6.27	1.00	0.02	1.00	100
J4	6.46	0.08	6.38	1.01	0.01	0.71	72
J6	7.11	0.09	7.02	1.11	0.01	0.74	82

[1] The areas evaluated refer to cultivation with *Jatropha* spp. over 1 (J1), 2 (J2), 3 (J3), 4 (J4), 5 (J5), 6 (J6), and 7 (J7) years, pasture, annual crops, and native vegetation (*Cerrado*, Atlantic Forest, and *Caatinga*). [2] The area with native vegetation was taken as a reference at each depth to calculate CPI, LI, and CMI. [3] CPI: C stock in the cultivated area/C stock in the reference area. [4] Lability (L): stock of labile C in the cultivated area/stock of non-labile C in the cultivated area. [5] LI: lability in the cultivated area/lability in the reference area. [6] CMI = CPI × LI × 100.

The carbon management index (CMI) is an integrated measure of the quantitative and qualitative characteristics of the SOM to help evaluate the performance of a determined soil use or management system regarding loss or gain in quality of the SOM in comparison to a reference area (Vieira et al., 2007).

The areas in pasture and *Jatropha* spp. for longer periods exhibited CPI values near to or greater than those of native vegetation (Table 2). According to Vieira et al. (2007), the CPI is strongly correlated with the yearly addition of C to the soil. Therefore, the results reflect the potential of well-managed pastures and cultivation of *Jatropha* spp. for accumulating C in a larger amount than in the areas with native vegetation.

By contributing different quantities of C to the soil, the land uses also altered the L and LI of the SOM, that is, the proportion of labile in relation to non-labile organic matter. In general, the values of L and LI were higher in the native vegetation areas than in the other areas, and in the areas planted to *Jatropha* spp., these values increased progressively with longer cultivation times. In Dourados, the L and LI values in the *Jatropha* spp. areas were greater than in the area still used for annual cropping. This result can be explained by the larger input of plant residues in the soil surface in the areas with *Jatropha* spp. plants in relation to the area used to grow corn.

With the exception of the soil samples from the surface layer of the pasture area in Planaltina and *Jatropha* spp. area in Dourados, the other soil uses had lower CMI values than those of the reference area in the surface and intermediate layers. Additionally, in the *Jatropha* spp. areas, the CMI increased in accordance with cultivation time, with the highest value being observed for J7 (124) in the surface layer in Dourados (Table 2). The system with the greatest soil turnover and lowest maintenance of plant residues on the surface (annual cropping) had the lowest CMI values, at 52 and 8 for the depths of 0.00-0.10 and 0.20-0.30 m, respectively.

The existence of soil management or use systems with CMI values greater than or equal to that of native vegetation (100), used as a reference, demonstrates the ability of these systems to improve the soil quality and promote the sustainability of agroecosystems. In turn, CMI values lower than 100 indicate a negative impact of soil management or use practices on carbon contained in the SOM (Blair et al., 1995).

Therefore, the higher CMI (116) found in the pasture in the surface layer reflects the potential of well-managed pastures to accumulate C in the soil in quantities greater than or equal to those observed in areas with native vegetation. Schiavo et al. (2011), comparing areas with annual cropping and pasture against areas with native vegetation, observed that the pasture areas had CMI values near to or higher than in the native vegetation area. However, Assmann et al. (2014) stated that high grazing intensity in pastures results in losses of C in the soil and lower CMI in comparison with areas with native vegetation.

In the areas planted to *Jatropha* spp. for longer periods in Planaltina and Dourados, the CMI values were close to or greater than those in the reference areas in the surface layer (Table 2), due to the higher LI values in these areas. Management systems with CMI values greater than or equal to those of the reference area (better preserved areas) help promote the sustainability of agroecosystems in tropical regions due to the maintenance of C in the soil (Silva et al., 2011).

Therefore, the fact that cultivating *Jatropha* spp. increases the CMI with longer cultivation times demonstrates the capacity of these plants to improve the SOM by maintaining the lability of the SOM at a level similar to or greater than in the reference areas.

Soil organic matter humification index (H_{LIF})

The values of the SOM humification index (H_{LIF}) were lowest in the surface layer (0.00-0.10 m) for all the soil uses and locations evaluated (Figure 2). This is a result of deposition of

labile C from plant residues on the soil surface, causing dilution of the more humified organic matter, resulting in high C concentrations and a low degree of humification of organic matter on the surface (Favoretto et al., 2008; Segnini et al., 2013).

The H_{LIF} values increased with greater depth. The values in the deepest layer (0.80-1.00 m) were three times those observed in the surface layer, indicating that the deeper the soil is, the more recalcitrant SOM is.

The H_{LIF} values observed in the areas studied in Araripina were approximately four and five times those of the different soil uses in Dourados and Planaltina, respectively, in all the layers sampled, indicating that preservation of the more aromatic components of the SOM is a predominant mechanism in this environment.

The difference in the H_{LIF} between contrasting locations, such as the regions analyzed in this study, is related to the C content, composition of the SOM, characteristics of the mineral fraction, and/or soil structure (Baldock and Skjemstad, 2000; Tivet et al., 2013). Therefore, in the *Caatinga* biome, the higher H_{LIF} values in the soil samples can be attributed to the characteristics of the plant matter contributed to the soil, with high concentrations of lignin, a precursor of humic substances (Santos et al., 2008).

In Planaltina, the H_{LIF} value was statistically greater in the *Cerrado* soil at all depths evaluated (Figure 2). Among the other soil uses, there were no statistical differences in the degree of humification, with the highest values being observed in the pasture soil.

These results indicate that increases in the levels of C after conversion of native vegetation to pasture and *Jatropha* spp. are associated with increases in the less stable organic matter. Xavier (2014), comparing degraded and rehabilitated pasture areas and a reference area with native vegetation (Atlantic Forest), observed higher levels of C and lower H_{LIF} values in the soils from the recovered pasture.

In Dourados, the highest H_{LIF} values ($p<0.05$) were observed in the soil under annual cultivation at the depths of 0.00-0.10 and 0.20-0.30 m. This finding can be attributed to the lower contribution of labile organic matter on the surface from conventional annual cropping, causing a relative increase in the more humified organic matter, thus resulting in lower levels of C and a higher degree of humification of the organic matter (Favoretto et al., 2008).

Furthermore, the use of conventional tillage, with intense soil turnover, increases the preferential oxidation of the more labile fractions of the SOM and reduces the preservation of these structures by physical protection through aggregation (Favoretto et al., 2008; Segnini et al., 2013; Tivet et al., 2013). The lower H_{LIF} values in the soil in the Atlantic forest and *Jatropha* spp. areas, for their part, suggest greater physical protection of the more labile portion of the SOM in these systems.

In Araripina, the H_{LIF} values were similar for all the soil uses (*Caatinga*, J4, and J6), at all the depths analyzed. The conversion of *Caatinga* to cultivation of *Jatropha* spp. did not alter the levels of C and the degree of humification of the SOM, probably because the residues of *Jatropha* spp. plants have high levels of lignin, which is resistant to decomposition. Therefore, the system remained in equilibrium over the years of cultivating these plants.

Carbon and nitrogen in the soil microbial biomass

The concentrations of C and N in the microbial biomass (C-MB and N-MB) varied significantly ($p<0.05$) among the types of soil use (Table 3). In Planaltina and Dourados, the soils under native vegetation (*Cerrado* and Atlantic Forest) had the highest values of C and N in the microbial biomass. The high values of C-MB in areas with native vegetation can be attributed to the higher input and greater diversity of the organic substrate produced in these systems (Pulrolnik et al., 2009).

In the *Caatinga* biome in Araripina, reduction in the levels of C-MB was smaller than in the other biomes evaluated. This can be attributed to the natural selection of microbial communities adapted to stressful conditions (high temperatures and intermittent droughts), such that the disturbances connected with agriculture were not sufficient to reduce the microbial biomass.

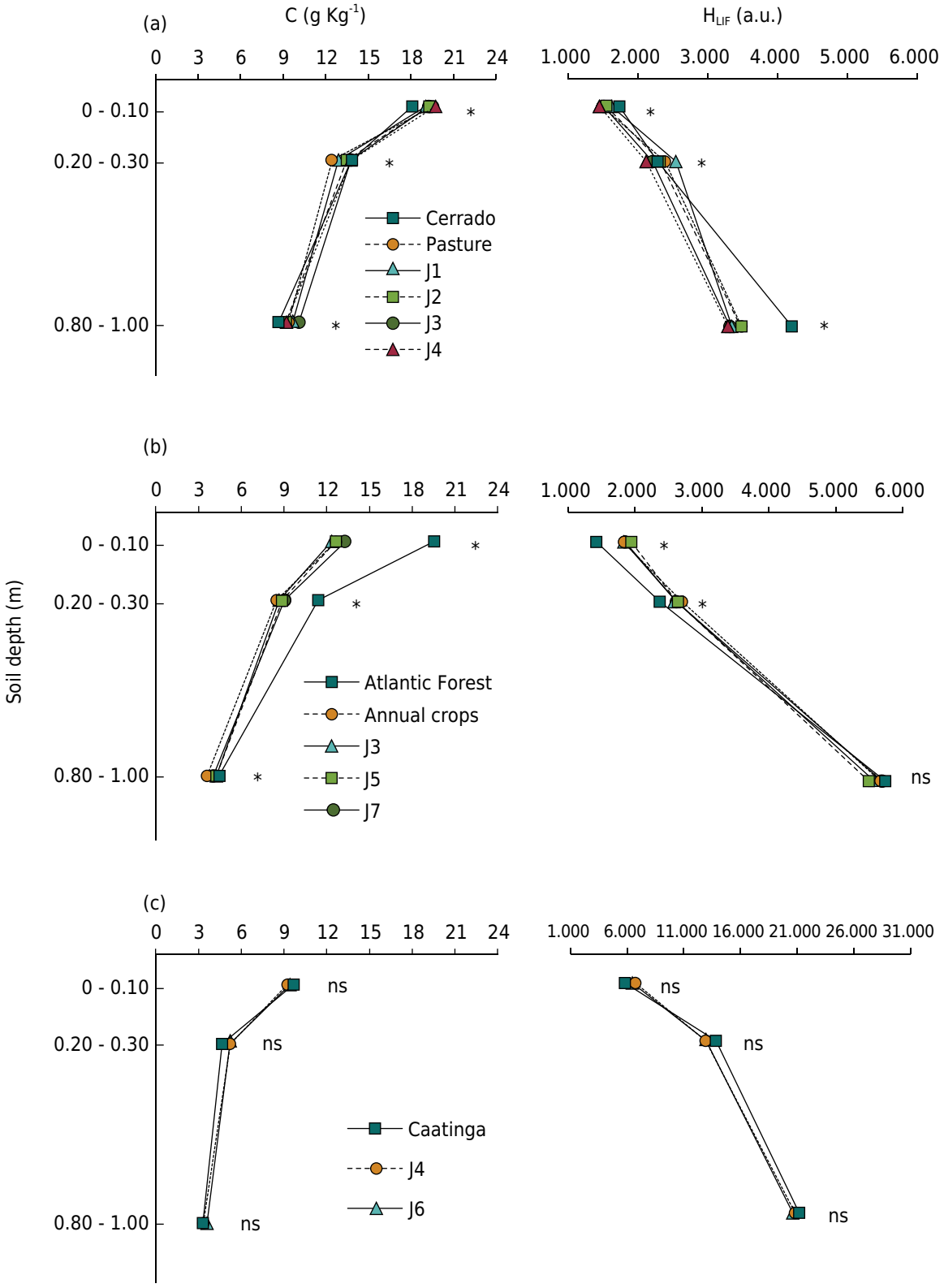

Figure 2. Carbon content and soil organic matter humification index (H_{LIF}) in soil samples from depths of 0.00-0.10, 0.20-0.30, and 0.80-1.00 m in areas under different uses in Planaltina-DF (a), Dourados-MS (b), and Araripina-PE (c), Brazil. The areas evaluated refer to cultivation with *Jatropha* spp. over 1 (J1), 2 (J2), 3 (J3), 4 (J4), 5 (J5), 6 (J6), and 7 (J7) years, pasture, annual crops, and areas with native vegetation (*Cerrado*, Atlantic Forest, and *Caatinga*). * and ns: significant and not significant, respectively, by the Tukey test ($\alpha<0.05$).

Table 3. Concentrations of carbon and nitrogen and C/N ratio of the microbial biomass of soils with different uses, at a depth of 0.00-0.10 m in Planaltina-DF, Dourados-MS, and Araripina-PE, Brazil

Area[(1)]	C	N	C/N
	mg kg^{-1}		
Planaltina			
Cerrado	467.3 a	50.4 a	9 a
Pasture	415.7 ab	47.1 a	9 a
J1	277.2 ab	19.5 b	14 a
J2	258.5 ab	21.9 b	12 a
J3	224.2 b	20.3 b	11 a
J4	308.4 ab	28.7 ab	11 a
Dourados			
Atlantic Forest	645.4 a	111.0 a	6 b
Annual crops	135.9 c	20.2 b	7 b
J3	242.2 bc	29.3 b	8 ab
J5	297.9 b	27.3 b	11 a
J7	281.4 b	33.8 b	8 ab
Araripina			
Caatinga	287.9 ab	19.4 a	15 a
J4	248.4 b	19.8 a	13 a
J6	337.7 a	19.9 a	16 a

[(1)] The areas evaluated refer to cultivation with *Jatropha* spp. over 1 (J1), 2 (J2), 3 (J3), 4 (J4), 5 (J5), 6 (J6), and 7 (J7) years, pasture, annual crops, and native vegetation (*Cerrado*, Atlantic Forest, and *Caatinga*). Means followed by the same lowercase letter in the same column do not differ by the Tukey test ($\alpha<0.05$).

The change from native vegetation to pasture, annual cropping, and cultivation of *Jatropha* spp. reduced the levels of C-MB by 11, 79, and 14 % in Planaltina, Dourados, and Araripina, respectively. According to Kaschuk et al. (2011), the conversion from native vegetation to agropastoral systems tends to alter the microbial biomass in the soil, reducing the levels of C. The meta-analysis carried out by those authors regarding the effects of introducing farming in areas previously under natural vegetation in the Amazon, *Caatinga, Cerrado*, Atlantic Forest, and *Pantanal* biomes indicated an average reduction of 33 % in the levels of C-MB.

Furthermore, according to those authors, the greatest reductions occur when native vegetation is cleared to plant annual crops (53 %), followed by pasture (27 %), and perennial crops (21 %). The results of this study also corroborate the observations of Silva et al. (2012), since the conversion of native vegetation to farming or grazing also reduced the quantity of C immobilized by microorganisms in the soil.

Among the areas cultivated with *Jatropha* spp., the C-MB values ranged from 224 to 338 mg kg^{-1} (Table 3). The areas with shorter cultivation times obtained lower C-MB values in all three locations studied. In Planaltina and Dourados, the C-MB values increased in accordance with longer *Jatropha* spp. cultivation time, but these values were lower than those observed for the soils under native vegetation (*Cerrado* and Atlantic Forest). In Araripina, the area cultivated with *Jatropha* spp. plants for six years had a C-MB value 17 % higher than that measured for the native vegetation area (*Caatinga*).

In the *Caatinga* biome, where the prevailing conditions are stressful to the microbial community (high temperatures and extended droughts), the ability of C use by microorganisms is low. Therefore, microorganisms may have been stimulated by the improved soil fertility from the input of N and P from fertilizers applied to the *Jatropha* spp. plants.

In the soils studied, the C-MB values ranged from 1.1 to 3.6 % of the total organic C, and the lowest values were associated with the cultivated soils. Therefore, in the locations analyzed, microbial biomass was an indicator sensitive to changes in soil quality in accordance with different uses, as also observed by Fabrizzi et al. (2009), Kaschuk et al. (2011), and Pessoa et al. (2012).

In the areas under cultivation, besides the lower C-MB levels, the contents of N-MB in the soil in Planaltina and Dourados also declined (Table 3). In Planaltina, the reductions in N-MB were 7, 61, 57, 60, and 43 % for the pasture, J1, J2, J3, and J4 areas, respectively. The same pattern was observed when comparing the areas under annual cropping and *Jatropha* spp. in Dourados, with reductions of approximately 75 % caused by agricultural activities.

Evaluating the biomass and microbial activity of soil under native vegetation and different soil uses, Silva et al. (2012) observed that farming practices (annual and perennial cropping), compared to native vegetation, can cause disturbances in the microbial community, which. in turn, can reduce the quantity of N immobilized as microbial biomass in the soil.

CONCLUSIONS

Among the instruments used to assess the quality of SOM, the CMI and the C and N levels in the microbial biomass were the most responsive to the changes in soil use for all the biomes studied.

The cultivation of *Jatropha* spp. increased the C stocks, the concentrations of C in the SOM fractions, the CMI, and the C and N levels in the microbial biomass in accordance with time of cultivation. These results demonstrate that this cultivation system has the ability to improve the quality of organic matter in the soil. Additionally, the lower values of H_{LIF} in the soils cultivated with *Jatropha* spp. suggest greater physical protection of the more labile portion of the SOM in this system.

REFERENCES

Assmann JM, Anghinoni I, Martins AP, Costa SEVGA, Cecagno D, Carlos FS, Carvalho PCF. Soil carbon and nitrogen stocks and fractions in a long-term integrated crop-livestock system under no-tillage in southern Brazil. Agric Ecosyst Environ. 2014;190:52-9. https://doi.org/10.1016/j.agee.2013.12.003

Bailis RE, Baka JE. Greenhouse gas emissions and land use change from *Jatropha Curcas*-based jet fuel in Brazil. Environ Sci Technol. 2010;44:8684-91. https://doi.org/10.1021/es1019178

Bailis R, Mccarthy H. Carbon impacts of direct land use change in semiarid woodlands converted to biofuel plantations in India and Brazil. GCB Bioenergy. 2011;3:449-60. https://doi.org/10.1111/j.1757-1707.2011.01100.x

Baldock JA, Skjemstad JO. Role of the soil matrix and minerals in protecting natural organic materials against biological attack. Org Geochem. 2000;31:697-710. https://doi.org/10.1016/S0146-6380(00)00049-8

Blair GJ, Lefroy RDB, Lisle L. Soil carbon fractions based on their degree of oxidation, and the development of a carbon management index for agricultural systems. Aust J Agric Res. 1995;46:1459-66. https://doi.org/10.1071/AR9951459

Bayer C, Martin-Neto L, Mielniczuk J, Dieckow J, Amado TJC. C and N stocks and the role of molecular recalcitrance and organomineral interaction in stabilizing soil organic matter in a subtropical Acrisol managed under no-tillage. Geoderma. 2006;133:258-68. https://doi.org/10.1016/j.geoderma.2005.07.012

Cambardella CA, Elliott ET. Particulate soil organic matter change across a grassland cultivation sequence. Soil Sci Soc Am J. 1992;56:777-83. https://doi.org/10.2136/sssaj1992.03615995005600030017x

Carvalho JLN, Raucci GS, Cerri CEP, Bernoux M, Feigl BJ, Wruck FJ, Cerri CC. Impact of pasture, agriculture and crop-livestock systems on soil C stocks in Brazil. Soil Till Res. 2010;110:175-86. https://doi.org/10.1016/j.still.2010.07.011

Claessen MEC, organizador. Manual de métodos de análise de solo. 2a ed. Rio de Janeiro: Centro Nacional de Pesquisa de Solos; 1997.

Corazza EJ, Silva JE, Resck DVS, Gomes AC. Comportamento de diferentes sistemas de manejo como fonte ou depósito de carbono em relação à vegetação de Cerrado. Rev Bras Cienc Solo. 1999;23:425-32. https://doi.org/10.1590/S0100-06831999000200025

Deon DS. Mudança de uso da terra e impacto na matéria orgânica do solo em dois locais no Leste da Amazônia [tese]. Piracicaba: Escola Superior de Agricultura "Luiz de Queiroz" - Universidade de São Paulo; 2013.

Fabrizzi KP, Rice CW, Amado TJC, Fiorin J, Barbagelata P, Melchiori R. Protection of soil organic C and N in temperate and tropical soils: effect of native and agroecosystems. Biogeochemistry. 2009;92:129-43. https://doi.org/10.1007/s10533-008-9261-0

Favoretto CM, Gonçalves D, Milori DMBP, Rosa JA, Leite WC, Brinatti AM, Saab SC. Determinação da humificação da matéria orgânica de um Latossolo e de suas frações organo-minerais. Quim Nova. 2008;31:1994-6. https://doi.org/10.1590/S0100-40422008000800015

Gama-Rodrigues EF, Gama-Rodrigues AC. Biomassa microbiana e ciclagem de nutrientes. In: Santos GA, Silva LS, Canellas LP, Camargo FAO, editores. Fundamentos da matéria orgânica do solo: ecossistemas tropicais e subtropicais. 2a ed rev atual ampl. Porto Alegre: Metrópole; 2008. p.159-70.

Grossman RB, Reinsch TG. Bulk density and linear extensibility. In: Dane JH, Topp GC, editors. Methods of soil analysis. IV: Physical methods. Madison: Soil Science Society of America; 2002. p.201-28.

Hartman DC, Sá JCM, Briedis C, Santos JZ, Schimiguel R. Evidências de saturação de carbono em solos sob plantio direto em agro-ecosistemas subtropical e tropical no Brasil. Snyerg Scyent. 2014;9:1-6.

Heid DM, Vitorino ACT, Tirloni C, Hoffmann NTK. Frações orgânicas e estabilidade dos agregados de um Latossolo Vermelho Distroférrico sob diferentes usos. Rev Cienc Agrár. 2009;51:143-60.

Intergovernmental Panel on Climate Change - IPCC. Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2014. Available at: https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_full.pdf.

Joergensen RG, Brookes PC. Ninhydrin-reactive nitrogen measurements of microbial biomass in 0.5 M K_2SO_4 soil extracts. Soil Biol Biochem. 1990;22:1023-7. https://doi.org/10.1016/0038-0717(90)90027-W

Kaschuk G, Alberton O, Hungria M. Quantifying effects of different agricultural land uses on soil microbial biomass and activity in Brazilian biomes: inferences to improve soil quality. Plant Soil. 2011;338:467-81. https://doi.org/10.1007/s11104-010-0559-z

Ladd JN, Foster RC, Skjemstad JO. Soil structure: carbon and nitrogen metabolism. Geoderma. 1993;56:401-34. https://doi.org/10.1016/0016-7061(93)90124-4

La Scala Junior N, Figueiredo EB, Panosso AR. A review on soil carbon accumulation due to the management change of major Brazilian agricultural activities. Braz J Biol. 2012;72:775-85. https://doi.org/10.1590/S1519-69842012000400012

Lardy LC, Brossard M, Assad MLL, Laurent JY. Carbon and phosphorus stocks of clayey Ferralsols in Cerrado native and agroecosystems, Brazil. Agric Ecosyst Environ. 2002;92:147-58. https://doi.org/10.1016/S0167-8809(01)00303-6

Lisboa CC, Conant RT, Haddix ML, Cerri CEP, Cerri CC. Soil carbon turnover measurement by physical fractionation at a forest-to-pasture chronosequence in the Brazilian Amazon. Ecosystems. 2009;12:1212-21. https://doi.org/10.1007/s10021-009-9288-7

Milori DMBP, Galeti HVA, Martin-Neto L, Dieckow J, González-Pérez M, Bayer C, Salton J. Organic matter study of whole soil samples using laser-induced fluorescence spectroscopy. Soil Sci Soc Am J. 2006;70:57-63. https://doi.org/10.2136/sssaj2004.0270

Nelson DW, Sommers LE. Total carbon, organic carbon, and organic matter. In: Page AL, Miller RH, Keeney DR, editors. Methods of soil analysis. 2nd ed. Madison: American Society of Agronomy; 1982. Pt 2. p.539-79.

Ogunwole JO, Chaudhary DR, Ghosh A, Daudu CK, Chikara J, Patolia JS. Contribution of *Jatropha curcas* to soil quality improvement in a degraded Indian Entisol. Acta Agric Scand B Soil Plant Sci. 2008;58:245-51. https://doi.org/10.1080/09064710701628925

Pandey VC, Singh K, Singh JS, Kumar A, Singh B, Singh RP. *Jatropha curcas*: a potential biofuel plant for sustainable environmental development. Renew Sustain Energy Rev. 2012;16:2870-83. https://doi.org/10.1016/j.rser.2012.02.004

Pessoa PMA, Duda GP, Barros RB, Freire MBGS, Nascimento CWA, Correa MM. Frações de carbono orgânico de um Latossolo húmico sob diferentes usos no agreste brasileiro. Rev Bras Cienc Solo. 2012;36:97-104. https://doi.org/10.1590/S0100-06832012000100011

Pulrolnik K, Barros NF, Silva IR, Novais RF, Brandani CB. Estoques de carbono e nitrogênio em frações lábeis e estáveis da matéria orgânica de solos sob eucalipto, pastagem e cerrado no Vale do Jequitinhonha - MG. Rev Bras Cienc Solo. 2009;33:1125-36. https://doi.org/10.1590/S0100-06832009000500006

Raij Bvan, Andrade JC, Cantarella H, Quaggio JA. Análise química para avaliação da fertilidade de solos tropicais. Campinas: Instituto Agronômico; 2001.

Rossi CQ, Pereira MG, Giácomo SG, Betta M, Polidoro JC. Frações lábeis da matéria orgânica em sistema de cultivo com palha de braquiária e sorgo. Rev Cienc Agron. 2012;43:38-46. https://doi.org/10.1590/S1806-66902012000100005

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

Santos GA, Silva LS, Canellas LP, Camargo FAO. Fundamentos da matéria orgânica do solo: ecossistemas tropicais e subtropicais. 2a ed rev atual ampl. Porto Alegre: Metrópole; 2008.

Schiavo JA, Rosset JS, Pereira MG, Salton JC. Índice de manejo de carbono e atributos químicos de Latossolo Vermelho sob diferentes sistemas de manejo. Pesq Agropec Bras. 2011;46:1332-8. https://doi.org/10.1590/S0100-204X2011001000029

Segnini A, Carvalho JLN, Bolonhezi D, Milori DMBP, Silva WTL, Simões ML, Cantarella H, de Maria IC, Martin-Neto L. Carbon stock and humification index of organic matter affected by sugarcane straw and soil management. Sci Agric. 2013;70:321-6. https://doi.org/10.1590/S0103-90162013000500006

Silva CF, Pereira MG, Miguel DL, Feitora JCF, Loss A, Menezes CEG, Silva EMR. Carbono orgânico total, biomassa microbiana e atividade enzimática do solo de áreas agrícolas, florestais e pastagem no médio Vale do Paraíba do Sul (RJ). Rev Bras Cienc Solo. 2012;36:1680-9. https://doi.org/10.1590/S0100-06832012000600002

Silva EF, Lourente EPR, Marchetti ME, Mercante FM, Ferreira AKT, Fujii GC. Frações lábeis e recalcitrantes da matéria orgânica em solos sob integração lavoura-pecuária. Pesq Agropec Bras. 2011;46:1321-31. https://doi.org/10.1590/S0100-204X2011001000028

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

Souza GM, Victoria RL, Verdade LM, Joly CA, Netto PEA, Cantarella H, Chum HL, Diaz-Chavez R, Fernandes E, Fincher G, Goldemberg J, Nogueira LAH, Huntley BJ, Johnson FX, Karp A, Leal MRLV, Lynd LR, Macedo IC, Maciel Filho R, Massafera MP, Nassar AM, Nigro FEB, Osseweijer P, Richard TL, Saddler JN, Samseth J, Seebaluck V, Somerville CR, van der Wielen L, Sluys MAV, Woods J, Youngs H. Bioenergy numbers. In: Souza GM, Victoria RL, Joly CA, Verdade LM, editors. Bioenergy & Sustainability: bridging the gaps. São Paulo: SCOPE; 2015. p.28-57.

Srivastava P, Sharma YK, Singh N. Soil carbon sequestration potential of *Jatropha curcas* L. growing in varying soil conditions. Ecol Eng. 2014;68:155-66. https://doi.org/10.1016/j.ecoleng.2014.03.031

Stavi I, Lal R. Agroforestry and biochar to offset climate change: a review. Agron Sustain Dev. 2013;33:81-96. https://doi.org/10.1007/s13593-012-0081-1

Tivet F, Sá JCM, Lal R, Milori DMBP, Briedis C, Letourmy P, Pinheiro LA, Borszowskei PR, Hartman DC. Assessing humification and organic C compounds by laser-induced fluorescence and FTIR spectroscopies under conventional and no-till management in Brazilian Oxisols. Geoderma. 2013;207-208:71-81. https://doi.org/10.1016/j.geoderma.2013.05.001

Vance ED, Brookes PC, Jenkinson DS. An extraction method for measuring soil microbial biomass C. Soil Biol Biochem. 1987;19:703-7. https://doi.org/10.1016/0038-0717(87)90052-6

Vieira FCB, Bayer C, Zanatta JA, Dieckow J, Mielniczuk J, He ZL. Carbon management index based on physical fractionation of soil organic matter in an Acrisol under long-term no-till cropping systems. Soil Till Res. 2007;96:195-204. https://doi.org/10.1016/j.still.2007.06.007

von Lutzow M, Kögel-Knabner I, Ludwig B, Matzner E, Flessa H, Ekschmitt K, Guggenberger G, Marschner B, Kalbitz K. Stabilization mechanisms of organic matter in four temperate soils: Development and application of a conceptual model. J Plant Nutr Soil Sci. 2008;171:111-24. https://doi.org/10.1002/jpln.200700047

Walkley A, Black IA. An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 1934;37:29-38.

Wani SP, Chander G, Sahrawat KL, Rao CS, Raghvendra G, Susanna P, Pavani M. Carbon sequestration and land rehabilitation through *Jatropha curcas* (L.) plantation in degraded lands. Agric Ecosyst Environ. 2012;161:112-20. https://doi.org/10.1016/j.agee.2012.07.028

Xavier AAP. Avaliação do acúmulo e emissão de carbono do solo sob sistemas produtivos de pastagem [dissertação]. São Carlos: Universidade de São Paulo; 2014.