Original Article

Fertilization and Irrigation Affect Soil Carbon under Eucalyptus Plantation in the Cerrado

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ABSTRACT

This study aimed: i) to evaluate the influence of fertilization and irrigation management on eucalyptus plantations for soil carbon (C) dynamics; ii) to evaluate the impact of fertilization and irrigation management on eucalyptus plantations in the C allocation in depth compared to the Cerrado biome. This study was carried out in an eucalyptus plantation at the end of the third rotation (7 years), which received different fertilizations and irrigations, and a Cerrado area was used as reference. Soil samples were collected in trenches and the gases (CO_2 and CH_4) on the surface. The total organic carbon (TOC) is more influenced by the availability of water than nutrients. Soils under eucalyptus stands are more efficient at C stocks in depth than the Cerrado and act as a liquid drain of CO_2 and CH_4 from the atmosphere.

Keywords: CO_2, CH_4, carbon management index, planted forests.

1. INTRODUCTION AND OBJECTIVES

The current scenario of global climate change has awakened the interest of the scientific community in the elaboration of strategies that seek to mitigate greenhouse gases (GHG) emissions and increase C sequestration, especially in systems that give greater stability like the soil (IPCC, 2014). In Brazil, agriculture is responsible for a large part of the emissions of the main GHGs (CO_2, CH_4 and N_2O), due to deforestation and intensive soil management. However, this scenario has been currently altered by the reduction of deforestation and the recovery of degraded areas (Hansen et al., 2013; Inpe, 2015).

Eucalyptus planted forests show rapid growth and high resource efficiency, which results in a large accumulation of biomass, both in the aerial part and in the root system of the plant (Stape et al., 2010). This high efficiency gives these effective forests potential to sequester atmospheric CO_2 with subsequent C stabilization in the soil compartments when the plant residues are added to the soil (Gatto et al., 2010). Turner et al. (2005), evaluating the *Eucalyptus grandis* plantations aged 0-35 years in Australia, found a decrease in the soil organic carbon (SOC) and affirmed that this trend occurs until the end of the forest cycle. In Brazil, Zinn et al. (2002) found SOC losses under initial eucalyptus plantation in relation to the Cerrado. These authors found recovery of SOC at the end of the second rotation, led by regrowth (Zinn et al., 2011). Fialho & Zinn (2014), in a meta-analysis about the potential of C accumulation in soils under eucalyptus and native vegetation in Brazil, did not find significant changes in the SOC content and stocks under eucalyptus when compared to native vegetation. These authors found that even at more advanced ages, no trends for SOC accumulation are observed and SOC losses associated with eucalyptus cultivation are not a concern. Thus, it is not clear how the C dynamics occur and if the accumulation or losses are favored during the cultivation of eucalyptus forests.

Management techniques that provide less soil revolving, higher root/aerial part ratio (Rasse et al., 2005) and higher productivity (Gatto et al., 2011) may contribute to a greater accumulation of SOC. In addition, physical and chemical processes restrict the microbial decomposition of COS in depth, increasing its

permanence in the system and consequent stabilization (Bernal et al., 2016; Schmidt et al., 2011). So, the studies which approach the C evaluation in depth are of greater relevance when aimed at management strategies that favor a greater C sequestration in soil. However, studies in Brazil that evaluate the SOC allocation at greater depths are scarce.

The SOC accumulation can be influenced by climatic factors such as water deficit which is the most limiting to obtain high yields for eucalyptus (Gatto et al., 2010; Stape et al., 2004).

However, the cultivation of forest species with higher availability of water and/or fertilizers may provide increased productivity (Stape et al., 2004) and consequent plant litter input to soil, C allocation in the root system (Lai et al., 2016), as well as changes in soil microbial activity. Fertigated cultivation has been shown to be more effective in increasing C and N in soil (Li et al., 2007), possibly by narrowing the C:N ratio and favoring the SOC stabilization (Forrester et al., 2006).

This study aimed to evaluate the influence of fertilization and irrigation management in eucalyptus plantations for soil C dynamics and the impact of fertilization and irrigation management on eucalyptus plantations in the C allocation in depth compared to the Cerrado biome.

2. MATERIALS AND METHODS

2.1. Characterization of the study area

The study was carried out in eucalyptus plantations (*Eucalyptus urophylla* × *Eucalyptus grandis*; 3 × 3 m spacing) at the end of the third rotation (7 years), located in the region of Bocaiúva, MG (17°20'S and 43°50'W, 900 m of elevation). The average annual temperature is 23.6°C and the average annual rainfall is 848 mm, with dry season well accented. In addition to the areas with eucalyptus, the native Cerrado was evaluated as a reference. The soil is classified as clayey dystrophic Red Latosol (Stape et al., 2010).

2.2. Treatments and experimental design

Five treatments (CN, CI, FN, FI and Cerrado) were set up in a randomized block design with three

replications. Treatments were arranged in a split-plot in time design that consisted of: i) CN: with conventional fertilization (C – N: 79; P: 55; K: 66; Ca: 280; Mg: 60; and B: 6 kg ha[1]) + without irrigation (N); ii) CI: with conventional fertilization (C) + with irrigation (I – irrigation by spraying, with a mean blade water of 22.5 mm applied twice a week in the total area); iii) FN: with potential fertilization (F – N: 444; P: 160; K: 369; Ca: 280; Mg: 60; and B: 8 kg ha[1]; divided into three applications during the first three years) + without irrigation (N); iv) FI: with potential fertilization (F) + with irrigation (I); v) Cerrado: native forest as reference.

2.3. Gas collection, litter and soil analysis

Gas and soil sampling were performed in July 2014, and irrigation management was interrupted for approximately one year. In each treatment were opened six trenches of 1 m³, being three rows (R) and three inter-row (IR). Deformed and undisturbed soil samples were collected in the layers 0-10, 10-20, 20-40, 40-60 and 60-100 cm of depth.

For the evaluation of the GHGs, static chambers (PVC columns; 0.2 m in height and 0.3 m in diameter) were installed in the soil, reaching a depth of 0.05 m, in each R an IR location. At the time of sampling, the chambers were sealed with PVC caps, fitted with a rubber septum to prevent air passage from the soil to the open atmosphere and to allow measurement of changes concentration of gases over collection time. The gases were collected at intervals of 0, 10, 20, 40-minute after sealing the chambers, using 60-ml syringes equipped with three-way valves for further determinations of CO_2 and CH_4 using the Cavity Ring Down Spectroscopy – CRDS (Picarro, Sunnyvale, CA).

The Equation 1 was used to calculate the gas fluxes (Smith & Conen, 2004).

$$\text{Soil } CO_2 \text{ or } CH_4 \text{flux(mg m}^{-2}\text{h}^{-1}) = \left(\frac{"Q}{"t}\right) \times M \times \left(\frac{P \times V}{R \times T}\right) \times \left(\frac{1}{A}\right) \times 3,6 \tag{1}$$

ΔQ/Δt: angular coefficient (ppm s[1]) obtained by adjusting the gas concentrations over time; M: molar mass of the gas (g mol[1]); P: constant pressure of 1 atm; V: chamber volume (L); R: gas constant (0.08205746); T: temperature in the soil (K); A: chamber area (m²); 3.6: units adjustment factor for µg m² s[1] to mg m² h[1].

The soil temperature and the soil moisture in the 0 to 0.05 m soil layer were measured using an EC-5 sensor (Decagon Devices Inc., Pullman, WA, USA) at the time of gas collection. The litter samples were collected randomly with a 0.5 × 0.5 m template, dried at 60 °C in a forced-air circulation oven until constant weight, which is done for further quantification of the dry mass (Figure 1c).

Soil sub-samples were air dried and passed through 100 mesh sieves to determine the total organic carbon (TOC) and total nitrogen (TN) contents by the dry combustion method in CHNS (Analyzer 2400 series II, Perkin Elmer Company), and the oxidizable carbon (Labile C) content according to methodology described by Shang & Tiessen (1997).

The TOC, TN and Labile-C stocks were estimated through the equations 2, 3, 4 and 5 described below, adapted from Ellert & Bettany (1995):

$$SM = D(Mg\ m^{-1}) \times VL(m^3) \tag{2}$$

$$Ma = (SM_{ref} - SM) \tag{3}$$

$$SM_{equiv} = Ma + SM \tag{4}$$

$$ST_{C,N\ or\ C_{labile}}(Mg\ ha^{-1}) = \frac{Con_{C,N\ or\ Clabile}}{SM_{equiv}} \tag{5}$$

SM: soil mass; D: soil density in Mg m³ (Table 1); VL: layer volume (m³); Ma: mass added; SM_{ref}: soil mass reference that presents greater density; SM_{equiv}: equivalent mass; $ST_{C,N\ or\ LabileC}$: TOC, TN or Labile-C stocks; $Con_{C,N\ or\ LabileC}$: TOC, TN or Labile-C contents.

The stocks per hectare in the eucalyptus plantations weights were made of the area occupied by R and IR (Equation 6).

$$STtotal_{C,N\ or\ C_{labile}}(Mg\ ha^{-1}) = \left(\left(\frac{1}{3}\right) \times ST_R\right) + \left(\left(\frac{2}{3}\right) \times ST_{IR}\right) \tag{6}$$

Moreover, the Carbon Management Index (CMI) was calculated (Blair et al., 1995) as shown on Equation 7.

$$CMI\ (\%) = CCI \times IL \times 100 \tag{7}$$

Where CCI is the carbon compartment index given by the ratio of TOC of the cultivated area and TOC of the reference area (Equation 8).

Table 1. Soil density for different treatments at depths of 0-10, 10-20, 20-40, 40-60 and 60-100 cm.

Depth	Cerrado	CN		FN		CI		FI	
		R	IR	R	IR	R	IR	R	IR
0-10	1.05	0.89	0.86	0.78	0.81	0.79	0.82	0.81	0.83
10-20	1.07	0.80	0.86	0.80	0.81	0.80	0.83	0.88	0.79
20-40	1.01	0.84	0.89	0.82	0.83	0.85	0.87	0.87	0.84
40-60	1.11	0.82	0.84	0.78	0.78	0.88	0.87	0.87	0.87
60-100	0.96	0.84	0.87	0.85	0.84	0.82	0.80	0.84	0.84

Depth in cm; R: plant rows; IR: plant inter-row; CN: eucalyptus cultivation with conventional non-irrigated fertilization; CI: eucalyptus cultivation with irrigated conventional fertilization; FN: eucalyptus cultivation with potential fertilization, not irrigated; FI: eucalyptus cultivation with irrigated potential fertilization.

$$CCI = \frac{TOC_{euc}}{TOC_{Cerrado}} \qquad (8)$$

The LI is the lability index given by the ratio of C lability of cultivated area and C lability of the reference area, where C lability is given by the ratio of Labile-C to Non-labile-C (Equation 9).

$$LI = \frac{L_{euc}}{L_{Cerrado}} \qquad (9)$$

In turn, the L values represents the C lability, being calculated according to Equation 10.

$$L = \frac{Labile-C}{Non\text{-}labile\text{-}C} \qquad (10)$$

Where Non-labile-C is the difference between TOC and Labile-C.

2.4. Statistical analysis

The data were subjected to analysis of variance (Anova) and the Post-hoc Tukey's test (α = 0.10). The partitioned TOC values were compared by the Dunnett's test (α = 0.05), where each treatment is compared to a predetermined reference, in the case of the Cerrado. The statistical analyses were performed using Statistica 12.0 software (Stat soft Inc., Tulsa, USA).

3. RESULTS

3.1. CO_2 and CH_4 fluxes

Soil CO_2 effluxes were observed for all treatments (Figure 1). The Cerrado had the highest ($p < 0.1$) soil CO_2 emissions, about 148 mg m^2 h^1, while the eucalyptus soil emissions ranged from 117 to 57 mg m^{-2} h^{-1} (Figure 1). Eucalyptus soil emissions presented differences regarding the position (R and IR) of the gas evaluation (Figure 1) and the evaluated treatments. The soils under eucalyptus without irrigation (CN and FN) presented the highest CO_2 efflux values in the R when compared to the IR. For the treatments that received irrigation (CI and FI), the inverse was verified (Figure 1).

In relation to the CH_4, all soils provided a CH_4 inflow independent of the treatments (Figure 1); the soil behaved as a drain of atmospheric CH_4. Some difference ($p < 0.1$) in the position of collection of the evolved gases of the soil was also verified when considering the CH_4 influx (Figure 1). The soil under non-irrigated eucalyptus (CN and FN) provided the highest ($p < 0.1$) CH_4 influx in the R when compared to the Cerrado and irrigated eucalyptus (CI and FI) (Figure 1).

3.2. Soil carbon and nitrogen stocks

TOC stocks differences were not verified ($p > 0.1$) in the 0-10 and 10-20 cm soil layers. To the subsurface soil layers (20-40 to 60-100 cm) the inverse is verified, the soil under eucalyptus (independent of irrigation) presented larger TOC stocks than the soil under Cerrado, differing statistically ($p < 0.1$) (Table 2).

TN did not present statistical difference ($p > 0.1$) between treatments (Table 2). The soil C:N ratio under eucalyptus differ ($p < 0.1$) from the Cerrado only in the 0-10 cm soil layer (Table 2), while the others did not differ among themselves ($p > 0.1$).

Partitioning TOC stocks of the soil profile (0-100 cm) in Labile-C and Non-labile-C, it is verified that all treatments
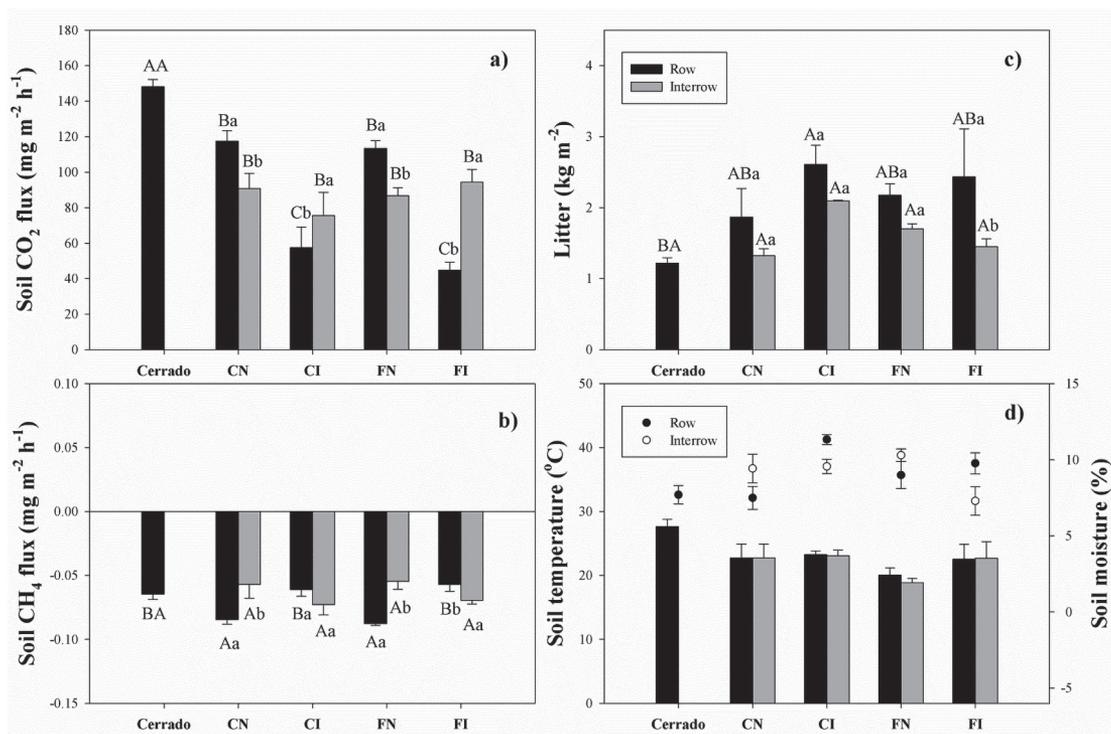
Figure 1. Soil CO_2 flux (a, mg m^{-2} h^{-1}), soil CH_4 flux (b, mg m^{-2} h^{-1}), Litter (c, kg m^{-2}), soil surface temperature (d, ºC), and superficial soil moisture (d, %). CN: Eucalyptus cultivation with conventional non-irrigated fertilization; CI: eucalyptus cultivation with irrigated conventional fertilization; FN: Eucalyptus cultivation with potential fertilization not irrigated; FI: Eucalyptus cultivation with irrigated potential fertilization. Means followed by upper case letters do not differ from treatments within the same position (R and IR) by the Tukey's test ($p < 0.1$). Means followed by lower case letters do not differ from each other regarding the position (R and IR) within the same treatment by the Tukey's test ($p < 0.1$). Comparisons in the Cerrado between treatments only.

differed ($p < 0.05$) from the Cerrado only for Non-labile-C (Figure 2). Although there is no difference between soil Labile-C stocks (layer 0-100 cm) this corresponds to 26.95, 19.67, 20.51, 22.77 and 24.63% of the TOC stocks

of the Cerrado, CN, FN, CI and FI, respectively (Figure 2). When the Labile-C stock is evaluated by soil layer, the Cerrado differs from treatments under eucalyptus only in the topsoil (0-10 cm) (Table 2).

Table 2. Total carbon stocks (TOC, Mg ha^{-1}), Total nitrogen stock (TN, Mg ha^{-1}), C:N ratio and labile carbon stock (Labile-C, Mg ha^{-1}) in different soil layers under cultivation of eucalyptus and Cerrado.

TOC					
Soil layers	Cerrado	CN	FN	CI	FI
cm	Mg ha^{-1}				
0-10	47.08 a	48.66 a	55.75 a	39.94 a	43.51 a
10-20	31.89 a	45.87 a	46.77 a	44.15 a	38.07 a
20-40	40.88 b	65.72 ab	73.33 a	63.41 ab	55.55 ab
40-60	34.52 c	56.81 ab	64.14 a	57.03 ab	50.81 b
60-100	39.06 b	79.74 a	85.32 a	80.12 a	80.23 a

Table 2. Continued...

TN					
Soil layers	**Cerrado**	**CN**	**FN**	**CI**	**FI**
cm			Mg ha^{-1}		
0-10	3.49 a	1.94 a	2.63 a	1.52 a	1.85 a
10-20	2.98 a	1.91 a	2.44 a	1.79 a	2.06 a
20-40	2.26 a	3.05 a	3.32 a	2.25 a	3.20 a
40-60	1.61 a	2.87 a	2.16 a	2.23 a	2.74 a
60-100	2.50 a	4.07 a	3.54 a	2.54 a	5.66 a
C:N ratio					
Soil layers	**Cerrado**	**CN**	**FN**	**CI**	**FI**
cm			Mg ha^{-1}		
0-10	14.12 b	24.96 ab	23.09 ab	33.49 a	23.83 ab
10-20	11.92 a	26.73 a	21.28 a	25.85 a	19.34 a
20-40	18.91 a	22.52 a	25.78 a	28.64 a	19.04 a
40-60	24.82 a	20.06 a	30.73 a	28.26 a	21.57 a
60-100	15.51 a	28.70 a	27.01 a	37.50 a	17.41 a
Labile-C					
Soil layers	**Cerrado**	**CN**	**FN**	**CI**	**FI**
cm			Mg ha^{-1}		
0-10	16.30 a	9.83 b	13.40 ab	9.84 b	11.23 ab
10-20	8.11 a	8.98 a	10.20 a	11.08 a	9.59 a
20-40	8.66 a	18.20 a	15.23 a	15.53 a	15.47 a
40-60	7.04 a	10.25 a	11.91 a	11.52 a	12.71 a
60-100	12.02 a	11.15 a	15.99 a	16.85 a	17.05 a

CN: Eucalyptus cultivation with conventional non-irrigated fertilization; CI: eucalyptus cultivation with irrigated conventional fertilization; FN: eucalyptus cultivation with potential fertilization not irrigated; FI: Eucalyptus cultivation with irrigated potential fertilization. Means followed by the same letter within the same layer do not differ by Tukey's test ($p < 0.1$).

3.3. Carbon management index (CMI)

Considering the CMI as an indicator of soil quality, when the soil profile is evaluated as a whole, 0-100 cm soil depth, the CMI of the treatments does not differ ($p > 0.05$) from each other (Figure 2).

4. DISCUSSION

4.1. CO$_2$ and CH$_4$ fluxes

The Cerrado provided the highest CO$_2$ emissions from the soil to the atmosphere because it had the largest Labile-C stocks in the 0-10 cm soil layer, lower litter contribution, higher temperature (Figure 1 and Table 2), the action of the decomposing microorganisms and a more heterogeneous vegetal stratum in relation to eucalyptus.

The effect of soil cover on temperature reduction is a controlling factor of CO$_2$ emission, once the microbial activity is accelerated with increases in soil temperature and the consequent higher C mineralization rate (Ussiri & Lal, 2009).

For the soils under eucalyptus, the probable difference of the distribution of the root system in
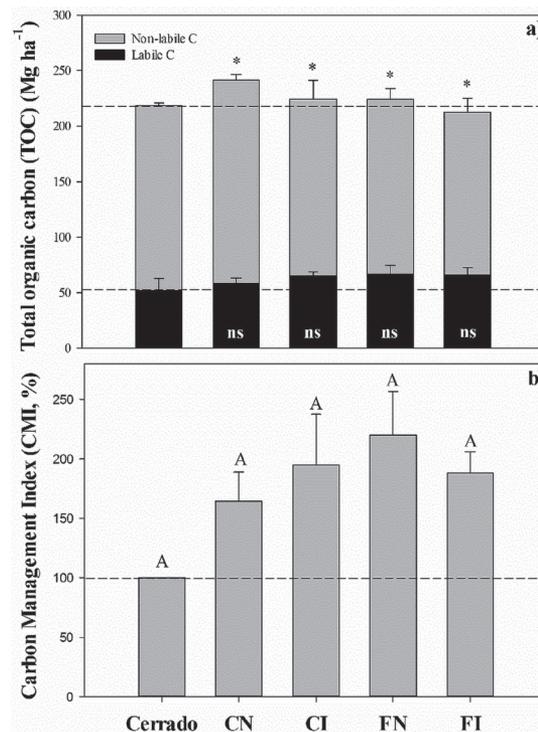
Figure 2. Total soil carbon stocks (a, TOC, Mg ha^{-1}) partitioned in Labile-C (a, Mg ha^{-1}) and Non-labile-C (a, Mg ha^{-1}) in the layer 0-100 cm and soil carbon management index (b, CMI, %) under eucalypt and Cerrado cultivation. CN: Eucalyptus cultivation with conventional non-irrigated fertilization; FN: Eucalyptus cultivation with potential fertilization not irrigated; CI: eucalyptus cultivation with irrigated conventional fertilization; FI: Eucalyptus cultivation with irrigated potential fertilization. *Significant by the Dunnett's test ($p < 0.05$). Means followed by the same letter do not differ by Tukey's test ($p < 0.05$).

the soil profile led to changes in the CO_2 and CH_4 fluxes as well as the sampling position of the gases. Due to the lower water availability during cultivation, the CN and FN treatments possibly invested more in the root system, mainly verticalized, and presented higher CO_2 efflux (autotrophic contribution) in the R. The larger C partition to the roots (greater root/aerial part), almost always associated with the deepening of the root system, makes it possible to capture water in deeper soil layers (Gonçalves & Passos, 2000). In order to avoid the lack of water, the plants use some strategies such as leaf and superficial roots loss, proliferation of deep roots (Reis et al., 2006), and osmotic adjustment for the maintenance of cellular turgor, which may result in lower soil humidity and, consequently, less power to oxidize CH_4. However, for soils under irrigated eucalyptus (CI and FI), plants do not need to invest so much in the root system, since irrigation sprays the total area and the root system tends to be more horizontal (Sant'Ana et al.,

2012), which may justify the higher gas flux in the IR than in the R.

The limited availability of water also favors soil aeration and promotes the increase of the soil methanotrophic bacteria activity and the consequent soil CH_4 influx. The process of CH_4 influx is a consequence of the oxidation of CH_4 by soil methanotrophic bacteria, under aerated conditions, use CH_4 as source of energy and C (Lemer & Roger, 2001; Saggar et al., 2008). Jacinthe & Lal (2005), in a study on the CH_4 oxidation in different crop management, concluded that soils that undergo management require decades to partially restore the CH_4 oxidation capacity. They also report that the slow recovery of the ability to sequester CH_4 is indicative of the damage to the niche of soil methanotrophic bacteria and that this damage is difficult to reverse. In the current study, it is evident that the potential soils under eucalyptus sequester CH_4 from the atmosphere, as well as acting as a liquid drain of CO_2 and CH_4 of the atmosphere when it surpasses the Cerrado.

4.2. Soil carbon and nitrogen stocks

In the soils under eucalyptus the presence of active irrigation to the soil microbiota favors the decomposition of the most labile compounds and fine roots and entails a probable positive "*priming effect*", which may be contributing to the lower TOC stocks (Fontaine et al., 2003) in surface and CI treatments. During the decomposition process, the microorganisms use the C in their metabolism and the excess can be released by respiration in the CO_2 form (Vishwakarma et al., 2006).

For the soils under eucalyptus that did not receive irrigation, the largest TOC stocks are probably due to the investment in a deeper root system and a higher root/aerial part due to the need to exploit a larger soil volume to capture water. Reis et al. (1985) observed for *Eucalyptus grandis* that the root biomass accumulation was higher in a site of poorer quality (soil under water deficit) in relation to another of better quality (without water deficit). They also verified that in a condition of less availability of water and nutrients the trees tend to increase the C partition in the roots in order to increase their water acquisition surface.

The quantification of TOC stocks does not provide values that extrapolate for different management situations, sites, climates and soils (Nicoloso et al., 2008), which makes it necessary to divide into more sensitive compartments, such as Labile-C and Non-labile-C. The largest Non-labile-C contribution to the soil TOC profile (0-100 cm) was probably due to two reasons: 1) Organo-mineral interactions that provide chemical protection to the TOC, since it refers to a well-developed Oxisol with clay content, high Fe and Al oxides; 2) The higher soil C:N ratio observed under eucalyptus in the deeper layers, predominantly a more recalcitrant C, which decomposition is difficult.

When the 0-10 cm soil layer is considered, the Cerrado sowed the largest Labile-C and TN stocks. This is due to the diversity and quality of the material contributed, once the composition of the Cerrado is given by an herbaceous stratum that coexists with sparse shrubs and trees, besides having grasses and species with lower C:N ratios in their composition, unlike the homogeneous material of eucalyptus crops. However, the soil under irrigated eucalyptus that received potential fertilization presented expressive values of TN stocks in the subsurface soil layers, explained by: 1) N leached in the soil profile through irrigation water may have interacted with soil TOC and rhizodeposition providing greater stabilization of C and N in the soil profile (Dijkstra et al., 2004). The higher amounts of N absorbed by eucalyptus plants, due to their high efficiency, increased the root biomass production allowing C and N stocks at higher soil depths (Stape et al., 2004).

The lower TN and larger TOC stocks in the 60-100 cm layer observed that soils under eucalyptus receiving conventional fertilization (independent of irrigation) provided a higher C:N ratio. This higher C:N (37.50 and 28.70) stoichiometry with the O_2 limitation in depth gives CI and CN a more recalcitrant C and less accessible to the microbial action, favoring the soil C accumulation (Lamparter et al., 2009). In the current study, for soils under eucalyptus that received potential fertilization (irrespective of irrigation) N is probably carried (as previously mentioned) to the deeper layers of the soil and promotes a lower C:N ratio.

4.3. Carbon Management Index (CMI)

CMI is used as an indicator of the impact of land use and management practices on soil C levels and quality. The soil surface layer, the Cerrado stratum, for reasons already discussed, favors the best quality of the COS (Portugal et al., 2008). However, when the soil profile is considered as a whole, eucalyptus cultivation recovers the SOC quality as it provides greater soil C stocks in the deeper layers. This probably has a more developed root system that favors the soil exploration in depths where the action of the microorganisms is restricted favoring the C accumulation. In addition, the cultivation of eucalyptus contributes to large amounts of litter fall to the soil and provides lower emissions of gases to the atmosphere.

5. CONCLUSIONS

After 7 years of eucalyptus cultivation, water availability (irrigation management) had a higher effect on soil C stocks (profile 1 m) in relation to nutrient availability (fertilization).

Eucalyptus soils (after 7 years of different fertilization and irrigation managements) were more efficient in C stocks in depth (profile 1 m) in relation to the native Cerrado, acting as a liquid drain of CO_2 and CH_4 of the atmosphere.

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