Agroforest Syst (2020) 94:2343–2353
https://doi.org/10.1007/s10457-020-00554-x

Variation in soil carbon, nitrogen and microbial attributes within a silvopastoral system in the Brazilian Cerrado

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Received: 5 May 2020 / Accepted: 30 September 2020 / Published online: 6 October 2020

Abstract There is insufficient information about the dynamics of soil organic matter in integrated production systems. Therefore, we aimed to evaluate the variations in soil C and N stocks and microbial attributes as a function of the distances apart from the eucalyptus double rows within a silvopastoral system in the Brazilian Cerrado. Four treatments were considered, consisting of four distances (0.5 m, 1.6 m, 3.8 m and 6 m) apart from the double rows of eucalyptus for soil sampling within the silvopastoral system. The soil C and N contents and stocks, C/N ratio, microbial C (Cmic), soil basal respiration, metabolic quotient and microbial quotient were evaluated. Our results showed that soil C contents and stocks were significantly higher near the eucalyptus trees. Soil C stocks ranged from 99.91 (6.0 m) to 119.64 Mg ha^{-1} (0.5 m) up to 100 cm soil depth, with an increase of 19.73 Mg ha^{-1} nearest of the forest component. The same pattern was observed for N stocks, with values ranging from 9.52 (0.5 m) to 7.95 Mg ha^{-1} (6.0 m) and representing an increase of 1.57 Mg ha^{-1} near the eucalyptus. We also found an increase of 51.32% in the Cmic at 0.5 m apart from the forest component. Thus, we can infer that the presence of eucalyptus improved the soil quality within the silvopastoral system, indicating that the correct soil sampling and measurements must be performed considering all the transect cultivated with forage grass and double rows of eucalyptus.

Keywords Integrated forage-forestry system · Microbial carbon · Soil organic matter · Soil quality

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Introduction

The conversion of native vegetation for food production can promote degradation and the decline of the ecosystem sustainability. Agricultural management and practices are factors that are directly associated with the changes in soil quality (Wezel et al. 2014). In the Brazilian Cerrado, there is a predominance for monoculture cultivation, with low investment in maintaining soil quality over time.

In this context, several studies have reported that agroforestry or integrated production systems, when compared to conventional systems, result in improvements in soil quality regarding the physical (Chen et al. 2017; Moreira et al. 2018; Cabral Filho et al.

2017), chemical (Schwab et al. 2015; Araújo et al. 2017; Pardon et al. 2017) and biological properties (Udawatta et al. 2014; Portilho et al. 2018; Guillot et al. 2019). These conservationist systems are also considered as a strategy for mitigating climate change, as they can promote atmospheric C sequestration (Lorenz and Lal 2014; Srinivasarao et al. 2014; Abbas et al. 2017; Tumwebaze and Byakagaba 2016; Dhillon and Rees 2017; Franzluebbers et al. 2017).

Agroforestry is cited as sustainable systems because they advocate the use of available nutrients, water and light with maximum efficiency (Lorenz and Lal 2014). In addition, they bring economic returns to farmers through the production of several agricultural products. In these agroecosystems, important edaphic processes such as the dynamics of soil organic matter (SOM) and nutrient cycling are favored and positively influenced by the higher plant density (Cezar et al. 2015).

The constant litter inputs and soil cover associated with the existence of extensive root systems in intercropped forest systems contribute to the increase in the levels of soil organic C and N, improving soil quality over time (Chen et al. 2017; Rodrigues et al. 2015) reported a reduction in the soil organic C in a monoculture of grass (*Brachiaria brizantha*) and increase when the cultivation was intercropped with trees. Gelaw et al. (2014) also reported significant increases in the C and N stocks after the introduction of a silvopastoral system. However, Borges et al. (2019) have reported that an agricultural system composed by eucalyptus intercropped with annual crops and pastures leads to a lack of uniformity in soil properties. Similar pattern was also reported by Guillot et al. (2019) in an agroforestry system, where spatial heterogeneity in soil C and N contents and microbial biomass was found at different distances from the tree lines.

On the other hand, Lorenz and Lal (2014) reported that the inclusion of trees in integrated production systems can favor the storage of soil organic C. In this context, Dhillon and Van Rees (2017) highlighted the need for further research to better understand and explore the potential for mitigating atmospheric CO_2 emissions in forest agroecosystems and also to determine the influence of trees in the accumulation of soil C stocks. Freitas et al. (2020) pointed out that C4 species for grain and forage production in agrosilvopastoral systems can be used to increases in soil C and N stocks over time.

In the Brazilian Cerrado, integrated production systems have been adopted using single, double or triple eucalyptus lines (Tonini et al. 2019). Thus, it is important to understand how these arrangements can contribute to the heterogeneity of soil attributes over time.

In order to support the adoption of strategies to representative measurements of soil attributes in agroforestry systems, we aimed to evaluate the variation in soil C and N stocks and microbial attributes as a function of the several distances apart from the double rows of eucalyptus within a silvopastoral system in the Brazilian Cerrado.

Materials and methods

The experimental field site was located at Buritis Farm (16° 42′ 25″ S e 44° 04′ 36″ W), in the municipality of Montes Claros, Minas Gerais State, Brazil. The study was undertaken from August 2014 to February 2015. Elevation of the area was approximately 652 m, with rolling topography and *Cerrado* (Savanna) biome type. The climate is tropical savanna (Aw) with rainfall concentrated in the summer (October to April). The average of annual precipitation in the municipality over the last 15 years was 945 mm, and the mean temperature was 24.1 °C (Instituto Nacional de Meteorologia [INMET] 2018). Soil samples were collected to determine the particle size, soil density and nutrient contents at 0–5, 5–10, 10–20, 20–30, 30–50, 50–75 and 75–100 cm depths layers. The soil was characterized as dystrophic and with medium texture and classified as Orthic Ferralsol (Table 1).

The silvopastoral system was introduced in 2011 in an area previously cultivated with low productivity pasture of marandu grass. The spacing adopted for introducing the integrated production system was 3.2 × 1.5 inside the double rows of trees and 12 m between double rows (alley). The area was cultivated with eucalyptus (144 seedlings of *Eucalyptus urograndis* hybrid [*E. grandis* × *E. urophylla*] clones) in double rows intercropped with maize in the first year (*Zea mays* hybrid [SHS 7920]) and *B. brizantha* cv. Marandu after maize harvest (used as forage).

During planting of *E. urograndis*, fertilization with 300 g per pit with simple superphosphate was used.

Table 1 Granulometric composition, soil density and nutrient contents ($n = 4$) in the evaluated silvopastoral system in the Brazilian Cerrado

Soil attribute	Soil depth (cm)							
	0–5	5–10	10–20	20–30	30–50	50–75	75–100	Mean
Sand (g kg^{-1})	349	407	422	384	412	440	424	405
Silt (g kg^{-1})	210	165	145	160	195	200	205	183
Clay (g kg^{-1})	235	220	245	265	215	200	205	226
Soil density (g cm^{-3})	1.12	1.15	0.97	0.93	0.89	0.95	0.95	0.99
pH H_2O	5.3	5.1	4.8	4.7	4.7	4.8	5.1	4.9
Available P (mg dm^{-3})	1.8	0.7	0.6	0.5	0.4	0.4	0.5	0.7
K (mg dm^{-3})	20.5	13.1	14.6	13.7	12.1	13.7	15.4	14.7
Ca ($cmol_c$ dm^{-3})	1.7	1.1	0.5	0.2	0.2	0.2	0.6	0.6
Mg ($cmol_c$ dm^{-3})	0.5	0.3	0.2	0.1	0.1	0.1	0.2	0.2
H + Al ($cmol_c$ dm^{-3})	3.8	4.7	4.8	4.3	3.7	3.0	2.8	3.9
SB ($cmol_c$ dm^{-3})	2.2	1.5	0.7	0.4	0.3	0.4	0.8	0.9
CECe ($cmol_c$ dm^{-3})	6.0	6.2	5.5	4.7	4.1	3.4	3.7	4.8
m (%)	11.0	19.2	45.6	66.0	64.0	57.3	49.7	44.7
BS (%)	36.7	26.1	15.2	8.9	9.6	11.1	18.7	18.0
SOM (g kg^{-1})	36.0	33.0	29.0	26.0	22.0	19.0	20.0	23.0

SB sum of bases, *CECe* effective cation exchange capacity, *m* Al saturation, *BS* base saturation, *SOM* soil organic matter

The cover fertilization of eucalyptus was applied 8 and 60 days after transplanting, and comprizing 160 g per plant of NPK fertilizer (4:26:10) and 160 g per plant of NPK fertilizer (20:00:20), respectively. In February and October 2012, respectively, 25 g per plant of boric acid and 100 g per plant of potassium chloride (KCl) were applied. Before the pasture introduction, 2 t ha^{-1} of lime was applied between the lines of eucalyptus followed by plowing and harrowing. The last fertilizer application in the eucalyptus before soil sampling was carried out in February 2014, using 25 g per plant of boric acid.

The experimental design adopted was completely randomized (CRD), with 4 treatments and 4 replications. The treatments consisted of the four distances from the double rows of eucalyptus in the silvopastoral system: 0.5 m, 1.6 m, 3.8 m and 6 m, in plots of 30.4 m^2 (3 × 15.2 m) spaced 50 m from each other (Fig. 1). Soil sampling for analysis of soil C and N contents and stocks and C/N ratio was carried out in pits (0.5 × 0.5 × 1.0 m) at 0–5, 5–10, 10–20, 20–30, 30–50, 50–75 and 75–100 cm depths, accounting to 112 soil samples (4 treatments × 4 repetitions × 7 depths). Soil microbial carbon (Cmic), basal respiration (SBR), metabolic quotient (qCO_2) and microbial quotient (qMIC) were determined at 0–5, 5–10 and 10–20 cm depths, accounting to 48 soil samples (4 treatments × 4 repetitions × 3 depths).

After collection, the soil samples were air-dried. The roots were then removed from the samples and passed through 2 mm sieves. After this initial processing, the soil samples were ground and passed through 0.150 mm sieves. The soil C and N contents were determined by dry combustion with a LECO TruSpec CN analyzer (Leco Corp., St. Joseph, MI, USA) using, respectively, infrared absorption and thermal conductivity. The soil C and N stocks were determined from the multiplication of C or N content by the soil density and respective soil depth layer.

The soil samples for determination of microbiological attributes were preincubated at 60% humidity of the field capacity for a period of seven days. The soil microbial biomass extraction was carried out using the fumigation-extraction method (Reis Junior and Mendes 2007; Silva et al. 2007), and the determination of Cmic was performed using the wet oxidation method (Walkley and Black 1934). The SBR was determined by the means of evolved CO_2 and extraction with sodium hydroxide NaOH (Jenkinson and Powlson 1976). The soil organic C of the samples destined for microbiological analysis was determined according to the methodology proposed by Embrapa (1997). Subsequently, qCO_2 index was obtained by the ratio between SBR and Cmic, and qMIC index by the ratio between Cmic and organic C (Anderson and Domsch 1993; Reis Junior and Mendes 2007).

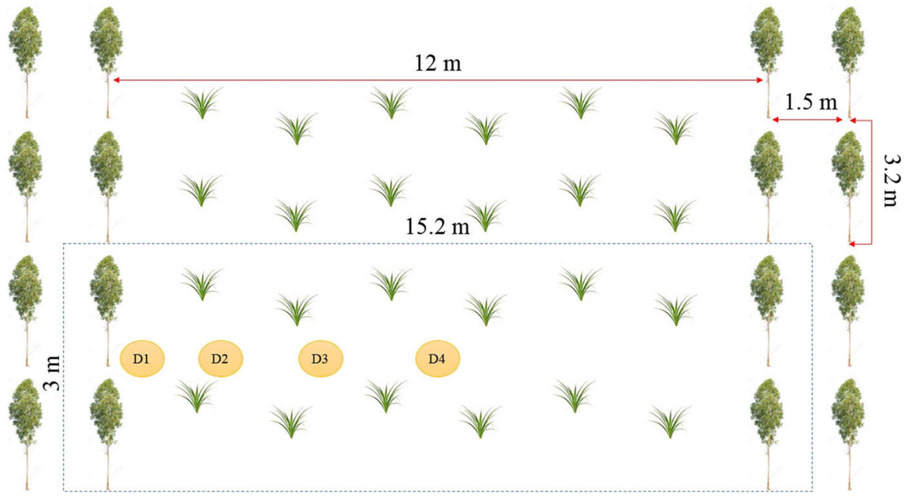

Fig. 1 Scheme of the experimental unit. Dotted line delimits the experimental unit (3 m × 15.2 m). Circles correspond to the distances of the trees used for soil sampling (D1: 0.5 m; D2: 1.6 m; D3: 3.8 m; and D4: 6 m)

The Shapiro-Wilk test was used to verify if the values of each variable satisfied a normal distribution, while the Cochran and Bartlett test was used to assess the results for homogeneity of variances. After validating the normal distribution and homogeneity of variances, analysis of variance (ANOVA) was performed and subsequently the means were compared by the Duncan test ($p < 0.05$), using R statistical software (R Development Core Team 2016). In order to select explanatory variables to discriminate the different soil sampling positions within the silvopastoral system, a principal component analysis (PCA) was performed. In the PCA, we considered the mean values at 0–20 cm and 0–100 cm soil layers for microbiological attributes and others parameters, respectively.

Results

Our results indicated that the parameters evaluated were influenced ($p < 0.05$) by the distances from the double rows of eucalyptus in the 10–20 cm layer and in the soil profile (0–100 cm) (Tables 2, 3 and 4). Thus, we can infer that to perform a correct assessment of the SOM dynamics in a silvopastoral system, soil sampling must be representative for all the transect, including the forest and forage components.

Considering the soil profile (0–100 cm), the C contents were significantly higher (1.49 g kg^{-1}) near the double rows of eucalyptus (0.5 m), since in the 1.6, 3.8 and 6 m distances showed lower and similar soil C levels (1.30, 1.27 and 1.28 g kg^{-1}, respectively) (Table 2). Figure 2 confirms that the difference in C levels was more pronounced in the region near the double rows of eucalyptus, which has the highest concentration of roots and is constantly shaded. The results obtained for soil N contents and C/N ratio showed small variability among the distances of the eucalyptus planting lines. The N contents ranged from 0.10 to 0.11 g kg^{-1}, while the C/N ratio ranged from 12.41 to 12.99 (Table 2).

Variation in the soil C and N stocks ($p < 0.05$) as a function of the distance from the double rows of eucalyptus were observed at 10–20 and 20–30 cm depths (Table 3), and this result can be attributed to the management practices for introducing pasture into the alley cropping. Considering the evaluated soil profile (0–100 cm), C stocks ranged from 99.91 (6.0 m distance) to 119.64 Mg ha^{-1} (0.5 m distance), showing an increase of 19.73 Mg ha^{-1} when the soil sampling was performed near the double rows of eucalyptus. The soil N stocks were higher at 0.5 m when compared to 3.8 and 6.0 m distances from the tree component. Considering the soil profile (0–100 cm), the N stocks ranged from 9.52 (0.5 m distance) to 7.95 Mg ha^{-1} (6.0 m distance), which represented an increase of 1.57 Mg ha^{-1} when soil sampling was performed near the trees within the silvopastoral system.

Table 2 Soil C and N contents and C/N ratio at different distances from the double rows of eucalyptus within a silvopastoral system in the Brazilian Cerrado

Soil depth (cm)	Distance from the double rows of eucalyptus (m)			
	0.5	1.6	3.8	6.0
C content (g kg^{-1})				
0–5	1.98 a[a]	1.82 a	1.81 a	1.94 a
5–10	2.15 a	1.86 a	1.86 a	1.68 a
10–20	1.83 a	1.50 b	1.52 b	1.51 b
20–30	1.40 a	1.21 a	1.19 a	1.14 a
30–50	1.19 a	1.02 a	0.98 a	1.04 a
50–75	1.09 a	0.86 a	0.85 a	0.86 a
75–100	0.78 a	0.82 a	0.66 a	0.76 a
0–100	1.49 a	1.30 b	1.27 b	1.28 b
N content (g kg^{-1})				
0–5	0.13 a	0.13 a	0.13 a	0.14 a
5–10	0.15 a	0.14 a	0.14 a	0.13 a
10–20	0.13 a	0.12 a	0.11 a	0.12 a
20–30	0.11 a	0.10 a	0.09 a	0.09 a
30–50	0.10 a	0.09 a	0.08 a	0.08 a
50–75	0.09 a	0.07 a	0.07 a	0.07 a
75–100	0.07 a	0.07 a	0.06 a	0.06 a
0–100	0.11 a	0.10 a	0.10 a	0.10 a
C/N ratio				
0–5	14.94 a	13.66 a	13.78 a	14.14 a
5–10	14.54 a	13.56 a	13.40 a	12.66 a
10–20	13.89 a	12.73 a	13.77 a	12.85 a
20–30	12.88 a	12.28 a	12.78 a	12.69 a
30–50	11.86 a	12.04 a	12.34 a	12.87 a
50–75	11.63 a	11.61 a	11.81 a	11.97 a
75–100	11.17 a	10.98 a	11.80 a	12.34 a
0–100	12.99 a	12.41 a	12.81 a	12.79 a

[a]The values represent the mean ($n = 4$). Means within each line of the same parameter followed by the same letter are not significantly different by the Duncan test ($p < 0.05$)

The soil microbial attributes also showed variation in relation to the soil sampling position within the silvopastoral system (Table 4). In the rainy season, at 10–20 cm soil depth, Cmic values ranged from 146.6 (6.0 m distance) to 284.5 mg kg^{-1} (0.5 m distance), showing an increase of 51.32% when soil sampling was performed near the eucalyptus trees within the silvopastoral system. Considering the 0–20 cm soil depth, similar values for Cmic were found in both evaluated seasons, but we can infer about a higher microbial biomass in the rainy season.

Similar results were obtained for qMIC, since we found higher values ($p < 0.05$) in the rainy season at 10–20 cm soil depth in the 0.5 m distance (Table 4). We also found the highest qMIC values in February 2015, confirming an increase in soil microbial biomass in the rainy season. On the other hand, we not found differences in SBR and qCO_2 for all evaluated distances, which showed a uniform microbial activity within the silvopastoral system since the points near the eucalyptus trees (0.5 m) until to the center of the alleys cultivated with forage grasses (6.0 m).

The PCA (Fig. 3) showed the projection of soil quality variables and soil sampling points (0.5, 1.6, 3.8 and 6.0 m). The first two axis explained 99.99% of the variance. The PCA 1 correlated strongly D1 position (0.5 m) with soil C and N content and stocks, Cmic in the wet and dry seasons, qMIC and SBR in the wet season. The PCA 2 correlated D2 (1.6 m) position with SBR in dry season and D3 (3.8 m) with qCO_2 in both evaluated seasons.

Table 3 Soil C and N stocks at different distances from the double rows of eucalyptus within a silvopastoral system in the Brazilian Cerrado

Soil depth (cm)	Distance from the double rows of eucalyptus (m)			
	0.5	1.6	3.8	6.0
Soil C stocks (Mg ha^{-1})				
0–5	11.06 a[a]	10.12 a	10.14 a	10.85 a
5–10	12.37 a	10.71 a	10.68 a	9.59 a
10–20	17.83 a	14.57 b	14.78 b	14.68 b
20–30	13.00 a	11.17 b	10.98 b	10.56 b
30–50	21.15 a	17.98 a	17.43 a	18.38 a
50–75	25.70 a	20.23 a	20.14 a	20.53 a
75–100	18.53 a	19.57 a	15.77 a	18.09 a
0–100	119.64 a	104.35 b	102.68 b	99.91 b
Soil N stocks (Mg ha^{-1})				
0–5	0.74 a	0.74 a	0.74 a	0.77 a
5–10	0.85 a	0.79 a	0.80 a	0.76 a
10–20	1.28 a	1.15 a	1.07 a	1.15 a
20–30	1.01 a	0.91 ab	0.86 b	0.83 b
30–50	1.77 a	1.52 a	1.42 a	1.43 a
50–75	2.21 a	1.75 a	1.71 a	1.76 a
75–100	1.67 a	1.78 a	1.35 a	1.46 a
0–100	9.52 a	8.65 ab	8.16 b	7.95 b

[a]The values represent the mean ($n = 4$). Means within each line of the same parameter followed by the same letter are not significantly different by the Duncan test ($p < 0.05$)

Table 4 Soil microbial attributes in the dry and wet seasons at different distances from the double rows of eucalyptus within a silvopastoral system in the Brazilian Cerrado

Distance (m)	Soil depth (cm)							
	0–5		5–10		10–20		0–20	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Cmic (mg kg^{-1})								
0.5	127.2 a[a]	264.5 a	166.2 a	177.9 a	111.7 a	284.5 a	135.1 a	242.3 a
1.6	102.5 a	279.7 a	144.7 a	161.3 a	92.9 a	154.3 b	113.4 a	198.4 a
3.8	114.8 a	200.9 a	90.5 a	195.7 a	120.5 a	151.1 b	108.6 a	181.1 a
6.0	135.0 a	173.8 a	103.3 a	154.5 a	110.6 a	146.6 b	116.3 a	159.8 a
qMIC (%)								
0.5	0.64 a	1.36 a	0.79 a	0.83 a	0.60 a	1.58 a	0.68 a	1.26 a
1.6	0.58 a	1.61 a	0.78 a	0.87 a	0.63 a	1.02 b	0.66 a	1.17 a
3.8	0.63 a	1.10 a	0.52 a	1.09 a	0.80 a	0.98 b	0.65 a	1.06 a
6.0	0.71 a	0.90 a	0.63 a	0.95 a	0.75 a	1.03 b	0.69 a	0.95 a
SBR (mg C–CO_2 kg^{-1} soil h^{-1})								
0.5	0.51 a	0,27 b	0.43 a	0.32 a	0.35 a	0.37 a	0.42 a	0.32 a
1.6	0.49 a	0,38 a	0.41 a	0.22 a	0.41 a	0.22 a	0.44 a	0.27 a
3.8	0.46 a	0,25 b	0.40 a	0.35 a	0.39 a	0.32 a	0.42 a	0.31 a
6.0	0.48 a	0,28 b	0.41 a	0.22 a	0.34 a	0.22 a	0.41 a	0.24 a
qCO_2 (mg C–CO_2 g^{-1} Cmic h^{-1})								
0.5	4.17 a	1.27 a	2.91 a	2.12 a	3.27 a	1.31 a	3.45 a	1.57 a
1.6	4.73 a	1.71 a	2.90 a	1.36 a	4.60 a	1.49 a	4.08 a	1.52 a
3.8	4.08 a	1.29 a	4.67 a	1.79 a	3.29 a	2.33 a	4.01 a	1.81 a
6.0	3.87 a	1.62 a	3.92 a	1.45 a	3.15 a	1.45 a	3.65 a	1.51 a

[a]The values represent the mean ($n = 4$). Means within each column of the same parameter followed by the same letter are not significantly different by the Duncan test ($p < 0.05$)

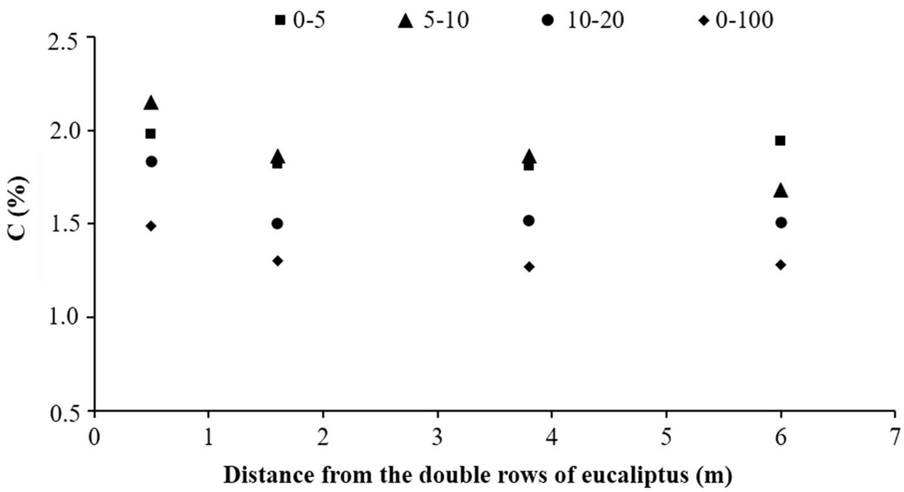

Fig. 2 Soil C contents (%) considering different distances from the double rows of eucalyptus within a silvopastoral system in the Brazilian Cerrado

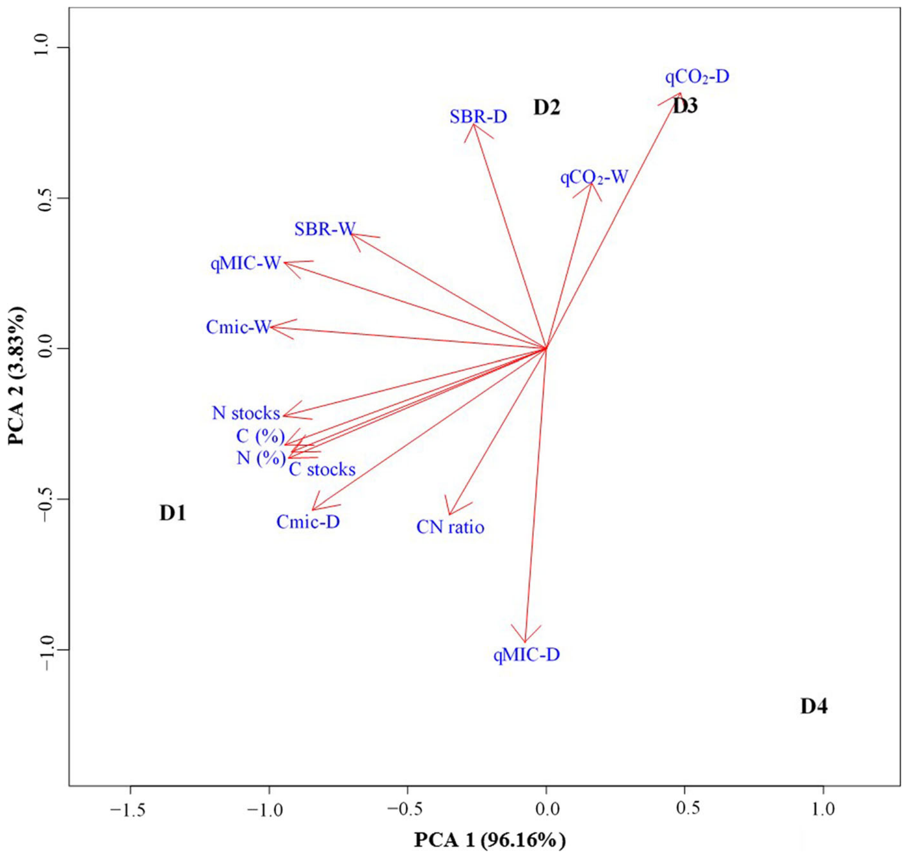

Fig. 3 Projection of soil quality variables and soil sampling points ((D1: 0.5 m; D2: 1.6 m; D3: 3.8 m; and D4: 6 m) in the factorial space (F1 and F2) of a principal component analysis (PCA). Abbreviations: carbon and nitrogen contents (C (%) and N (%)) and stocks (Cstocks and Nstocks); microbial carbon, soil basal respiration, microbial quotient and metabolic quotient in dry (Cmic-D, SBR-D, qMIC-D and qCO_2-D) and wet seasons (Cmic-W, SBR-W, qMIC-W and qCO_2-W)

Discussion

Our study showed results from a 4-years-old silvopastoral system introduced in an area previously cultivated with forage grasses. Thus, the tree component was introduced during the conversion of forage monoculture to integrated production system. The highest levels of soil C content was obtained near the eucalyptus planting lines (0.5 m) in relation to the center of the alleys (6.0 m). Our results can be related to the deposition of the aerial and subsoil residues (leaf and root exudates, leaves, stems, flowers, seeds and roots) from the forest component (double rows of eucalyptus), contributing to the SOM accumulation. Chen et al. (2017) reported that the constant inputs of litter and the presence of extensive root systems increase the levels of soil C and N contents. In addition, Dhillon and Van Rees (2017) also highlighted that the age of the stand and characteristics such as height and diameter of trees, canopy diameter and inputs of litter showed a positive correlation with increases in soil C contents. In this sense, the roots, leaves and branches of the forest component are gradually decomposed contributing to an increase in SOM over time (Udawatta et al. 2014).

In agreement with our findings, Borges et al. (2019) also found an increase in SOM in planting lines of eucalyptus in relation to the different distances until to the center of the alleys. Another study in an agroforestry system with 21-years old also showed that exist spatial heterogeneity in soil C and N contents in relation to the different distances from the trees planting lines (Guillot et al. 2019). These authors reported that the C and N contents were decreasing as the soil sampling points moved away from the tree component.

Pardon et al. (2017) pointed out about the potential of tree components in increasing soil C and making nutrients available to the intercropped cultures within the agrosilvopastoral systems. The authors found increases in soil C, N and nutrients contents near the eucalyptus planting lines and gradual reduction when increased the distance from the trees. These results were attributed to the litter deposition composed mainly by leaves, and exudates from the tree component.

Our results about C/N ratio indicated similarity among the different soil sampling points in the evaluated transect within the silvopastoral system. Considering the soil depths (0–100 cm) and distances from the double rows of eucalyptus, the values ranged from 10.98 to 14.94, and indicated that the N mineralization was more effective than immobilization process. Similar results were found by Lu et al. (2015) in a study evaluating changes in soil C and N contents in croplands converted to walnut-based agroforestry systems in China.

As observed for the C contents, the highest soil C stocks were found near the double rows of eucalyptus. Although there was no difference in soil N content among the evaluated distances, we found the highest soil N stocks at 0.5 m apart from the tree component. These results demonstrated the soil spatial heterogeneity within the silvopastoral system and the potential of eucalyptus cultivation in increasing soil C and N stocks when it is intercropped with forage grass. Pardon et al. (2017) reported that the insertion of tree component in agroforestry systems has a potential in increasing the soil C stocks and nutrients, and this result that may favor the other components within the production system. Another study performed by Lana et al. (2018) reported that the integrated systems with eucalyptus showed an increase in soil C stocks due the higher litter production of this forest component.

Several studies also reported that the insertion of the tree component contribute to increase the soil C and N stocks, with significant increases in the canopy area (Pardon et al. 2017; Beuschel et al. 2019; Borges et al. 2019; Guillot et al. 2019; Chen et al. 2017) also report that the accumulation of C and N can promote improvements in soil aggregation and reduction of erosion processes, resulting in a positive effect on the soil physical and chemical properties.

The heterogeneity verified in Cmic values within the silvopastoral system is also in accordance with other studies carried out in integrated production systems. Guillot et al. (2019) reported spatial heterogeneity in soil microbial biomass in an agroforestry system, with higher microbial activity near the tree lines. According to these authors, the forest component can modify the soil microclimate contributing to the maintenance of soil moisture and lower temperatures and increasing the soil microbial activity. Thus, modifications in microclimate combined to the entry of organic matter and can promote changes in the soil microbiota behavior. According to Albuquerque et al. (2015), a higher proportion of roots is found under the stem base, which also contributes to a greater microbial development in this region, since the labile C is made available via root exudation, which is used as a food source by the soil microbiota (Pausch and Kuzyakov 2018).

Li et al. (2019) highlighted that the soil C and N is high correlated to the soil microbial biomass, which corroborates with our findings, since the highest soil C and N stocks and Cmic values were found at the same sampled points. Beuschel et al. (2019) also demonstrated that the insertion of tree lines into the cultivation systems improved soil quality through increases in soil C and microbial activity over a period of 5–8 years. According to these authors, their results are due to the higher quality of the residues deposited on the soil surface and subsurface, and also due to the absence of soil tillage after the introduction of the forest component. According to Pardon et al. (2017), factors such as the stage of plant development and the distance between the tree planting lines have a significant influence on soil attributes.

The Cmic values represent between 1 and 4% of the soil organic C, and qMIC values below 1% may occur due to the occurrence of any ecological or management factor that limiting the activity of soil microbial biomass (Anderson and Domsch 1989; Jakelaitis et al. 2008). On the other hand, higher qMIC values mean that organic C is more easily accessible to the soil microbiota (Almeida et al. 2016). Considering the soil depths evaluated in this study (0–20 cm), the qMIC values were less than 1% in the dry period at all evaluated distances from the double rows of eucalyptus within the silvopastoral system. However, in the rainy season, the values were higher than 1%, except for 6.0 m distance, allowing us to conclude that the qMIC reduction probably occurred due to the decrease on soil microbial activity during the dry season. In addition, the double rows of eucalyptus planting lines also had a positive impact to the soil microbiota.

Regarding to SBR, we found that the highest values were resulted from a greater biological activity, in response to the increase in local diversity (Azar et al. 2013; Santos et al. 2015). The greatest diversity was due to the presence of the eucalyptus planting lines intercropped with forage grass. However, the qCO_2 values showed no variation along the evaluated transect, only increase in the dry season. This result is associated to the similar efficiency in the use of organic compounds by microorganisms within the silvopastoral system (Anderson and Domsch 1993).

Agreeing with our findings, several studies have reported improvements in soil quality with the inclusion of the forest component within the integrated production systems. Weerasekara et al. (2016) observed that the insertion of perennial species can also increase the capacity to decomposition of organic substances due to the higher microbial activity, improving the nutrient cycling. According to Cardinael et al. (2015), increases in soil C stocks may favor the soil fertility and consequently, to reducing the need for inorganic fertilizers and to decreasing the GHG emissions to the atmosphere.

We emphasize, therefore, that others studies with integrated production systems must be carried out to understand and validate the influence of several forest components in soil quality, addressing methodologies that can to evaluate soil spatial variability. These studies can be used to assist the making decisions about the adoption of management strategies and correct measurement of the soil attributes.

Conclusions

In this study, we found that the insertion of the eucalyptus as a forest component into the silvopastoral system contributes to increases in soil C and N stocks and Cmic, since these parameters showed increases near the double rows of eucalyptus (0.5 m). At this sampled point, the soil C and N stocks showed a difference of 19.73 and 1.57 Mg ha^{-1}, respectively, in relation to the furthest point from the trees (6.0 m). We also found a 51.32% increase in Cmic values near to the double rows of eucalyptus.

Thus, in order to correctly evaluate the dynamics of soil organic matter in a silvopastoral system, soil sampling and measurements must be performed considering different points within all the transect cultivated with forage grass and double rows of eucalyptus.

Acknowledgements The authors are grateful for all the logistical support provided by the owners of Buritis Farm during this study.

Funding This study was funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES; Finance Code 001), and the Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG; Grant Nos. APQ-00953-14 and PPM-00133-15). The funding agencies had no

role in the design of the study and collection, analysis, and interpretation of data and in.

Availability of data and materials The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request..

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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