Pesquisa Agropecuária Tropical
ISSN: 1517-6398
ISSN: 1983-4063
Escola de Agronomia/UFG

Silva, Pedro Luan Ferreira da; Oliveira, Flávio Pereira de; Martins, Adriana Ferreira; Tavares, Danillo Dutra; Amaral, André Julio do
Fertility, carbon stock and aggregate stability of an Alfisol under integrated farming systems
Pesquisa Agropecuária Tropical, vol. 51, e66505, 2021
Escola de Agronomia/UFG

DOI: https://doi.org/10.1590/1983-40632021v5166505

Research Article

Fertility, carbon stock and aggregate stability of an Alfisol under integrated farming systems[1]

Pedro Luan Ferreira da Silva[2], Flávio Pereira de Oliveira[3],
Adriana Ferreira Martins[3], Danillo Dutra Tavares[4], André Julio do Amaral[5]

ABSTRACT

Integrated farming systems are promising strategies for the recovery of pastures and degraded soils. This study aimed to evaluate the effect of integrated farming systems arrangements, after four years of implementation, on the fertility, carbon stock and aggregate stability of an Alfisol, in the semiarid region of the Paraíba state, Brazil. A randomized block experimental design was used, with 5 treatments and 4 replications: *Brachiaria decumbens*; *B. decumbens* + *Tabebuia impetiginous*; *B. decumbens* + *Gliricidia sepium*; *B. decumbens* + *Mimosa caesalpiniifolia*; and *B. decumbens* + maize. The soil chemical attributes, fertility, carbon stock and structural and aggregate stability were evaluated in the 0.00-0.10, 0.10-0.20 and 0.20-0.30 m layers. The *B. decumbens* + maize system presented an organic matter content 11.93 % higher than *B. decumbens*, and was higher than the other systems evaluated. Concerning the carbon stock in the 0.00-0.10 m layer, in *B. decumbens* the uptake was 2.66 Mg ha^{-1} higher than that of the *B. decumbens* + maize system and, on average, 4.69 Mg ha^{-1} higher than for the systems with the arboreal component. In the medium-term, *B. decumbens* is more efficient in adding carbon to the soil. The soil structural stability, aggregate stability index and fertility were not affected by the different arrangements after four years of implementation.

KEYWORDS: Carbon uptake, soil quality, Brazilian semiarid.

RESUMO

Fertilidade, estoque de carbono e estabilidade de agregados em Planossolo sob sistemas integrados de produção agropecuária

Sistemas integrados de produção agropecuária são estratégias promissoras para a recuperação de pastagens e solos degradados. Objetivou-se avaliar o efeito de arranjos com sistemas integrados de produção agropecuária, aos quatro anos de implantação, sobre a fertilidade, estoque de carbono e estabilidade de agregados de um Planossolo Háplico, no semiárido da Paraíba. O delineamento experimental foi de blocos casualizados, com 5 tratamentos e 4 repetições: *Brachiaria decumbens*; *B. decumbens* + ipê; *B. decumbens* + gliricídia; *B. decumbens* + sabiá; e *B. decumbens* + milho. Avaliaram-se os atributos químicos e de fertilidade, estoque de carbono, estabilidade estrutural e de agregados do solo nas camadas de 0,00-0,10; 0,10-0,20; e 0,20-0,30 m. O sistema *B. decumbens* + milho apresentou teor de matéria orgânica 11,93 % maior que *B. decumbens* e foi superior aos demais sistemas avaliados. Em relação ao estoque de carbono na camada de 0,00-0,10 m, em *B. decumbens* o aporte foi 2,66 Mg ha^{-1} maior que em *B. decumbens* + milho e, em média, 4,69 Mg ha^{-1} superior aos sistemas com o componente arbóreo. No médio prazo, *B. decumbens* mostra-se mais eficiente no aporte de carbono ao solo. A estabilidade estrutural, o índice de estabilidade de agregados e a fertilidade do solo não apresentaram alteração, em relação aos arranjos, após quatro anos de implantação.

PALAVRAS-CHAVE: Aporte de carbono, qualidade do solo, semiárido brasileiro.

INTRODUCTION

Crop-livestock-forest integration is a production system that integrates agricultural, livestock and forest components in rotation, intercropping or succession, within the same production area, over a production cycle (Balbino et al. 2011). This production system is used to intensify the soil use with minimum impact to ecosystem functions (Valani et al. 2020), and is more advantageous than conventional systems by presenting higher yields, lower production costs, better efficiency of inputs and lower systematic risk, due to the diversified income sources (Kichel et al. 2014).

Studies have shown the potential of integrated farming systems to improve the soil physical,

[1] Received: Nov. 03, 2020. Accepted: Mar. 24, 2021. Published: June 18, 2021. DOI: 10.1590/1983-40632021v5166505.
[2] Universidade Estadual de Maringá, Maringá, PR, Brasil. *E-mail/ORCID:* pedroluanferreira@gmail.com/0000-0001-5520-7920.
[3] Universidade Federal da Paraíba, Areia, PB, Brasil. *E-mail/ORCID*: flavio.oliveira@academico.ufpb.br/0000-0001-7968-6145; biol.adriana@gmail.com/0000-0002-8960-3101.
[4] Universidade Federal Rural de Pernambuco, Recife, PE, Brasil. *E-mail/ORCID*: danilodutrat@hotmail.com/0000-0001-7763-6793.
[5] Empresa Brasileira de Pesquisa Agropecuária, Recife, PE, Brasil. *E-mail/ORCID*: andre.amaral@embrapa.br/0000-0001-7246-2974.

chemical and biological quality (Conceição et al. 2014, Torralba et al. 2016, Zonta et al. 2016, Bünemann et al. 2018, Souza et al. 2019). These systems promote a high carbon uptake, favor the nutrient cycling, improve the soil biota (Conte et al. 2011), reduce the soil density and compaction degree, and increase the soil total porosity and aggregation, as well as the water availability and infiltration rate (Pezarico et al. 2013). This favors the complexation of toxic elements, improves the soil cation exchange capacity (Cogo et al. 2013) and increases the soil enzymatic activity, mainly hydrolases and oxidoreductases, when compared to conventional systems (Zago et al. 2020). However, Valani et al. (2020) pointed out that integration systems are underexplored, despite their potential for soil management in global scale, especially for the recovery of degraded pastures.

The semiarid region of the Brazilian Northeast has a pasture area of approximately 30.5 million hectares, 38 % of it at some degradation stage (Dias-Filho 2014). Sustainable alternatives to revert this process, such as the use of the crop-livestock-forest integration system, have been studied for this region, to assess the potential of these production systems for the recovering of degraded pastures (Rangeli et al. 2016). Preliminary data have shown promising results (Silva et al. 2019). However, the effects of integrated farming systems on the soil quality under the edaphoclimatic conditions of the semiarid region and the integration system strategies adopted (crop-livestock, crop-livestock-forest, crop-forest or livestock-forest, which show more satisfactory results) are little known.

The hypotheses presented in this study is that changes in the soil depend on the complexity of the arrangement adopted, and simple systems, such as crop-livestock, are less efficient than complex ones, such as crop-livestock-forest, for the improvement of soil quality in the medium- and long-term. Thus, this study aimed to evaluate the effect of integrated farming systems arrangements on the fertility, carbon stock and aggregate stability of an Alfisol previously used for pasture, in the semiarid region of the Paraíba state, after four years of implementation.

MATERIAL AND METHODS

The experiment was implemented in July 2015, at the experimental area of the Empresa Paraibana de Pesquisa, Extensão Rural e Regularização Fundiária, in Alagoinha, Paraíba state, Brazil (06º57'0''S, 35º32'42''W and altitude of 317 m).

The climate of the region is As', tropical hot and wet, according to the Köppen-Geiger classification (Silva et al. 2019), with a rainy season in the autumn-winter, from March to August, mean annual rainfall depth of 995 mm, temperatures ranging from 22 to 26 ºC, and mean relative air humidity of 65 %. The soil of the experimental area was classified as a Planossolo Háplico Eutrófico mésico solódico (Alfisol; USA 2014), with moderate A horizon and sandy-loam texture (Santos et al. 2018). The soil physical and chemical characteristics and fertility (0.00-0.20 m layer) before the implementation of the experiment showed 684 g kg^{-1} of sand; 159 g kg^{-1} of silt; 157 g kg^{-1} of clay; 45 g kg^{-1} of water dispersible clay; flocculation degree of 67.4 %; soil density of 1.55; particle density of 2.61 g cm^{-3}; total porosity of 0.40 m^3 m^{-3}; pH (H_2O 1:2.5) of 5.44; 4.53 mg dm^{-3} of P; 135.84 mg dm^{-3} of K; 0.03, 6.14, 0.22, 2.47, 1.26 and 4.11 $cmol_c$ dm^{-3} of Na^+, $H^+ + Al^{+3}$, Ca^{+2}, Mg^{+2}, sum of bases and cation exchange capacity, respectively; and 10.83 g kg^{-1} of total organic carbon.

Before the implementation of the experiment, the area had been used for pasture (*Brachiaria decumbens*), for the grazing of Sindi and Guzera bovines. In September 2015, plants of the forest species *Gliricidia sepium*, *Mimosa caesalpiniaefolia* and *Handroanthus impetiginosus* were transplanted to experimental plots with spacing of 2 × 3 m and six rows per plot, three in each side of the plot. Annual crop systems were implemented in different crop seasons: maize + *B. decumbens* in 2015/2016; soybean + sorghum in 2016/2017; cotton + cowpea in 2017/2018, and sesame + sorghum + peanut in 2018/2019. Thirty Sindi bovine animals were added in January 2019 to the experimental area and grazed for 35 days. The animals were then removed, and the soil sampling was carried out.

A randomized block experimental design with five treatments and four replications was used, totaling 20 experimental plots with a total area of 760 m^2 each. The treatments consisted of the following systems: *B. decumbens* + *Tabebuia impetiginous*; *B. decumbens* + *Gliricidia sepium*; *B. decumbens* + *Mimosa caesalpiniifolia*; *B. decumbens* + maize; and single *B. decumbens*, used as a reference.

In the experimental plots with arboreal components, the soil samples were collected in the tree rows, in two points of each side of the plot, with distances of 10 m within and 20 m between the rows. In the plots without arboreal components, the soil samples were collected in points pre-defined by a sample grid with 10 m between points. The 0.00-0.10, 0.10-0.20 and 0.20-0.30 m soil layers were evaluated.

Undisturbed soil samples were collected using 100 cm^3 Uhland cylinders, and disturbed ones using a spade for textural, chemical and fertility analysis. The soil samples were crushed, air dried, sieved and taken to the laboratory.

The following soil attributes were analyzed: K^+, P, Na^+, Ca^{2+}, Mg^{2+}, $Ca^{2+} + Mg^{2+}$, Al^{3+}, $H + Al^{3+}$, pH, cation exchange capacity, sum of bases, base saturation, total organic carbon and carbon stock.

The soil pH (H_2O; 1:2.5), available phosphorus, exchangeable cations (Ca^{2+}, Al^{3+} and Mg^{2+}), K^+ and Na^+ contents, and potential acidity ($H^+ + Al^{3+}$) were determined according to Teixeira et al. (2017). These analyses enabled the calculation of the soil exchangeable complex variables, mainly cation exchange capacity, sum of bases and base saturation.

The soil organic carbon contents were determined in a wet basis by oxidation with potassium dichromate ($K_2Cr_2O_7$) at 0.0667 mol L^{-1} (Teixeira et al. 2017). The carbon stock was calculated as described by Veldkamp (1994), taking into account the differences in soil mass suggested by Carvalho et al. (2009), using the following equation: CS = TOC x Bd x [(Bdref/Bd x Z)]/10, where CS is the carbon stock (Mg ha^{-1}); TOC the total soil organic carbon contents (g kg^{-1}); Bd the soil bulk density (g cm^{-3}); Bdref the soil bulk density reference (g cm^{-3}); and Z the thickness of the soil layer evaluated (cm).

The soil structural stability index, wet and dry percentages of macro and microaggregates, weighted mean diameter of wet and dry aggregates, and aggregate stability index were also evaluated. The soil structural stability index was determined as described by Pieri (1992), using the organic carbon, silt and clay contents of the soil samples, according to the equation: SSI = [(TOC * 1.7240)/(silt + clay)] x 100, where SSI is the structural stability index (%), TOC the total organic carbon and 1.7240 the conversion factor for soil organic matter. Structural stability indexes are classified according to the ranges of SSI > 9 % (stable structure), 7 % < SSI ≤ 9 % (low risk of structural degradation), 5 % < SSI ≤ 7 % (high degradation index) and SSI ≤ 5 % (structurally degraded soil).

The weighted mean diameter of wet (WMD-WA) and dry (WMD-DA) aggregates, and wet and dry percentages of macro and microaggregates were determined according to Silva & Mielniczuk (1997). The aggregate stability index was estimated by the WMD-WA to WMD-DA ratio.

The means of the variables were submitted to analysis of variance and, when significant, to the Tukey test ($p < 0.05$), using the R software (R Development Core Team 2013).

RESULTS AND DISCUSSION

The evaluated systems presented no significant difference ($p < 0.05$) for the soil fertility attributes (Table 1). However, the K^+ contents varied from medium to very high.

The K^+ contents varied from 58.6 to 129.5 mg dm^{-3} in the 0.00-0.10 m layer, from 25.9 to 109.3 mg dm^{-3} in the 0.10-0.20 m layer, and from 63.6 to 116.2 mg dm^{-3} in the 0.20-0.30 m layer (Table 1). Similar results were found by Ferreira et al. (2009), in soils under crop-livestock-forest integration, in the Rio Grande do Sul state, Brazil. They reported that the high K^+ contents in pasture areas are due to the digestion process of animals, since 90 % of the K^+ in these environments are from feces and urine and are in ionic form, readily available to plants.

The P contents varied from very low to medium, with decreasing values as the soil depth was increased (Table 1). This is related to intrinsic properties of tropical soils, which present a high phosphorus fixation (Diel et al. 2014). Na^+ is commonly found in Alfisols, but the contents found were practically insignificant (Table 1). The Ca^{2+} contents varied from low to medium, with decreasing values as the soil depth was increased. Santos et al. (2013) reported that high Ca^{2+} concentrations in surface layers are related to high organic carbon contents, high nutrients cycling, and use of soil conditioners and fertilizers. The Mg^{2+} contents were high in all evaluated systems (Table 1). A similar result was found by Silva et al. (2019), in soils under integration system. The systems evaluated presented low Al^{3+} contents and potential acidity ($H^+ + Al^{3+}$), with no significant differences from each other (Table 1).

The means for soil organic matter contents, pH, cation exchange capacity, sum of bases and base saturation (Table 2) showed that only the soil organic matter contents in the 0.00-0.10 m layer

Table 1. Chemical and fertility analyses of an Alfisol after four years of implementation of integrated agricultural systems and pasture.

Systems	K^+	P	Na^+	Ca^{2+}	Mg^{2+}	$Ca^{2+} + Mg^{2+}$	Al^{3+}	$H + Al^{3+}$
	mg dm^{-3}		$cmol_c$ dm^{-3}					
				0.00-0.10 m soil layer				
LFI1	74.6	3.66	0.00	2.13	2.15	4.28	0.125	6.07
LFI2	71.4	4.12	0.00	1.84	2.06	3.90	0.175	6.16
LFI3	58.6	6.26	0.00	2.92	1.84	4.76	0.112	5.93
CLI	106.1	18.36	0.00	2.35	2.18	4.53	0.112	5.71
Pasture	129.5	11.02	0.00	2.86	1.92	4.78	0.138	5.48
CV (%)	60.3	79.20	0.00	22.1	20.80	17.30	42.800	13.30
				0.10-0.20 m soil layer				
LFI1	48.9	2.33	0.00	2.12	1.70	3.81	0.50	8.22
LFI2	34.6	2.29	0.00	2.11	1.05	3.16	0.42	7.89
LFI3	25.9	3.87	0.00	2.33	1.23	3.56	0.50	8.00
CLI	56.0	10.47	0.00	1.87	1.68	3.55	0.60	8.44
Pasture	109.3	3.87	0.00	2.79	1.20	3.99	0.23	6.58
CV (%)	101.2	85.80	0.00	29.10	51.80	24.50	63.10	17.20
				0.20-0.30 m soil layer				
LFI1	72.6	1.69	0.02	2.29	1.58	3.87	0.56	7.85
LFI2	63.6	1.86	0.01	1.63	2.21	3.84	0.80	8.89
LFI3	69.5	2.04	0.03	1.88	1.53	3.42	0.51	7.30
CLI	116.2	2.22	0.01	1.87	1.73	3.60	0.55	7.51
Pasture	66.5	2.65	0.00	1.99	1.47	3.46	0.65	8.20
CV (%)	53.7	19.70	54.10	30.80	24.00	15.20	39.10	11.10

LFI1: *Brachiaria decumbens* + *Tabebuia impetiginous*; LFI2: *B. decumbens* + *Gliricidia sepium*; LFI3: *B. decumbens* + *Mimosa caesalpiniifolia*; CLI: *B. decumbens* + maize; Pasture: *B. decumbens*; CV: Coefficient of variation.

were significantly different among the treatments ($p < 0.05$), with the highest contents in the *B. decumbens* + maize system (28.5 g kg^{-1}) and the lowest ones in the *B. decumbens* + *G. sepium* system (18.6 g kg^{-1}).

The high organic matter contents in the *B. decumbens* + maize system are related to the high biomass production and absence of soil turning. Similar results were found by Gazolla et al. (2015), in a Dystrophic Ferralsol under integrated farming systems. The absence of soil turning and permanence of organic matter on the soil surface in conservationist production systems favor the activity of microorganisms and the release of essential elements for the functioning of the ecosystem (Bartz et al. 2014).

The soil pH varied from medium to high (Table 2), with the lowest values in the 0.10-0.20 m layer, no significant differences between the evaluated systems, and the lowest values in the *B. decumbens* + *G. sepium* system. The soil acidity may increase in areas with harvested crops, due to the absorption of alkaline cations by plants, soil erosion and exposure, excessive use of nitrogen fertilizers, and sulfur and organic matter oxidation (Souza et al. 2007).

The cation exchange capacity, sum of bases and base saturation were not different among the treatments in the evaluated soil layers; however, the cation exchange capacity was classified as medium (Table 2), with more expressive values in the 0.10-0.20 and 0.20-0.30 m soil layers. This may be due to the high clay contents and cation exchange capacity of the B horizon of Alfisols. According to Reichert et al. (2008), the medium cation exchange capacity found in the systems may be related to the detrimental effect of soil acidity on the activities of Ca^{2+}, Mg^{2+} and K^+. The partial neutralization of soil acidity releases negative charges from the exchangeable complex occupied by Ca^{2+}, Mg^{2+} and K^+, increasing the soil fertility, cation exchange capacity and agricultural production (Reichert et al. 2008). The highest sum of bases in the *B. decumbens* + maize system (Table 2) was probably due to the residual liming effect before the planting of maize in the 2018/2019 crop season.

The total organic carbon differed between the evaluated systems only in the 0.00-0.10 m soil layer (Table 3). The soil carbon stock and structural stability index were similar among the treatments ($p < 0.05$).

Table 2. Organic matter contents (OM), pH, cation exchange capacity (CEC), sum of bases (SB) and base saturation (BS) of an Alfisol after four years of implementation of integrated agricultural systems and pasture.

Systems	OM	pH	CEC	SB	BS
	g kg^{-1}	H_2O (1:2.5)	—— cmol$_c$ dm^{-3}	——	%
	0.00-0.10 m soil layer				
LFI1	23.5 ab	5.55	10.5	4.47	42.3
LFI2	18.6 b	5.17	10.2	4.08	39.9
LFI3	25.6 ab	5.67	10.8	4.91	45.7
CLI	28.5 a	5.67	10.5	4.80	46.0
Pasture	25.1 ab	5.62	10.6	5.12	47.9
CV (%)	12.8	7.30	7.9	15.50	13.8
	0.10-0.20 m soil layer				
LFI1	24.1	5.40	12.2	3.94	33.9
LFI2	20.5	4.95	11.1	3.25	29.1
LFI3	20.2	4.97	11.7	3.66	31.4
CLI	22.4	5.17	12.1	3.69	30.5
Pasture	21.1	5.42	10.8	4.27	39.3
CV (%)	9.3	5.90	7.7	22.10	23.4
	0.20-0.30 m soil layer				
LFI1	19.8	5.33	11.9	4.08	34.1
LFI2	19.8	4.95	12.9	4.02	31.6
LFI3	18.3	5.12	10.9	3.62	33.5
CLI	19.5	5.25	11.4	3.91	34.2
Pasture	19.0	5.08	11.8	3.64	30.3
CV (%)	9.0	3.10	7.7	13.30	12.3

LFI1: *Brachiaria decumbens* + *Tabebuia impetiginous*; LFI2: *B. decumbens* + *Gliricidia sepium*; LFI3: *B. decumbens* + *Mimosa caesalpiniifolia*; CLI: *B. decumbens* + maize; Pasture: *B. decumbens*; CV: coefficient of variation. Means followed by the same letter in the column are not different by the Tukey test ($p < 0.05$).

Table 3. Total organic carbon (TOC), carbon stock (CS) and structural stability index (SSI) of an Alfisol after four years of implementation of integrated agricultural systems and pasture.

Systems	TOC	CS	SSI
	g kg^{-1}	Mg ha^{-1}	%
	0.00-0.10 m soil layer		
LFI1	13.7 ab	18.65 b	4.73
LFI2	10.8 b	20.27 b	3.63
LFI3	14.8 ab	14.74 c	4.58
CLI	16.5 a	19.91 b	4.46
Pasture	14.6 ab	22.57 a	5.18
CV (%)	12.8	12.46	13.00
	0.10-0.20 m soil layer		
LFI1	14.0	19.11	3.81
LFI2	11.9	16.23	3.91
LFI3	11.7	16.04	4.01
CLI	13.0	16.70	4.32
Pasture	12.2	17.74	3.71
CV (%)	9.3	12.05	9.40
	0.20-0.30 m soil layer		
LFI1	11.5	15.65	3.52
LFI2	11.5	14.53	3.95
LFI3	10.6	15.69	3.62
CLI	11.3	15.07	3.06
Pasture	11.0	15.44	3.45
CV (%)	9.0	11.62	8.80

LFI1: *Brachiaria decumbens* + *Tabebuia impetiginous*; LFI2: *B. decumbens* + *Gliricidia sepium*; LFI3: *B. decumbens* + *Mimosa caesalpiniifolia*; CLI: *B. decumbens* + maize; Pasture: *B. decumbens*; CV: coefficient of variation. Means followed by the same letter in the column are not different by the Tukey test ($p < 0.05$).

The soil total organic carbon contents of the *B. decumbens* + maize system differed from those of the *B. decumbens* + *G. sepium* system, with 16.5 g kg^{-1}, which is an adequate value (Table 3). The other evaluated systems showed low carbon contents, without significant differences. The carbon stock and structural stability index presented no significant differences among the evaluated systems. The high organic carbon contents in the soil surface layers are related to the diversity of residues added and the high biomass production of leguminous and grass species (Faccin et al. 2016). Blanco-Canqui (2021) found that the use of leguminous species as soil cover plants in a production system can add, on average, 1 Mg ha^{-1} year^{-1} of organic carbon, in the 0.00-0.30 m layer. Silva et al. (2011) evaluated the dynamics of the soil organic matter in a crop-livestock integration system and found an addition of organic carbon similar to that of the no-tillage system. In addition, Sant-Anna et al. (2017) evaluated the changes in the soil organic carbon uptake for 22 years, in different production systems in the Brazilian Savanna, and found that the crop-livestock integrated system was the most efficient for the addition of carbon to the soil, confirming the result presented in Table 3.

However, in comparison to the experiment conducted by Silva et al. (2019) in the same experimental area of the present study, the organic carbon contents presented a slight decrease in the *B. decumbens* + *T. impetiginous*, *B. decumbens* + *G. sepium*, *B. decumbens* + *M. caesalpiniifolia* and *B. decumbens* + maize systems. This was probably due to the climate seasonality and the plant residues added to these treatments in the period preceding the soil sample collection. The *B. decumbens* system presented a mean carbon stock of 22.57 Mg ha^{-1} in the 0.00-0.10 m soil layer, differing from the other systems evaluated (Table 3). In the 0.10-0.30 m layer, the *B. decumbens* + *G. sepium* system presented a trend of increases in carbon stocks as the soil depth was increased. This result was due to increases in the soil density in subsurface layers, since changes in soil density tend to affect the soil carbon stock (Veldkamp & Verburg 2004).

The use of grass species combined with forest species in integrated farming systems is important for the improvement of the soil physical, chemical and biological qualities, since it favors the maintenance of carbon stocks. The combination of these species contributes to decrease greenhouse gas emissions and increase the sustainability of production systems (Carvalho et al. 2010). According to Silva et al. (2011), the high carbon uptake in conservationist systems reinforces the hypothesis that integrated agricultural systems are promising for the improvement of quality and sustainability of agroecosystems in tropical environments.

The soil structural stability index varied among the systems from highly structured to structurally degraded, with most mean values below 5 % (Table 4). In addition, this index decreased as the soil depth increased, probably due to the high sand and low carbon contents in the subsurface. The structural stability index varied from 3.63 to 5.18 % in the 0.00-0.10 m layer, from 3.71 to 4.01 % in the 0.10-0.20 m layer, and from 3.06 to 3.95 % in the 0.20-0.30 m layer (Table 4). In fact, the evaluated Alfisol presented structural problems in deep layers, and could present severe degradation risks (Silva et al. 2019).

The weighted mean diameter of wet aggregates showed a significant difference in the 0.00-0.10 m layer, and the highest mean was found for the *B. decumbens* + *T. impetiginous* system, with 1.70 mm (Table 4).

The soil attributes presented in Table 4 showed no significant differences among the systems evaluated for the 0.10-0.20 m soil layer. However, significant differences were found in the 0.20-0.30 m layer for dry macroaggregates, dry microaggregates and weighted mean diameter of dry aggregates, with the highest means found in the *B. decumbens* + maize system for dry macroaggregates (86.2 %), in the *B. decumbens* + *G. sepium* system for dry microaggregates (30.8 %) and in the *B. decumbens* + *T. impetiginous* system for weighted mean diameter

Table 4. Percentages of wet and dry macro (WMacro and DMacro) and microaggregates (WMicro and DMicro), weighted mean diameter of wet and dry aggregates (WMD-WA and WMD-DA), and aggregate stability index (ASI) of an Alfisol after four years of implementation of integrated agricultural systems and pasture.

Systems	WMacro	WMicro	DMacro	DMicro	WMD-WA	WMD-DA	ASI
	%				mm		
			0.00-0.10 m soil layer				
LFI1	73.7	26.3	79.6	20.4	1.70 a	2.04	0.711
LFI2	66.3	33.6	77.5	22.5	1.60 ab	2.31	0.528
LFI3	58.1	41.9	76.8	23.2	1.16 ab	1.91	0.533
CLI	60.6	39.4	76.5	23.4	1.21 ab	2.25	0.544
Pasture	61.4	38.6	69.2	30.8	0.99 b	2.21	0.472
CV (%)	12.7	22.7	6.6	20.9	18.30	18.70	23.400
			0.10-0.20 m soil layer				
LFI1	52.0	48.0	79.7	20.4	1.36	2.29	0.598
LFI2	70.7	29.3	84.2	15.8	1.09	1.97	0.485
LFI3	51.3	48.7	79.2	20.8	0.88	2.18	0.417
CLI	62.0	38.0	78.3	21.7	1.03	2.17	0.488
Pasture	65.0	35.0	79.9	20.1	0.81	1.90	0.448
CV (%)	12.8	19.4	8.1	33.0	21.50	16.70	21.300
			0.20-0.30 m soil layer				
LFI1	56.1	43.9	81.4 ab	18.6 ab	1.08	2.51 a	0.433
LFI2	62.3	37.7	69.2 b	30.8 a	0.86	1.96 ab	0.444
LFI3	59.3	40.7	70.5 ab	29.4 ab	0.89	2.46 a	0.374
CLI	58.9	41.1	86.2 a	13.8 b	1.15	2.39 a	0.471
Pasture	64.3	35.7	78.3 ab	21.7 ab	1.07	1.53 b	0.705
CV (%)	17.6	26.6	7.4	25.1	32.60	13.60	29.600

LFI1: *Brachiaria decumbens* + *Tabebuia impetiginous*; LFI2: *B. decumbens* + *Gliricidia sepium*; LFI3: *B. decumbens* + *Mimosa caesalpiniifolia*; CLI: *B. decumbens* + maize; Pasture: *B. decumbens*; CV: coefficient of variation. Means followed by the same letter in the column are not different by the Tukey test ($p < 0.05$).

of dry aggregates (2.51 mm). The weighted mean diameter of dry aggregates was higher than the critical value for an Alfisol (2.44 mm), as described by Lima et al. (2008).

The highest percentage for wet microaggregates was found in the *B. decumbens* + *M. caesalpiniifolia* system (48.7 %), denoting that the soil in this treatment present a low structural stability, with higher predominance of aggregates with diameters lower than 2 mm. Lima et al. (2008) found higher microaggregate contents in managed soils, when compared to native fields, and reported that areas without disturbances (native field) present higher organic matter and root contents, which are bound to the soil mineral fraction, contributing to the formation of aggregates. High microaggregate contents in surface layers are also related to the soil exposure to climate factors, especially rainfall, since the impact of raindrops causes the disruption and disaggregation of soil particles, mainly when using soil turning (Marcolan & Anghinoni 2006).

Despite the low soil aggregate stability index found, it increased after the implementation of the experiment (Table 4). Silva et al. (2019) evaluated the aggregate stability index in the same experimental area, in 2017, and found lower mean values for the *B. decumbens* + *T. impetiginous* and *B. decumbens* + maize systems than those found in the present study (Table 4), denoting increases of 0.095 for the *B. decumbens* + *T. impetiginous* system and 0.058 for the *B. decumbens* + maize system, from 2017 to 2019.

These increases in the aggregate stability index are related to the increase in the organic carbon contents over time. According to Silva et al. (2019), the formation of soil aggregates is a slow process, and to reach similar aggregate levels to those found in forest soils, the soils should be covered with a high diversity of grass and leguminous species and be under a low impact management, which may be achieved by decreasing the mechanized soil preparation and maintaining soil cover plants.

CONCLUSIONS

1. The soil chemical and fertility attributes, structural stability and aggregate stability index had no satisfactory responses to the integrated farming systems, when compared to the single *Brachiaria decumbens* system, after four years of implementation;
2. The *B. decumbens* + maize system presented soil organic matter contents 11.93 % higher than the single *B. decumbens* system, and were higher than for the other evaluated systems. The single *B. decumbens* system presented carbon stock 2.66 Mg ha^{-1} higher than for the *B. decumbens* + maize system, and, on average, 4.69 Mg ha^{-1} higher than the livestock-forest integration systems;
3. The single *B. decumbens* system showed to be more efficient in soil carbon uptake in the medium-term than the *B. decumbens* + maize system and the systems with arboreal components.

REFERENCES

BALBINO, L. C.; CORDEIRO, L. A. M.; SILVA, V. P.; MORAES, A.; MARTÍNEZ, G. B.; ALVARENGA, R. C.; KICHEL, A. N.; FONTANELI, R. S.; SANTOS, H. P.; FRANCHINI, J. C.; GALERANI, P. R. Evolução tecnológica em arranjos produtivos de sistemas de integração lavoura-pecuária-floresta no Brasil. *Pesquisa Agropecuária Brasileira*, v. 46, n. 10, p. 1-12, 2011.

BARTZ, M. L. C.; BROWN, G. G.; ROSA, M. G.; KLAUBERG, F. S.; JAMES, W. S.; DECAENS, T.; BARRETTA, D. Earthworm richness in land-use systems in Santa Catarina, Brazil. *Applied Soil Ecology*, v. 83, n. 1, p. 59-70, 2014.

BLANCO-CANQUI, H. No-till technology has limited potential to store carbon: how can we enhance such potential? *Agriculture, Ecosystems and Environment*, v. 313, n. 1, p. 1-6, 2021.

BÜNEMANN, E. K.; BONGIORNO, G.; BAI, Z.; CREAMER, R. E.; DEYN, G. de; GOEDE, R. G. M.; FLESKENS, L.; GEISSEN, V.; KUYPER, T. W.; MÄDER, P.; PULLEMAN, M.; SUKKEL, W.; VAN GROENIGEN, J. W.; BRUSSAARD, L. Soil quality: a critical review. *Soil Biology and Biochemistry*, v. 120, n. 1, p. 105-125, 2018.

CARVALHO, J. L. N.; AVANZI, J. C. S.; NAVES, M. L. N.; MELLO, C. R.; CERRI, C. E. P. Potencial de sequestro de carbono em diferentes biomas do Brasil. *Revista Brasileira de Ciência do Solo*, v. 34, n. 2, p. 277-290, 2010.

CARVALHO, J. L. N.; CERRI, C. E. P.; FEIGEL, B. J.; PICCOLO, M. C.; GODINHO, V. P.; CERRI, C. C. Carbon sequestration in agricultural soils in the Cerrado region of the Brazil Amazon. *Soil and Tillage Research*, v. 103, n. 1, p. 342-349, 2009.

COGO, F. D.; ARAÚJO-JUNIOR, C. F.; ZINN, Y. L.; DIAS JUNIOR, M. S.; ALCÂNTARA, E. N.; GUIMARÃES, P. T. G. Estoques de carbono orgânico do solo em cafezais sob diferentes sistemas de controle de plantas invasoras. *Semina: Ciências Agrárias*, v. 34, n. 3, p. 1089-1098, 2013.

CONCEIÇÃO, P. C.; BAYER, C.; DIECKOW, J.; SANTOS, D. C. Fracionamento físico da matéria orgânica e índice de manejo de carbono de um Argissolo submetido a sistemas conservacionistas de manejo. *Ciência Rural*, v. 4, n. 5, p. 794-800, 2014.

CONTE, O.; FLORES, J. P. C.; CASSOL, L. C.; ANGHINONI, I.; CARVALHO, P. C. F.; LEVIEN, R.; WESP, C. L. Evolução de atributos físicos de solo em sistema de integração lavoura-pecuária. *Pesquisa Agropecuária Brasileira*, v. 46, n. 10, p. 1301-1309, 2011.

DIAS-FILHO, M. B. *Diagnóstico das pastagens no Brasil*. Belém: Embrapa Amazônia Oriental, 2014.

DIEL, D.; BEHLING, M.; FARIAS NETO, A. L.; ISENHAGEN, E. C. C. Distribuição vertical do fósforo em sistemas de cultivo exclusivos de soja e de integração lavoura-pecuária-floresta. *Pesquisa Agropecuária Brasileira*, v. 49, n. 38, p. 639-647, 2014.

FACCIN, F. C.; MARCHETTI, M. E.; SERRA, A. P.; ENSINAS, S. C. Frações granulométricas da matéria orgânica do solo em consórcio de milho safrinha com capim-marandu sob fontes de nitrogênio. *Pesquisa Agropecuária Brasileira*, v. 51, n. 12, p. 2000-2009, 2016.

FERREIRA, E. V. O.; ANGHINONI, I.; CARVALHO, P. C. F.; COSTA, S. E. V. G. A.; CAO, E. G. Concentração do potássio do solo em sistema de integração lavoura-pecuária em plantio direto submetido a intensidades de pastejo. *Revista Brasileira de Ciência do Solo*, v. 33, n. 9, p. 75-84, 2009.

GAZOLLA, P. R.; GUARESCHI, R. F.; PERIN, A.; PEREIRA, M. G.; ROSSI, C. Q. Frações de matéria orgânica do solo sob pastagem, sistema plantio direto e integração lavoura-pecuária. *Semina: Ciências Agrárias*, v. 36, n. 2, p. 693-704, 2015.

KICHEL, A. N.; COSTA, J. A. A.; ALMEIDA, R. G.; PAULINO, V. T. Sistemas de integração lavoura-pecuária-floresta: experiências no Brasil. *Boletim da Indústria Animal*, v. 71, n. 1, p. 94-105, 2014.

LIMA, J. S. S.; OLIVEIRA, P. C.; OLIVEIRA, R. B.; XAVIER, A. C. Métodos geoestatísticos no estudo da resistência do solo à penetração em trilha de tráfego de tratores na colheita de madeira. *Revista Árvore*, v. 32, n. 5, p. 931-938, 2008.

MARCOLAN, A. L.; ANGHINONI, I. Atributos físicos de um Argissolo e um Latossolo Vermelho sob diferentes sistemas de manejo. *Pesquisa Agropecuária Brasileira*, v. 40, n. 11, p. 1135-1139, 2006.

PEZARICO, C. R.; VITORINO, A. C. T.; MERCANTE, F. M.; DANIEL, O. Indicadores de qualidade do solo em sistemas agroflorestais. *Revista de Ciências Agrárias*, v. 56, n. 1, p. 40-47, 2013.

PIERI, J. C. M. G. *Fertility of soils*: a future for farming in the west African Savannah. Berlin: Spring-Verlog, 1992.

R DEVELOPMENT CORE TEAM. *R*: a language and environment for statistical computing. Vienna: R Foundation for Statistical Computing, 2013.

RANGELI, J. H. A.; MUNIZ, E. N.; MORAES, S. A.; SOUZA, S. F.; AMARAL, A. J.; PIMENTEL, J. C. M. Integração lavoura-pecuária-floresta na região Nordeste do Brasil. *Ciência Veterinária Tropical*, v. 19, n. 3, p. 1-10, 2016.

REICHERT, J. M.; PEIVA, T. A.; REINERT, D. J.; SILVA, V. R. Variabilidade espacial de Planossolo e produtividade da soja em várzea sistematizada: análise geoestatística e de regressão. *Ciência Rural*, v. 38, n. 4, p. 981-988, 2008.

SANT-ANNA, S. A. C.; JANTALIA, C. P.; SÁ, J. M.; VILELA, L.; MARCHÃO, R. L.; ALVES, B. J. R.; URQUIAGA, S.; BODDEY, R. M. Changes in soil organic carbon during 22 years of pastures, crop or integrated crop/livestock systems in the Brazilian *Cerrado*. *Nutrient Cycling in Agroecosystems,* v. 108, n. 1, p. 101-120, 2017.

SANTOS, H. G.; JACOMINE, P. K. T.; ANJOS, L. H. C.; OLIVEIRA, V. Á.; LUMBRERAS, J. F.; COELHO, M. R.; ALMEIDA, J. A.; ARAÚJO FILHO, J. C.; OLIVEIRA, J. B.; CUNHA, T. J. F. *Sistema brasileiro de classificação de solos*. Brasília, DF: Embrapa, 2018.

SANTOS, S. P. M.; CRUZ, P. G.; ARAÚJO, L. C.; PEZZOPANE, J. R. M.; VALLE, C. B.; PEZZOPANE, C. G. Response mechanisms of *Brachiaria brizantha* cultivars to water deficit stress. *Revista Brasileira de Zootecnia*, v. 42, n. 11, p. 767-773, 2013.

SILVA, E. F.; LOURENTI, E. P. R.; MARCHETTI, M. E.; MERCANTE, F. M.; FERREIRA, A. K. T.; FUJII, G. C. Frações lábeis e recalcitrantes da matéria orgânica em solos sob integração lavoura-pecuária. *Pesquisa Agropecuária Brasileira*, v. 46, n. 10, p. 1321-1331, 2011.

SILVA, I. F.; MIELNICZUK, J. Ação do sistema radicular de plantas na formação e estabilização de agregados do solo. *Revista Brasileira de Ciência do Solo*, v. 21, n. 1, p. 113-117, 1997.

SILVA, P. L. F.; OLIVEIRA, F. P.; TAVARES, D. D.; NÓBREGA, C. C.; AMARAL, A. J. Water availability under integrated crop-livestock-forestry systems in agreste region of Paraíba, Brazil. *Revista Caatinga*, v. 32, n. 2, p. 449-457, 2019.

SOUZA, D. M. G.; MIRANDA, L. N.; OLIVEIRA, S. A. Acidez do solo e sua correção. *In*: NOVAIS, R. F.; ALVAREZ, V. V. H.; BARROS, N. F.; FONTES, R. L. F.;

CANTARUTTI, R. B.; NEVES, J. C. L. (org.). *Fertilidade do solo*. Viçosa: Sociedade Brasileira de Ciência do Solo, 2007. p. 206-274.

SOUZA, E. D.; SILVA, C. R. M.; PINTO, F. A.; CARNEIRO, M. A. C.; PAULINO, H. B.; PACHECO, L. P.; TERRA, F. D.; LAROCA, J. V. S. Soil quality indicators after conversion of "murundu" fields into no-tillage cropping in the Brazilian *Cerrado*. *Pesquisa Agropecuária Brasileira*, v. 54, n. 1, p. 1-9, 2019.

TEIXEIRA, P. C.; DONAGEMMA, G. K.; FONTANA, A.; TEIXEIRA, W. G. *Manual de métodos e análise de solos*. Brasília, DF: Embrapa, 2017.

TORRALBA, M.; FAGERHOLM, N.; BURGESS, P. J.; MORENO, G.; PLIENINGER, T. Do European agroforestry systems enhance biodiversity and ecosystem services?: a meta-analysis. *Agriculture, Ecosystems and Environment*, v. 230, n. 1, p. 150-161, 2016.

USA. Soil Survey Staff. *Keys to soil taxonomy*. 12. ed. Washington, DC: USDA, 2014.

VALANI, G. P.; MARTINI, A. F.; SILVA, L. F. S.; BORI, R. C.; COOPER, M. Soil quality assessment in integrated crop-livestock-forest: a review. *Soil Use and Management*, v. 37, n. 1, p. 22-36, 2020.

VELDKAMP, A.; VERBURG, P. H. Modelling land use change and environmental impact. *Journal of Environmental Management*, v. 72, n. 1-2, p. 1-3, 2004.

VELDKAMP, E. Organic carbon turnover in three tropical soils under pasture after deforestation. *Soil Science Society of America Journal*, v. 58, n. 1, p. 175-180, 1994.

ZAGO, L. M. S.; RAMALHO, W. P.; SILVA-NETO, C. M.; CASAMORI, S. S. Biomechanical indicators drive soil quality in integrated crop-livestock-forestry system. *Agroforestry Systems*, v. 94, n. 1, p. 2249-2260, 2020.

ZONTA, J. H.; SOFIATTI, V.; SILVA, O. R. R. F.; RAMOS, E. N.; BARBOSA, H. F.; CORDEIRO JUNIOR, A. F.; LIRA, A. J. S. *Sistemas integração lavoura-pecuária (ILP) para região agreste do Nordeste*. Campina Grande: Embrapa Algodão, 2016. (Documentos, 266).