



Soil Quality and CO₂ Emissions in Response to Six Years of Conventional and Integrated Agricultural Production in the Central-West Region of Brazil

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Abstract

Determine the soil quality and the emissions of mineralizable soil carbon (C-CO₂) in conventional and integrated systems in the Midwest region of Brazil. Methods: The evaluated systems include original pasture (OP), reformed pasture (RP), conventional tillage (CT), direct seeding (DS), and cultivated eucalyptus forest (CF), as well as crop-livestock integration (CLI) and crop-livestock-forest integration (CLFI) systems in both the pasture phase (p) and crop phase (c). The soil organic carbon (SOC), carbon and carbon stock (StoC) of the particulate organic matter (C-POM) and mineral-associated organic matter (C-OMM) fractions, indexes of soil quality, and daily CO₂ emission and accumulation in the 0–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.40 m layers were determined. Results: The CLI_p and CLI_c systems had the highest SOC contents, reaching 15.47 and 15.04 g kg⁻¹ of C in the 0–0.05 m layer, respectively. For C-POM, the integrated systems in the pasture phase had the highest contents and stocks, storing up to 19 t ha⁻¹ at 0.4 m. For C-OMM, CLI_c had the highest contents and stocks, storing up to 57 t ha⁻¹ of C up to 0.4 m. The systems with pasture had the best carbon management indexes. The LI, L, C-POM stock, and CMI remained the most representative variables related to the CLFI_p system. Conclusions: integrated systems improve soil quality and store Carbon, especially in recalcitrant fractions of the SOM, with reduced C-CO₂ emissions, helping to mitigate climate change in the Central-West region of Brazil.

Keywords Agroforestry systems · Carbon storage · Environmental sustainability · Mineralizable carbon · Soil organic matter

Highlights

1. Helping to reduce greenhouse gas emissions in agricultural production in Brazil.
2. Sustainable alternatives for the replacement of conventional systems in Brazilian agriculture.
3. Integrated systems improve soil quality by reducing CO₂ emissions, replacing conventional systems.
4. Long-term pasture is the main agent for maintaining soil quality.

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1 Introduction

The advancing effects of global climate change have led to a search for measures to mitigate the emission of greenhouse gases (GHG), especially carbon dioxide (CO₂). Among economic activities, the agricultural sector is one of the largest emitters of GHG into the atmosphere (SEEG 2021); however, when managed properly, it can become one of the greatest mitigators of the effects of climate change when considering the carbon (C) balance of the soil (Berglund et al. 2021; Potenza 2021; Machado et al. 2022).

Soil is considered a large reservoir of C, acting as a strategy for mitigating the effect of climate change due to its C storage capacity, regulating the emission of CO₂ into the atmosphere (Fan et al. 2019; Lim et al. 2022). Different land covers and uses can contribute to releasing CO₂ and

enhancing sequestration and storage in the soil, generating a positive balance for the natural CO₂ reservoir (Lal 2018).

The largest contributor to the increase in C emissions from the soil is degraded pastures and crops under conventional tillage systems (CTS) (Potenza 2021). Brazil's climate change mitigation management plan, renamed the Sectoral Plan for Climate Change Adaptation and Low Carbon Emissions in Agriculture and Livestock (ABC + Plan), foresees the expansion of agricultural technologies to reduce 37.9 million tons of CO₂ equivalent emissions by 2030, just considering integrated agricultural production systems (IAPS) (MAPA 2022).

In Brazil, areas of planted pasture occupy 154.7 million hectares, 52.3% of which have some degree of degradation (MapBiomass 2021). Converting degraded pasture areas into areas with greater productive potential reduces the pressure to open up new agricultural areas, allowing for the expansion of good management practices and the application of technologies for sustainable production without compromising natural forest areas.

Among the measures set out in the ABC + Plan are the transition from areas in a state of degradation to areas with a sustainable production system, the no-till system (NTS), and IAPS (MAPA, 2021). From 2006 to 2017, the adoption of NTS in Brazil grew exponentially, from 17.9 to 33 million hectares, representing an increase of 84.9% in the areas cultivated with NTS, showing the expansion of conservation farming practices in the country (Fuentes Llanillo et al. 2021).

In addition to NTS, IAPS is another promising alternative for advancing sustainable production. These systems are part of the set of management practices that make up conservation agriculture, as they are capable of integrating various means of production on small plots of land, extracting maximum productivity while restoring the sustainability of the agricultural ecosystem (Bender et al. 2016; Ribeiro et al. 2023). Studies indicate improvements in the physical (Dhaliwal and Kumar 2022), chemical (Krupek et al. 2022), and biological attributes of the soil (Sekaran et al. 2021) in IAPS, as highlighted in other studies in the Brazilian context (Rego et al. 2023; Valani et al. 2021).

There are various ways of assessing the changes in soil attributes caused by different management systems, one of the most common being the assessment of the quantity and quality of organic carbon, as it is extremely sensitive to changes in the environment and can be altered to varying degrees depending on the degree of disturbance to the soil (Farias et al. 2022; Ozório et al. 2020; Rosset et al. 2019). To facilitate the characterization and understanding of C dynamics in the soil, SOM is viewed by differentiating its constituents through fractionation methods.

The physical granulometric fractionation of SOM consists of the segregation of components based on particle size,

resulting in the fraction of particulate organic matter (POM) and organic matter associated with minerals (OMM). POM consists of plant and animal residues in a slightly advanced stage of decomposition (Cambardella and Elliot 1992; Lavallee et al. 2020). POM has a particle size greater than 53 µm without association with other particles and is, therefore, more vulnerable to decomposition by microorganisms. OMM is smaller than 53 µm and is at a more advanced stage of decomposition, but because it is associated with the mineral fraction of the soil, it is less susceptible to the action of microorganisms (Cotrufo and Lavallee 2022).

It is believed that replacing conventional production systems with systems that adopt the systematization of heterogeneous components, such as CLI and CLFI integration systems, is a sustainable alternative that can be used as a strategy to mitigate the effects of climate change by reducing CO₂ emissions and, above all, increasing soil quality (Oliveira et al. 2024; Rede ILPF 2020; Silva et al. 2024). Thus, we hypothesize that six years after the conversion of degraded pasture, integrated production systems will have increased soil C levels compared to conventional cultivation systems. It is expected that, due to the combination of different components in the same cultivation area, integrated production systems will not only enhance higher levels of soil C but also improve the quality of organic matter compared to conventional systems. We also hypothesize that higher CO₂ emissions are associated with low-quality SOM, and therefore, management systems that improve soil quality result in lower CO₂ emissions. It is anticipated that integrated systems will serve as a tool for improving soil quality and mitigating CO₂ emissions in agricultural areas.

This study aimed to determine the quality of the soil through the particulate (POM) and mineral-associated (OMM) fractions of the SOM, as well as the stocks and emissions of mineralizable C from the soil in conventional and integrated agricultural production systems in the Midwest region of Brazil.

2 Material and Methods

2.1 Description of the Study Area

The study was conducted at a Technological Reference Unit (TRU) in 2014 in Naviraí, located in the Cone Sul region of Mato Grosso do Sul, Brazil (Fig. 1). The experiment was conducted in partnership between the Embrapa Western-Region Agriculture (Embrapa—CPAO) (Dourados MS) and the Cooperativa Agrícola Sul-mato-grossense (COPASUL).

The experiment comprised areas in conventional and integrated agricultural production systems located in the Atlantic Forest biome, under soil classified as Latossolo Vermelho Distroférico (Santos et al. 2018), with a medium

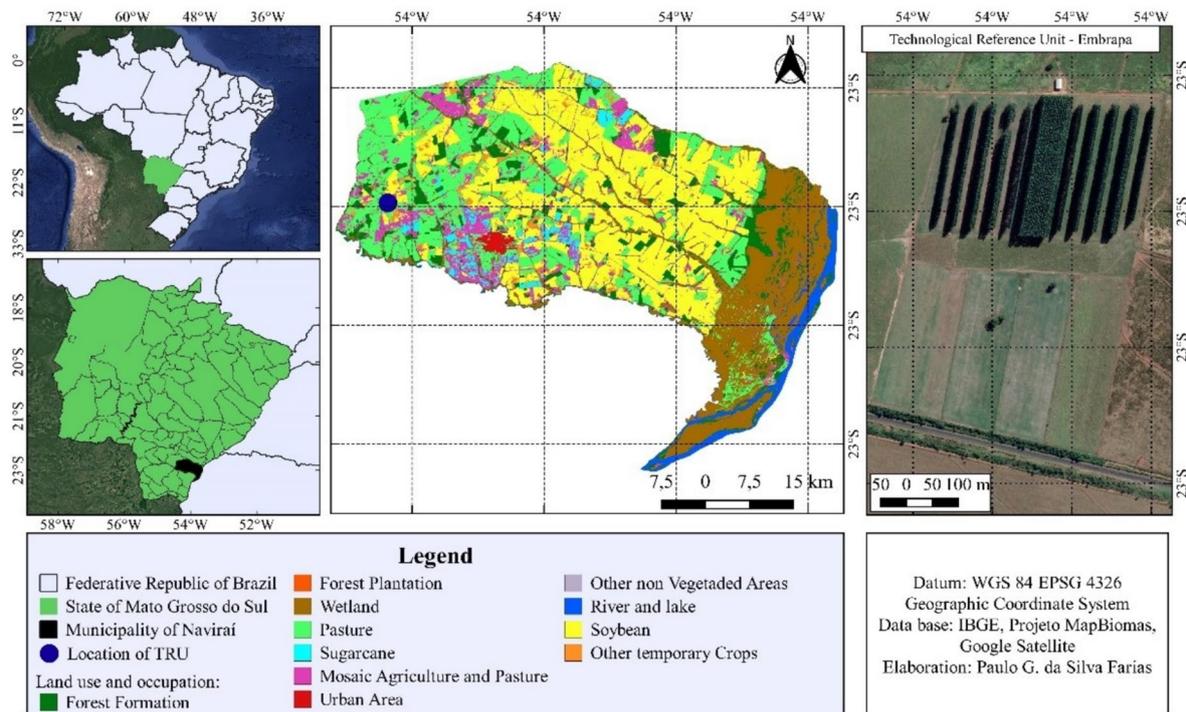


Fig. 1 Map of the geographical location of the Technological Reference Unit (TRU) and land use and occupation in Naviraí—Mato Grosso do Sul. Map elaborated through QGIS software, version 3.20.1 "Odense"

texture. According to the Köppen classification, the climate is subtropical (Cfa-type), with an average rainfall of 1400 to 1700 mm per year and an average temperature of 22 °C, with a maximum of 28 °C and a minimum of 12 °C (SEMADE 2015).

2.2 Systems Evaluated and History of Use

Two groups were selected with different management systems, comprising conventional systems of original pasture (OP), reformed pasture (RP), conventional tillage (CT), direct seeding (DS), and cultivated forest (CF), and integrated systems evaluated in the two phases of integration between crop and pasture, comprising crop-livestock integration (CLI) in the pasture phase (p) and crop phase (c), and crop-livestock-forest integration (CLFI) in the pasture phase (p) and crop phase (c). The management practices used in the respective systems are detailed in Table 1, and the dynamics between the crops are shown in Fig. 2.

Before implementing the different management systems, the area was used for pasture with the *Urochloa brizantha* species, which was already in a state of degradation (original pasture, OP) when it was prepared for conversion into managed systems. The area received 2 t ha⁻¹ of dolomitic limestone with an ECCE of 100%, incorporated into the soil at a depth of 20 cm. Agricultural gypsum was

applied during the interval between the last harrowing. Additionally, 250 kg ha⁻¹ of simple superphosphate and 150 kg ha⁻¹ of potassium chloride were added to the soil to replace the macronutrients.

The only system where the cattle did not graze was the CT system due to the short period that the pasture remained there. The weight of the animals and the availability of forage were the factors that limited animal stocking, with an average of 2 to 3.5 AU (animal unit) ha⁻¹, where each AU is equivalent to 450 kg (Table 2).

2.3 Soil Sampling

The soil samples were collected in the summer of 2020, six years after the experiment was set up and approximately 18 months after the rotation of the pasture and crop phases in the integrated systems. Five pseudo-replications were conducted in a plot layout of 400 m² each for each study area, arranged randomly in the evaluated systems. Each composite sample represented a combination of five single subsamples collected from the 0–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.40 m layers. Part of the samples from the 0–0.05 m layer were immediately frozen after collection for later assessment of C-CO₂ evolution in the laboratory.

Table 1 Description of the management performed in both conventional and integrated production systems

Management systems	Description
Conventional Systems	
OP	Original pasture area with the species <i>Urochloa brizantha</i> cv. Piatã. It shows visible signs of degradation. Used as a reference of the original soil condition. Area: 0.50 ha
RP	Reformed pasture area with <i>Brachiaria brizantha</i> cv. Piatã. Area: 2.52 ha
CT	Succession system of soybean (summer) and corn (second crop), with <i>U. ruziziensis</i> between the crops, under conventional tillage system. Area: 1.66 ha
DS	Succession system of soybean (summer) and corn + <i>U. ruziziensis</i> (second crop) under no-tillage system. Area: 1.32 ha
CF	Forest area cultivated with eucalyptus, clone I144, with spacing of 2×3 m. Area: 1.77 ha
Integrated Systems	
CLIP _p	Crop-livestock integration: soybean/corn crop + <i>Urochloa ruziziensis</i> in NT in rotation with pasture every two years (Pasture phase). Area: 3.93 ha
CLIC _c	Crop-livestock integration: soybean/corn crop + <i>U. ruziziensis</i> in NT in rotation with pasture every two years (Crop phase). Area: 3.61 ha
CLFIP _p	Crop-livestock-forest integration: soybean/corn crop + <i>Urochloa ruziziensis</i> in NT in rotation with pasture every two years between eucalyptus lines (clone I144 ¹) with spacing of 30 m. (Pasture phase). Area: 5.47 ha
CLFIC _c	Crop-livestock-forest integration: soybean/corn crop + <i>U. ruziziensis</i> in NT in rotation with pasture every two years between eucalyptus lines (clone I144) with spacing of 30 m. (Crop phase). Area: 5.43 ha

¹ Hybrid clone of *Eucalyptus* sp L'Hér (VM01 *Eucalyptus urophylla* × *E. camaldulensis*). OP: original pasture, RP: reformed pasture, CT: conventional tillage system, DS: Direct seeding, CF: cultivated forest, CLIP: crop-livestock integration (Pasture phase); CLIC: crop-livestock integration (Crop phase), CLFIP: crop-livestock-forest integration (Pasture phase), CLFIC: crop-livestock-forest integration (Crop phase)

		2014		2015		2016		2017		2018		2019		2020	
		winter	summer	winter	summer	winter	summer	winter	summer	winter	summer	winter	summer	winter	summer
OP		Original pasture													
RP		Reformed pasture													
CT	Oat	Soybean1	C	Soybean1	C	Soybean1	C	Soybean1	C	Soybean1	C	Soybean1	C	Soybean1	
DS	Oat	Soybean2	C+B	Soybean2	C+B	Soybean2	C+B	Soybean2	C+B	Soybean2	C+B	Soybean2	C+B	Soybean2	
CF	Oat	Eucalyptus cultivated forest													
CLIP	Oat	Soybean2	C+B	Pasture				Soybean2	C+B	Soybean2	C+B	Pasture			
CLIC	Oat	Pasture		Soybean2	C+B	Soybean2	C+B	Pasture				Soybean2	C+B	Soybean2	
CLFIP	Oat	DS+F	C+B+F	Pasture + F				DS+F	C+B+F	DS+F	C+B+F	Pasture + F			
CLFIC	Oat	Pasture + F		DS+F	C+B+F	DS+F	C+B+F	Pasture + F				DS+F	C+B+F	DS+F	

Fig. 2 Dynamic of cultivation in the management systems in the last six years. **Original pasture:** Pasture with the species *Urochloa brizantha* cv Piatã; **Reformed pasture:** Pasture implanted after soil correction; **Soybean₁:** soybean grown in conventional tillage system (CT) with soil tillage using disc harrow; **C:** corn grown in CT; **Soybean₂:** soybean grown in the direct seeding (DS); **C + B:** integration of corn and *Brachiaria* crops in DS; **Eucalyptus cultivated forest:** eucalyptus cultivation (clone I144); **Pasture:** Pasture with *Urochloa* species; **DS + F:** soybean in rotation with pasture in DS between

eucalyptus rows with spacing of 30 m; **C + B + F:** corn in consortium with *Urochloa* in DS between eucalyptus rows with spacing of 30 m; **Pasture + F:** Pasture between eucalyptus rows with spacing of 30 m. OP: original pasture, RP: reformed pasture, CT: conventional tillage system, DS: Direct seeding, CF: cultivated forest, CLIP: crop-livestock integration (Pasture phase); CLIC: crop-livestock integration (Crop phase), CLFIP: crop-livestock-forest integration (Pasture phase), CLFIC: crop-livestock-forest integration (Crop phase)

2.4 Physical Granulometric Fractionation

The physical granulometric fractionation of the SOM was conducted according to the method described by Cambardella and Elliott (1992). 60 ml of sodium hexametaphosphate solution (5 g L⁻¹) was added to 20 g of soil (FADS), and the samples were shaken for 16 h in a horizontal shaker. After this procedure, wet sieving was conducted using

a sieve with an opening of 53 µm. The material retained on the 53 µm sieve consisted of particulate organic matter (POM) associated with the sand fraction, and that which passed through the 53 µm sieve consisted of mineral-organic matter (OMM) associated with the silt and clay fractions. The (POM) retained on the 53 µm sieve was then dried in an oven at 50°C, then ground on a porcelain grater and analyzed for the C content of particulate organic matter (C-POM)

Table 2 Soil physical and chemical attributes in conventional and integrated agricultural production systems

MS	Sand	Silt	Clay	pH	P	Ca	Mg	K	Al	H + Al	CEC efetiva	CEC pH 7,0	V%	m%	
	g kg ⁻¹				mg dm ⁻³	-cmol _c dm ⁻³ -							-%		
0–0,20 m															
OP	779,13	14,75	206,12	4,07	04,33	0,22	0,11	0,13	0,70	3,77	1,16	4,24	10,95	60,17	
RP	759,53	26,82	213,65	4,58	08,51	0,69	0,38	0,14	0,36	3,60	1,58	4,82	25,27	22,93	
CT	729,86	19,29	150,84	4,81	30,13	0,73	0,36	0,23	0,36	3,19	1,69	4,52	29,28	20,29	
DS	705,87	90,69	203,44	4,68	48,99	0,73	0,30	0,19	0,20	3,43	1,43	4,65	26,39	14,01	
CF	748,19	22,85	228,96	4,23	04,66	0,48	0,19	0,07	0,50	3,77	1,24	4,51	16,39	40,34	
CLIP _p	778,58	15,31	206,11	4,95	20,80	0,90	0,58	0,27	0,16	3,08	1,92	4,83	36,30	8,68	
CLIC _c	755,86	40,42	203,72	5,32	10,11	0,98	0,56	0,52	0,10	2,73	2,17	4,80	43,14	4,61	
CLFIP _p	724,52	28,95	246,53	5,11	09,00	0,92	0,49	0,25	0,20	2,61	1,87	4,28	38,94	10,71	
CLFIC _c	766,73	29,75	203,52	5,62	05,66	0,99	0,50	0,20	0,10	1,51	1,79	3,20	53,03	5,59	
0,20–0,40 m															
OP	760,73	08,02	231,25	4,09	3,22	0,21	0,07	0,09	0,50	3,43	1,08	3,81	10,00	64,78	
RP	746,33	57,61	196,06	4,66	3,82	0,59	0,21	0,06	0,23	2,32	1,11	3,20	27,56	20,96	
CT	709,72	28,81	261,47	4,32	5,20	0,41	0,19	0,15	0,56	3,48	1,32	4,24	17,87	42,51	
DS	755,60	66,08	178,32	4,37	43,84	0,73	0,32	0,12	0,43	3,60	1,61	4,77	24,57	26,68	
CF	713,21	12,53	274,26	3,98	2,90	0,21	0,11	0,03	0,90	3,89	1,25	4,24	8,31	71,87	
CLIP _p	757,69	18,60	223,71	4,64	8,42	0,63	0,26	0,22	0,23	3,31	1,36	4,44	25,41	17,03	
CLIC _c	730,94	18,16	250,90	4,75	5,47	0,65	0,29	0,34	0,20	3,02	1,49	4,31	29,90	13,45	
CLFIP _p	685,07	33,18	281,75	4,67	4,17	0,59	0,24	0,17	0,33	2,67	1,34	3,68	27,37	24,83	
CLFIC _c	747,09	29,30	223,61	4,49	4,36	0,47	0,22	0,06	0,36	2,90	1,13	3,66	20,74	32,43	

pH Hydrogen potential, *P* Phosphor, *Ca* Calcium, *Mg* Magnesium, *K* Potassium, *Al* Aluminum, *H + Al* Hydrogen + Aluminum, *CEC* Cation Exchange Capacity, *V%* Base saturation, *m%* Aluminum saturation. Original pasture (OP); Reformed pasture (RP); Conventional tillage (CT); Direct Seeding (SD); Cultivated forest (CF); crop-livestock integration (Pasture phase) (CLIP); crop-livestock integration (Crop phase) (CLIC); crop-livestock-forest integration (Pasture phase) (CLFIP), crop-livestock-forest integration (Crop phase) (CLFIC)

according to the method described by Yeomans and Bremner (1988), using potassium dichromate to oxidize soil organic matter in a sulfuric medium. C-OMM was obtained from the difference between SOC and C-POM.

The indexes used to assess the quality of the soil organic fraction: carbon stock index (CIS), SOM lability (L), lability index (LI), and carbon management index (CMI), were calculated as follows: The CIS was obtained from the ratio between the SOC content of the treatment and that of the reference. The L of the SOM of each treatment was obtained from the ratio between the (C-POM) and (C-OMM) contents. The LI was obtained by the ratio between the SOM lability of the treatment and that of the reference. CMI is estimated by the product between LI and CIS multiplied by 100 (Blair et al. 1995). In addition, (POM) and (OMM) carbon stocks were calculated using the equivalent mass method (Reis et al. 2018; Signor et al. 2014).

2.5 Mineralizable Carbon

The evolution of C-CO₂ (mineralizable carbon) was quantified following the methodology of Mendonça and Matos (2005), in which 50 g of soil, a vial with 30 ml of 0.5 mol L⁻¹ NaOH solution to capture the emitted C-CO₂ and

another vial with 30 ml of H₂O are placed inside a plastic jar with a capacity of 0.5 L, which is hermetically sealed. On each evaluation day, 10 ml of the NaOH solution was removed from the bottle, and 10 ml of the 0.05 mol L⁻¹ BaCl₂ solution and four drops of 1% phenolphthalein were added, followed by titration with 0.25 mol L⁻¹ HCl. After removing the 30 mL vial of 0.5 mol L⁻¹ NaOH solution from the container, a new vial with another 30 mL was inserted for the next evaluation, leaving the vial open for 15 min for gas exchange before the next incubation. Titrations and evaluations were conducted at intervals of 24 h during the first seven days, 48 h between the 8th and 17th days, and 96 h between the 18th and 33rd days, as adapted by Loss et al. (2013).

2.6 Statistical Analysis

RStudio software (R Core Team 2020) was used for all statistical analyses. Initially, the data were submitted to the Shapiro–Wilk and Bartlett tests for normality and homogeneity, respectively. Using the ExpDes.pt package in a completely randomized design (Ferreira et al. 2024), the data were submitted to the analysis of variance and the F-test, and the means were compared using the Scott-Knott test at

a 5% significance level. Principal component analysis was used to verify the interaction between the management systems and the variables studied using the Factoextra package (Kassambara and Mundt 2020).

3 Results

3.1 Soil Organic Carbon and Carbon Stock in Particulate and Mineral-Associated Organic Matter Fractions

SOC in the conventional systems reached 14.99 g kg^{-1} in the 0–0.05 m layer in the RP, the only conventional system with similar levels to the integrated CLI p and CLIC systems, with 15.47 and 15.04 g kg^{-1} , respectively (Table 3). Approximately 34% of the SOC in the RP was concentrated in the 0–0.05 m layer, with a downward trend as the depth increased. Among the integrated systems, there was a similarity between the different arrangement systems, but in particular, the CLFIc showed the lowest levels in all layers, matching the original pasture with a level of 6.14 g kg^{-1} in the 0.20–0.40 m layer. In the CLI system, there was a tendency for SOC levels to decrease between cultivation phases, but in general, both phases of the CLI showed a higher increase in SOC than the CLFI, which suggests negative interference from the forest component in the increase of C in the soil by crops.

The highest levels of C POM were observed in integrated production systems, with CLI and CLFI standing out during the grazing phase. These systems showed high levels in all the layers evaluated, reaching 4.73 and 4.63 g kg^{-1} for CLFIp and CLIp in the 0–0.05 m layer, with the surface layer being responsible for 34.7 and 33.5% of the increase in C in this fraction in the soil, respectively, which is equivalent to 1.6 times more (C-POM) when compared to (OP) in the same layer. The OP had a similar content to CLIC and other conventional systems, reaching 2.94 g kg^{-1} in the 0–0.05 m layer (Table 3).

For C-OMM, the highest levels were observed in the integrated CLI (crop-phase) system in all the layers evaluated, reaching 12.18 g kg^{-1} in the 0–0.05 m layer, with only RP being similar at 12.10 g kg^{-1} (Table 3). CLIp increased by 5.36 g kg^{-1} more than OP, equivalent to ≈ 2 times more C-OMM, considering only the topsoil. Comparing the same cultivation phase in the different integration systems, the C-OMM content decreased by 4.35 g kg^{-1} when the forest component was added to the integrated system CLFIc, with similar and even lower levels than the OP. The highest levels of conventional systems were observed in RP with 12.10 g kg^{-1} in the 0–0.05 m layer and DS with 9.56 g kg^{-1} in the 0.05–0.10 m layer. RP not only proved capable of increasing SOC levels but also had the potential to complex SOM into

more stable compartments, with ≈ 2 times more C-OMM compared to OP.

The SOC stock (sum of StoC-POM and StoC-OMM) was considerably higher in the integrated agricultural production systems, especially in the CLI, regardless of the stage of cultivation, reaching 69.25 t ha^{-1} in the CLIp and 66.96 t ha^{-1} in the CLIC, up to 0.40 m (Table 3). The highest C-POM stocks were observed in the CLIp and CLFIp systems, which showed stocks of 7.20 Mg ha^{-1} and 7.36 Mg ha^{-1} in the 0–0.05 m layer, respectively. These systems store 18.98 and 19.18 Mg ha^{-1} of C in the POM fraction up to 0.40 m, equivalent to 1.34 and $1.37 \text{ Mg ha}^{-1} \text{ year}^{-1}$. For StoC-OMM, the RP and CLIC systems had the highest stocks, with 18.83 and 18.95 Mg ha^{-1} values in the 0–0.05 m layer. Since the conversion of the OP areas to the different managed systems, there has been an increase of $\approx 8 \text{ Mg ha}^{-1}$ in the stock of C in this fraction in the RP and CLIC systems, considering only the 0–0.05 m layer and ≈ 12 and $\approx 21 \text{ Mg ha}^{-1}$ considering the 0–0.40 m section.

3.2 Soil Quality Index

The soil organic matter quality indexes were higher in the integrated agricultural production systems, emphasizing the pasture phase integrations. CLFIp had a CMI almost five times higher than the reference area (original pasture) (Fig. 3). RP had the best quality indexes among the conventional cropping systems, surpassing the reference area.

Except for the reference (OP), the systems tended to increase the potential C stock in deeper layers, as indicated by the CIS (Fig. 4). CLFIp showed twice the CIS of the reference (original pasture OP), reaching 2.0 in the 0.20–0.40 m layer.

3.3 Emission and Accumulation of Mineralizable Soil Carbon

The highest C-CO₂ emission peaks observed among the conventional cultivation systems were in the DS (Fig. 5), as well as the accumulation of C-CO₂, which reached $565.43 \text{ mg of C-CO}_2 \text{ kg of soil}^{-1}$, showing similarity with integrated production systems (Fig. 6).

Among the integrated production systems, the highest peaks were seen in the crop livestock integration systems in both phases (Fig. 5), pasture (CLIp) and crop (CLIC), reaching accumulations of 571.19 and $545.99 \text{ mg of C-CO}_2 \text{ kg soil}^{-1}$, respectively (Fig. 6).

3.4 Multivariate Analysis of Soil Quality Indicators

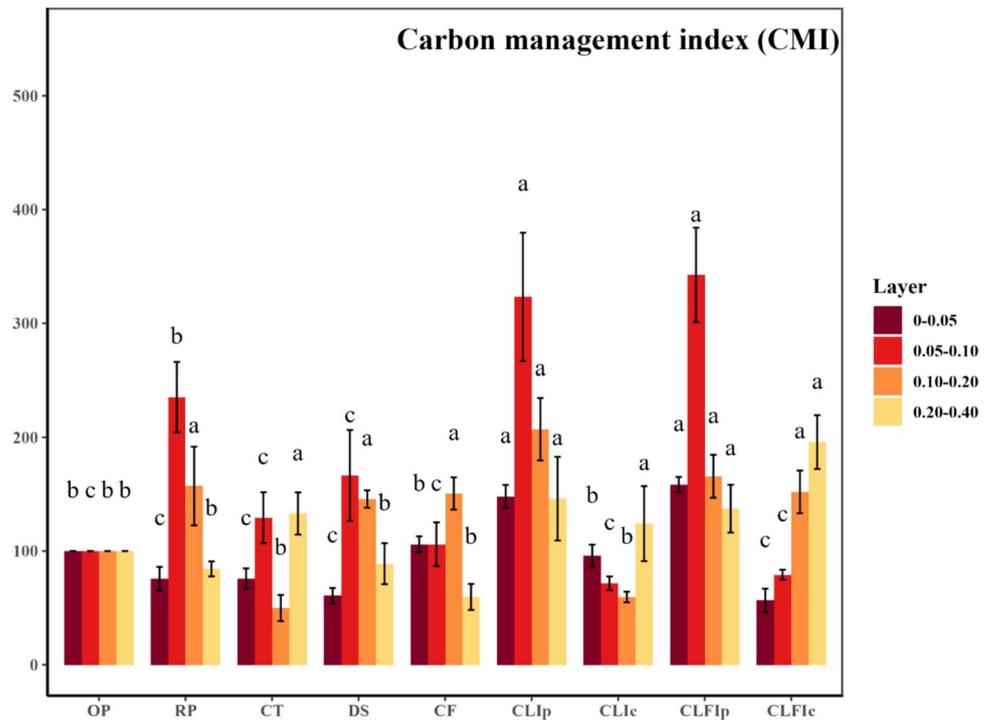
Principal component analysis (PCA) for the 0–0.05 m layer showed that axes 1 and 2 explained 80.85% of the data, with 43.6% for axis 1 and 40.1% for axis 2. PC1, with

Table 3 Soil organic carbon content (SOC), carbon content and carbon stocks of the particulate organic matter fractions (C-POM and StoC-POM) and organic matter associated with minerals (C-OMM and StoC-OMM) in conventional and integrated agricultural production systems

Management systems	SOC	C-POM	C-OMM	StoC-POM	StoC-OMM
	g kg ⁻¹			-Mg ha ⁻¹	
<i>0–0,05 m</i>					
OP	9,76 ± 0,31e	2,94 ± 0,22b	6,82 ± 0,53e	4,58 ± 0,35b	10,61 ± 0,82e
RP	14,99 ± 0,31a	2,89 ± 0,29b	12,10 ± 0,46a	4,49 ± 0,45b	18,83 ± 0,71a
CT	12,02 ± 0,19c	2,78 ± 0,29b	9,24 ± 0,27c	4,33 ± 0,44b	14,38 ± 0,41c
DS	12,14 ± 0,18c	2,32 ± 0,22c	9,82 ± 0,34c	3,61 ± 0,34c	15,28 ± 0,53c
CF	10,85 ± 0,25d	2,80 ± 0,13b	8,05 ± 0,19d	4,35 ± 0,20b	12,53 ± 0,30d
CLIp	15,47 ± 0,18a	4,63 ± 0,17a	10,84 ± 0,26b	7,20 ± 0,27a	16,87 ± 0,40b
CLIC	15,04 ± 0,31a	2,86 ± 0,16b	12,18 ± 0,24a	4,46 ± 0,25b	18,95 ± 0,37a
CLFIp	13,80 ± 0,26b	4,73 ± 0,33a	9,07 ± 0,56c	7,36 ± 0,51a	14,11 ± 0,87c
CLFIC	9,84 ± 0,19e	2,01 ± 0,22c	7,83 ± 0,37d	3,13 ± 0,34c	12,19 ± 0,57d
CV%	4,39	16,74	8,81	16,74	8,81
<i>0,05–0,10 m</i>					
OP	8,81 ± 0,37c	1,43 ± 0,20d	7,38 ± 0,51b	2,19 ± 0,30d	11,26 ± 0,79a
RP	10,99 ± 0,38a	2,49 ± 0,38c	8,51 ± 0,71b	3,79 ± 0,58c	12,99 ± 1,08a
CT	10,95 ± 0,39a	1,39 ± 0,16d	9,56 ± 0,50a	2,12 ± 0,26d	14,60 ± 0,76a
DS	9,82 ± 0,25b	1,68 ± 0,14d	8,14 ± 0,21b	2,56 ± 0,21d	12,43 ± 0,32a
CF	10,17 ± 0,28b	1,71 ± 0,35d	8,46 ± 0,54b	2,61 ± 0,54d	12,91 ± 0,82a
CLIp	11,21 ± 0,26a	3,35 ± 0,36b	7,85 ± 0,50b	5,12 ± 0,56b	11,99 ± 0,76a
CLIC	11,54 ± 0,25a	1,30 ± 0,12d	10,24 ± 0,30a	1,99 ± 0,18d	15,64 ± 0,46a
CLFIp	11,11 ± 0,29a	4,17 ± 0,26a	6,95 ± 0,47b	6,36 ± 0,40a	10,61 ± 0,72a
CLFIC	8,76 ± 0,29c	1,46 ± 0,18d	7,30 ± 0,41b	2,24 ± 0,28d	11,14 ± 0,63a
CV%	6,69	27,45	12,97	27,45	12,97
<i>0,10–0,20 m</i>					
OP	8,74 ± 0,27d	1,79 ± 0,20b	6,95 ± 0,32c	2,71 ± 0,30b	10,48 ± 0,49c
RP	9,52 ± 0,44c	2,13 ± 0,23a	7,39 ± 0,53c	3,21 ± 0,35a	11,14 ± 0,80c
CT	9,58 ± 0,19c	1,13 ± 0,23b	8,45 ± 0,22b	1,70 ± 0,35b	12,74 ± 0,33b
DS	10,46 ± 0,14b	2,69 ± 0,22a	7,79 ± 0,34c	4,05 ± 0,33a	11,74 ± 0,52c
CF	8,63 ± 0,36d	2,64 ± 0,17a	6,00 ± 0,39d	3,97 ± 0,26a	9,04 ± 0,59d
CLIp	12,85 ± 0,32a	2,87 ± 0,19a	9,98 ± 0,19a	4,33 ± 0,28a	15,04 ± 0,29a
CLIC	11,09 ± 0,34b	1,30 ± 0,15b	9,79 ± 0,30a	1,96 ± 0,23b	14,76 ± 0,46a
CLFIp	9,56 ± 0,27c	2,44 ± 0,12a	7,12 ± 0,37c	3,67 ± 0,19a	10,73 ± 0,55c
CLFIC	6,69 ± 0,26e	2,07 ± 0,35a	4,62 ± 0,40e	3,11 ± 0,52a	6,97 ± 0,60e
CV%	6,95	22,69	10,46	22,69	10,46
<i>0,20–0,40 m</i>					
OP	6,12 ± 0,24f	1,86 ± 0,27b	4,26 ± 0,25d	1,47 ± 0,22b	3,35 ± 0,20d
RP	8,37 ± 0,35d	1,65 ± 0,22b	6,72 ± 0,54c	1,30 ± 0,17b	5,29 ± 0,43c
CT	10,53 ± 0,25b	2,19 ± 0,28a	8,34 ± 0,22b	1,73 ± 0,22a	6,57 ± 0,18b
DS	9,17 ± 0,18c	1,39 ± 0,16b	7,77 ± 0,32b	1,10 ± 0,13b	6,12 ± 0,25b
CF	7,37 ± 0,44e	1,50 ± 0,28b	5,88 ± 0,68c	1,18 ± 0,22b	4,63 ± 0,54c
CLIp	11,04 ± 0,26b	2,95 ± 0,28a	8,09 ± 0,44b	2,33 ± 0,22a	6,37 ± 0,34b
CLIC	11,70 ± 0,48a	1,89 ± 0,20b	9,81 ± 0,66a	1,49 ± 0,16b	7,73 ± 0,52a
CLFIp	11,94 ± 0,34a	2,27 ± 0,07a	9,67 ± 0,37a	1,79 ± 0,06a	7,62 ± 0,29a
CLFIC	6,14 ± 0,19f	2,49 ± 0,16a	3,65 ± 0,22d	1,96 ± 0,13a	2,87 ± 0,17d
CV%	7,82	24,99	13,94	24,99	13,94

Means followed by equal letters in the column, in each layer, do not differ by the Scott-Knott test (p 0.05). CV Coefficient of variation, OP original pasture, RP reformed pasture, CT conventional tillage system, DS Direct seeding, CF cultivated forest, CLIp crop-livestock integration (Pasture phase), CLIC crop-livestock integration (Crop phase), CLFIp crop-livestock-forest integration (Pasture phase), CLFIC crop-livestock-forest integration (Crop phase)

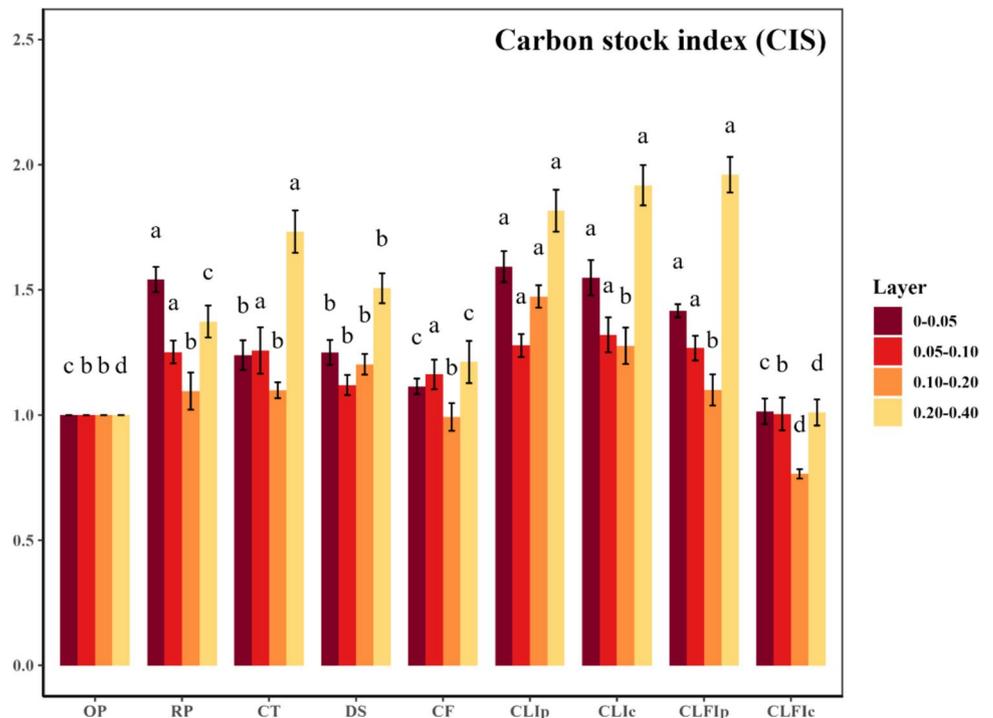
Fig. 3 Carbon management index (CMI) of soil organic matter in conventional and integrated agricultural production systems in the 0–0.05, 0.05–0.10, 0.10–0.20 and 0.20–0.40 m layers. Means followed by equal letters in the bars, in each layer, do not differ by the Scott-Knott test (p 0.05). OP: original pasture, RP: reformed pasture, CT: conventional tillage system, DS: Direct seeding, CF: cultivated forest, CLIP: crop-livestock integration (Pasture phase); CLIC: crop-livestock integration (Crop phase), CLFIP: crop-livestock-forest integration (Pasture phase), CLFIC: crop-livestock-forest integration (Crop phase)



an eigenvalue of 3.25, explained 43.6% of the variation in the data, with the highest positive loading values of 0.717 for L, 0.663 for LI, and 0.620 for StOC-OMM, contributing most to this PC. PC2, explaining 40.1% of the data, had the highest values of 0.762 for SOC and 0.673 for StOC-POM (Table 4).

Figure 7 shows the variation of the data in the biplot graph, where it can be seen that the LI and L variables remained highly correlated, as did StOC-POM and CMI. On the other hand, StOC-OMM and CO₂ accumulation remained highly correlated in PC2, as did CIS and SOC.

Fig. 4 Carbon stock index (CIS) of soil organic matter in conventional and integrated agricultural production systems in the 0–0.05, 0.05–0.10, 0.10–0.20 and 0.20–0.40 m. Means followed by equal letters in the bars, in each layer, do not differ by the Scott-Knott test (p 0.05). OP: original pasture, RP: reformed pasture, CT: conventional tillage system, DS: Direct seeding, CF: cultivated forest, CLIP: crop-livestock integration (Pasture phase); CLIC: crop-livestock integration (Crop phase), CLFIP: crop-livestock-forest integration (Pasture phase), CLFIC: crop-livestock-forest integration (Crop phase)



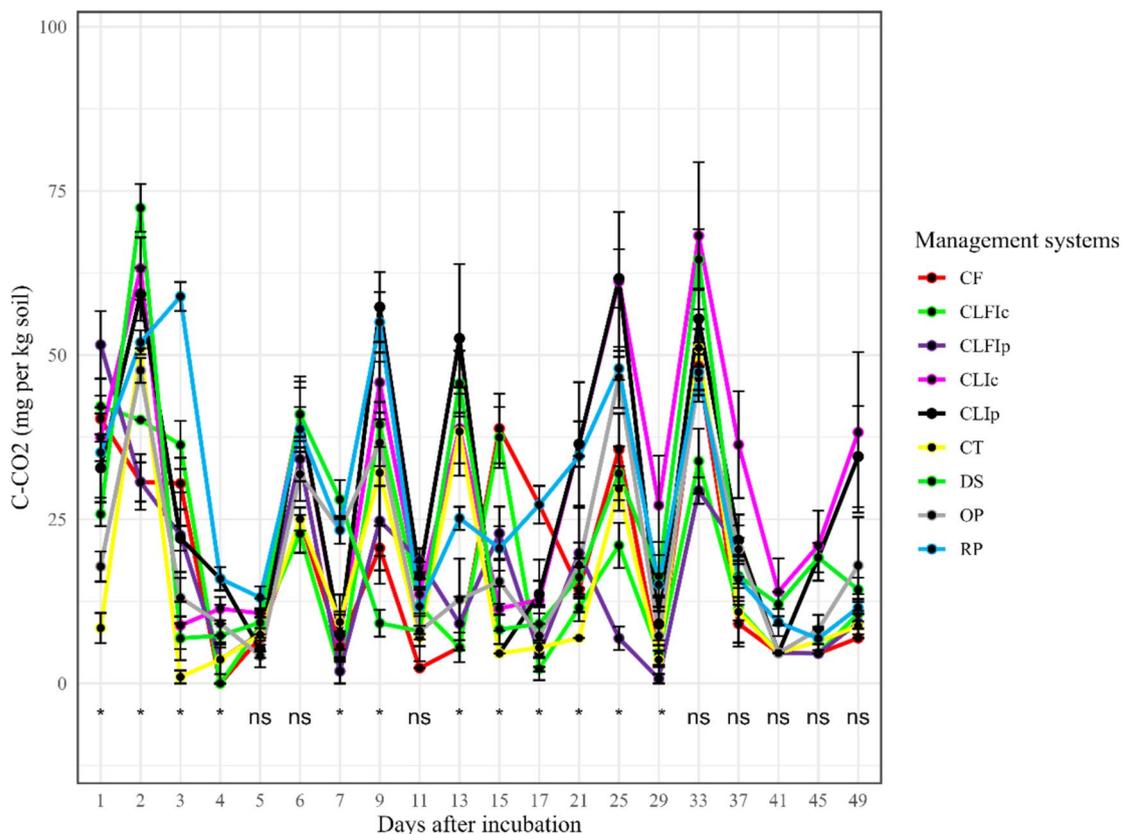


Fig. 5 Evolution of the daily emission of mineralizable carbon (C-CO₂) from conventional and integrated agricultural production systems in the 0–0.05 m layer. Means represented by the symbol "*" differ, and those represented by the letters "ns" do not differ by the Scott-Knott test (*p* 0.05). OP: original pasture, RP: reformed pasture,

CT: conventional tillage system, DS: direct seeding, CF: cultivated forest, CLIP: crop-livestock integration (grassland phase); CLIC: crop-livestock integration (crops phase), CLFIP: crop-livestock-forest integration (grassland phase), CLFIC: agriculture-livestock-forestry integration (tillage phase)

Fig. 6 Accumulation of mineralizable carbon (C-CO₂) in conventional and integrated agricultural production systems in the 0–0.05 m layer. Means followed by equal letters in the bars, do not differ by the Scott-Knott test (*p* 0.05). OP: original pasture, RP: reformed pasture, CT: conventional tillage system, DS: Direct seeding, CF: cultivated forest, CLIP: crop-livestock integration (Pasture phase); CLIC: crop-livestock integration (Crop phase), CLFIP: crop-livestock-forest integration (Pasture phase), CLFIC: crop-livestock-forest integration (Crop phase)

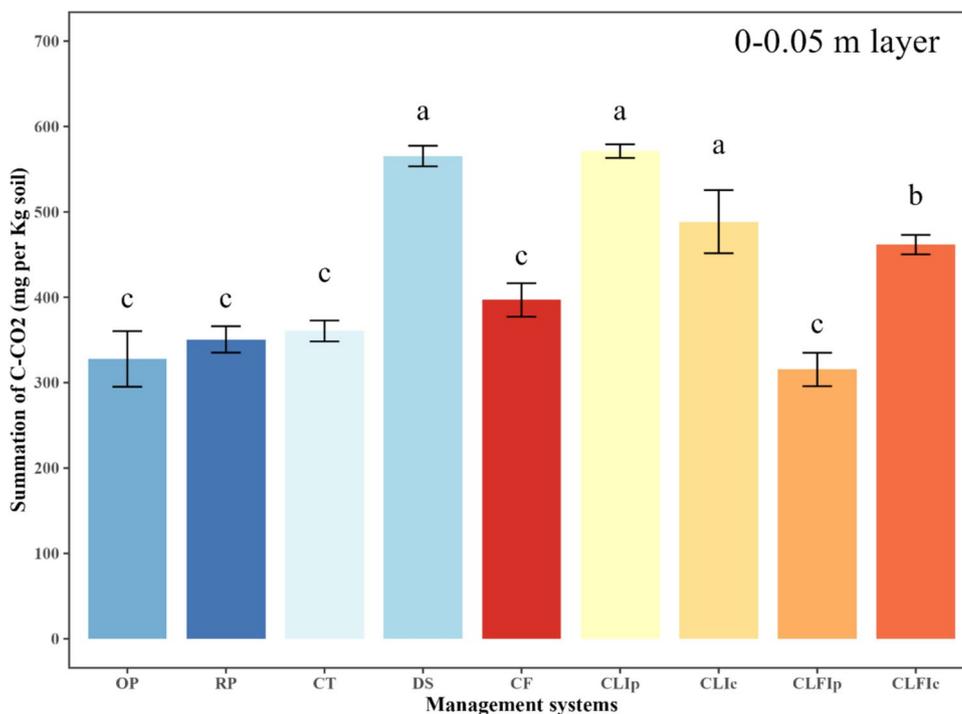


Table 4 Loading values and percentage contribution of soil quality indicators in the 0–0.05 m layer on the principal component axes

Soil quality indicators	PC1		PC2	
	Eigenvectors	Contribution of variables (%)	Eigenvectors	Contribution of variables (%)
SOC	0.211	6.45	0.762	23.73
StoC-POM	0.259	7.97	0.673	20.97
StoC-OMM	0.620	19.03	0.316	9.85
CIS	0.237	7.27	0.673	20.95
L	0.717	22.02	0.128	3.99
LI	0.663	20.37	0.078	2.44
CMI	0.263	8.10	0.552	17.21
CO ₂ Accumulation	0.284	8.74	0.027	0.855
Eigenvalues		3.49		3.22
Variability (%)		40.71		40.13
Cumulative variability (%)		40.71		80.85

SOC Soil organic carbon, StoC-POM Carbon stock of particulate organic matter, StoC-OMM Carbon stock of mineral-associated organic matter, CIS Carbon stock index, L Liability, LI Liability index, CMI Carbon management index

The most representative variables, LI, L, StoC-POM, and CMI, remained related to the CLFip, indicating that the management adopted allows the input of higher quality organic residues, compared to the other pasture management (RP, PP, CLIp). The CLIp came close to the CLFip regarding the quality of plant residues, indicating that the

system is moving towards the highest soil quality levels. On the other hand, when in the tillage phase, the CLIC system has resulted in greater release of C from the soil. The conventional CT, DS, CF, and integrated CLFic systems and the OP were close to each other but were not associated with soil quality indices (Figs. 4, 8, 9 and 3).

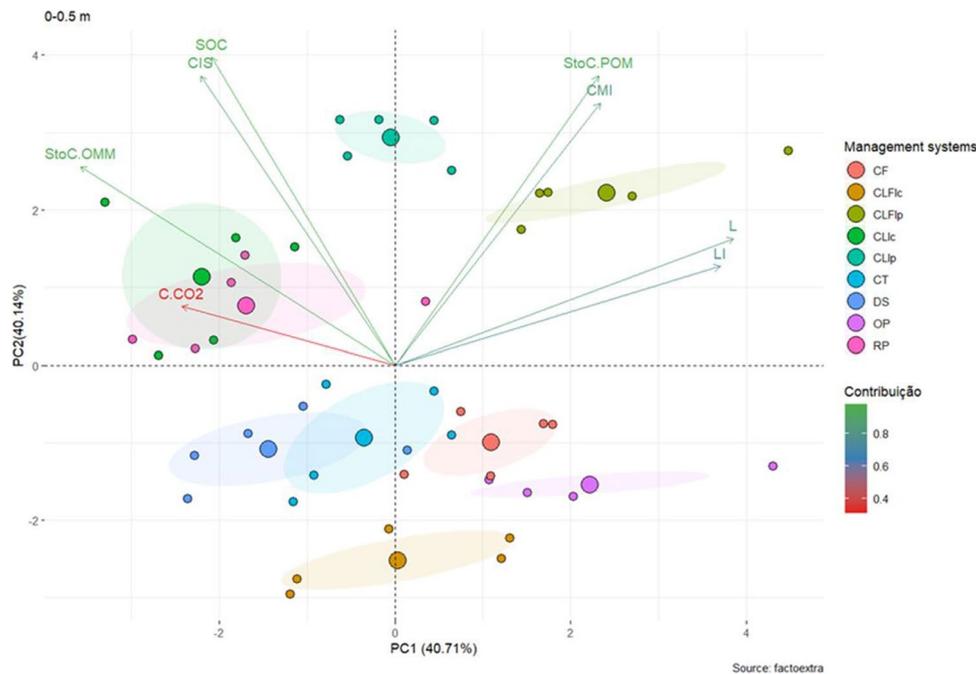
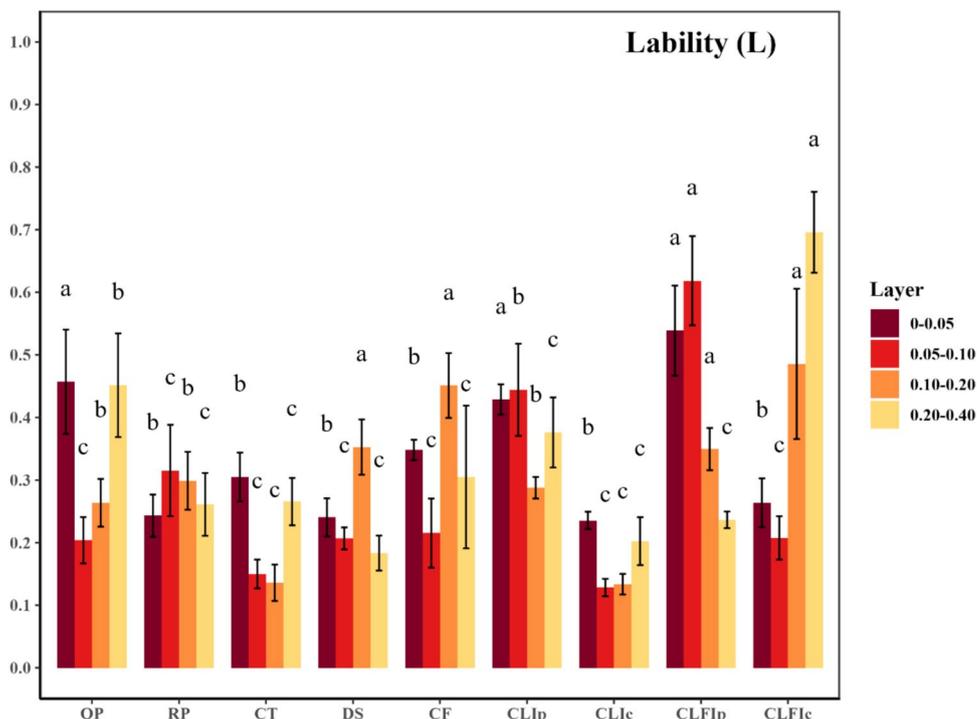


Fig. 7 Principal component analysis of soil quality indicators of conventional and integrated agricultural production systems in the 0–0.05 m layer. SOC: Soil organic carbon, StoC-POM: Carbon stock of particulate organic matter, StoC-OMM: Carbon stock of mineral-associated organic matter, CIS: Carbon stock index, L: Liability, LI: Liability index, CMI: Carbon management index, C.CO2: Accumula-

tion of mineralizable carbon. OP: original pasture, RP: reformed pasture, CT: conventional tillage system, DS: Direct seeding, CF: cultivated forest, CLIP: crop-livestock integration (Pasture phase); CLIC: crop-livestock integration (Crop phase), CLFIP: crop-livestock-forest integration (Pasture phase), CLFIC: crop-livestock-forest integration (Crop phase)

Fig. 8 Lability (L) of soil organic matter in conventional and integrated agricultural production systems in the 0–0.05, 0.05–0.10, 0.10–0.20 and 0.20–0.40 m layers. Means followed by equal letters in the bars, in each layer, do not differ by the Scott-Knott test ($p < 0.05$). OP: original pasture, RP: reformed pasture, CT: conventional tillage system, DS: Direct seeding, CF: cultivated forest, CLIP: crop-livestock integration (Pasture phase); CLIC: crop-livestock integration (Crop phase), CLFIP: crop-livestock-forest integration (Pasture phase), CLFIC: crop-livestock-forest integration (Crop phase)

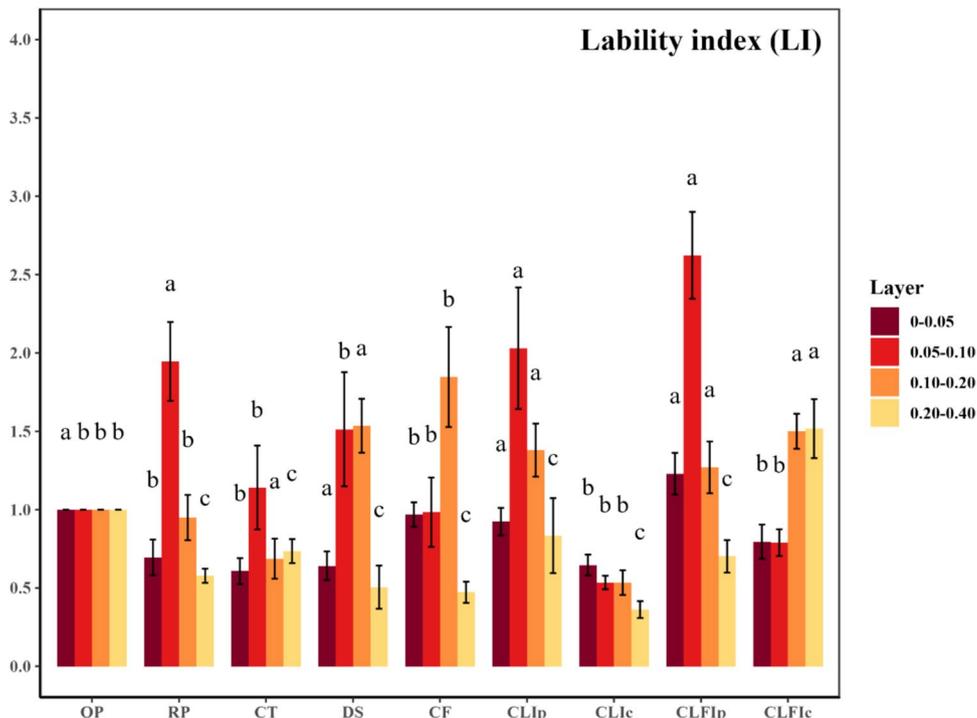


4 Discussions

The increase in soil C levels in integrated systems compared to conventional systems six years after the conversion of degraded pasture may be related to the diversity of species in these areas (Paramesha et al. 2025), mainly

due to the succession between crops and pasture. Grasses are highly efficient in adding organic matter to the soil through abundant production of plant material both above and below ground (Sapkota et al. 2024), significantly contributing to soil C storage (Douglas et al. 2020; Freitas et al. 2020; Lin et al. 2020; Santos et al. 2024; Souza et al.

Fig. 9 Lability index (LI) of soil organic matter in conventional and integrated agricultural production systems in the 0–0.05, 0.05–0.10, 0.10–0.20 and 0.20–0.40 m layers. Means followed by equal letters in the bars, in each layer, do not differ by the Scott-Knott test ($p < 0.05$). OP: original pasture, RP: reformed pasture, CT: conventional tillage system, DS: Direct seeding, CF: cultivated forest, CLIP: crop-livestock integration (Pasture phase); CLIC: crop-livestock integration (Crop phase), CLFIP: crop-livestock-forest integration (Pasture phase), CLFIC: crop-livestock-forest integration (Crop phase)



2024a, b, c). However, their potential seems to increase when cultivated in an integrated system. We attribute the differences in C increments in pastures within integrated systems to soil fertility management (Souza et al. 2024a, b, c), which can be linked to the dynamic interactions between system components (Camargo et al. 2024). Prior to pasture cultivation, crop cultivation ensures favorable soil fertility conditions to support crop production, indirectly benefiting subsequent pastures. Additionally, positive results have been associated with the integration of legumes and grasses in agroecosystems (Blesh 2019). The study by Coonan et al. (2019) clearly demonstrated increased C accumulation in permanent pasture with soil fertilization, reaching up to 12 Mg C ha⁻¹ at 60 cm depth compared to unfertilized pasture, attributing the result to enhanced root growth in response to fertilization. In Souza et al. (2024a, b, c), soil C levels and stocks returned to their original native vegetation state in long-term pastures associated with forage legumes or fertilized with N.

Considering the scenario of degradation of grassland in Brazil, although the values of emissions on grassland have not been the highest, they are still significant and deserve attention. The CO₂ emissions observed in pasture area may be related to two factors: 1) the lack of soil fertility maintenance may be inducing delayed root development and, consequently, lower straw production and C input (Campos et al. 2022), progressing towards a degraded condition, as confirmed by the decrease in C levels at depth and CO₂ emissions. In a recent study, Campos et al. (2022) highlighted that despite the positive contributions of SOC, degraded pastures are the main sources of atmospheric CO₂ compared to managed pastures. 2) soil disturbance during the ploughing for RP implementation. Segura et al. (2023) observed higher SOC levels in undisturbed pasture areas compared to areas converted into new pastures, even four years after soil ploughing. In contrast, pastures in integrated systems were implemented under the same conditions and within the same period as RP but showed contrasting results, suggesting that management practices influence the rapid recovery. Arije et al. (2024) selected pasture as a tool to restore SOC levels in an annual wheat cultivation area in arid and semi-arid regions. Their results indicated that pasture increments grow over the years but may take decades to reach peak SOC levels with grass-only cultivation.

It was expected that the inclusion of trees would enhance the deposition of organic matter into the soil, which, due to its naturally recalcitrant composition, would increase the C content in more stable fractions compared to systems without trees (CLI). However, this expectation was not fully realized. Shading limits the annual growth of crops and reduces the deposition of plant material into the soil (Bieluczyk et al. 2021), consequently affecting SOC levels and stocks. Quantitative analysis reveals that eucalyptus forest (CF) and direct

seeding (DS) contribute more to carbon accumulation than CLFI during the cultivation phase. Bieluczyk et al. (2020) observed that intensifying the integrated system by introducing the tree component reduced soil C and N levels and stocks over six years, where the major source of C contributing to SOM originated from C4 plants. This suggests that forests do not stimulate an increase in soil C, at least not in the short term. According to Ma et al. (2022), a wooded area within an agroforestry system stored 178.5 t ha⁻¹ more C than agricultural land and pasture in western Canada. Their findings showed a positive relationship between C storage and tree age. Although trees affect the crop phase, they still contribute significantly more to improving soil quality than conventional systems. The microclimate created reduces CO₂ emissions to the atmosphere (Carvalho et al. 2016), unlike what happens in CLI, which, besides presenting the highest accumulation of CO₂ (Fig. 6), was associated with C-CO (Fig. 7).

The pasture phase of CLFI is practically unaffected by the presence of the forest component, as the trees may create an environment with better humidity and temperature conditions, favoring pasture development (Carvalho et al. 2016). Results from Dube et al. (2012) showed a positive synergistic effect between trees and pastures, where trees in the silvopastoral system sequestered nearly 30% more C in total biomass compared to single pine plantations. Another important finding from the same study was the optimized growth of trees intercropped with leguminous pastures, where the availability of N from the pastures benefited tree development, further increasing C sequestration. In the present study, the pastures are not leguminous but do include soybeans during the crop phase. However, we believe that the establishment period of the cropping is insufficient to bring significant improvements to the trees. Analyzing each phase separately seems unfair, as the system works as a whole. It is undeniable that SOC levels vary considerably across different phases, but overall, integrated systems surpass conventional tillage systems in C storage, and better soil quality indices. Puech and Starkb (2023) suggest that soil quality assessment should consider the interference of all components across different phases, which may influence rotation timing. In this study, we observed that the crop phase disturbs soil quality, and further research is needed to determine the optimal rotation interval between each component. Soil quality may be less affected by the crop phase if the cultivation period is reduced or gains are increased through prolonged leguminous cultivation, as observed in the study by Dube et al. (2012).

The best balance between source and sink of CO₂ was observed in systems specifically integrated into forest systems, where high levels of C are stored in the soil, and the total accumulation of C-CO₂ is lower when compared to others, for example. Lustosa Filho et al. (2024) evaluated

carbon stocks in the conversion of native forests to different systems and observed higher carbon storage in silvopastoral systems and higher CO₂ emissions in intensively managed pastures on sandy soils. Sharrow and Ismail (2004) compared C accumulation in silvopastoral, forestry (planted forests), and pastures, where accumulation in silvopastoral systems was 740 kg ha⁻¹ year⁻¹ more than in planted forests and 520 kg ha⁻¹ year⁻¹ more than in pastures. Carvalho et al. (2016) measured CO₂ efflux in agroforestry and full-sun coffee systems, finding lower CO₂ efflux in agroforestry systems, which the authors attributed to the ideal microclimate formed by the presence of trees. This differed from full-sun systems in terms of soil temperature and humidity, corroborating the results found in this study, where C-CO₂ emissions tended to be lower in the forest system. All evidence suggests that the presence of trees prevents C loss to the atmosphere even under unfavorable conditions, as seen during the cropping phase in integrations.

The decline in C-POM levels in integrated systems after the crop phase may result from lower contributions of plant material to the soil. However, this does not imply a regression in quality during this phase, as there was an increase in C content in more stable fractions, such as C-OMM. When pasture is converted to cropland, it leaves a legacy in the form of previously mineralized material in the soil (C-POM). Following the cropping period, C-POM levels are lower, decreasing over time due to reduced straw volume being added. In contrast, C-OMM increases in response to higher N content, particularly from soybean cultivation (Alves et al. 2020), which confirms greater organic matter addition from pasture. The increase in SOM and the increment of C-POM improve soil aggregation (Souza et al. 2024a, b, c). Aggregates and the association of SOM with the mineral fraction are the main protection mechanisms against microbial attack, preventing atmospheric losses (Shoumik et al. 2025). The pasture phase may consume available N, producing significant organic matter and increasing C-POM levels. When this phase ends, the cropping phase recharges N levels (Carlos et al. 2022), boosting microbial activity (Tang et al. 2024) and leading to increased C-OMM levels until the cropping cycle concludes.

The results found by Shoumik et al. (2025) are in agreement with the current study, where the highest levels of C-POM and C-OMM were observed in pasture areas compared to cropland areas. However, their levels were considerably higher, reaching 12.21 and 23.19 g kg⁻¹ in pasture and 4.45 and 13.62 g kg⁻¹ in cropland for C-POM and C-OMM, respectively. One of the greatest challenges for carbon accumulation in Brazilian soils is its tropical climate, where climatic conditions promote higher activity of soil decomposer agents, and the rapid mineralization of SOM results in carbon loss to the atmosphere before it becomes stabilized in mineral fractions. Therefore, land management

systems must ensure not only the addition of a larger volume of plant material but also materials that are slowly decomposing, such as woody materials, and minimize soil disturbance to protect the added carbon within soil aggregates. Systems such as conventional tillage typically show lower carbon levels due to the constant disruption of aggregates (Reichert et al. 2022; Souza et al. 2024a, b, c).

Another important factor to mention is the clay content, an example of which is the study by Souza et al. (2024a, b, c), where similar land management systems were compared, but in soils of different textures. Both areas reached carbon levels corresponding to the native vegetation of each location, with pastures achieving high productivity levels. However, the C-OMM contents were considerably different, which was explained by the soil use history and clay content. Baah-Acheamfour et al. (2014) measured the carbon content and its distribution in different soil fractions in agroforestry systems and concluded that most of the C-OMM was associated with the fine fraction in all the systems studied. Silva et al. (2024) observed a decrease in C-OMM stocks in the CLFI system in sandy-clay soils, while they increased in clay soils. This demonstrates that not only the management system matters, but also the soil characteristics influence the C pools in the soil and the respective fractions of SOM.

Integrated systems have shown to improve soil quality rapidly in the conversion of degraded pastures compared to conventional tillage systems, such as conventional tillage (CT). Several studies have confirmed the improvement in soil quality through the adoption of no-tillage (NT), however, for improvements in soil attributes to be significant, a prolonged period is required (Farias et al. 2022; Rosset et al. 2014, 2016, 2019, 2022; Souza et al. 2024a, b, c), which may explain the similarity between the CT and DS systems in this study. The characteristic that distinguishes these systems is the absence of soil ploughing in CT, but the soil disturbance during preparation before the implementation of the systems may still be affecting the consolidation of no-tillage. Blanco-Canqui and Ruis (2018) reported that once the soil is prepared under no-tillage, it would not affect the soil properties, but the duration of management and soil texture class are the main determining factors for the effect of no-tillage on soil properties. Colunga et al. (2025), in a meta-analysis, revealed a 10.06% increase in SOC accumulation under no-tillage compared to conventional tillage in sandy soils, but among the conservation systems, no-tillage showed the smallest difference in SOC levels compared to conventional tillage. Furthermore, there was a progressive increase in SOC accumulation over time; however, studies that analyzed conservation systems beyond 15 years did not detect significant changes in C-OMM levels after this period in sandy soil classes. This means that under the conditions found in this experiment, direct seeding (SD) was not able

to recover SOC levels following the prolonged cropping of the original degraded pasture (OP), and also presented the highest values of CO₂ emission into the atmosphere.

Similarly, the pasture only during the intervals between direct seeding harvests as a cover crop was not effective, which once again reinforces the better use of pasture in prolonged cropping systems and not just as soil cover. Besen et al. (2024) tested different cover crops such as common vetch, fodder radish, and black oat in conventional tillage, reduced tillage, and no-tillage, where no-tillage, regardless of the cover crop, achieved the highest C stocks, reaching 80.22 Mg ha⁻¹. Jones et al. (2016) monitored changes in soil quality during the conversion of native forest to cropland and from cropland to pasture, observing a decline in soil quality under long-term cropland and subsequent recovery under pasture cultivation. However, the capacity for soil quality recovery decreased in areas with longer-term cropland cultivation, with a loss of resilience due to prolonged cropland cultivation, even with pasture periods for soil cover. This highlights a limitation of prolonged succession cropping systems (Jones et al. 2016) and pasture in soil quality recovery as a cover crop in short periods, even more prominent in challenging soil and climatic conditions (Colunga et al. 2025). It may be that cover crop cultivation is a more favorable strategy in this case compared to the use of pasture for increasing SOM in short periods (Besen et al. 2024).

Although the analysis of CO₂ presented limitations as an isolated indicator of soil carbon emission dynamics, the results provide relevant insights into the impact of converting degraded pastures under different management practices and how this affects CO₂ emissions over six years. Despite some systems having contributed considerable amounts of soil organic matter (SOM), the disturbance caused by the initial soil preparation before implementing the management practices altered properties that persist, hindering the identification of key factors influencing emissions in response to stimuli from different systems. Current trends point to the replacement of traditional systems with intensified management practices, which condition the soil for storing large amounts of C. However, few studies have evaluated CO₂ emissions during periods of management transition. The required adaptation period remains unknown, and the lack of differences when evaluated over short periods may discourage the transition to sustainable systems before observing the real contribution of these systems to mitigating carbon emissions.

5 Conclusions

After six years of converting the original degraded pasture, the integrated cultivation systems increased soil C levels and improved soil quality. The individual evaluation of

each cultivation phase in the integrated systems allowed for the identification of each component's contribution to soil improvement and CO₂ emission mitigation, where integrated cultivation brought multiple benefits compared to isolated cultivation in conventional systems. Although pasture is widely used to increase plant material for replenishing SOM (soil organic matter) levels, our study indicated a better use of pasture when cultivated in the long term, where soil fertility management can determine the greater or lesser contribution of pasture over time. Therefore, cultivation in an integrated system can optimize production. The interaction of different species cultivated over the long term was essential for increasing soil C levels, stabilizing SOM (soil organic matter) in the mineral fraction of the soil, improving soil quality, and reducing CO₂ emissions. Soil texture class may be the main limiting factor for improving soil quality in conventional systems, especially for reformed pasture (RP) and direct seeding (DS). Therefore, integrated production systems make the soil a valuable tool for mitigating climate change, replacing conventional systems, and enabling the rapid recovery and storage of C in previously degraded areas, helping to mitigate climate change in the Central-West region of Brazil.

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Data Availability The authors declare that data will be made available when requested.

Declarations

Competing Interests The authors declare that they do not have a competing interest.

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