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Land use change effect on organic matter dynamics and soil carbon sequestration in the Brazilian Cerrado: A study case in Mato Grosso do Sul state (Midwest-Brazil)

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A B S T R A C T

Pasture restoration and conservative agricultural practices, such as those used in Integrated Crop-Livestock-Forestry Systems (ICLF), can enhance soil protection and SOC stocks. This study, conducted in the Mato Grosso do Sul state, aimed to analyze the effect of land use conversion on C and N stocks and Soil Organic Matter (SOM) fractions to comprehend the C and N dynamic in 1-meter depth. Soil samples were collected in five different land uses in adjacent areas on the same farm: (1) Native Vegetation (NV); (2) Extensive Pasture (EP); (3) Managed Pasture (MP); (4) Integrated Crop-Livestock (ICL); and (5) Integrated Livestock-Forestry (ILF). Disturbed soil samples were collected using a soil auger at seven soil depths for elemental and isotopic analysis for soil C and N. Undisturbed samples were collected to assess the soil bulk density. The soil physical fractionation obtained the Particular Organic Matter (POM) and Mineral Associated Organic Matter (MAOM). The C and N stock varied from 86.02 in MP and 67.37 Mg ha^{-1} in ICL and was statistically similar for all studied land uses. The δ^{13}C signature varied between land uses and through the soil profile, with more negative values for NV and ILF (−27.83 and −21.73 ‰, respectively) in the topsoil. The POM fraction indicated changes in land use, and the POM in ICL shows the potential to restore soil C and health since it is just in the second year of intervention. The managed pastures with grass species Brachiaria promoted better soil C and N content and stocks. This study pointed out other alternatives to land use, such as integrated systems (ICL and ILF), which should be the target for the Brazilian policies to mitigate greenhouse gas emissions and enhance the diversification and resilience of the agroecosystem.

1. Introduction

The Cerrado biome occupies 23 % of the Brazilian territory or about two million km^2 in central Brazil (Ratter et al., 1997), recognized as the most diverse savannah in the world, sheltering 11,627 known native plant species (de Oliveira et al., 2015). That is also the source of economically relevant commodities such as soybeans, maize, and beef cattle that are key for the gross domestic product of the Country (BRASIL, 2023; de Carvalho et al., 2023). Soils from Cerrado are generally evolved, weathered, and well-drained, associated with a colloidal fraction of low cation exchange capacity, high natural acidity, and aluminum saturation (Lopes & Guimarães, 2016). Thus, their

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fertility is highly dependent on soil organic matter (SOM) (Vieira et al., 2022), and preserving the soil quality of this crucial biome holds utmost importance.

Raising beef cattle with management practices of low efficiency has been historically employed in the occupation of Brazilian agricultural frontiers like the Cerrado, frequently to ensure land possession in inhabited areas (Pires, 2020). Overgrazing and lack of fertilization and liming are generalized and can lead to pasture degradation in the long term (Antunes et al., 2022; Sone et al., 2020). In 2022, the pasture area reached 50 million hectares within the Cerrado biome, of which almost 67 % are in a severe or intermediated degradation stage, deserving attention for some improvement or even a complete restoration (Lapig, 2022). Pasture restoration improves beef productivity while reducing greenhouse gases due to the "land sparing" effect, avoiding deforestation of native forests for food production (Bragança et al., 2022). Moreover, productive pastures increased soil organic matter even to levels above those found under native vegetation (Braz et al., 2013), contributing to enhanced soil fertility.

In addition to pasture recovery, integrated crop-livestock-forestry systems (ICLF) have also been encouraged. In these systems, pasture follows a sequence of grain crops, the harvest of which covers the expenses for soil fertilization and pasture establishment. This process typically repeats every two to four years (Alves et al., 2017; de Carvalho et al., 2017; dos Reis et al., 2021; Leite et al., 2023).

Pasture intensification triggers increased GHG emissions due to chemical inputs, mechanical operations, higher stocking rates, and the consequent storage of C in the soil, which works to offset emissions (de Figueiredo et al., 2017). Many studies only assess SOC stocks to 30 cm depth, potentially underestimating the capacity to sequester atmospheric CO_2 (Carvalho et al., 2014; Conceição et al., 2017; López-Santiago et al., 2019). On the other hand, several studies recommend measurements down to a depth of 1 m as a more comprehensive approach to accounting for changes in SOC stock in the deep-weathered soils of Brazil (Boddey et al., 2010; Oliveira et al., 2023; IPCC, 2019; FAO, 2019; Bernoux et al., 2009).

The change in SOC stock due to land use change lacks easy detection in the short term (Stockmann et al., 2013). In addition, the stability of the stored C in soil is also essential as a driver of crop management. Thus, the physical fractionation of SOM into particulate organic matter (POM) and mineral-associated organic matter (MAOM) can be a proxy of the land use change effect and contribute to an easier understanding of the SOM dynamics (Lavallee et al., 2020; Schiebelbein et al., 2023). These two fractions are different in terms of their properties, persistence (time), functioning, and formation processes, while the POM is more sensitive to land use change and soil management effects (Lugato et al., 2021; Witzgall et al., 2021). In addition to SOM fractionation, changes in the $\delta^{13}C$ isotopic signatures of soil carbon (C) can give evidence of the SOC origin (plant metabolism C3 or C4) and quantify the fate of the different sources of C in the soil (Smith et al., 2021).

Under this context, it is necessary to comprehend both soil quantity and quality (lability and origin) of carbon and nitrogen (N) due to land use change to more diverse and sustainable management practices in 1-meter soil depth. Thus, this study aims to analyze the effect of land use conversion on total C and N stocks and SOM fractions to comprehend the C and N dynamic in Brazilian Cerrado pasturelands. In light of that, we aim to understand two main questions: which system is more efficient in sequestering carbon, and the magnitude of such gain, thus providing a baseline for public policies on land use conversion and climate change mitigation.

2. Material and Methods

2.1. Study area description

The study was conducted in Bandeirantes (19°43′31.66″S and 54°22′14.79″W) at Mato Grosso do Sul, Brazil (Fig. 1). Bandeirantes County has an area of approximately 3,116 km^2, with an average altitude of 630 m a.s.l. and an Aw tropical climate, according to Koppen climate classification. The site has a rainy summer, from November to April, and a marked dry winter, from May to October (July is the driest month) (Pereira et al., 2012). The study area is at the central-eastern portion of Mato Grosso do Sul, characterized by the remarkable homogeneity in the morpho-structure as ramped plateaus, with sandstone and basalt as parental material and quartz and hematite as existing minerals. The rocks of that region are part of the "Arenito Caiuá" formation, which is characterized by the presence of red and rosy sandstones, from medium to coarse granulation, red clay matrix conglomerates, usually silicified, with rounded pebbles.

The average annual rainfall on the study site (Pontinha Farm) for the last seven years was 1,425 mm, with minimum precipitation recorded in July (9 mm). The average annual air temperature was 23.1 °C. The soil is classified as Ferrasols (IUSS Working Group WRB, 2015) or *Latossolo Vermelho distrófico* based on the Brazilian Soil Classification System (dos Santos et al., 2018). Soil samplings were conducted in five land uses in adjacent areas of the same farm: (1) Native Vegetation (NV); (2) Extensive Pasture (EP); (3) Managed Pasture (MP); (4) Integrated Crop-Livestock (ICL); and (5) Integrated Livestock-Forestry (ILF) (Fig. 1).

Due to the lack of long-term field experiments in this region, we employed the chronosequence approach, a "space-for-time" substitution (Yang et al., 2022) to evaluate land use conversion effects on soil

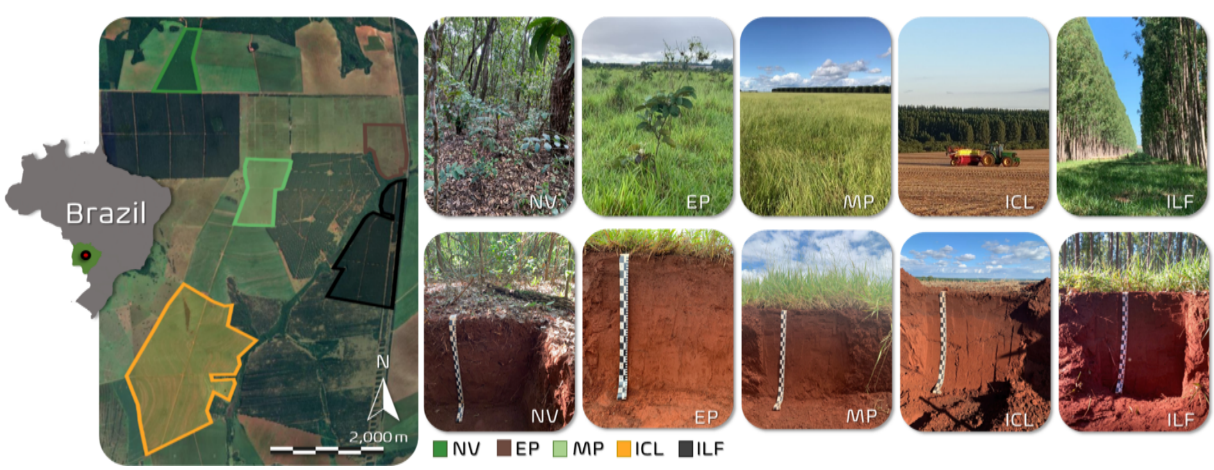

Fig. 1. Location of the study site (Bandeirantes, Mato Grosso do Sul, Brazil) and land uses assessed inside the farm. NV: Native Vegetation; EP: Extensive Pasture; MP: Managed Pasture; ICL: Integrated Crop-Livestock; ILF: Integrated Livestock-Forestry.

properties. This approach has the advantage of doing just one sampling campaign instead of waiting several years to resample the areas (Cerri et al., 2013). The selected land uses present similar topography, soil type, texture, drainage, and climate as minima premisses for a chronological comparison. We used the native vegetation as the reference area since it represents the Cerrado in the Mato Grosso do Sul state. The native vegetation area consists of a forest formation known as "Cerradão", a phytophysiognomy of the Cerrado biome, characterized by dense and tall vegetation, where medium to large trees form a continuous canopy that creates a shaded and humid environment (Veloso et al., 1991; Sano et al., 2008). This vegetation, commonly found in interfluves, elevated areas between river and stream valleys, where soils exhibit better drainage and depth, promotes the development of robust plant communities (IBGE, 2012).

The landowner and farm management provided information on the history of land use change for all systems (Table 1). All the studied areas were converted from Cerrado native vegetation to pasturelands in the 70 s when the Brazilian government incentives to develop inhabited areas and maintain national sovereignty in remote areas. Due to the commercial purchase of this farm in 2000, the landowner lacked the management records before that date but informed us that the land was used for pastures (Brachiaria decumbens cv. Basilisk) with low input levels. After 2000, different species were planted on distinct plots with typical management practices and lime application with rates recommended for that period. The species and management practices for such land uses in this study site are usual for this biome and adapted for that climate and soil.

A complete characterization of the land use history and species used of each land use is presented in Table 1.

The land use history and current management practices affect soil chemical parameters, e.g., ICL presented high V% and m% (recent amendments application) and ILF with low values (without recent amendments). Soil chemical and texture analysis was carried out according to the methodology proposed by Embrapa (Teixeira et al., 2017). The following parameters were determined: pH in water, potential acidity (H + Al), exchangeable aluminum (Al^{3+}), calcium (Ca^{2+}), potassium (K^+), magnesium (Mg^{2+}), and phosphorus (P). The Sum of Bases (SB) was obtained by summing up the Ca^{2+}, K^+, and Mg^{2+}. Details about soil texture and chemical characterization of each land use assessed are presented in Table 2.

Table 1
Land use change history and management of each area.

Land use	Area (ha)	Previous land use and management	Current land use and management
Integrated Livestock –Forestry (ILF)	171 ha: 32.04 ha (18.74 %) of eucalypt and 138.9 ha (81.26 %) of pasture	The pasture was the main land use until 2000, with no amendment application. From 2000 to 2004, this area was leased for soybean monoculture cultivation, and from 2005 to 2008, estilosante campo grande was planted.	In 2008 *Eucalyptus* GG100 was planted in triple lines with *Brachiaria marandu* in the alleys. The alley spacing between tree rows was 20 m. The space between the *Eucalyptus* plants was 1.5 m, and 2 m between the lines inside the Eucalypt row. In 2014, one line was thinned, and the system currently has double lines. It has an East-West planting direction. Fertilizer and ant killer were applied at the planting stage.
Integrated Crop-Livestock (ICL)	300	From the 70 s to 2000, it was a pasture with Brachiara decumbens with no amendment application. In 2005 and 2006, Brachiaria cv. marandu (80 %) and Brachiaria cv. decumbens (20 %) were planted with lime application.	In 2020, plowing and harrowing were carried out in the area, then the rotation between soybeans in the main season and *Brachiaria ruziziensis* in the off-season started. Crop fertilization and liming were applied at a varied rate according to precision agriculture analysis.
Managed Pasture (MP)	72.20	From the 70 s to 2000, it was a pasture with brachiara decumbens. From 2000 to 2005, sugarcane was planted (with base fertilization and lime for this culture). From 2006 until 2022 the land use is pasture.	*Brachiaria decumbens* with a stocking rate of 0.6 AU/ha
Extensive Pasture (EP)	55	From the 70 s to 2000, it was a pasture with brachiara decumbens. In 2002 Mombaça pasture (with lime application) was planted but had a bad formation, and the Brachiaria decumbens took place until the present day.	*Brachiaria decumbens* with a stocking rate of 0.5 AU/ha with no amendment application

2.2. Soil sampling design and laboratory analysis

The soil sampling campaign was carried out in March 2022, at the end of the rainy season following the soybean harvest. The soil sampling scheme comprised a grid of 1 ha (100 m × 100 m) (Cerri et al., 2013; Santos et al., 2022), in which nine sampling points spaced 50 m apart were established for the ILF considering the spatial variability of the trees (inter-rows, in-rows, and at 3 m from the tree canopy) and three repetitions in each. The monoculture systems (MP, EP, and ICL) and the reference area (NV) had five points in the grid, with 100 m between each other. Disturbed soil samples were collected using a soil auger at all the points at seven depths: 0–5, 5–10, 10–20, 20–30, 30–40, 40–70, and 70–100 cm. At each point, three simple samples were homogenized in a bucket to form a compost sample for each depth. That resulted in 203 disturbed samples: 140 samples from MP, EP, ICL, and NV (5 replicates × 7 depths x 4 land uses) and 63 from the ILF (7 depths × 9 replicates, considering 3 samples from each component).

Undisturbed samples (5 cm height × 5 cm diameter) were collected at three grid points to access the soil bulk density. In the central point of the grid, a trench of 100 × 100 × 100 cm was dug to sample at the depths of 0–5, 5–10, 10–20, 20–30, 30–40, 40–70, and 70–100 cm (three replicates from 40-100 cm). The other two diagonal points of the grid were used to collect undisturbed samples through small trenches of 40x40x40 cm in the depths of 0–5, 5–10, 10–20, and 20–30 cm. We collected 105 undisturbed samples (7 depths x 3 replicates x 5 land uses). Thus, soil bulk density was determined by the mass of dried samples (105 °C until constant weight) and the volume of the sample (Eq. (1).

$$Soilbulkdensity = Dryweightofsample(g)/Ringvolume(cm^3) \quad (1)$$

2.2.1. Soil total organic carbon (TOC), total nitrogen (TN), and isotopic composition ($\delta^{13}C$ and $\delta^{14}N$)

The disturbed samples were used to obtain total soil organic carbon (TOC) and total nitrogen (TN) and their isotopic composition. Samples

Table 2
Soil texture and chemical characteristics for the five land uses in the Cerrado biome, Mato Grosso do Sul State, Brazil.

Land Use	Soil Depth (cm)	Clay	Sand	pH H_2O	P	Al	H + AL	SB	CEC	V	m
		g kg^{-1}		–	mg. dm·3	cmolc. dm·3	cmolc. dm·3	cmolc. dm·3	cmolc. dm·3	%	%
Native Vegetation (NV)	0–5	133	845	4.49	2.77	1.37	7.00	0.27	7.27	3.67	83.33
	5–10	141	846	4.69	2.23	1.27	5.90	0.27	6.17	4.33	82.67
	10–20	133	844	4.89	2.50	1.03	4.67	0.13	4.80	2.67	89.33
	20–30	133	843	5.00	1.63	0.87	3.80	0.20	4.00	5.00	81.00
	30–40	141	835	5.05	1.47	0.87	3.83	0.00	3.83	0.00	100.00
	40–70	158	829	5.09	1.33	0.93	3.80	0.03	3.83	1.00	97.00
	70–100	166	818	5.08	1.10	0.70	3.23	0.03	3.27	1.00	96.00
Extensive Pasture (EP)	0–5	191	790	5.87	2.57	<0.1	3.53	2.60	6.13	42.33	0.00
	5–10	191	784	5.63	1.07	0.60	4.03	1.40	5.43	23.67	30.67
	10–20	216	769	5.81	1.47	0.25	4.07	1.83	5.90	31.00	9.67
	20–30	216	760	5.76	1.17	0.30	3.80	1.43	5.23	26.67	14.67
	30–40	232	746	5.75	1.10	0.35	3.63	1.17	4.80	24.00	18.00
	40–70	233	741	5.58	1.03	0.40	3.77	0.67	4.43	14.67	28.00
	70–100	266	718	5.31	0.90	0.53	3.17	0.17	3.33	4.67	76.33
Managed Pasture (MP)	0–5	174	805	5.92	5.57	<0.1	4.07	2.33	6.40	36.67	0.00
	5–10	199	791	5.78	3.57	0.25	4.17	1.93	6.10	31.67	7.67
	10–20	199	771	5.83	2.30	0.20	3.97	1.63	5.60	29.67	3.67
	20–30	224	750	5.90	1.57	0.20	3.30	1.43	4.73	30.00	4.33
	30–40	224	748	5.88	1.47	0.20	3.10	1.33	4.43	30.00	9.67
	40–70	224	744	5.76	1.17	0.25	2.97	0.87	3.83	22.67	17.00
	70–100	249	737	5.56	0.97	0.35	2.70	0.50	3.20	15.00	36.67
Integrated Crop-Livestock (ICL)	0–5	91	894	6.93	10.10	<0.1	1.33	4.17	5.50	75.33	0.00
	5–10	99	887	6.74	13.03	<0.1	2.13	3.53	5.67	62.67	0.00
	10–20	74	912	6.61	7.60	<0.1	2.13	3.17	5.30	59.67	0.00
	20–30	116	863	6.11	2.20	0.30	2.90	1.77	4.67	38.00	7.00
	30–40	137	855	5.45	1.47	0.40	2.90	0.77	3.67	20.67	35.00
	40–70	108	872	5.36	1.30	0.55	3.17	0.70	3.87	17.33	35.33
	70–100	141	838	5.01	1.10	0.43	2.47	0.37	2.83	13.00	53.33
Integrated Livestock-Forestry (ILF)	0–5	149	830	5.55	4.10	0.60	5.23	1.70	6.93	24.00	24.00
	5–10	158	824	5.28	3.73	0.97	5.60	0.60	6.20	9.33	65.00
	10–20	158	815	5.14	4.40	1.07	5.43	0.43	5.87	7.00	72.33
	20–30	174	793	5.07	1.97	0.97	3.90	0.23	4.13	5.67	81.33
	30–40	183	807	5.07	1.77	0.87	3.90	0.17	4.07	4.00	84.33
	40–70	191	789	5.08	1.37	0.80	3.47	0.07	3.53	1.67	92.67
	70–100	191	790	5.02	1.20	0.63	3.13	0.23	3.37	6.67	73.33

P: Phosphorus; Al: Exchangeable aluminum; H + Al: potential acidity; SB: Sum of bases; CEC: Cation exchange capacity; V%: Base Saturation; m%: Aluminum saturation.

were air-dried, crushed, homogenized, and passed through a sieve with a 2 mm mesh, removing roots and plant debris (Teixeira et al., 2017). Then, subsamples of around 1 g were ground to powder, of which from 20 to 60 mg were weighed in tin capsules to enable the characterization of total C and N contents and ^{13}C and ^{15}N isotopic abundances. The analyses were carried out in an elemental analyzer (Carlo Erba, model CHN1110; Milan, Italy) coupled to an isotope ratio mass spectrometer (ThermoQuest-FinniganDelta Plus, Finnigan-MAT, CA, USA) at the Laboratory of Isotope Ecology (CENA-USP, Brazil).

Stable isotope ratios were measured according to internationally recognized standards (Atropine, Yeast, and LECO) and considered in every sample analysis. Stable isotope values are reported in "delta" (δ) unities or parts per thousand (‰), so that the natural abundance of ^{13}C, or ^{15}N, in a sample is represented by $\delta^{13}C$, or $\delta^{15}N$ (‰) = (R sample/R standard – 1) × 1000, where R is the molar ratio of the rare to abundant isotope ($\delta^{15}N$/ $\delta^{14}N$ or $\delta^{13}C/\delta^{12}C$) in the sample and the standard.

2.2.2. Soil organic matter fractionation

The particle-size separation method (Cambardella & Elliott, 1993) used disturbed samples to physically fractionate soil organic matter for five depths: 0–10, 10–20, 20–40, 40–70, and 70–100 cm. Firstly, the soil dispersion was performed with a 5 g L^{-1} sodium hexametaphosphate solution, added to 6 g of soil (<2mm), and put in a horizontal shaker for 16 h. After the dispersion, the solution was sieved in a 53 µm sieve, where the fraction retained in the sieve was the particulate organic matter (POM), and the fraction passed in the sieve was the mineral-associated organic matter (MAOM). The separated fractions were oven-dried at 45 °C and crushed using a porcelain mortar and pestle. TOC and TN content of the fractions was determined through the dry combustion method (CHNS).

2.3. Soil carbon and nitrogen stocks in bulk soil and SOM fractions

The C and N stocks of each land use were calculated considering the soil bulk density, C and N content, and thickness of each evaluated layer (Equation (2); Veldkamp, 1994). Therefore, the total C and N stocks in 1 m of the soil profile are the sums of the respective stocks of each analyzed depth. The same procedure was conducted for the C and N in the physical fractions (POM and MAOM).

$$SOCstock = (SOC \times BD \times d)/10 \quad (2)$$

where:SOC Stock = SOC stock at a given layer depth ($Mg.ha^{-1}$).SOC = total SOC content in the sampled layer ($g.kg^{-1}$).BD = soil bulk density of the layer ($kg.dm^{-3}$).d = layer thickness (cm).

As C and N stocks are also a function of soil bulk density, factors such as machine traffic and soil tillage can influence stocks. We corrected C and N stocks for soil compression, considering the same soil mass of a reference area (Cerri et al., 2013). The mathematical equation of Sisti et al. (2004), based on Ellert and Bettany (1995), was used for the mass correction (Equation (3).

$$Cs = \sum_{i=1}^{n-1} Cti + \left[Mtn - \left(\sum_{i=1}^{n} Mti - \sum_{i=1}^{n} Msi\right)\right] * Ctn \quad (3)$$

where:Cs = total C stock, in Mg ha^{-1}, corrected as a function of soil mass in a reference area;$\sum_{i=1}^{n-1} Cti$ = sum of soil C stocks from the first to the penultimate layer sampled in the treatment considered (Mg ha^{-1});Mtn = soil mass of the last layer sampled in the treatment (Mg ha^{-1});$\sum_{i=1}^{n}$Mti = sum of the total mass of soil sampled under the treatment (Mg ha^{-1});$\sum_{i=1}^{n}$Msi = sum of the total mass of soil sampled in the reference area (Mg ha^{-1});Ctn = soil C content in the last sampled layer (Mg C Mg^{-1} of soil).

2.4. Statistical analysis

An ANOVA statistical analysis was performed using the R Studio software (R Team, 2022) to assess significant differences in the soil attributes in each soil layer (bulk density, carbon, and nitrogen content in the bulk soil and fractions, C and N stock) among land uses. For this, the ANOVA assumptions were tested with the Shapiro-Wilk test (normality of residues), and Bartlett's test (homogeneity of variance) for the data of the chronosequences studied. We transformed the data when these assumptions were violated using Log (x) and Box-Cox transformation, and a new ANOVA ($p < 0.05$) was performed. A Tukey test was conducted at a probability level of 95 % to assess the differences among land uses. Some variables did not meet the assumptions of ANOVA even after transformation. In those cases, they were tested using the non-parametric Kruskal–Wallis test followed by Fisher's Least Significant Difference (LSD) to check for differences between land uses. The graphics were elaborated in the program Grapher®.

3. Results and discussion

3.1. Soil bulk density, C and N contents, and C/N ratio

In the current study, the area under native vegetation (NV) represented the reference for the original condition of the soils used in the other four different land use systems. The area under NV presented the lowest soil bulk density values with an increasing trend with depth (Fig. 2A). Significant differences between the managed land uses and NV was observed for the soil layers above 30 cm. However, in the deepest layer, the soil bulk density in NV showed no difference between ILF and MP.

These differences in the 0–30 cm depth can be attributed to the

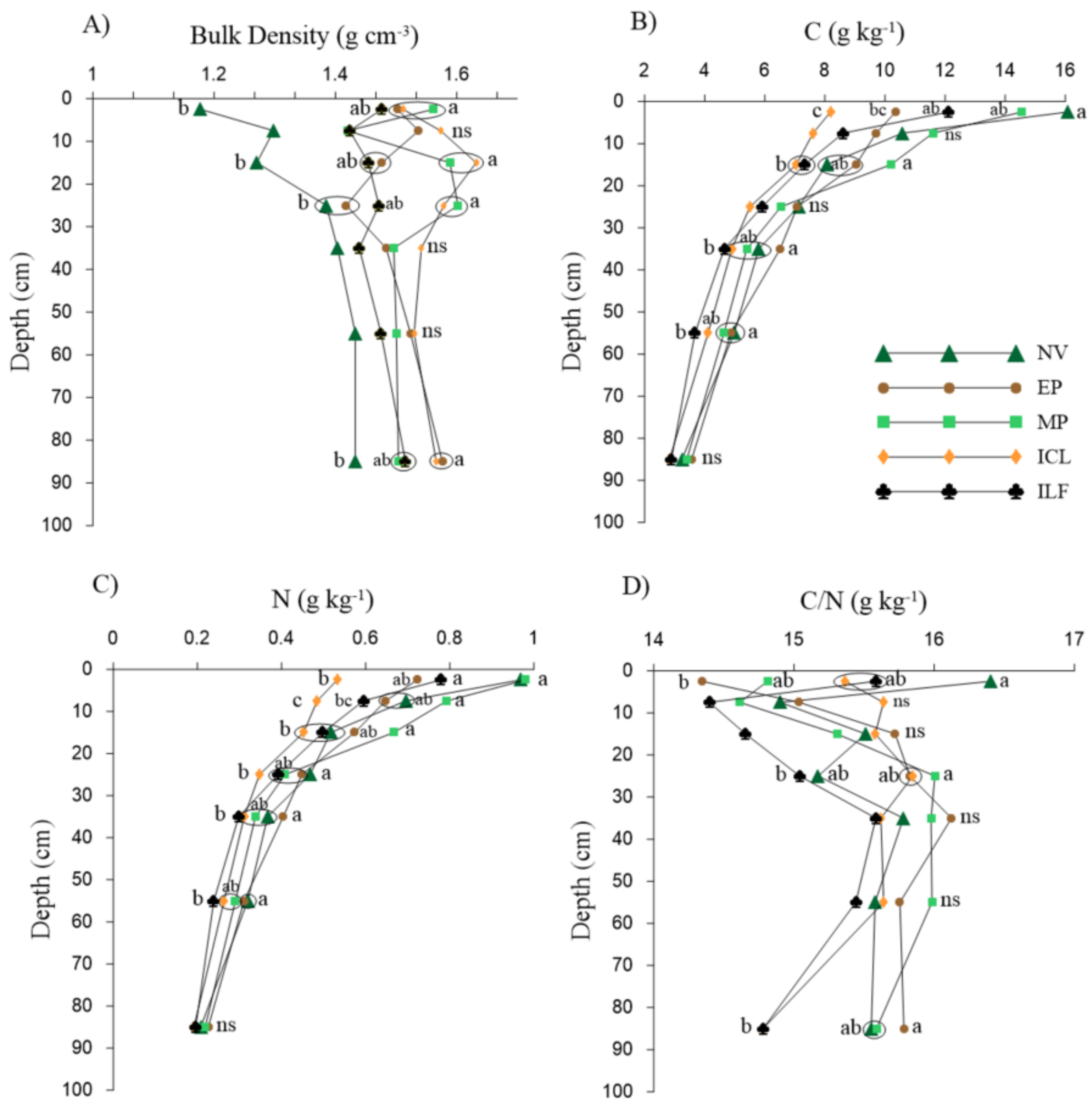

Fig. 2. Soil bulk density (g cm^{-3}) (A), Carbon content (B), Nitrogen content (C), and C/N ratio (D) for 0–5; 5–10; 10–20; 20–30; 30–40; 40–70; 70–100 cm from native vegetation and land uses in the Cerrado biome, Mato Grosso do Sul State, Brazil. NV: native vegetation; EP: extensive pasture; MP: managed pasture; ICL: integrated crop-livestock; ILF: integrated livestock-forestry. Different letters in the same soil layer between areas represent a significant difference in the Tukey test or the LSD test ($p < 0.05$), ns = no significant difference.

compaction effects of mechanical operations and animal trampling, as well as the higher C/N ratio of the increased fresh residue input (Almeida et al., 2021; Bonetti et al., 2021; de Lima et al., 2021). Below this depth, C/N variations were also significantly reduced, with a trend towards converging values (Fig. 2D). According to Braz et al. (2013), that pattern points to the chronosequence approach as a valid methodology for assessing the impact of land use systems on soil C and N stocks. The occurrence of charcoal in Cerrado soils can be responsible for the observed variability in the C/N ratio for the deepest layer (Sisti et al., 2004).

Managed pasture (MP) obtained higher C content values in the topsoil, similar to NV (Fig. 2B). All four managed systems have the same species (*Brachiaria*). This African grass promotes higher soil C and N content values in the upper layers due to a higher proportion of fine roots, which could be even higher than the Cerrado native vegetation value (Garcia et al., 2022). Our study showed that the NV had significantly equal C content than single pastures in the 40–70 cm (between 4.63 and 4.87 g kg^{-1}). The presence of grasses such as *Brachiaria* increased the soil C content due to its extensive root system, increasing the protection and preventing SOM oxidation in an ICL and managed pastures system in the Cerrado biome (Sato et al., 2019; Santos et al., 2021).

The highest values in the 0–5 cm depth for total N were observed at MP, NV, and ILF (Fig. 2C). The lack of fertilization of N and the high stocking rate in extensive pastures (EP) decreased N content, mainly in the topsoil, a pattern also resonated in the study by Soares et al. (2020). Considering that the N cycling is closely associated with the C cycle (Kirkby et al., 2011), the reduction in N availability results in lower plant biomass and, consequently, a decrease in SOM content, which explains the degradation process in extensive pastures (Dias-Filho, 2012; Wieder et al., 2015). Thus, N supply is pivotal to improving soil biochemical parameters and bacterial community structure in pasturelands (Damian et al., 2021a).

3.2. The natural abundance of $\delta^{13}C$ and $\delta^{15}N$

The isotopic signature of soil organic carbon ($\delta^{13}C$) varied between land uses and through the soil profile, with NV presenting the lowest values (ranging from −24.74 to −27.83 ‰) and MP the highest values (−15.69 until −18.39 ‰) (Fig. 3A). The isotopic signature of $\delta^{13}C$ can help in the identification of which plant metabolism (C3 or C4) the SOM was derived, as plants with C3 metabolism (trees) have the isotopic composition ($\delta^{13}C$) from −24 to −34 ‰, and the C4 plants (grasses) ranges from −6 to −19 ‰ (Smith & Epstein, 1971).

The $\delta^{15}N$ isotopic signal was lower in the NV than the other land uses in all the depths (ranging from 3.11 to 8.91 ‰) (Fig. 3B). It was the highest for ICL compared to other land uses, except MP for 0–5 cm depth. The isotopic value of $\delta^{15}N$ can be used to indicate the decomposition level of the SOM, where enriched $\delta^{15}N$ values are related to higher mineralization of SOM (Oliveira et al., 2021). In our study, the NV presented the lowest value of $\delta^{15}N$, which could be associated with leguminous plants and less decomposed SOM in Cerrado soils (Costa Junior et al., 2011).

Extensive pastures have the highest $\delta^{13}C$ (‰) than natural Cerrado vegetation, ranging from −17.4 ‰ to −18.3 ‰ in the superficial layer, with the contribution of C4 plants higher than 70 % in this land use (Oliveira et al., 2021). The ^{13}C natural abundance in another study in the Cerrado region with 12 years of *Brachiaria* pasture revealed a contribution of organic matter from C4 plants to at least 1-meter depth, confirming previous studies (de Sant-Anna et al., 2017). The soil C addition by grasses in ICL systems in Southeastern Brazil led to a higher $\delta^{13}C$ and lower $\delta^{15}N$ in the soil surface layers (0–20 cm) when compared to the forest area (Bieluczyk et al., 2020).

3.3. Soil C and N stocks

The soil C and N stocks for the whole depth to 100 cm in NV were not statistically different from the other four land uses assessed ($p > 0.05$) (Fig. 4A and 4B). However, the MP had a C stock of 86 Mg ha^{-1}, while EP reached 83 Mg ha^{-1}, which is significantly higher than the C stock in ICL. The fact that the ICL had lower C and N stocks in the soil than in the single pastures (EP and MP) is related to the timing of system implementation. While the MP system was implemented in 2006 (16 years) and the EP in 2002 (20 years), the ICL was established just in 2020 (2 years) and had activities such as plowing and harrowing for soil preparation in the implementation.

Soil C and N losses are enhanced through management practices that result in soil physical disturbance and exposure of soil organic matter to microbial decomposition mainly on the topsoil (Damian et al., 2021b). The age of the system and the time duration of each component (grasses

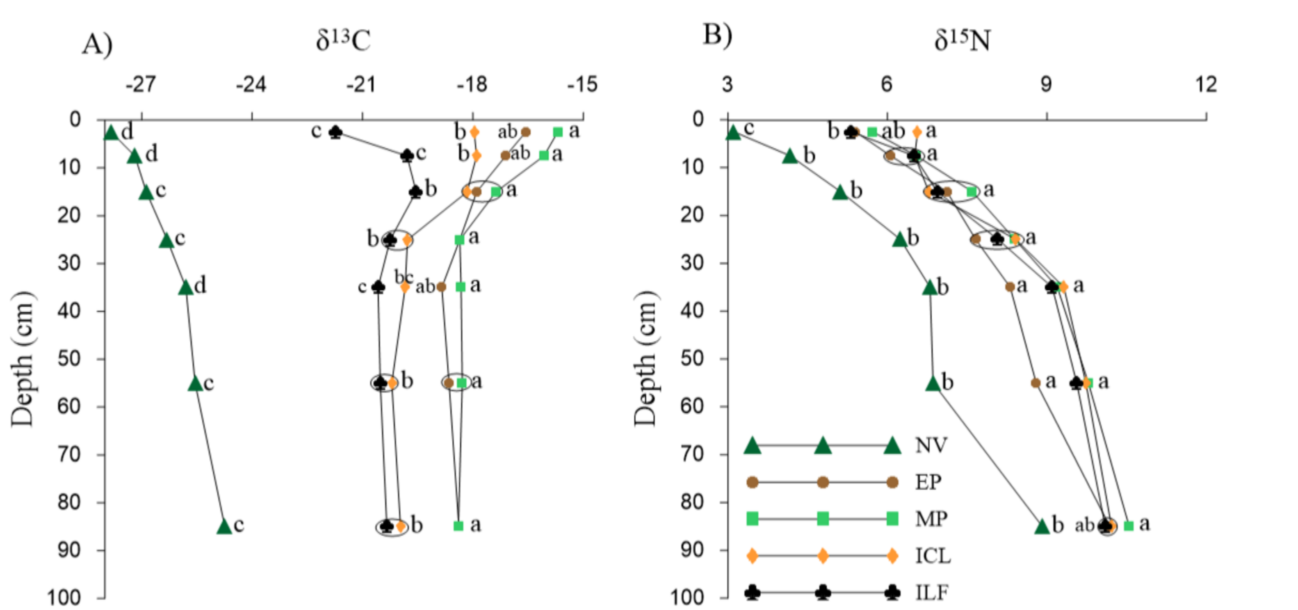

Fig. 3. $\delta^{13}C$ (A) and $\delta^{15}N$ (B) for 0–5; 5–10; 10–20; 20–30; 30–40; 40–70; 70–100 cm from native vegetation and land uses in the Cerrado biome, Mato Grosso do Sul State, Brazil. NV: native vegetation; EP: extensive pasture; MP: managed pasture; ICL: integrated crop-livestock; ILF: integrated livestock-forestry. Different letters in the same soil layer between areas represent a significant difference in the Tukey test or the LSD test ($p < 0.05$), ns = no significant difference.

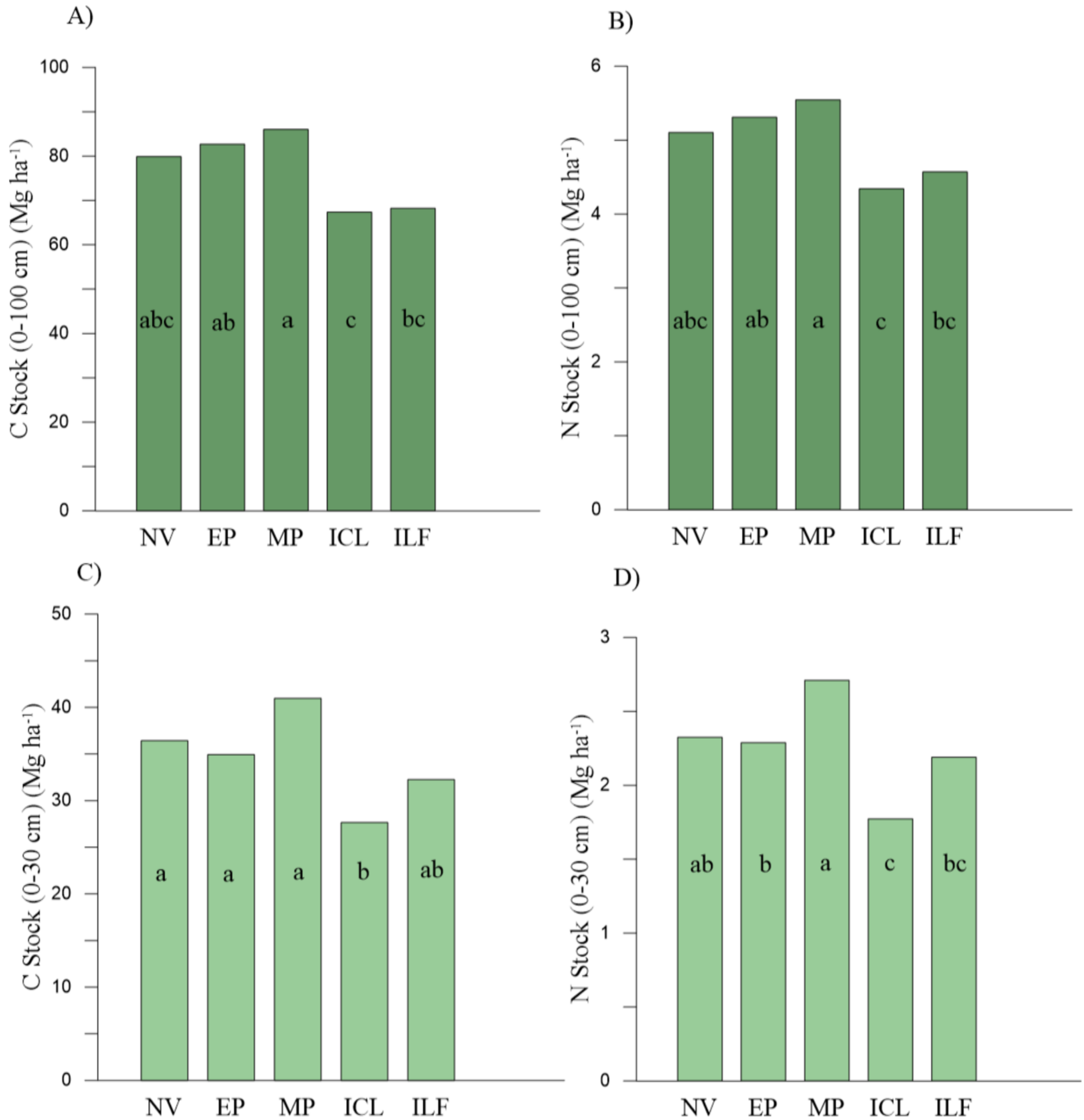

Fig. 4. Soil carbon stock (A), soil N stock (B) for 0–100 cm, and soil carbon stock (C), soil N stock (D) for 0–30 from different land uses in the Cerrado biome, Mato Grosso do Sul State, Brazil. NV: native vegetation; EP: extensive pasture; MP: managed pasture; ICL: integrated crop-livestock; ILF: integrated livestock-forestry. Different letters in the same soil layer between areas represent a significant difference in the Tukey test or in the LSD test ($p < 0.05$), ns = no significant difference.

or crops) in the ICL system affect the soil carbon sequestration (Soares et al., 2020). Thus, the ICL system will take longer to induce C in the soil as it was an extensively degraded pasture before its conversion.

In general, conservation systems induce changes in soil C stocks in the medium and long term (Loss et al., 2016) in the transition and consolidation phases, usually after 5 years of implementation (de Sá et al., 2004). While the ICL system expectations rely on continuous yielding for significant carbon gains in the coming years, the MP is reaching the so-called stabilization state (NV stocks). The Intergovernmental Panel on Climate Change (IPCC) assumes that C stocks stabilize to a new steady state 20 years after all management changes are made (IPCC, 2006).

The Eucalyptus trees in silvopastoral systems contribute mainly to the deeper soil layers (below 60 cm), and the upper soil layer is enriched by the extensive grassroots (Sarto et al., 2020). The consortium between trees and grasses offered litter and residue inputs in the ICLF system, enhancing the C and N soil stock after 3 years of establishment, but it is necessary for continuous monitoring to assess the potential of the C accumulation system over time (Freitas et al., 2020). SOC stocks at 0–40 cm layer increased from 52.6 to 66.5 Mg ha^{-1} after four years of converting degraded pasture into an ICLF system in the Brazilian Cerrado in the study of Coser et al. (2018). Our study showed that the implementation of the silvopastoral system (ILF) did not impact the C stocks when compared to the reference area, the same as found in the literature above.

However, Damian et al. (2021) showed that the smaller the row spacing of the trees, the smaller the stock of C and N in the soil. According to the authors, that occurs due to the shading of the tree culminates in the reduction of the above and belowground biomass production capacity by the pasture component. Thus, it is recommended to implement management strategies for the tree component by thinning and pruning over the years after planting to avoid severe shading conditions, hence increasing the persistence and sustainability of integrated systems in the long term (Lima et al., 2019).

3.4. Elementary carbon and nitrogen and isotopic ratio in the POM and MAOM fractions

The C content in the POM (C-POM) and MAOM (C-MAOM) was higher for NV (Cerrado) and MP in the topsoil (0–10 cm) and decreased with depth (Fig. 5A and 5B). The C-POM and C-MAOM contents in the uppermost layer for the NV had no significant difference with MP. The POM and MAOM fractions have different formation processes, persistence, and function; hence varied organic matter should be assessed separately (Lavallee et al., 2020). Good management pastures have the potential to keep the recalcitrant carbon in the MAOM fraction due to better aggregate structure and low soil disturbance and also increase the POM from the inputs of the extensive root biomass (Gmach et al., 2018). The existence of stable organo-mineral complexes and the protection provided by hydrophobic groups are essential mechanisms for aggregate stabilization and erosion resistance in areas with forests (Hanke & Dick, 2017).

The mineralogical composition of the Cerrado soil is formed with Fe and Al oxides and hydroxides, which enhance the formation of stable organo-mineral complexes (Soares et al., 2020). The MAOM formation is mediated through microbial transformation and deposition of low molecular weight litter or exudate compounds with a lower C/N ratio when compared to the POM (Cotrufo & Lavallee, 2022).

A study in southeastern Brazil found that the conversion of NV to ICLF and ICL systems did not change the C-MAOM in the superficial soil layer, and the ICLF system presented higher C-MAOM content than in ICL in the deeper layer (10–40 cm) (Bieluczyk et al., 2020). In our study, the ILF was similar to NV for the C-MAOM content in the whole soil profile. That shows the importance of the tree root systems and the

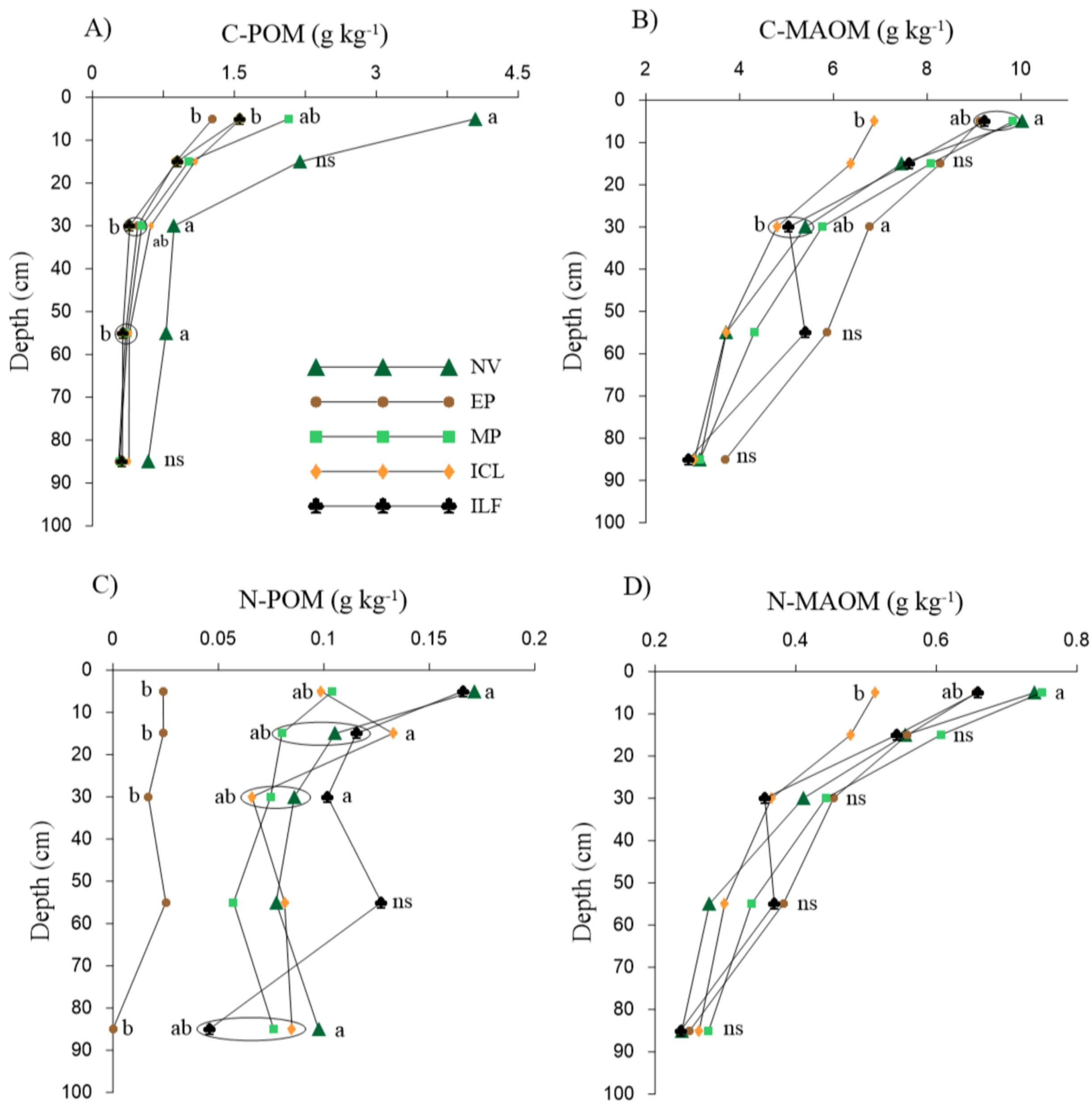

Fig. 5. Soil carbon content (g kg^{-1}) in the POM (A), in the MAOM (B), soil Nitrogen content (g kg^{-1}) in the POM (C) and in the MAOM (D) in 0–5; 5–10; 10–20; 20–30; 30–40; 40–70; 70–100 cm from native vegetation and land uses in the Cerrado biome, Mato Grosso do Sul State, Brazil. NV: native vegetation; EP: extensive pasture; MP: managed pasture; ICL: integrated crop-livestock; ILF: integrated livestock-forestry. Different letters in the same soil layer between areas represent a significant difference in the Tukey test or the LSD test ($p < 0.05$), ns = no significant difference.

mineral association in the process for C stabilization in conservationist management systems in oxisols (Gazolla et al., 2015). However, the pasture degradation process and low residue input in the soil favor the decomposition of the MAOM fraction (Soares et al., 2020), such as occurred in the ICL in the first depth (0–10 cm), which still had characteristics from the previous land use (degraded pasture). Since grasslands are mostly covered by MAOM fraction, grasslands with C saturation deficits should be the target for C accrual and recovery (Cotrufo et al., 2019). The tillage practices, such as plowing and harrowing, applied before implementing ICL exposed organic matter to microorganism attack, contributing to decreased C-MAOM levels in the topsoil of this land use (Piano et al., 2020).

The labile carbon represented by the POM is an indicator of soil functions such as nutrient cycling, soil aggregation, carbon sequestration, and provision for biodiversity (Bongiorno et al., 2019). The land use EP demonstrated that the poor or lack of management practices significantly reduced N-POM levels (Fig. 5C). The POM is a sensitive indicator for land use management change, such as implementing the ICLF system and no-tillage, and can show differences even in short-term periods (months) (Coser et al., 2018; Ferreira et al., 2020). The POM is composed of lightweight fragments derived from plant litter/residues from the organic layer and rhizosphere, which are fragmented and partially processed by microorganisms and are the fraction with a lower mean residence time (Lavallee et al., 2020).

The isotopic signature (^{13}C) for the ILF in the POM fraction was −24.56 ‰, which was lower than in the bulk soil (−21.73 ‰) in the 0–10 cm (Fig. 6B). The value for δ^{15}N also reduced in the POM once compared with the bulk soil values for all land uses, with more intensity in the ILF and ICL (Fig. 6D). On the other hand, the isotopic signal (^{13}C and ^{15}N) in the MAOM fraction was very similar to the values in the bulk soil (ranging from −15.94 for MP and −27.10 ‰ for NV), thus did not present a prominent change in that fraction (Fig. 6A and 6C). The δ^{13}C

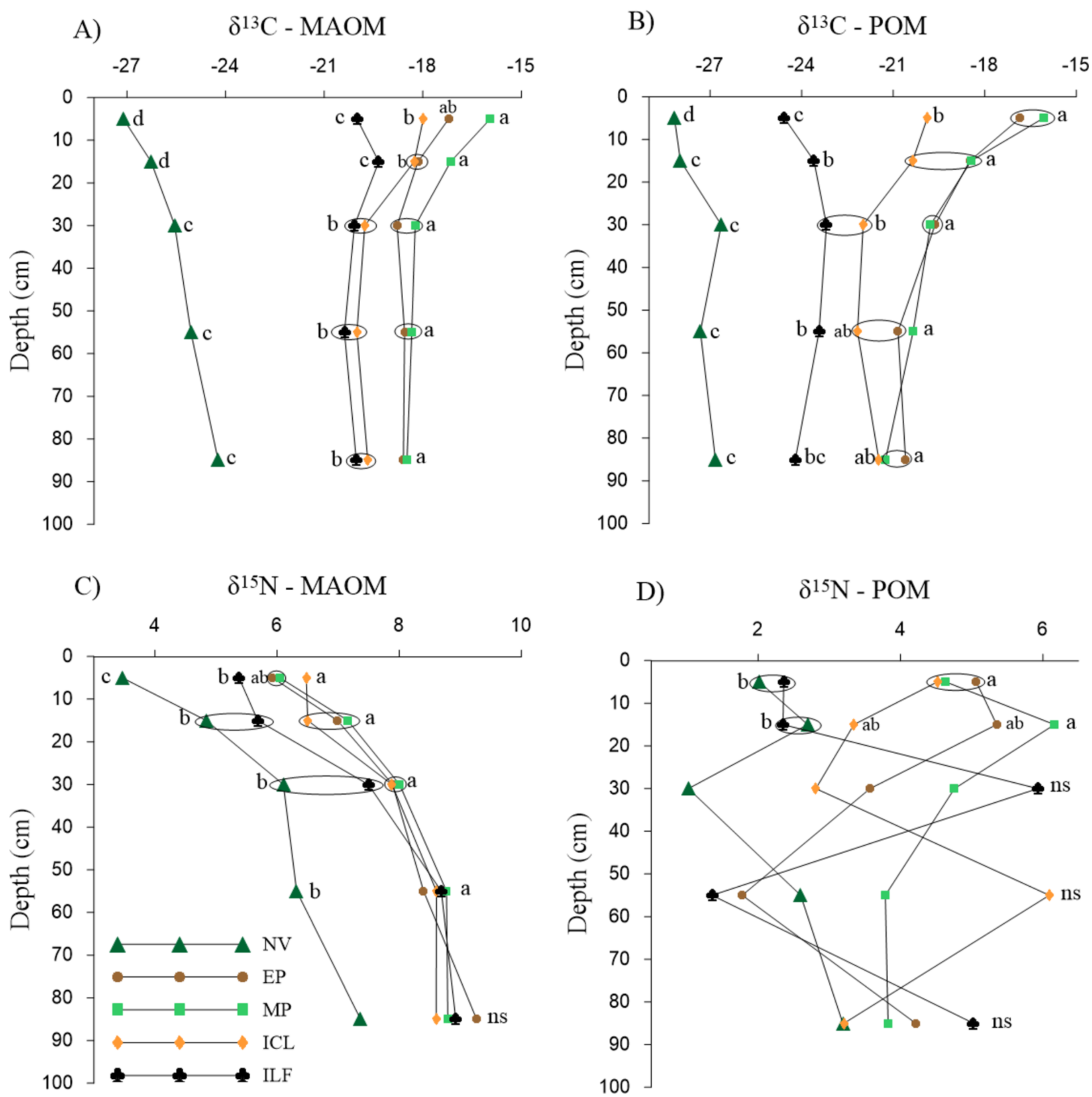

Fig. 6. δ^{13}C in the MAOM (A), in the POM (B), δ^{15}N in the MAOM (C) and in the POM (D) in 0–5; 5–10; 10–20; 20–30; 30–40; 40–70; 70–100 cm from native vegetation and land uses in the Cerrado biome, Mato Grosso do Sul State, Brazil. NV: native vegetation; EP: extensive pasture; MP: managed pasture; ICL: integrated crop-livestock; ILF: integrated livestock-forestry. Different letters in the same soil layer between areas represent a significant difference in the Tukey test or in LSD test ($p < 0.05$), ns = no significant difference.

signal in the POM fraction was lower than in MAOM, demonstrating that the POM fraction has more lability and less degree of humification (Alves et al., 2006). Moreover, the lower enrichment of $\delta^{15}N$ in POM than in MAOM at the upper soil layer also indicates the lability of that fraction constituted of fresh plant litter (Desrochers et al., 2022).

3.5. C and N stock for the POM and MAOM fractions

The C-POM stock for 0–40 cm and the 1-meter depth had similar significances in the statistic test for the land uses. The conversion of NV to MP and ICL was observed to not change the C stock in the POM fraction at 40 cm (Fig. 7A) and 100 cm depth (Fig. 7B). However, the conversion of NV to EP reduced the C-POM found in the 0–40 cm layer, with EP reaching the lowest value between land uses. The C-MAOM stock was not impacted by the conversion from NV to all the assessed land uses.

The conversion of NV to EP reduced by 83 % the N-POM stock for 0–40 cm and for the 1-meter depth but did not have a difference for the other land uses. The N stock for the MAOM fraction did not present a difference between land uses for 0–40 cm and 0–100 cm depth (Fig. 7C and 7D). The genus *Brachiaria* is the tropical grass most used in integrated systems in Brazil and is the main cause of the promotion of the increase in the POM stocks because of its abundance of biomass in the above and mainly in belowground (root system) when well managed (Lima et al., 2019; Moraes et al., 2019; Piano et al., 2020).

But Locatelli et al. (2022) showed that the conversion of NV to an extensive pasture in the Cerrado biome reduced in 55 % the POM stock fraction in the superficial soil layer (0–30 cm) due to the low C input and

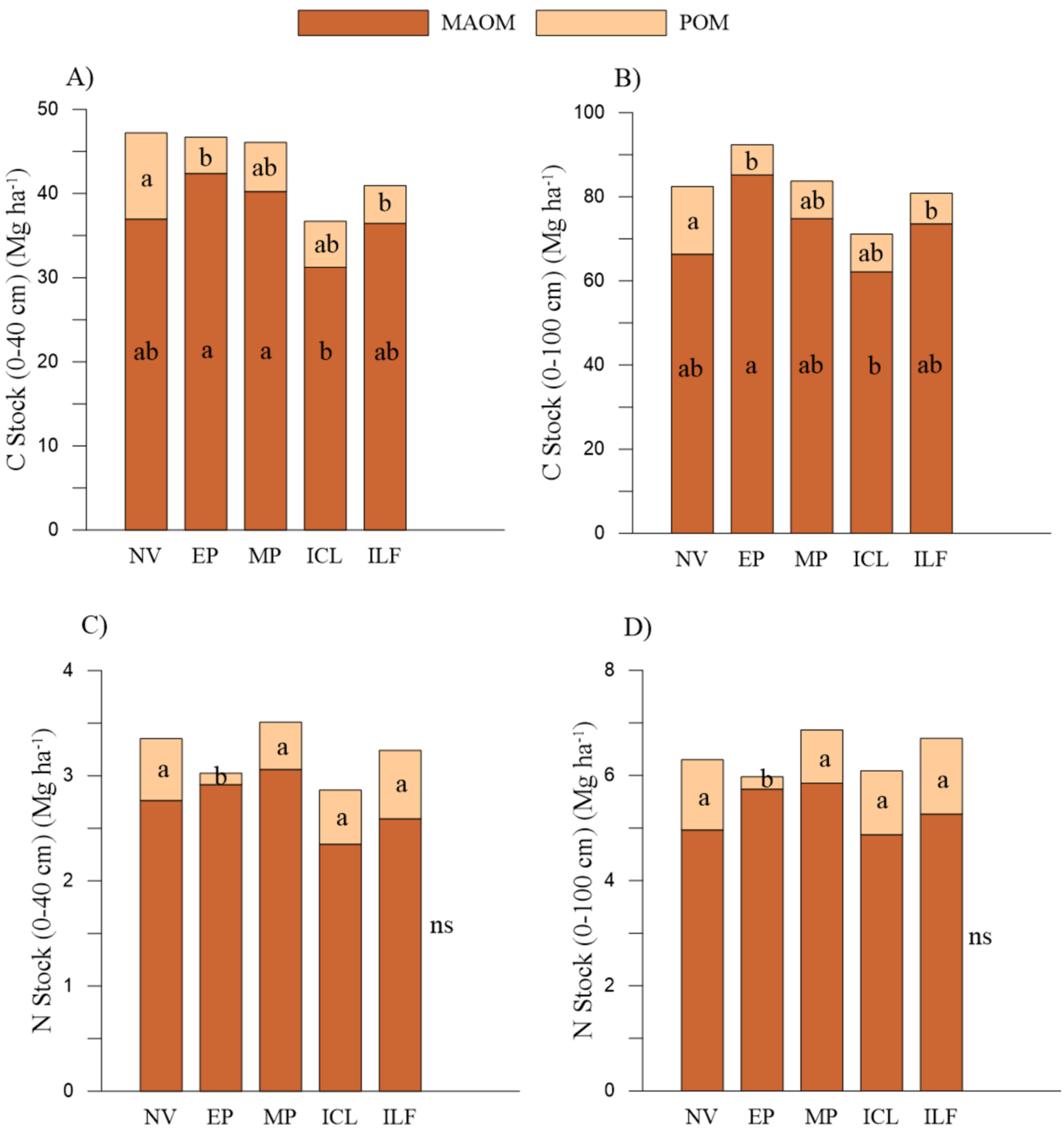

Fig. 7. Carbon Stock for MAOM and POM for 0–40 cm (A), and 0–100 cm (B), Nitrogen Stock for MAOM and POM for 0–40 cm (C) and 0–100 cm (D) for the five land uses in the Cerrado biome, Mato Grosso do Sul State, Brazil. NV: native vegetation; EP: extensive pasture; MP: managed pasture; ICL: integrated crop-livestock; ILF: integrated livestock-forestry. Different letters in the same soil layer between areas represent a significant difference in the Tukey test or the LSD test ($p < 0.05$), ns = no significant difference.

because this fraction is more susceptible to microbial decomposition (Locatelli et al., 2022). That was also observed in the current study since the EP decreased 69 % for C-POM and 86 % for N-POM stock in the 0–10 cm layer. In contrast, the increase of N-POM in the ICL system is due to the nitrogen inputs with mineral fertilization and the soybean residue inputs (Alves et al., 2020).

4. Conclusions

Our study showed the behavior and storage of organic matter in different managed systems in relation to the natural system (NV) in the Cerrado biome, considering SOM dynamics in the soil profile. In general, it changed the isotopic signature of ^{13}C and ^{15}N in the bulk soil and the POM and MAOM fractions but did not significantly impact the 1-meter C stock compared to the reference area. This study highlights the potential of pastures with *Brachiaria* species to enhance, or at least maintain, soil C stocks. Our findings suggest that the POM fraction was more sensible to indicate changes in land use, even with recent interventions, such as in the case of ICL, indicating this system has the potential to recover soil organic matter since it is just in the second year of implementation. On the other hand, poorly managed pasture (EP) causes substantial losses in the C and N stocks from labile organic matter forms (POM).

This study showed the necessity of preserving and maintaining the existing well-managed pastures in Cerrado, which can have higher C stock values. However, it also brought to light the potential to recover the degraded pastures or low-managed pastures (far from their C saturation), which should be the target for the Brazilian policies to reduce greenhouse gas emissions. Integrated systems are an alternative to sustainable land use, which shows the capacity to enhance the diversification of production and resilience of the agroecosystem. Thus, we recommend further works to monitor the systems from this study to verify the effect of soil management on their organic matter dynamic and soil carbon sequestration potential in the long term. Also, assessing other types of soils, farms, and climate change scenarios is necessary to advance in this field of research.

CRediT authorship contribution statement

Fernanda Figueiredo Granja Dorilêo Leite: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Ademir Fontana:** Conceptualization, Data curation, Methodology, Supervision, Visualization, Writing – review & editing. **Gabriel Nuto Nóbrega:** Conceptualization, Data curation, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. **Felipe Martini Santos:** Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing. **Bruno José Rodrigues Alves:** Data curation, Investigation, Project administration, Resources, Supervision, Validation, Writing – review & editing, Writing – original draft. **Júlia Graziela da Silveira:** Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Renato Campello Cordeiro:** Conceptualization, Data curation, Investigation, Supervision. **Carlos Eduardo Cerri:** . **Rosemery Alesandra Firmino dos Santos:** Conceptualization, Data curation, Formal analysis, Methodology, Resources, Writing – original draft, Writing – review & editing. **Renato de Aragão Ribeiro Rodrigues:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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