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Organic carbon stocks in a chronosequence of an integrated crop-livestock-forestry system

Estoques de carbono orgânico em uma cronossequência de um sistema integrado lavoura-pecuária-floresta

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RESUMO: This study quantified the soil carbon content and stock in a chronosequence of an Integrated Crop-Livestock-Forest (ICLF) system in Maranhão, Brazil, comparing it with degraded pasture and reference areas. The experiment included two reference environments: secondary regenerating vegetation for approximately 20 years and native "babaçu" palm forest. Additionally, five successional stages were considered: Degraded pasture, ICLF 2016, 2017, 2018, and 2019, which were compared with the reference environments (Forest and "Capoeira"). Undisturbed soil samples for analysis were collected to a depth of 100 cm, spanning seven depths: 0-10, 10-20, 20-30, 30-40, 40-60, 60-80, and 80-100 cm. Carbon concentrations were higher in the surface layer in the native forest area, while at other depths, the ICLF pasture of 2018 exhibited superiority over the pasture in 2016. There was an increase in accumulated carbon stock (0-100 cm) compared to the Native Forest with the use of the ICLF pasture of 2018 after the maize-grass intercropping, which amounted to 16%. The ICLF pasture of 2018 increased carbon stock (0-100 cm) by 31% compared to the degraded pasture (2016). The integrated crop-livestock-forestry system is an important strategy for promoting carbon sequestration in the soil profile in an area with degraded pasture.

Palavras-chave: Degraded pasture; Organic matter; *Urochloa brizantha*.

ABSTRACT: Este estudo quantificou o teor e o estoque de carbono do solo em uma cronossequência de um sistema integrado lavoura-pecuária-floresta (ILPF) no Maranhão, Brasil, comparando-o com pastagem degradada e áreas de referência. O experimento incluiu dois ambientes de referência: vegetação secundária em regeneração por aproximadamente 20 anos e mata nativa de palmeiras "babaçu". Adicionalmente, foram considerados cinco estágios sucessionais: pastagem degradada, ILPF 2016, 2017, 2018 e 2019, que foram comparados com os ambientes de referência (mata e "Capoeira"). Amostras de solo indeformadas para análise foram coletadas até a profundidade de 100 cm, abrangendo sete profundidades: 0-10, 10-20, 20-30, 30-40, 40-60, 60-80 e 80-100 cm. As concentrações de carbono foram maiores na camada superficial da área de floresta nativa, enquanto em outras profundidades, a pastagem ICLF de 2018 apresentou superioridade em relação à pastagem de 2016. Houve um aumento no estoque de carbono acumulado (0-100 cm) em comparação com a floresta nativa com o uso da pastagem ICLF de 2018 após o consórcio milho-gramíneas, que correspondeu a 16%. A pastagem ICLF de 2018 aumentou o estoque de carbono (0-100 cm) em 31% em comparação com a pastagem degradada (2016). O sistema de integração lavoura-pecuária-floresta é uma estratégia importante para promover o sequestro de carbono no perfil do solo em uma área com pastagem degradada.

Keywords: Pastagem degradada; Matéria orgânica; *Urochloa brizantha*.

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1 INTRODUÇÃO

In Brazil, there is currently a cultivation area of approximately 173 million hectares of pastures. However, it is concerning that around 57% of these pastures exhibit some degree of degradation, as pointed out by Feltran-barbieri and Féres (2021). Pasture degradation stands as one of the primary challenges in livestock farming (Bolfe *et al*., 2024), and this situation is exacerbated due to the lack of proper soil maintenance and management. These challenges can be mitigated through the correct adoption of pasture planting and management practices (Oliveira *et al*., 2022).

A worrying scenario is evident in the municipality of Pindaré-Mirim and in other regions of the Amazon, where the conversion of native forests into pastures for extensive livestock farming or agriculture prevails. According to MapBiomas project data spanning from 1985 to 2018, for every 10 hectares of deforested land, 3 are left abandoned, 6 are converted into pastures, and 1 is utilized for agriculture, urbanization, mining, and other uses (Azevedo, 2019). It is estimated that up to 80% of deforested areas in the Amazon are utilized as pastures. One of the most notable environmental impacts of livestock farming is the emission of polluting gases that contribute to global warming, (Meo-Filho *et al*., 2022).

The increase in greenhouse gas concentration in the atmosphere, along with its impact on global climate changes, has prompted international interest in understanding the dynamics of carbon entry and retention in the atmosphere (Medeiros *et al*., 2025). This increase is a result of human activities, such as deforestation, burning, and changes in land use (Kamarposhti *et al*., 2024).

A critically important factor in assessing recovery processes is soil organic matter (SOM), as it enhances physical, chemical, and biological soil attributes, imparting sustainability to the recovering system (Rego *et al*., 2023a; Santos *et al*., 2024). Changes in soil carbon stocks are strongly influenced by the amount of organic matter present in the soil (Gerke, 2022). Generally, higher levels of organic carbon are found in the upper soil layer (Zhang *et al*., 2022), improving soil structure, favoring greater water infiltration rates, root penetration (Souza *et al*., 2025), and reducing soil density in the upper layer (Heshmati; Gueitury; Parvizi, 2025).

Integrated Crop-Livestock-Forest (ICLF) systems have the capacity to increase soil organic matter levels in the medium and long term, contributing to the recovery of degraded soils (Molina *et al*., 2026). Well-managed, productive pastures effectively accumulate carbon (Oliveira *et al*., 2022), resulting in increased soil carbon stocks, which help mitigate the adverse effects of global warming (Vogado *et al*., 2024).

In this context, this study hypothesized that the adoption of ICLF systems, replacing degraded pastures, improves carbon input and storage in the soil due to residues from previous crops. The objective of this work was to quantify the levels of carbon content and storage in a pasture integrated within an ICLF system located in the municipality of Pindaré-Mirim, in the state of Maranhão, Brazil.

2 MATERIALS AND METHODS

2.1 STUDY LOCATION

The study was conducted at the Technological Reference Unit in Integrated Crop-Livestock-Forest (ICLF) of Empresa Brasileira de Pesquisa Agropecuária (Embrapa) Cocais, located at Muniz Farm, in the municipality of Pindaré-Mirim, in the state of Maranhão, whose geographical coordinates are: 03° 46' S (latitude) and 45° 29' W (longitude), with an average altitude of 38 m.

The regional climate, according to Koppen's classification, is of the Aw type (hot and humid), with an average annual temperature of 26 °C, a minimum of 22.3 °C, and a maximum of 33.5 °C. There are two well-defined seasons, which are the rainy period (January to July) and the dry period (August to December), with annual rainfall between 2,000 to 2,400 mm and annual relative humidity between 79% and 82% (Batistella *et al*. 2013).

The soil in the study area is classified as typical Dystrophic Clayey Plinthosol (Santos *et al*., 2025), with sandy loam textural classification, originally covered by Open Lowland Ombrophilous Forest vegetation, predominantly with babassu palm.

2.2 CHARACTERIZATION OF THE MANAGEMENT EVALUATED

For evaluation purposes, the experiment included two reference environments and five succession periods - Reference Environment: secondary growth forest (Capoeira) in regeneration for approximately 20 years and native babaçu forest. Soil sampling from the reference environments took place in 2016. Succession periods: degraded pasture (soil sampling in 2016 before the experiment), ICLF 2016, 2017, 2018, and 2019 (annual soil sampling, conducted in the month of June of the respective years), which were compared with the reference environments (Table 1).

The implementation area of the ICLF corresponded to three and a half hectares, subdivided into 14 paddocks, with intercropping and succession of corn, eucalyptus, pasture, and beef cattle. In 2016, the soil was corrected 90 days before corn planting using the base saturation method, with a dose of 1.8 mg ha^{-1} of dolomitic limestone (PRNT 80%).

The limestone was incorporated across the entire area with plowing, harrowing, and leveling, up to a depth of 20 cm. The Santa Fé system (Cobucci *et al*., 2007) was used for establishing *Urochloa brizantha* cv. Marandu grass intercropped with hybrid corn KWS 9304. Simultaneous seeding was carried out with 20 and 10 kg ha^{-1} of corn and grass seeds, respectively, using a spacing of 0.6m x 0.3m for corn and pasture in the inter-row, using the third box of the planter. At 70 days after corn planting, eucalyptus seedlings were transplanted in rows, with a spacing of 3m x 2m and 28m between double rows. Two eucalyptus clones (MA-2000 and MA-2001) were randomly distributed in the rows and originated from controlled pollination between *Eucalyptus urophylla* and *Eucalyptus tereticornis* species.

Table 1. Description and history of the different land uses evaluated in Pindaré-Mirim, MA

Year	Land use	Historical
2016	Native forest	No use of soil for agronomic purposes. Babassu being the main species.
2016	Capoeira	Regenerating environment, previously used for pasture. Unused for approximately 20 years.
2016	Degraded pastureland	Area cultivated with *Urochloa brizantha* cv. Marandu and followed by 15 years of overgrazing in an extensive system. In this area, the soil was collected before the implementation of the ICLF system in 2016.
2016	ICLF I	Recovery of degraded pasture with corn cultivation in intercropping with *Urochloa brizantha* cv. Marandu and eucalyptus for implementation of the ICLF system. Soil sampling was carried out in this area in the first year of the ICLF system, immediately after the corn harvest.
2017	ICLF II	Area preceded by ICLF I, in the second year of corn cultivation intercropped with *Urochloa brizantha* cv. Marandu and eucalyptus, under the ICLF system carried out in direct planting, on grass straw produced in ICLF I. Soil sampling was carried out in this area immediately after the second year of the corn harvest.
2018	ICLF III	Area preceded by ICLF II, one year after the implementation of *Urochloa brizantha* cv. Marandu and eucalyptus. The pasture remained fallow until the month of November. After that month, grazing with Nelore cattle for beet production began, with an entry weight of 250 kg and a stocking rate of 3 AU/ha/year (grazing in the year of 2018 as the soil was collected before the animals entered the system). Soil collection was carried out in June.
2019	ICLF IV	Area preceded by ICLF III, two years after the implementation of *Urochloa brizantha* cv. Marandu and eucalyptus. First year of grass in continuous cattle grazing, same stocking rate as the previous year, the animals remained in the system until April 2019, at the exit there was a 28 cm residue in the straw. Soil collection was carried out in June.

Note: ICLF: Integrated Crop-Livestock-Forest: AU/ha/year: animal units (AU) per hectare per year; 1 AU = 450 kg of live weight.

In 2017, corn and grass were cultivated using no-tillage in furrows over the 2016 residue (Miranda *et al.*, 2005), with the same amount of seeds and spacing as the previous year. Fertilization in 2016 and 2017 for corn crops occurred as follows: planting fertilization = 400 kg ha^{-1} of the formula (04 - 30 - 10 + Zn); 1st topdressing = 200 kg ha^{-1} of the formula (36 - 00 - 30), 10 days after corn emergence (DAE, 4 leaves); and 2nd topdressing = 200 kg ha^{-1} of the formula (36 - 00 - 30), 20 days after the first topdressing (DAE, 8 leaves).

In 2018, the pasture was divided into twelve paddocks of 2250 m^2 and two reserve paddocks of 5000 m^2, which remained fallow until November of the same year, when the first batch of ten yearling steers, with an average weight of 250 kg and a stocking rate of 3 AU ha^{-1} $year^{-1}$, entered and stayed until April 2019. In May 2019, the second batch of 41 yearling steers, with an average weight of 165 kg and a stocking rate of 2.7 AU ha^{-1} $year^{-1}$, entered. In 2018, the entry of animals took place after soil collection, with no grazing effect for that year. In these two years, no fertilization of the grass in the collected paddocks occurred.

2.3 SAMPLE COLLECTION AND ANALYSIS

For soil collection, three one-square-meter trenches were randomly opened along the collection environment. In each year, new trenches were opened between the rows. Undisturbed samples for analysis were collected up to 100 cm deep, covering seven depths: 0-10, 10-20, 20-30, 30-40, 40-60, 60-80, and 80-100 cm. In each layer, three sides (walls) of the trench were sampled. A stainless-steel volumetric ring collector with a volume of 100 cm^3 was used for soil collection. Soil density was determined using the volumetric ring method, according to the methodology proposed by Teixeira *et al*. (2017). Around the trenches, in all cardinal directions, twelve equidistant points were marked for collecting disturbed samples for carbon analysis. The twelve disturbed soil samples were combined into one composite sample for each collected depth.

The carbon content (C) was determined in air-dried fine soil samples, ground in a porcelain mortar and passed through a 60-mesh sieve. Subsequently, 0.5 g of fine soil was weighed into digestion tubes, and 5 ml of 0.167 M $K_2Cr_2O_7$ and 7.5 ml of concentrated PA sulfuric acid were added. Under these same conditions, two blanks were prepared with only the reagents, including one heated and one not heated tube. The set of tubes containing the soil samples was placed in a digestion block at 170 °C for 30 minutes. After this procedure, the samples in each tube were transferred to 125 ml Erlenmeyer flasks, using 50 ml of distilled water. After cooling, 4 drops of ferroin indicator were added, and titration was carried out with 0.2 M ammoniacal ferrous sulfate until a color change from green to red.

Carbon stocks (mg ha^{-1}) were calculated from the total carbon content using Equation 1 (Bernoux *et al*., 1998):

$$\text{Stock} = \text{content x density x thicknes} \quad (1)$$

Where content refers to the content of the carbon element in the soil in %; density is the soil density in g cm^{-3}, and thickness is the thickness of the layer for which the stock is being calculated, measured in cm.

It is known that soils subjected to different management systems can have different densities, which implies comparing different soil masses when considering the same thickness of depth, as used in the sampling in this study. Therefore, to properly compare the C stocks between areas, it was necessary to compare equal soil masses, which generated the need for an adjustment in the values of the depths used in the calculations (Ellert; Bettany, 1995).

This adjustment, referred to as correction for equivalent soil mass, was performed using the native babaçu vegetation area as a reference. It involves finding a new depth value for each area, which was then used in the new calculation of C stocks, ensuring that the new depth represents the same soil mass in all areas. The adjustment is only made in the deepest layer to avoid error propagation, and the corrected depth was calculated using Equation 2 (Ellert; Bettany, 1995):

$$Corrected\ depth\ (cm) = \frac{DMP_{ref}}{DMP_{cor}} \times\ Depth_{cor} \quad (2)$$

Where DMP_{ref} represents the weighted average bulk density of the reference area in g cm^{-3}; DMP_{cor} is the weighted average bulk density of the area being corrected in g cm^{-3}; $Depth_{cor}$ is the original depth of the layer being corrected in cm.

2.4 DATA ANALYSIS

The results were subjected to analysis of variance with the application of the F test, and the mean values were compared using the Tukey test (5% probability level), with the assistance of the Sisvar program (Ferreira, 2014).

3 RESULTS AND DISCUSSION

The bulk density of the soil did not differ between the chronosequences and the reference areas in the 0-10, 10-20 and 40-60 cm layers (Figure 1). In the 20-30 and 30-40 cm layers, the native forest area showed lower density compared to the study areas. A similar result was observed in the deeper layers (60-80 and 80-100 cm).

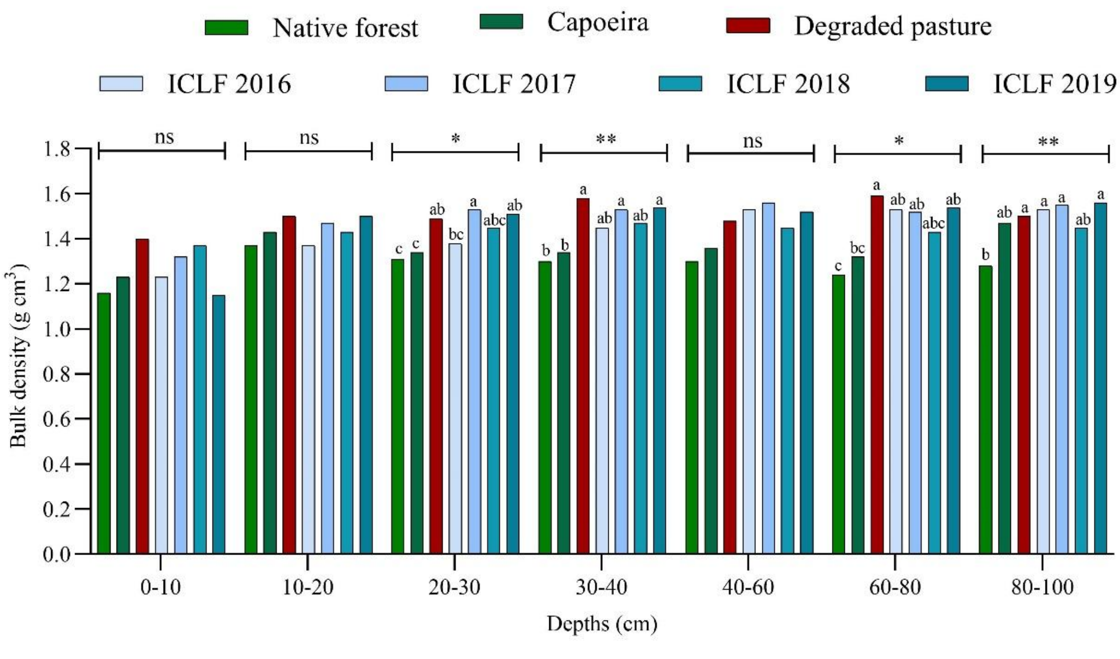

Figure 1. Average soil bulk density values in a degraded pasture area, native forest, secondary growth (Capoeira), and pasture in ICLF (2016 to 2019) at different soil depths (0-10, 10-20, 20-30, 30-40, 40-60, 60-80, and 80-100 cm). Means followed by the same letters in the column do not differ from each other according to Tukey's test at a 5% probability level. ICLF: Integrated Crop-Livestock-Forest; ns: not significant by Tukey's test; *: significant at 5% probability by Tukey's test; **: significant at 1% probability by Tukey's test.

It is important to note that in 2019, there was animal grazing in the chronosequence study area (ICLF). The presence of animals in the pasture area justifies the higher soil density values, as noted by Bonetti *et al.* (2015). However, the use of machinery for planting, crop management, and harvesting of intercropped corn with forage may have also contributed to the increase in soil density compared to the native forest and secondary growth (capoeira) areas.

According to Reinert and Reichert (2006), soil density values that may pose risks to root development are around 1.65 g cm^{-3} for sandy soils and 1.45 g cm^{-3} for clayey soils. The soil in the pasture under study has a sandy loam texture. Analyzing all depths of ICLF 2019, we found values ranging from 1.15 g cm^{-3} to 1.56 g cm^{-3}, which fall within the restrictive limits for root development in the pasture.

Soils under no-till management tend to reduce density over time in shallower soil depths due to increased organic matter content. Rossetti and Centurion (2015), when quantifying organic carbon stocks and physical attributes of an Oxisol in a chronosequence under different managements, observed an increase in soil density at depth attributed to low levels of plant residues.

Organic carbon content in the soil showed higher concentrations in the native forest in the superficial layer (0-10 cm), with 1.27 g kg^{-1} of carbon, surpassing the ICLF pastures from 2017 and 2019. However, in the subsoil (20-100 cm), the ICLF pasture management in 2018 stood out. The 2018 ICLF was superior to the secondary vegetation and ICLF pastures of 2016, 2017, and 2018 at a depth of 20-30 cm; superior to the ICLF pasture from 2016 and 2017 at the 30-40 cm depth; superior to other managements at the 40-60 cm depth; superior to degraded pasture, capoeira; ICLF pastures from 2016 and 2017 at the 60-80 cm depth; and superior to degraded pasture and ICLF pastures from 2016 and 2017 at the 80-100 cm depth (Figure 2).

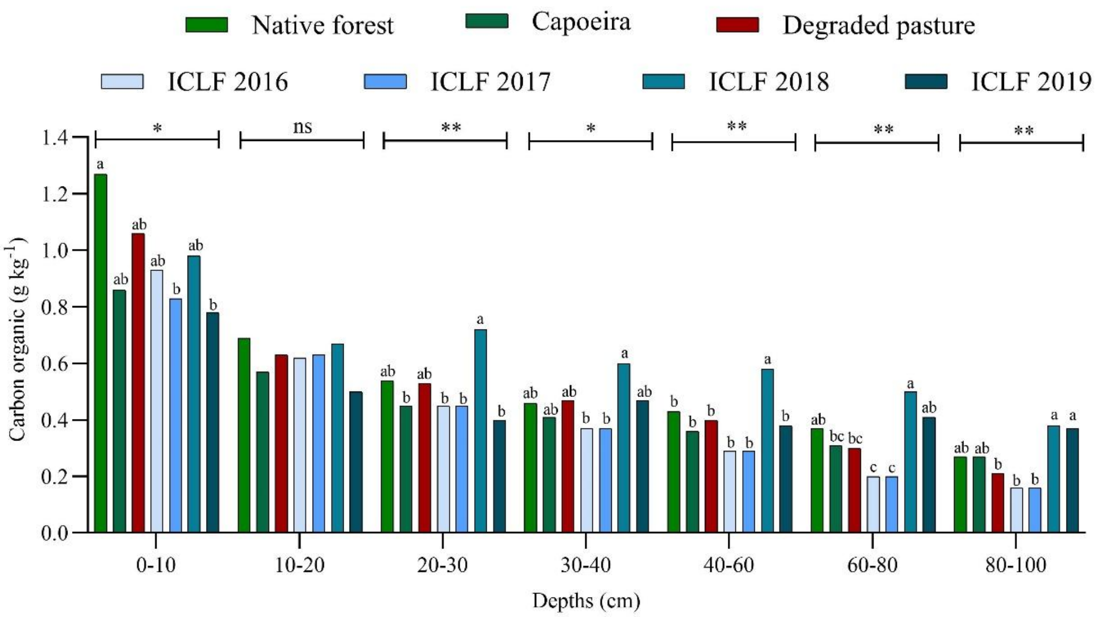

Figure 2. Average carbon content values in degraded pasture area, native forest, secondary growth (Capoeira), and pasture in ICLF (2016 to 2019) at different soil depths (0-10, 10-20, 20-30, 30-40, 40-60, 60-80, and 80-100 cm). Means followed by the same letters in the column do not differ from each other according to Tukey's test at a 5% probability level. ICLF: Integrated Crop-Livestock-Forest; ns: not significant by Tukey's test; *: significant at 5% probability by Tukey's test; **: significant at 1% probability by Tukey's test.

The superiority of the ICLF pasture in terms of soil carbon content in the year 2018 can be justified by the accumulation of biomass from the intercropped corn with cultivated grass in the previous year (2017), coupled with the absence of annual crop cultivation and consequent avoidance of soil disturbance, which contributes to the stabilization of organic carbon in the soil. Thus, there is a synergy between these factors that favor the accumulation of organic carbon in the soil, especially at depth. It is important to highlight that soil correction may also have contributed to stimulating the root growth of *U. brizantha* and consequently increasing the carbon input in deeper layers of the soil profile.

The lower values of soil organic carbon observed in the 2019 ICLF, compared to the 2018 ICLF, can be attributed to the lack of nutrient replenishment through fertilization. This lack of replenishment negatively and directly impacts pasture biomass growth, a source of carbon for the soil. Furthermore, in 2019, animals grazed in the area, which may have caused not only soil compaction but, above all, the removal of plant biomass, consequently limiting the input of organic carbon as the biomass decomposed.

According to Loss *et al*. (2014), ICLF systems implemented in the Amazon region prove that the introduction of forest species in conjunction with annual crops and forage can be a good option for carbon sequestration, improving soil quality, and contributing to long-term global warming mitigation.

Study conducted by Gazolla *et al*. (2015) reported that the organic carbon content of the soil is higher near the surface due to organic matter inputs from vegetative cover, demonstrating the importance and strong influence of management type on the deposition of plant residues from agricultural crops for soil organic carbon accumulation (Sacramento *et al*., 2013). According to Rego *et al*. (2023b), well-managed and productive pastures sequester more carbon from the atmosphere and are more environmentally sustainable.

The decrease in the content of plant residues at depth, lower activity of decomposer organisms at deeper depths, and slower decomposition and mineralization rates result in reduced levels of organic carbon (Gazolla *et al*., 2015). Although a decrease in OC is expected with increasing depth, systems that promote sustainable soil management make it possible to increase carbon input compared to conventional systems (Damian *et al*., 2023). This factor is related to management practices that favor the maintenance of carbon at depth after the entry and decomposition of roots capable of reaching deeper soil layers. The entry of carbon into deeper layers is essential for the soil to function as a reservoir, as this carbon is less susceptible to changes in land management and loss to the atmosphere.

According to Prasad *et al*. (2016), changes in organic carbon occur three to five years after a change in the management system. It is worth noting that in 2016 and 2017, the intercropping of corn with forage was carried out using the no-till system, which favored greater organic matter accumulation in the ICLF pasture area of 2018, capable of increasing soil carbon content over the years.

Regarding carbon stocks, it can be observed that for the superficial layer (0-10 cm), the native forest area (Figure 3). However, in depths from 20 to 100 cm, the highest stocks were observed in the ICLF pasture area of 2018. In the 80-100 cm layer, in addition to ICLF 2018, ICLF 201 showed superiority in terms of soil carbon stock.

Management systems that add organic matter to the soil through plant residues promote an increase in soil carbon stocks (Ahmad *et al*., 2024). It is worth noting that long-term monitoring of soil organic matter is essential to determine changes in carbon stocks, which are often only noticeable after several years or decades (Knotters *et al*., 2022). This crop residue has the capacity to raise soil carbon stock levels, thus minimizing losses due to cultivation practices (Ansari *et al*., 2022).

In the same context, Rossetti and Centurion (2015), when evaluating carbon stocks in a chronosequence, indicated a decline in carbon stock as depth increases. Much of the carbon stored at depth comes from root carbon, which is the primary source of carbon input into deeper soil layers (Schmidt *et al*., 2011).

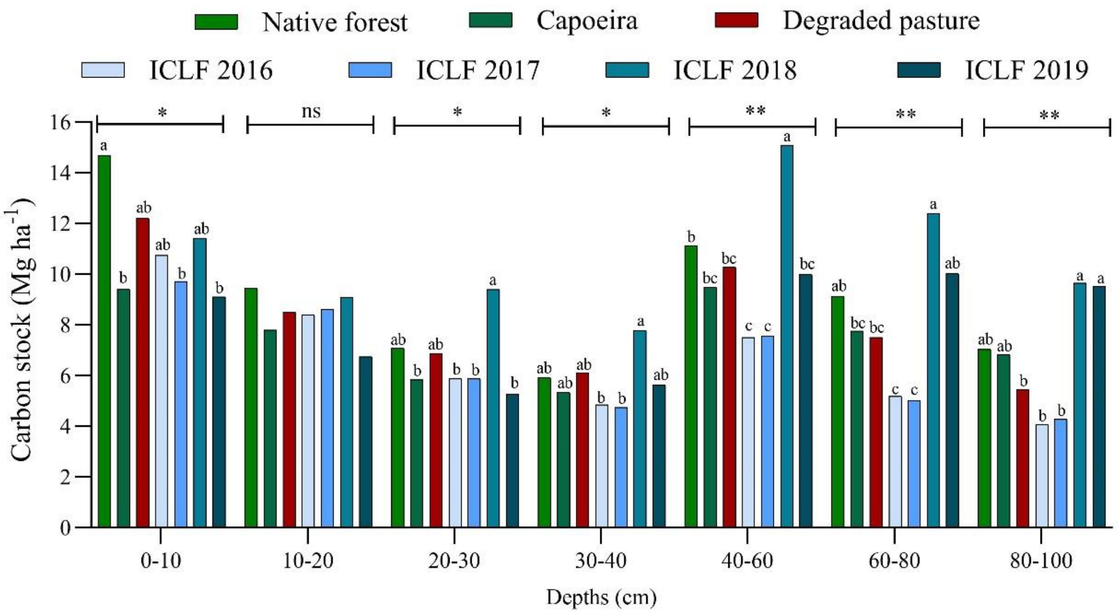

Figure 3. Average soil carbon stock values in degraded pasture area, native forest, secondary growth (Capoeira), and ICLF (2016 to 2019) at different soil depths (0-10, 10-20, 20-30, 30-40, 40-60, 60-80, and 80-100 cm). Means followed by the same letters in the column do not differ from each other according to Tukey's test at a 5% probability level. ICLF: Integrated Crop-Livestock-Forest; ns: not significant by Tukey's test; *: significant at 5% probability by Tukey's test; **: significant at 1% probability by Tukey's test.

Carbon stocks in pastures are attributed to the deposition of biomass from the root systems of grasses, which are mainly found in the upper depth of the soil (Damian *et al*., 2023). However, when the root system is well developed, it can reach greater depths (Stumpf *et al*., 2016). Thus, root exudates, their decomposition, and the renewal of this root system occur at depths greater than 30 cm, explaining the accumulation of carbon stocks at depths from 20 cm to the 100 cm layer. In research conducted by Linhares *et al*. (2016), considering soil depths of 0-10 cm and 10-20 cm, the highest carbon stock values were observed in the native forest. Costa *et al*. (2009) explain that soils under pastures have carbon stocks equal to or higher than those found in native forest environments due to the greater input of organic matter provided by the roots.

Considering the accumulated carbon stock in the 0-100 cm depth range, it is observed that the use of the ICLF pasture in the year 2018 increased the carbon stock with values higher than degraded pasture, secondary growth (capoeira), and the intercropped corn-grass systems (ICLF 2016 and 2017). The pasture in 2019, which was used for grazing after the intercropping of corn with grass, did not differ from the native forest area (Figure 4).

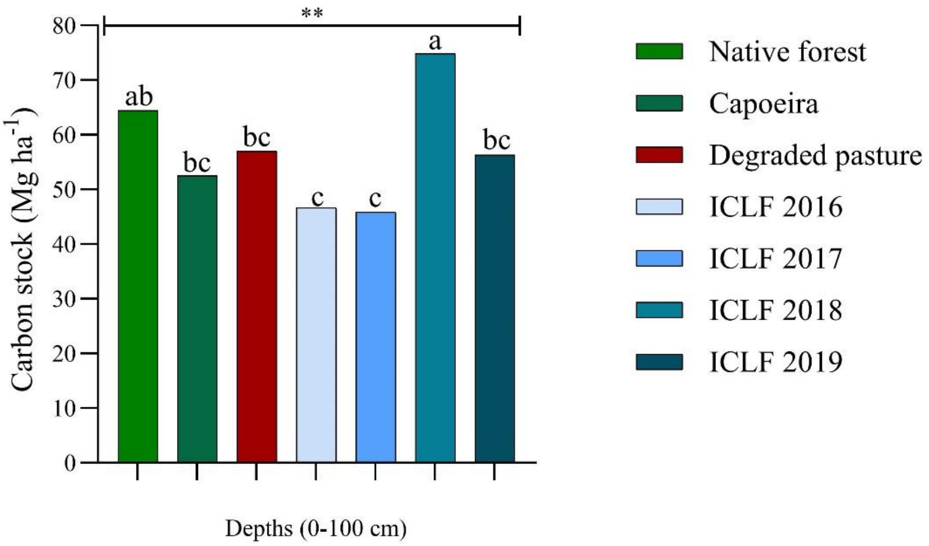

Figure 4. Accumulated soil carbon stock in degraded pasture area, native forest, secondary growth (Capoeira), and pasture in ICLF (2016 to 2019) in the soil layer of 0-100 cm. Means followed by the same letters in the column do not differ from each other according to Tukey's test at a 5% probability level. ICLF: Integrated Crop-Livestock-Forest; ns: not significant by Tukey's test; *: significant at 5% probability by Tukey's test; **: significant at 1% probability by Tukey's test.

As previously justified, the pasture in ICLF 2019 did not yield similar results to the previous year, likely due to the lack of nutrient replenishment. Furthermore, the superiority of the ICLF pasture in 2018 results from the accumulation of biomass from the intercropping of corn and grass in 2017, in addition to the residue from fertilization applied during the corn crop. Moreover, soil correction was carried out in 2016 (lime application), and the effects of this practice may have also contributed to the increased grass biomass production in 2018.

The exclusive use of forage as pasture after the corn-grass intercropping increases carbon stocks at depth, making it an interesting strategy as a carbon sink. The increase in accumulated carbon stock (0-100 cm) compared to the native forest with the use of the ICLF pasture in 2018 after the corn-grass intercropping was 16% (Figure 4).

This suggests that after three years it is possible not only to increase the carbon soil stock in a degraded area with the adoption of ICLF, but also to provide a higher carbon stock than an area where there were no anthropogenic activities. The results obtained with ICLF 2018 compared to previous years demonstrate that during this period there is a tendency towards a new soil carbon equilibrium, since initially soil disturbance practices may have caused a reduction in carbon stock. Despite this, the reduction in ICLF stock in 2019 indicates that carbon added more recently through sustainable management practices may also be more easily lost, especially compared to native forest which contains more recalcitrant carbon.

It is important to highlight the beneficial effect of using ICLF in the recovery of degraded areas, as they have shown positive results in organic carbon stocks. The degraded pasture accumulated 57.02 mg ha^{-1} of carbon stock. However, when the pasture was managed within an ICLF system in 2018, it accumulated 74.90 mg ha^{-1}, representing a 31% increase in carbon stock, with an annual gain of 5.96 mg ha^{-1} (from 2016 to 2018).

The management of the pasture in ICLF 2018 increased carbon sequestration levels in the soil compared to the degraded pasture. Rego *et al*. (2023b) identified an increase in soil carbon sequestration after the process of pasture recovery and improvement in the eastern Amazon. Costa *et al*. (2009) explain that soils under pastures have carbon stocks equal to or higher than those found in native forest environments due to the greater input of organic matter provided by the roots.

Likely, the accumulated carbon stock in the ICLF system was affected by the management practices adopted during implementation, such as plowing, harrowing, and leveling, which exposed organic matter to rapid decomposition due to microbial respiratory activity (ICLF 2016), as observed by Rehman *et al*., 2023. This demonstrates that properly cultivated and managed pasture can maintain carbon stock levels at depths ranging from 0 to 100 cm in the soil. However, according to Levy *et al*., 2024, to estimate the effects of land use on soil carbon stock, experiments capable of providing data over many years are required.

For the purpose of monitoring carbon stocks, the real effects of adopting sustainable management practices may be underestimated when considering only greater soil depths, as observed by Oliveira *et al*. (2022). This study stands out by evaluating soil carbon stocks at a depth of 100 cm, and the results highlight the importance of adopting the ILPF system and better understanding its long-term effects. This is because the results showed that ILPF positively impacted the increase in soil carbon stocks in deeper layers.

4 CONCLUSION

The integrated crop-livestock-forestry system, particularly after three years of establishment (ICLF 2018), has proven to be an effective strategy for recovering carbon stocks in degraded pasture soils, exceeding degraded pasture and even native forest by 31% in the 0-100 cm profile. This increase is associated with the continuous input of biomass, mainly root biomass, and the absence of soil disturbance, which favor carbon sequestration at depth. Nutritional replenishment in subsequent cycles is recommended to maintain productivity and carbon stocks. Long-term studies are needed to monitor the stability of these stocks under continuous grazing.

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