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Chemical, physical, and biological properties of soil with pastures recovered by integration crop-livestock system in Eastern Amazon

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ABSTRACT: Soil quality can be understood as its capacity to provide several essential services within the ecosystem and has been used to understand the impact of different managements, providing information that proves the benefits and your maintenance of the agroecosystem. To understand the impact of different managements, this study aimed to compare the chemical, physical, and biological soil properties in pasture areas managed with different recovery times in an integrated crop-livestock system about perennial pastures and secondary forest. The following management systems were evaluated: Secondary Forest (SF), Perennial Pasture (PP), pasture recovered to five years through the intercropping corn + *Brachiaria brizantha* (Palisade grass) (ICL5), and pasture recovered to eight years through the intercropping corn + *Brachiaria brizantha* (Palisade grass) (ICL8). Different soil properties were evaluated, namely: Chemical: pH, H+Al, Al^{3+}, P, K^+, Ca^{2+}, Mg^{2+}, TOC, SB, CEC, V, and m; Physical: soil bulk density (Bd), total porosity (Tp), macroporosity (Ma), microporosity (Mi), soil resistance to penetration (Pr), and gravimetric soil water content (GWc); and biological: soil microbial biomass carbon (SMB-C), basal soil respiration (BSR), metabolic quotient (qCO_2), and microbial quotient (qMic). Perennial pasture and ICL8 areas were the ones that most contributed to the increase in nutrients (Ca^{2+}, Mg^{2+}, and K^+), TOC and sorption complex. The ICL8 area showed the best results in soil physical variables Ma, Tp, Pr, and GWc were the best results for the ICL8 area. Secondary forest and ICL8 areas presented the best results from SMB-C and qMic. Between periods of pasture recovery through the integration of crops and livestock, the longer the recovery time, the greater its beneficial effects on the different chemical, physical and biological soil properties, overcoming secondary forest and perennial pasture.

Keywords: edaphic properties, Plintosol, management systems, integrated systems.

INTRODUCTION

Amazon biome occupies 34 % of the Maranhão State area and presents an accumulated deforestation from 1988 to 2021 of 26,103 km^2, ranking fifth among states that deforested the forest area in the Legal Amazon region (INPE, 2022). Many of these areas are converted to pastures, that are poorly managed, which induces negative impacts on soil functions, providing disturbance in the nutrient cycling, quality of organic matter, soil physics, increase in greenhouse gas emissions, decrease in the soil productive capacity, and soil quality (Rodrigues et al., 2017; Reis et al., 2018; Oliveira et al., 2022a,b).

It is estimated that 30 million hectares of pastures are in some stage of degradation due to inadequate management, which favors losses of yield and vigor, animal yield, and intensifies soil degradation (Barbieri et al., 2017; Bungenstab et al., 2019; Capristo et al., 2021). The recovery and/or renewal of pastures concomitant with the adoption of conservationist systems, such as no-tillage (NT) or integrated agricultural production systems (IAPS), are alternatives for improving production conditions, making it possible to increase the yield of national agriculture, reducing the impact on the soil and the need to open new areas (Dias-Filho, 2014; Barbieri et al., 2017; Sousa et al., 2020; Capristo et al., 2021).

Integrated agricultural production systems are a sustainable production strategy that integrates different activities in the same area, in intercropping, succession, or rotation, seeking synergistic effects between components (Bungenstab et al., 2019; Silva et al., 2021a). These systems have been widely highlighted in recent years due to the beneficial impacts that enable maintenance and/or improvement in physical, chemical, and biological soil properties (Bungenstab et al., 2019; Faccio Carvalho et al., 2021; Silva et al., 2021a).

Sustainability is directly linked to soil quality, and this assessment is often arduous and difficult to measure, given the complexity of the processes involved in the soil environment (Vezzani and Mielniczulk, 2009). Aspects such as soil fertility, physical structure, biological activity, and organic matter are widely indicated as parameters to be analyzed due to their ease of evaluation, sensitivity to short-term and long-term variations, and the possibility of measurements by quantitative or qualitative methods (Casalinho et al., 2007; Simon et al., 2022).

Different soil properties have been used to verify soil quality, helping to provide information that proves the benefits or negative impacts of the management (Silva et al., 2021a,b). For example, soil fertility levels help to understand nutrient cycling or soil impoverishment; soil physical structure is helpful to predict the water storage capacity and root exploitation capacity; while the soil biological properties can provide information about the microorganisms activity, greenhouse gas emissions, and many others (Rocha et al., 2022; Yin et al, 2022). It is when changes occur in the mentioned attributes, above the limits considered ideal in the literature, it can directly affect soil quality and crop productivity (Silva et al., 2021a,b).

In the Amazon Maranhense region, studies regarding the change of vegetation cover by agricultural environments and their influences on physical, chemical, and biological soil properties are incipient. It is highlighted by Santos et al. (2018a), Reis et al. (2018), and Celentano et al. (2020), who, evaluating different soil properties, did not observe differences between perennial pasture areas when compared to other alternatives.

This study hypothesizes that pasture recovery in different years can beneficially contribute to soil quality compared to perennial pastures and secondary forest in the same environment. Therefore, this study aimed to compare the chemical, physical, and biological soil properties in pasture areas managed with different recovery times in an integrated crop-livestock system about perennial pastures and secondary forest.

MATERIALS AND METHODS

Study site

The study was carried out at the Technological Reference Unit (TRU) of Embrapa Cocais and the State University of Maranhão (UEMA), in the municipality of Pindaré-Mirim/MA. According to the Köppen classification system, the climate of the region is Aw, with a dry winter, an average annual temperature of 26 to 27 °C and average annual precipitation between 1900 and 2100 mm (Araújo, 2013; Alvares et al., 2014). Climatic data for the region are shown in figure 1, obtained from the National Water Agency (ANA) and the National Institute of Meteorology (INMET).

The soil of TRU was classified as Plinthosols (IUSS Working Group WRB, 2015), which corresponds to *Plintossolo Argilúvico* according to the Brazilian Soil Classification System (Santos et al., 2018b). The soil has a medium texture (Table 1), originating from sediments of Itapecuru Formation and composed of fine sandstones (Moura, 2006; Araújo, 2013). Relief varies from mild-wavy to wavy and is covered by an Ombrophilous Forest associated with secondary forest vegetation, with a predominance of babassu palm (*Attalea speciosa* Mart.) (Mata dos Cocais), dominant in the Mid-North region of Maranhão state (Araújo, 2013).

Evaluated systems and usage history

The following areas were selected to carry out the study: Secondary Forest (SF), Perennial Pasture (PP), pasture recovered five years ago through the intercropping corn + *Brachiaria brizantha* (Palisade grass) (ILC5), and pasture recovered eight years ago through the intercropping corn + *Brachiaria brizantha* (Palisade grass) (ICL8). The history and characteristics of the management used are described in table 2 and figure 2.

Collection of samples and laboratory analysis

Five trenches with dimensions of 1 × 1 × 1 m were opened and randomly arranged in the evaluated areas. The samples were collected in the summer, when the highest rainfall occurs, causing the water content in the soil to reach values close to field capacity. On the opposite walls of the trench, undisturbed samples were collected using an Uhland collector with volumetric rings with a volume of 100 cm^3, the layers of 0.00-0.10; 0.10-0.20; 0.20-0.30, and 0.30-0.40 m were sampled. The collection of

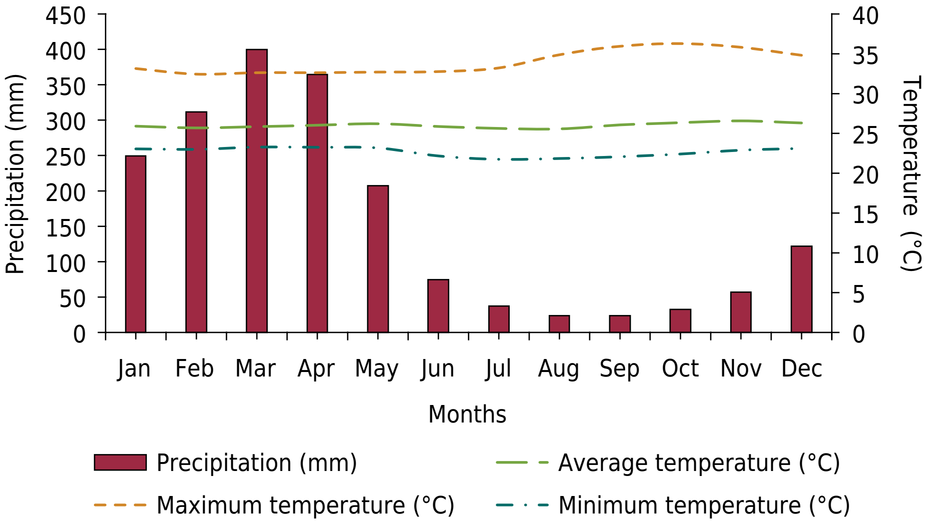

Figure 1. Monthly averages of historical temperature data (1973 - 2019) and rainfall (2004-2018) for the Pindaré-Mirim region obtained from the National Water Agency and the National Institute of Meteorology, respectively.

Table 1. Soil particle-size characterization in the different areas and layers in the Pindaré-Mirim region, Maranhão, Brazil

Area	Layer	Sand	Silt	Clay	Textural class
	m		g kg^{-1}		
SF	0.00-0.20	746.65	135.25	118.10	Sandy loam
	0.20-0.40	707.20	124.25	168.60	
PP	0.00-0.20	579.30	343.00	77.80	
	0.20-0.40	616.05	260.40	123.65	
ICL5	0.00-0.20	745.50	103.50	150.50	
	0.20-0.40	704.50	169.50	125.50	
ICL8	0.00-0.20	741.90	120.75	137.30	
	0.20-0.40	723.05	97.30	179.70	

SF: Secondary Forest; PP: Perennial pasture; ICL5: Pasture recovered in integrated crop-livestock to five years; and ICL8: Pasture recovered in integrated crop-livestock to eight years.

Table 2. History and characteristics of the management models studied in the technology reference unit in the Pindaré-Mirim region, Maranhão, Brazil

Areas	Area History
Secondary Forest (SF)	Transitional Amazon Forest to the babassu forest, with a strong expression of secondary vegetation, classified as Open Ombrophilous Forest, with babassu palms predominating (*Attalea speciosa* Mart.) (Mata dos Cocais) (Araújo, 2013; Reis et al., 2018). Also consisting of açaí palm (*Euterpe Oleracea* Mart.), bacaba (*Oenocarpus spp*.), andiroba (*Carapa spp*.), jatobá (*Hymenaea spp*.), and embaúba (*Cecropia spp*.) (Rios, 2001). This area was used to reference natural soil conditions due to its preservation history, as it has an average age of over 50 years.
Perennial pasture (PP)	Pasture area with Jaraguá grass (*Hyparrhenia rufa* (Ness) Stapf) was planted approximately in 1970 and remained until 1999. The pasture was renewed (without soil correction and fertilization) with *Brachiaria brizantha* cv. Marandu by mowing, burning plant remains, and broadcast seeding. The pasture was used for continuous grazing of beef cattle in an extensive regime with a stocking rate of approximately 0.7 AU/ha/year, with mechanized mowing being conducted periodically to contain the natural regeneration.
Pasture recovered in integrated crop-livestock to five years (ICL5)	Initial management similar to that of PP, with recovery in 2014 with an integrated crop-livestock system (ICLS), by removing vegetation with a loader machine, harrowing the total area, and correcting the soil (as needed). Subsequently, mechanized sowing of corn hybrid (DKB 175) + *Brachiaria brizantha* cv. Marandu, the forage seeds, were mixed with fertilizer at the sowing time, with 200 kg ha^{-1} of the formula 08-20-20 + Zn in the foundation and 100 kg ha^{-1} of urea in the topdressing. The formed pasture was used for rotational beef cattle grazing with a stocking rate of 1.0 AU/ha/year.
Pasture recovered in integrated crop-livestock to eight years (ICL8)	Initial management similar to that of PP, with recovery in 2012 with an ICLS, by removing the vegetation with a wheel loader machine, harrowing the entire area, and correcting the soil (as needed), followed by mechanized seeding. A corn hybrid (DKB 175) + *Brachiaria brizantha* cv. Marandu, the forage seeds, were mixed with fertilizer at the sowing time, with 200 kg ha^{-1} of the formula 08-20-20 + Zn with sowing and 100 kg ha^{-1} of urea in the topdressing. The formed pasture was used for rotational grazing of beef cattle with a stocking rate of 1.0 AU/ha/year.

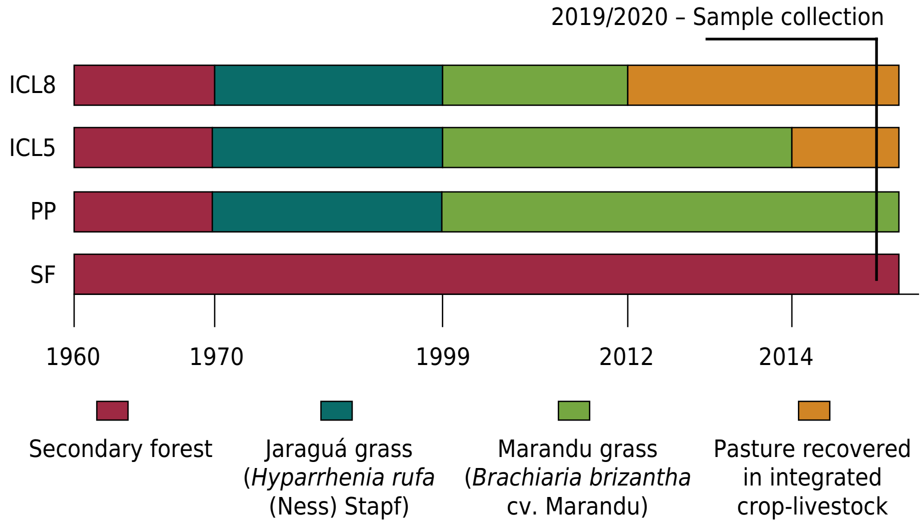

Figure 2. History of use of the evaluated areas, with the respective implementation and collected from samples. SF: Secondary Forest; PP: Perennial pasture; ICL5: Pasture recovered in integrated crop-livestock to five years; and ICL8: Pasture recovered in integrated crop-livestock to eight years.

deformed samples was performed at three points equidistant from the trench walls with a Dutch auger, totaling twelve simple samples to compose a representative sample in the same previously mentioned layers. After collection, the samples were stored in plastic bags for later drying at room temperature and sieving in sieves with 2 mm mesh. In this material, chemical and biological determinations were performed.

Physical soil properties of undisturbed samples were determined: soil bulk density (Bd), total porosity (Tp), macroporosity (Ma), microporosity (Mi), and gravimetric soil water content (GWc), by volumetric ring method in tension table (Teixeira et al., 2017), and soil penetration resistance (Pr), with the aid of electronic penetrograph, model penetroLOG-Falker-PLG1020, carried out in the field.

For chemical properties, pH was determined in $CaCl_2$ 0.01 mol L^{-1} (soil: solution ratio 1:2.5); total organic carbon (TOC), obtained from the method of Yeomans and Bremner (1988); aluminum (Al^{3+}), calcium (Ca^{2+}), and magnesium (Mg^{2+}), extracted with KCl 1 mol L^{-1}, Al^{3+} determined by titration with NaOH 0.015 mol L^{-1}; Ca^{2+} and Mg^{2+} determined by atomic absorption spectrophotometer; P and K^+ extracted by Mehlich^{-1} solution (HCl 0.5 mol L^{-1} + H_2SO_4 0.0125 mol L^{-1}), P being determined in a UV-VIS spectrophotometer, and K^+ by flame photometry; and the potential acidity (H+Al) extracted with 0.5 mol L^{-1} calcium acetate solution buffered at pH 7.0, determined by titration with NaOH 0.1 mol L^{-1} (Teixeira et al., 2017). With these data, the sum of bases (SB), cation exchange capacity (CEC), base saturation (V), and aluminum saturation (m) were calculated, according to Ronquim (2010).

Regarding biological properties, the determination was performed only in layers of 0.00-0.10 m, as it is considered the one with the highest biological activity. Basal soil respiration (BSR) was estimated following a procedure by Silva et al. (2007a) adapted from Jenkinson and Powlson (1976), using 50 g of soil packed in 500 mL hermetic flasks in the presence of 10 mL of NaOH 0.5 mol L^{-1} (capture solution) and 10 mL of distilled H_2O for seven days in a BOD chamber at a temperature of 25 ± 1 °C and in complete darkness, after this period, 2 mL of 10 % $BaCl_2$ and two drops of 1 % phenolphthalein were added to capture solution which was titrated with HCl 0.5 mol L^{-1}.

Determination of soil microbial biomass carbon (SMB-C) performed by fumigation and extraction method, as described by Silva et al. (2007b) adapted from Vance et al. (1987), using 20 g of soil from samples, fumigation with 1.0 mL of chloroform ($CHCl_3$)

applied directly to the soil sample and use of extraction solution with 50 mL of K_2SO_4 at 0.5 mol L^{-1}, then for determination of the carbon of the samples, were used 8 mL of extracting solution, 2 mL of $K_2Cr_2O_7$ 0.066 mol L^{-1}, 5 mL of H_3PO_4, 70 mL of deionized H_2O and four drops of diphenylamine to be titrated with $Fe(NH_4)_2$ $(SO_4)_2.6H_2O$ 0.033 mol L^{-1}.

After determining the levels of SMB-C and BSR, the metabolic quotient (qCO_2) and the microbial quotient (qMic) were obtained, first being estimated by the relationship between BSR and SMB-C and second by the relationship between SMB-C and total organic carbon (TOC) divided by 10 (Anderson and Domsch, 1993).

Statistical analysis

Data from different areas were subjected to normality and homogeneity tests using the Shapiro-Wilk and Bartlett tests, respectively. When these assumptions were met, the averages of the measured variables were calculated and compared using the t-test at 5 % probability; the present test of comparison of means was chosen because the experiment was about collecting data in management areas that did not follow a statistical design.

As a complementary analysis, the analysis of principal components was performed only in 0.00-0.10 m layer using all the variables and the choice of this layer is related to the reflection of greater biological activity of the same, as well as, it presented the largest responses of differences between the analyzed areas. For this analysis, we considered it based on the Euclidean distance. Statistical analyzes were performed using the R 4.0 software (R Development Core Team, 2021).

RESULTS

Chemical properties

In all evaluated areas, differences were verified in the chemical properties in different layers, except for Al^{3+} (Table 3). The average Al^{3+} contents, along the evaluated layers, ranged from 0.12 to 1.28 $cmol_c$ dm^{-3}. The pH only presented differences in the surface layer, with higher values in SF, PP, and ICL8 areas. SF (0.00-0.10 m), ICL8 (0.00-0.10, 0.10-0.20, and 0.30-0.40 m), and PP (0.20-0.30 and 0.30-0.40 m) areas presented the highest levels of TOC and the area ILC5 lowest levels.

In this study, no differences were found between the areas for P levels in the 0.00-0.10 m layer, varying on the surface contents between 1.27 and 1.90 mg dm^{-3}, with a general average of 1.62 mg dm^{-3} (Table 3). In the other layers of the SF area were found higher P levels, although not differing from the PP area.

For K^+, the highest levels were found in the PP area, ranging from 72 to 115 % more than in the SF area, and not differing in the deeper layer of the ICL8 area. There were no differences among SF, PP, and ICL8 areas for contents of Ca^{2+} in the surface layer, whereas in other layers PP area showed the highest levels. Exchangeable Mg and H+Al were evaluated in all layers, and the highest values were simultaneously found in the ICL8 area compared to other areas.

As for the sorption complex, the highest levels of the sum of bases, cation exchange capacity, and base saturation, and the lowest levels in aluminum saturation were verified in most of the layers on ICL8 and PP areas, not differing from SF and ILC5 areas in some layers.

Physical properties

We do not observe differences between the areas for Sd and Mi along the evaluated layers, observing a variation from 1.33 to 1.48 Mg m^{-3} and 0.29 to 0.35 m^3 m^{-3}, respectively (Table 4).

Table 3. Chemical properties of the *Plintossolo Argilúvico* under different managements in the Amazônia Maranhense

Areas	pH	TOC	P	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H+AL	SB	CEC	V	m
	CaCl²	g kg^{-1}	mg dm^{-3}	cmol$_c$ dm^{-3}							%	
						0.00-0.10 m						
SF	4.62 a	9.65 a	1.90 a	0.18 bc	1.90 a	1.68 bc	0.09 a	2.67 b	3.75 b	6.43 b	57.64 a	2.48 a
PP	4.61 a	7.27 b	1.72 a	0.31 a	2.14 a	2.15 b	0.10 a	2.44 b	4.60 ab	7.04 b	65.03 a	2.36 a
ICL5	4.39 b	7.66 b	1.60 a	0.17 c	0.68 b	1.24 c	0.17 a	2.87 b	2.09 c	4.96 c	41.38 b	8.15 b
ICL8	4.70 a	9.86 a	1.27 a	0.23 b	1.84 a	3.19 a	0.11 a	3.60 a	5.26 a	8.86 a	59.37 a	2.21 a
						0.10-0.20 m						
SF	4.36 a	4.31 c	1.67 a	0.13 bc	1.32 b	1.78 bc	0.42 a	2.67 b	3.23 b	5.90 bc	53.20 b	12.74 ab
PP	4.56 a	5.38 a	1.39 ab	0.26 a	2.59 a	2.40 ab	0.22 a	2.57 b	5.25 a	7.82 ab	66.31 a	4.30 c
ICL5	4.27 a	4.68 b	1.11 bc	0.10 c	0.48 c	1.23 c	0.40 a	2.81 b	1.81 b	4.62 c	38.20 c	18.66 a
ICL8	4.42 a	5.63 a	0.94 c	0.17 b	1.49 b	3.14 a	0.34 a	3.60 a	4.80 a	8.40 a	58.00 ab	6.36 bc
						0.20-0.30 m						
SF	4.23 a	3.75 d	1.81 a	0.13 c	1.10 b	2.04 b	0.78 a	3.20 b	3.27 b	6.47 b	48.72 b	20.94 a
PP	4.32 a	4.84 a	1.51 ab	0.28 a	2.57 a	3.19 a	0.86 a	3.83 b	6.05 a	9.88 a	61.33 a	12.02 b
ICL5	4.18 a	4.05 c	0.97 b	0.10 c	0.44 b	1.32 b	0.56 a	3.07 b	1.85 b	4.92 b	36.76 c	23.50 a
ICL8	4.42 a	4.49 b	0.96 b	0.20 b	1.28 b	3.70 a	0.57 a	4.85 a	5.18 a	10.04 a	53.16 ab	9.70 b
						0.30-0.40 m						
SF	4.13 a	3.79 b	1.67 a	0.15 b	0.83 bc	2.37 bc	1.04 a	4.09 b	3.36 b	7.45 b	44.40 a	25.16 a
PP	4.18 a	5.15 a	1.23 ab	0.30 a	2.26 a	3.71 ab	1.89 a	6.11 b	6.27 a	12.37 a	49.77 a	23.88 a
ICL5	4.13 a	4.06 b	0.87 b	0.10 b	0.32 c	1.34 c	0.68 a	3.10 b	1.76 b	4.87 b	36.13 a	27.22 a
ICL8	4.33 a	4.81 a	0.94 b	0.26 a	1.23 b	4.74 a	1.50 a	7.06 a	6.22 a	13.29 a	49.09 a	18.50 a

SF: Secondary Forest; PP: Perennial pasture; ICL5: Pasture recovered in integrated crop-livestock to five years; and ICL8: Pasture recovered in integrated crop-livestock to eight years; TOC: total organic carbon; P: Phosphorus; K: Potassium; Ca: Calcium; Mg: Magnesium; Al: Aluminum; H+Al: Potential acidity; SB: Sum of bases; CEC: cation exchange capacity (CEC); V: Base saturation; m: aluminum saturation. Means followed by the same letter in the column for each layer do not differ from each other by the t-test ($p<0.05$).

Differences were found between the managements only in the 0.10-0.20 m layer for Ma, with the largest pore space observed in the ICL8 area. In Tp and GWc, differences were found between the areas in 0.10-0.20 to 0.30-0.40 m soil layers, and the highest amount of soil pores and gravimetric soil water contained in the ICL8 area. For Pr, in 0.00-0.10 and 0.10-0.20 m layers, the SF area presented the lowest values but did not differ from the ICL8 area, and had 14 and 22 %, and 40 and 52 % less compaction compared to ILC5 and PP areas, respectively.

Biological properties

Regarding the biological soil properties, it was observed that the SF and ICL8 areas presented the highest values of SMB-C, which means 27.23 and 21.67 % more microbial C, respectively, when compared to the average of the other areas (Table 5). Still, concerning the SF and ICL8 areas, the highest values for qMic were verified, not differing from the PP area. As for BSR and qCO_2, no differences were found; however, it is possible to observe that the SF and ICL8 presented, numerically, the largest values of respiration and smallest metabolic quotients, an increase of 8.16 and 6.12 % and 38.57 and 28.72 %, respectively, compared to PP.

Principal component analysis

The principal components analysis (PCA) showed that the first two principal components (PC1 and PC2) explained 82.64 % of the total variation in data, with variations of

Table 4. Soil density (Sd), macroporosity (Ma), microporosity (Mi), total porosity (Tp), soil resistance to penetration (Pr), and gravimetric soil water content (GWc) under different areas in the Amazônia Maranhense

Areas	Sd	Ma	Mi	Tp	Pr	GWc
	Mg m^{-3}		cm^3 cm^{-3}		KPa	%
			0.00-0.10 m			
SF	1.33 a	0.08 a	0.33 a	0.41 a	522.96 b	25.04 a
PP	1.42 a	0.07 a	0.35 a	0.42 a	736.76 a	25.37 a
ICL5	1.35 a	0.06 a	0.35 a	0.41 a	686.70 a	23.33 a
ICL8	1.37 a	0.08 a	0.35 a	0.43 a	603.60 ab	27.50 a
			0.10-0.20 m			
SF	1.41 a	0.07 ab	0.30 a	0.36 bc	973.62 b	20.55 a
PP	1.43 a	0.07 ab	0.31 a	0.38 ab	1845.24 a	20.21 ab
ICL5	1.48 a	0.05 b	0.29 a	0.34 c	1694.63 a	18.33 b
ICL8	1.43 a	0.08 a	0.31 a	0.39 a	1211.10 b	22.05 a
			0.20-0.30 m			
SF	1.43 a	0.06 a	0.30 a	0.36 ab	969.75 a	21.61 a
PP	1.43 a	0.09 a	0.30 a	0.39 a	1322.44 a	20.68 ab
ICL5	1.43 a	0.06 a	0.29 a	0.35 b	1236.47 a	18.85 b
ICL8	1.43 a	0.09 a	0.30 a	0.39 a	1092.63 a	23.02 a
			0.30-0.40 m			
SF	1.48 a	0.06 a	0.31 a	0.36 b	940.56 a	21.69 ab
PP	1.45 a	0.08 a	0.31 a	0.39 ab	1088.56 a	21.66 ab
ICL5	1.43 a	0.06 a	0.29 a	0.36 b	1066.51 a	19.64 b
ICL8	1.44 a	0.07 a	0.33 a	0.40 a	1013.75 a	24.91 a

SF: Secondary Forest; PP: Perennial pasture; ICL5: Pasture recovered in integrated crop-livestock to five years; ICL8: Pasture recovered in integrated crop-livestock to eight years. Means followed by the same letter in the column for each layer do not differ from each other by the t-test ($p<0.05$).

Table 5. Basal soil respiration (BSR), soil microbial biomass carbon (SMB-C), metabolic quotient (qCO_2), and microbial quotient (qMic) under different managements in the 0.00-0.10 m layer

Areas	BSR	SMB-C	qCO_2	qMic
	mg C-CO_2 kg^{-1} soil h^{-1}	mg C microbial kg^{-1} soil	mg C-CO_2 kg^{-1} soil h^{-1}	%
SF	1.06 a	562.73 a	1.93 a	5.05 ab
PP	0.98 a	406.11 b	2.52 a	4.74 ab
ICL5	1.04 a	412.84 b	2.77 a	4.24 b
ICL8	1.04 a	522.76 a	2.04 a	5.54 a

SF: Secondary Forest; PP: Perennial pasture; ICL5: Pasture recovered in integrated crop-livestock to five years; ICL8: Pasture recovered in integrated crop-livestock to eight years. Means followed by the same letter in the column do not differ by the t-test ($p<0.05$).

54.15 and 28.49 % in PC1 and PC2, respectively (Figure 3 and Table 6). The highest correlations (>0.70) of soil properties with PC1 were with the variables pH, SB, GWc, CEC, m, Mg^{2+}, Ca^{2+}, V, Al^{3+}, qMic, Ma, BSR, and qCO_2, and for PC2 with Sd, Pr, K^+, Mi, SMB-C, and TOC (Table 6).

When checking the position of the areas about the axes of the principal component, we observe that the ICL8 area was influenced positively by the PC1, stimulated by results of 10 variables beneficial related to fertility, physical and biological soil, with high correlation this axis, while ILC5 area presented opposite behavior influenced by

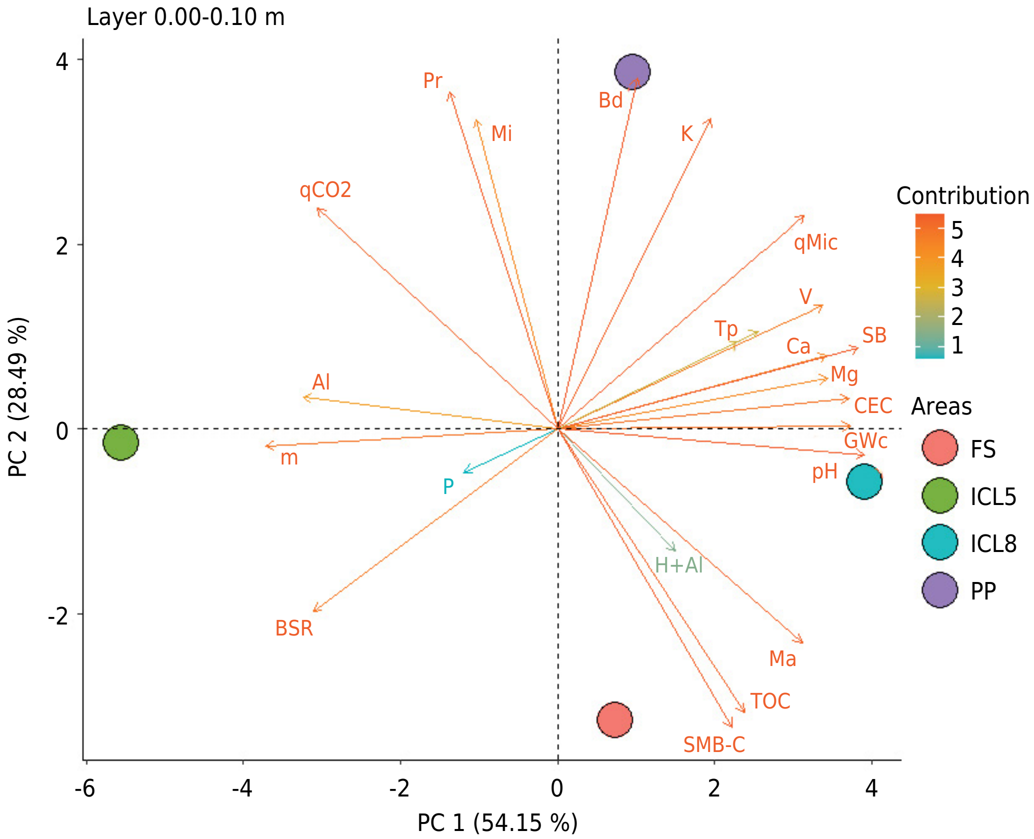

Figure 3. Biplot obtained by principal component analysis (PCA) in different areas in the Amazônia Maranhense and all variables in the 0.00-0.10 m soil layer. SF: Secondary Forest; PP: Perennial pasture; ICL5: Pasture recovered in integrated crop-livestock to five years; ICL8: Pasture recovered in integrated crop-livestock to eight years.

your high values of Al^{3+}, m, qCO_2, and BSR. On the other hand, the PP area had a high influence by the PC2, whereas the SF area followed the opposite behavior, influenced by variables SMB-C and TOC. By the construction of the principal component analysis (Figure 3 and Table 6), when checking the axis of PC1 it is possible to evidence the increasing order of ICL8 > PP > SF > ILC5 areas, when projecting their positions about that axis.

DISCUSSION

We did not find differences between areas for pH and Al^{3+}, but we confirmed features from active acidity ranging from high (4.5 - 4.8) to very high (<4.4), and exchangeable acidity low (<0.3 $cmol_c\ dm^{-3}$) to high (>1.0 $cmol_c\ dm^{-3}$), increasing levels with depth (Ronquim et al., 2010; Brasil et al., 2020). These results can be a reflection of the action of climate (high temperature and precipitation), combined with the nature of the material of sedimentary origin, and the flooding cycles present in these areas can explain the pH and Al^{3+} higher levels (Moura et al., 2006; Anjos et al., 2007; Araújo et al., 2013).

According to Anjos et al. (2007), a high acidity of the soil occurs parallel to the high levels of Al^{3+}, very common in the Plinthosols of the region. Reis et al. (2018), evaluating different areas, found results similar to ours, and these increased from acidity with depth, which can be related to the mineral complexation by the organic matter in most soil superficial layer and predominance of anaerobic conditions in-depth, due to compression, and process of active ferrolysis (Anjos et al., 2007). Another contributing factor is the high presence of clay minerals such as gibbsite,

Table 6. Weight coefficients (eigenvectors), eigenvalues, variance explained, correlation of variables by each principal component (PC1 and PC2) of the different soil properties for the 0.00-0.10 m layer under different areas in the Amazônia Maranhense

Variance component	Principal component	
	1	2
Eigenvalues	11.912	6.268
Proportion (%)	54.145	28.490
Cumulative proportion (%)	54.145	82.634
Variables		
pH	0.996	-0.070
TOC	0.604	-0.778
P	-0.304	-0.118
K^+	0.497	0.853
Ca^{2+}	0.871	0.202
Mg^{2+}	0.876	0.141
Al^{3+}	-0.822	0.088
H+Al	0.382	-0.334
SB	0.973	0.222
CEC	0.945	0.085
V	0.859	0.340
m	-0.944	-0.046
Sd	0.257	0.966
Ma	0.793	-0.586
Mi	-0.265	0.851
Tp	0.649	0.268
Pr	-0.351	0.925
GWc	0.949	0.009
BSR	-0.791	-0.500
SMB-C	0.564	-0.819
qCO_2	-0.777	0.606
qMic	0.800	0.588

whose composition is rich in aluminum, which can increase the toxicity and acidity of those soils (Bastos et al., 2021).

We found high levels of H+Al along all layers over the ICL8 area, which we suppose come from the ionizable hydrogen content formed partly by the decomposition of organic matter, biological activity due to the formation of organic acids, production of root exudates, and hydrolysis of other compounds, such as sulfur (Ebeling et al., 2008; Meurer et al., 2010).

Perene pasture and ICL8 areas were the ones that most contributed to the increase of nutrients (Ca^{2+}, Mg^{2+}, and K^+), TOC and sorption complex. These results may be related to the deposition of biomass, both from plant and animal origin, and the exploration and deposition of roots that contribute to a greater organic input of organic material via rhizodeposition, providing improvements in the nutrients cycling (Assis et al., 2017; Rego et al., 2020; Silva et al., 2021a). Rodrigues et al. (2017), when verifying the changes in the different managements' chemical properties, also observed higher nutrient availability when the implantation of pasture (*Brachiaria brizantha* cv. Marandu) with the less the soil is turned.

The P highest levels were found in SF and PP areas, which may come from the preparation with fire associated with the cycling efficiency of this nutrient (Melo et al., 2017).

Santos et al. (2018a), when evaluating different land-uses in the Legal Amazon, they did not observe differences in P between the areas of secondary forest and pasture, attributing this pattern to the preparation with fire in the primary forest that can collaborate with the input and cycling of this nutrient to the soil.

We did not find differences between the areas for variable Sd, however, they would be below the critical limit of 1.75 Mg m^{-3} for crop development in sandy textured soils (Reichert et al., 2015). Anjos et al. (2007) analyzed the horizons of Plinthosols in natural environments in the municipality of Pinheiro in different parts of the landscape, and Santos et al. (2018a), in different environments in the municipality of Monção, in Maranhão on a Plintosol, they observed Sd values similar to those verified in this study. Bastos et al. (2021), when analyzing Sd in different land-uses in the Amazon of the state of Rondônia in a Plinthosols, they did not find differences between areas of forests, pasture, and mixed plantation, despite the values being lower than those observed in this study.

We found within soil physical variables Ma, Tp, Pr, and GWc the best results for the ICL8 area. These can be a reflection of deposition and efficient exploitation of the fibrous root system with a fast growth rate, which contributes to soil decompaction, and a decrease of Pr, an increase in of total porosity of the soil, allowing greater water storage capacity, in addition to the increase in organic matter contents, which plays a fundamental role in the physical quality of the soil (Dias-Filho, 2014; Barbieri et al., 2017; Bungenstab et al., 2019; Sousa et al., 2020; Capristo et al., 2021). Chioderoli et al. (2012), when evaluating the changes in the physical properties of the soil provided by corn consortium with *Brachiaria*, observed improvements provided by the action of the roots on the physical properties of the soil.

It was verified that the values found for Ma, Tp, and Pr were lower than the critical limit from 0.07 to 0.10 m^3 m^{-3}, 0.32 to 0.47 m^3 m^{-3}, and 2000 KPa, respectively, in soils with a sandy texture (Reynolds et al., 2009; Reichert et al., 2015; Suzuki et al., 2022). Therefore, within acceptable limits, however, due to the constant cycles of wetting and drying that occur in the region, and the source material from the Itapecuru Formation, being sediment composed of fine sandstones, allied to the adoption of conventional management can favor the destruction of soil aggregates (Anjos et al., 2007; Araújo et al., 2013).

In addition, another factor would be the high levels of Mg^{2+} that can favor the dispersion of clay particles, providing changes in the arrangement of soil particles, causing greater packing and increased cohesion between particles, reducing Ma and Tp parallel to the increase in Mi, Sd, and Pr, which may cause soil densification/compaction (Silva et al., 2001).

We observed the best results from SMB-C and qMic in the areas of SF and ICL8, due to variations in the contents of organic carbon. In these areas, the highest levels of TOC were observed, which may provide improvements to the activity and quantity of soil microorganisms and, when performing the recovery of the pasture, combined with time, provide positive impacts on the biological activity of the soil (Silva et al., 2021b). Sousa et al. (2020), when evaluating different alternatives for crop and livestock integration in the Cerrado-Amazon ecotone region, verified improvements and/or maintenance of the microbiological soil attributes provided by rotation with forages compared to the forest area.

The absence of difference between the areas for BSR and qCO_2 may be related to the action of the roots by the formation of exudates, such as organic acids, since the forages of the genus *Brachiaria* have a very expressive root system and rapid growth in the soil, providing rapid renewal after stressful events such as grazing, which could help in the formation of compounds that benefit soil microorganisms (Lopes et al., 2015; Capristo et al., 2021).

Assis et al. (2017) and Assis et al. (2019) found that even in situations of poorly managed pastures, these can provide the satisfactory development of microbial activity due to the fibrous root system, resulting in increased C entry into the soil through the rhizosphere and plant residues, which activate the microbiota in the soil. Capristo et al. (2021), when evaluating forms of pasture renewal and recovery, also did not find differences in the biological soil attributes of BSR and qCO_2.

We observed that among the areas, soil conservation services such as nutrient cycling and biodiversity pool, and the provisioning services such as providing water, nutrients, and physical support for the growth of plants for human and animal use were higher in ICL8 than by areas PP, SF, and ILC5, in that order (Figure 3). This was due to the influence shown by principal component analysis, in which a set of 13 variables that presented greater weight and correlation with the PC1 axis made it possible to find an ordering of the areas that presented the greatest positive effects on soil quality (Oliveira et al., 2015; Hongyu et al., 2016; Batista et al., 2021). The principal component analysis is an alternative for evaluating soil quality from a set of indicators, where areas can be evaluated based on distance about variables with larger weight and size of the vectors, or through the correlation of soil indicators with the ordering axes (Chaer, 2010).

According to Oliveira et al. (2022a), by recovering pastures, we can increase soil carbon sequestration, thus reducing Brazilian emissions, as well as improving the soil. In addition, several examples of the benefits of different soil properties provided by the adoption of IAPSs are found in the literature (Lopes et al., 2015; Assis et al., 2019; Sousa et al., 2020; Capristo et al., 2021; Oliveira et al., 2022a,b). Pasture recovery has the effect of improving the ability of plants to grow again, distributing greater amounts of biomass, increasing nutrient cycling, and improving soil physical and microorganism diversity (Assis et al., 2019; Capristo et al., 2021; Oliveira et al., 2022a).

We observed when comparing areas that underwent pasture recovery through integration crops-livestock after eight years have beneficial change-over in soil properties about areas of perennial pasture and secondary forest (Tables 3, 4, and 5), similar results were also found by Lopes et al. (2015) and Sousa et al. (2020). About recovery up to five years, differences have not yet been observed, collaborating with the studies by authors Silva et al. (2021b), Assis et al. (2019), Reis et al. (2018), and Lopes et al. (2015) did not observe differences in the first years after recovery through IAPS, requiring more time for effective changes to occur.

CONCLUSIONS

Between periods of pasture recovery through the integration of crops and livestock, the longer the recovery time, the greater its beneficial effects on the different chemical, physical and biological soil properties, overcoming secondary forest and perennial pasture. Perennial pasture, in the subsurface layers, provided the best results when comparing the secondary forest for most of the chemical and physical soil properties.

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