

Chemical, physical, and biological attributes of sandy soil in integrated crop-livestock- forestry systems in Matopiba, Brazil

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Abstract

The adoption of integrated crop–livestock production systems, together with practices such as crop rotation, crop succession, and intercropping, has increased the need for integrated approaches to assess soil health. This study evaluated soil health under contrasting land-use systems in the Cerrado region of Maranhão, Brazil. The study was conducted in 2024 at Barbosa Farm (Brejo, Maranhão), comparing integrated crop–livestock (ICL), integrated livestock–forestry (ILF), no-tillage (NT), managed pasture (MP), and native vegetation (NV). Soil samples were collected from the 0–10, 10–20, and 20–30 cm layers to determine soil bulk density (D_b), soil pH, available phosphorus (P), exchangeable potassium (K), and total organic carbon (TOC). Soil health was assessed using the Soil Management Assessment Framework (SMAF), which integrates physical, chemical, and biological indicators into standardized indices. Native vegetation exhibited the lowest soil pH (4.28 in the 0–10 cm layer), whereas ICL showed the highest value (5.42). NT presented the highest concentrations of available P and K (46.94 and 31.28 mg dm⁻³, respectively). ILF had the highest TOC concentration (24.3 g kg⁻¹ in the 0–10 cm layer) and the greatest carbon stock (98.8 Mg ha⁻¹ in the 0–30 cm profile). According to SMAF, ILF (0.99) and NT (0.98) achieved the highest biological indicator scores in the surface layer, whereas ICL (0.72) and NT (0.73) showed the highest Soil Health Index values at the 10–20 cm depth. Overall, integrated production systems and no-tillage were more effective than managed pasture in maintaining soil health in the sandy soils of the Maranhão Cerrado.

1 INTRODUCTION

The concept of soil health has gained increasing prominence in the agricultural sector and in scientific research over the past decades, establishing itself as a central topic in research and the development of global policies (FAO 2022). Soil health is defined as the continued capacity of soil to function as a living ecosystem that sustains plants, animals, and humans. Soil health depends directly on the management practices adopted, as well-managed, highly fertile soils tend to exhibit greater productivity, improved soil structure, and lower nutrient losses (Morguán-Coronado et al. 2020).

In addition to its productive function, soil health is also closely associated with the provision of essential ecosystem services. Soil serves as the primary medium for plant growth, plays a key role in nutrient and water cycling, functions as a carbon sink, and supports a vast diversity of life, while sustaining these functions without degrading natural resources or causing environmental damage (Yang et al. 2020). This definition broadens the understanding of soil from a mere physical support and nutrient supplier to an active, multifunctional component that underpins the sustainability of agroecosystems. Therefore, maintaining soil health is essential to ensuring food security and enhancing the capacity of agricultural systems to adapt to climate change (Reis et al. 2021).

Strategies for the sustainable intensification of agriculture, with a particular emphasis on improving soil health, have gained increasing importance over recent decades, especially following the widespread adoption of integrated crop–livestock (ICL) and integrated livestock–forestry (ILF) systems in Brazil.

These integrated systems are estimated to occupy more than 17 million hectares nationwide, contributing significantly to both environmental sustainability and rural development (Rodrigues et al. 2023). The adoption of integrated crop–livestock–forestry (ICLF) systems is widely recognized for providing a range of benefits that directly enhance soil health (Bieluczyk et al. 2020).

The interspecific diversification and crop rotations inherent to these integrated systems accelerate organic matter inputs, optimize nutrient cycling, and stimulate subterranean biological activity and biodiversity (Morguán-Coronado et al. 2020). Furthermore, the deep root systems of trees and perennial pastures enhance soil porosity and aggregate stability, thereby mitigating compaction and erosion, degradative processes common to conventional monoculture systems (Sollenberger et al. 2019).

Within the Brazilian Cerrado, particularly across the MATOPIBA agricultural frontier (comprising the states of Maranhão, Tocantins, Piauí, and Bahia), conservation practices such as no-tillage (NT) farming and crop rotation play a critical role in mitigating soil degradation and carbon losses while improving soil health (Polizel et al. 2021; Santos et al. 2023). Nevertheless, net gains in total organic carbon (TOC) remain limited in this region. Although post-harvest crop residues and rhizodeposition contribute approximately 4 Mg ha⁻¹ of carbon annually, the warm and humid conditions characteristic of the MATOPIBA rainy season accelerate soil organic matter (SOM) decomposition, thereby limiting the long-term stabilization and accumulation of TOC (Gmach et al. 2020). These challenges are further compounded by the predominance of cohesive sandy soils, which are inherently nutrient-poor and highly susceptible to physical degradation (Nikzaad et al. 2023).

To provide an integrated assessment of soil health across contrasting management systems, researchers increasingly rely on frameworks that synthesize multiple soil properties into practical indices for evaluating sustainable land use. Among these, the Soil Management Assessment Framework (SMAF) has been widely adopted and successfully calibrated for Brazilian edaphoclimatic conditions (Nunes et al. 2020a; Amorim et al. 2025). SMAF applies scoring curves adjusted for site-specific factors, including soil class, texture, climate, and management history, to evaluate dynamic soil properties and quantify the effects of management practices (Karlen et al. 2019). By selecting, scoring, and integrating multiple indicators, the framework estimates the soil's intrinsic functional potential (defined as 100%) and generates a comprehensive Soil Health Index (SHI). Expressed on a relative scale, the SHI reflects the soil's capacity to perform essential functions and provide key ecosystem services, including sustaining agricultural productivity, enhancing nutrient cycling, and supporting environmental conservation (Amorim et al. 2025; Cherubin et al. 2017). Consequently, SMAF provides a robust tool for monitoring changes in soil health and guiding the transition toward more resilient and sustainable agricultural systems.

Across the Brazilian Cerrado, numerous studies have applied the Soil Management Assessment Framework (SMAF) or similar composite indices to evaluate soil health under a range of land-use and management systems, including native vegetation, pastures, NT farming, sugarcane cultivation, and integrated production systems (Cherubin et al. 2021). Collectively, these studies show that the

conversion of native Cerrado to conventional agriculture or extensive pasture reduces soil health, particularly in coarse-textured soils, whereas conservation practices such as NT, integrated systems, and organic residue amendments can partially restore degraded physical, chemical, and biological properties (Funniceili et al. 2025). More recent studies conducted in the Cerrado of Bahia and the broader MATOPIBA region have highlighted soil organic matter dynamics and enzymatic activity as key indicators of soil health in integrated production systems (Santos et al. 2025). Despite these advances, comprehensive assessments integrating physical, chemical, and biological indicators within cohesive sandy soils under integrated management remain scarce in eastern Maranhão, representing an important knowledge gap (Santos et al. 2021). Therefore, this study evaluated the physical, chemical, and biological attributes of soil health across no-tillage (NT), managed pasture (MP), integrated crop-livestock (ICL), and integrated livestock-forestry (ILF) systems in the sandy soils of the eastern Maranhão Cerrado.

2 MATERIALS AND METHODS

2.1 Site description and management systems

The study was conducted at Barbosa Farm, located in the municipality of Brejo, Maranhão, Brazil (3°42'44" S, 42°55'44" W, and 104 m above sea level) (Fig. 1). The soil is classified as a typical dystrophic Yellow Argisol according to the Brazilian Soil Classification System, corresponding to an Acrisol in the World Reference Base for Soil Resources (WRB) (IUSS Working Group WRB 2022). It is characterized by a cohesive subsurface horizon and a sandy texture. Cohesive soils exhibit hard to extremely hard consistency when dry and firm to friable consistency when moist, owing to the predominance of very fine clay particles and clay illuviation processes that promote soil cohesion (Corrêa et al. 2008; Lima Neto et al. 2009). Their mineralogy is dominated by kaolinite, with low concentrations of extractable iron and aluminum, indicating that soil cohesion is not associated with the cementation processes commonly observed in other cohesive soils of the region (Lima Neto et al. 2010). In addition, the expression of the cohesive horizon is influenced by landscape position, more pronounced in concave landforms, which are generally associated with greater soil fertility and organic matter content (Dantas et al. 2014). According to the Köppen climate classification, the region has an Aw (tropical savanna) climate, characterized by a rainy season from January to May (Alvares et al. 2013). The mean annual precipitation during the study period (2024) was 1,327 mm.

2.2 Management systems

Five management systems: (1) integrated crop-livestock (ICL); (2) integrated livestock-forestry (ILF); (3) no-tillage soybean cultivation (NT); (4) managed *Brachiaria* pasture (MP); and (5) area under native Cerrado vegetation (NV), used as a reference for natural soil conditions. The land-use history and management practices of each study area are summarized in Table 1.

Table 1
Land-use history and description of the management practices of each study area

Systems	Period	Land-use history and management practices
	Until 1990	Area covered with native Cerrado vegetation.
ICL	1990s	Native vegetation cleared and converted to cultivated pasture for beef cattle production.
	1990–2009	Area used exclusively as permanent pasture under grazing.
	2010/2011 Season	Soybean cultivated under no-tillage system.
	Second season 2011	Maize intercropped with <i>Urochloa ruziziensis</i> to establish pasture.
	Off-season 2011	Cattle grazing on pasture established after maize harvest.
	2011–2024	Annual production cycle maintained under no-tillage: soybean (summer) → maize intercropped with <i>Urochloa ruziziensis</i> (second crop) → cattle grazing (off-season). Soil fertility was corrected and fertilizers applied according to technical recommendations.
	Until 2016	Area covered with native Cerrado vegetation.
	2016	Native vegetation cleared. Conventional tillage (plowing, scarification, and leveling) performed, followed by incorporation of 5 t ha ⁻¹ of calcitic limestone.
ILF	2017	Rice cultivated with mineral fertilization (N, P ₂ O ₅ and K ₂ O).
	2018	Eucalyptus planted in triple rows with 4 × 3 m spacing and 30-m-wide corridors.
	2019	BRS Tamani grass established between tree rows.
	2020–2022	Cattle grazed the pasture while maintaining the forest component without further soil disturbance.
	2023–2024	Continuous livestock production maintained with the established forestry component and without soil disturbance.
	Until 2004	Area covered with native Cerrado vegetation.
	2005	Native vegetation cleared, followed by conventional tillage and application of 2 t ha ⁻¹ of calcitic limestone.
	2005–2024	No-tillage system established and maintained with soybean–millet crop rotation.
NT	2022	

Systems	Period	Land-use history and management practices
	Until 1990	Area covered with native Cerrado vegetation.
		Management included straw desiccation, mineral fertilization (MAP, KCl, and micronutrients), soybean inoculation, and phytosanitary control.
	2023–2024	Soybean–millet rotation continued under no-tillage without soil disturbance.
	Until the 1990s	Area covered with native Cerrado vegetation.
	1990s	Native vegetation cleared and converted to cultivated pasture for beef cattle production using <i>Urochloa</i> (<i>Brachiaria</i>) forage grasses.
MP	1990–2010	Area maintained as permanent pasture under continuous grazing, with weed control and maintenance fertilization when required.
	2010	A Technological Reference Unit (TRU) was established at Barbosa Farm for Integrated Crop–Livestock (ICL) and Integrated Livestock–Forestry (ILF) systems. The MP area remained exclusively under livestock production and was not converted to an integrated system.
	2010–2024	Area maintained as managed permanent pasture for beef cattle production, serving as a comparison treatment for the ICL, ILF, NT, and NV systems.
NV	1985–2020	Area maintained under native Cerrado vegetation and used as the reference ecosystem. Vegetation experienced sporadic fires, occurring almost annually during the dry season.

Soil particle-size analysis revealed a predominance of the sand fraction across all management systems and soil depths evaluated (Table 2).

Table 2
Soil particle size distribution, expressed by sand, clay, and silt contents (%), in the 0–10, 10–20 and 20–30 cm layers, in integrated crop-livestock (ICL), integrated livestock-forestry (ILF), no-tillagesoybean cultivation (NT), managed pasture (MP) and native vegetation (NV) systems, at Barbosa Farm, Brejo, Maranhão, Brazil.

Systems	Sand (%)	Clay (%)	Silt (%)
0–10 cm			
ICL	76.84	15.59	7.58
ILF	69.05	19.36	11.58
NT	72.69	18.85	8.45
MP	79.75	13.60	6.65
NV	76.44	9.27	14.29
10–20 cm			
ICL	72.21	19.79	8.00
ILF	67.80	21.50	10.70
NT	67.19	21.26	11.55
MP	78.30	16.12	5.58
NV	73.49	15.60	10.91
20–30 cm			
ICL	69.73	20.81	9.45
ILF	68.46	19.91	11.63
NT	70.89	17.75	11.36
MP	73.40	13.33	13.27
NV	70.84	16.23	12.93

In the 0–10 cm layer, average sand content ranged from 69.1% in the ILF system to 79.8% in MP, while clay content ranged from 9.3% in NV to 19.4% in ILF. In the 10–20 cm layer, average sand content ranged from 67.2% in the NT system to 78.3% in MP, whereas clay content ranged from 15.6% (NV) to 21.5% (ILF). At the 20–30 cm depth, average sand content ranged from 68.5% (ILF) to 73.4% (MP), while clay content ranged from 13.3% (MP) to 20.8% (ICL). Average silt content showed less variation among systems, ranging from 5.6% to 14.3%.

Overall, sand content tended to decrease with depth, whereas clay content generally increased, particularly in the ICL, ILF, and NT systems. Nevertheless, sand remained the dominant particle-size fraction across all soil layers and management systems. Considering the 0–30 cm profile, average sand content ranged from 68.4% (ILF) to 77.2% (MP), while clay content ranged from 13.7% (NV) to 20.3% (ILF), resulting in overall mean values of approximately 72.5% sand, 17.3% clay, and 10.3% silt. These results indicate that the experimental soils are predominantly sandy loam in texture, with localized occurrences of sandy clay loam depending on the management system and sampling depth, corroborating the classification of the study area as predominantly sandy soils.

2.3 Soil sampling and analysis

In July 2024, soil samples were collected from five land-use and management systems: integrated crop–livestock (ICL), integrated livestock–forestry (ILF), no-tillage (NT), managed pasture (MP), and native vegetation (NV). Sampling was performed at depths of 0–10, 10–20, and 20–30 cm. Within each management system, five sampling points were randomly distributed across the experimental area, and one sample was collected from each point at every depth. The experiment followed a completely randomized design (CRD), with the land-use and management systems considered as treatments.

In the ICL, NT, MP, and NV systems, soil samples were collected at five randomly distributed sampling points within each experimental area. In the ILF system, because of the presence of eucalyptus tree rows, sampling points were established between the tree rows while maintaining sufficient distance from the trunks to minimize their direct influence and ensure that sampling represented the pasture component of the integrated system. Each sampling point was considered a pseudoreplication, resulting in five pseudoreplications per management system at each of the three sampling depths, for a total of 75 soil samples (5 systems × 5 pseudoreplications × 3 depths).

The soil texture of the experimental area, determined for the 0–30 cm profile, was classified as predominantly sandy, with approximately 72% sand, 17% clay, and 10% silt. For chemical analyses, disturbed soil samples were air-dried at 40°C and passed through a 2-mm sieve. Soil pH was determined in water using a soil-to-water ratio of 1:2.5. Available phosphorus (P) and potassium (K) were extracted using the Mehlich-1 method and determined according to the procedures described by Raij et al. (2001) and Yeomans and Bremner (1988).

Undisturbed soil samples were collected using 100-cm³ stainless-steel cylinders. At each sampling point, a small trench was opened to the target depth, and the cylinders were carefully inserted horizontally into the soil profile wall to preserve the natural soil structure and minimize disturbance. These samples were used to determine soil bulk density (D_b), calculated as the oven-dry soil mass divided by the cylinder volume, following the methodology of Teixeira et al. (2017). For the Soil Management Assessment Framework (SMAF), soil organic carbon (SOC) was selected as the biological indicator, following Cherubin et al. (2016), because it reflects the amount of organic matter available to sustain soil biological activity and ecosystem functioning.

The soil organic carbon stock (SOC stock) for each sampled layer was calculated using soil organic carbon (SOC), bulk density (D_b), and layer thickness according to Eq. (1):

$$\text{SOC stock (Mg ha}^{-1}\text{)} = \text{SOC (g kg}^{-1}\text{)} \times D_b \text{ (Mg m}^{-3}\text{)} \times \text{layer thickness (cm)} / 10$$

where SOC stock is the soil organic carbon stock (Mg ha^{-1}), SOC corresponds to the total organic carbon (g kg^{-1}), D_b is the soil bulk density (Mg m^{-3}), and layer thickness is the depth of each sampled soil layer (cm).

2.4 Soil health assessment

Soil health was assessed using the Soil Management Assessment Framework (SMAF), following the three-step approach described by Bünemann et al. (2018): (i) selection of a minimum dataset, (ii) interpretation of measured soil indicators, and (iii) integration of indicator scores into an overall soil health index. A minimum dataset consisting of five indicators was selected: soil pH, available phosphorus (P), and available potassium (K) to represent the chemical dimension; soil bulk density (D_b) to represent the physical dimension; and soil organic carbon (SOC) to represent the biological dimension (Cherubin et al. 2016; Lisboa et al. 2019; Nunes et al. 2020b; Simon et al. 2022; Brichi et al. 2023). These indicators have been widely adopted to assess soil health across contrasting edaphoclimatic conditions, including agricultural systems in the United States, Europe, China, and Brazil, owing to their sensitivity to changes in land use and management practices (Oliveira et al. 2024).

In the second step, the measured values of each indicator were transformed into unitless scores ranging from 0 to 1 using SMAF nonlinear scoring functions. The scoring functions were parameterized using site-specific classification factors, including soil taxonomy, mineralogy, texture, climate, slope, and the analytical method used to determine available P (Wienhold et al. 2009). A texture class factor of 2 was assigned for scoring D_b and SOC. For D_b , the mineralogy factor was set to 3, representing soils dominated by 1:1 clay minerals and Fe and Al oxides. For SOC, the climate factor was set to 1, corresponding to regions with ≥ 170 growing degree days and ≥ 550 mm of mean annual precipitation, while the organic matter factor was set to 4, indicating soils with low organic matter content. Available P, determined using the Mehlich-1 extraction method, was interpreted using class 5. For this indicator, a slope factor of 2 (2–5% slope) and a tropical weathering factor of 2 were adopted. The scoring algorithms, fixed parameters, and site-specific classification factors used for each indicator are presented in Table 3.

In the third stage, the individual indicator scores were integrated into a single Soil Health Index (SHI) using a weighted additive approach (Eq. (2)):

$$\text{SHEu} = \sum S_i W_{eu} \text{ (2)}$$

SHEu $\rightarrow$ Final index (e.g., Soil Health Evaluation or Soil Health – unit: eu). It is the aggregate value that summarizes several variables into a single number.

$\sum$ → Summation symbol, indicating that the calculation is done by adding several terms.

S_i → the score assigned to i th soil health indicator (e.g., D_b , pH, organic carbon, phosphorus, etc.).

W_{eu} → Weight assigned to the corresponding indicator i for the evaluation unit (eu), reflecting the relative importance of this indicator in the final index.

The indicators were grouped into three soil health components: chemical (pH, available P, and exchangeable K), biological (total organic carbon [TOC]), and physical (soil bulk density [D_b]). Following Cherubin et al. (2016), each component contributed equally (33.3%) to the final Soil Health Index (SHI), irrespective of the number of indicators within each component.

Table 3
Algorithms used for interpreting soil health indicators.

Indicator	Shape of the scoring curve	Algorithm	Fixed parameters	Specific local parameters	Factor class*
D_b	Less is better	$y = a - b * \exp(-c * D_b^d)$	$a = 0.994$	$b, c, d = f(\text{texture and mineralogy})$	Factors 2 (0.794) and 3 (9.35872)
pH	Optimal value	$y = a * [-(pH - b)^2 / (2 * c^2)]$	$a = 1.0$	$b, c = f(\text{crop})$	Factor 107 (5.5)
P (if $P \leq$ maximum)	Optimal value	$y = (a * b + c * P^d) / (b + P^d)$	$a = 9.26 \times 106$ $c = 1$ $d = 3.06$	$b = f(\text{crop, TOC, texture, and analytical method})$	Factors 107 (10.00), measured as a percentage, 2 (0.99) and 1 (2.00)
P (if $P >$ maximum)	Optimal value	$y = a - b \exp(-c * P^d)$	$a = 1$ $b = 4.5$ $d = -2$	$c = f(\text{slope, TOC, texture, and analytical method})$	Factors 2 (9000), measured as a percentage, 2 (0.99) and 1 (2.00)
K	More is better	$y = a * (1 - \exp(-b * K))$	$a = 1.08$ $b = -0.014$	$a, b = f(\text{crop})$	Factor 107 (1.075 and - 0.021)
TOC	More is better	$y = a / [1 + b * \exp(-c * \text{TOC})]$	$a = 1$ $b = 50.1$	$c = f(\text{organic matter, texture, and climate class})$	Factors 4 (3.81), 2 (1.25), and 1 (0.15)

Source: Andrews; Karlen; Cambardella, 2004. D_b : soil bulk density; P: phosphorus; K: potassium; TOC: total organic carbon; * The threshold value is specific to the conditions of this study and may vary according to site characteristics, such as soil type and climate.

2.5 Statistical analyses

Analysis of variance (ANOVA) was used to evaluate the effects of land use and management systems on individual SMAF indicator scores and the overall Soil Health Index (SHI). Prior to the analyses, the assumptions of normality of residuals and homogeneity of variances were verified. When significant effects were detected, means were compared using Tukey's honestly significant difference (HSD) test at the 5% significance level ($p < 0.05$). Principal component analysis (PCA) was performed to examine the relationships between soil health indicators and the evaluated management systems. All statistical analyses were conducted using R software (R Core Team 2024).

3 RESULTS

3.1 Soil quality indicators

Compared with NV, the agricultural management systems exhibited improvements in the chemical (pH, P, and K), physical (D_b), and biological (TOC) indicators of soil health, demonstrating that integrated and conservation-oriented management practices have enhanced soil health over time (Table 4).

Table 4

Average values of physical (soil density), chemical (pH, P, K) and biological (total organic C) soil health indicators in the 0–10, 10–20, and 20–30 cm layers, in integrated crop-livestock (ICL), integrated livestock-forestry (ILF), no-tillagesoybean cultivation (NT), managed pasture (MP), and native vegetation (NV) systems, in eastern Maranhão, Brejo, Maranhão, Brazil, 2024.

	Chemical			Physical	Biological
Management systems	pH	P	K	D _b	TOC
	----- mg dm ^{- 3} -----			Mg m ⁻³	g kg ^{- 1}
	0–10 cm				
ICL	5.42 a	42.29 a	23.46 a	1.37 b	15.4 b
ILF	4.89 b	30.28 a	27.37 a	1.42 b	24.3 a
NT	4. 57 c	46.94 a	31.28 a	1.37 b	16.9 b
MP	4.81 b	28.2 a	23.46 a	1.50 a	12.3 c
NV	4.28 d	3.45 b	7.82 b	1.31 b	12. 2 c
	10–20 cm				
ICL	4.88 a	20.26 b	7.82 b	1.46 a	11.4 b
ILF	4.63 b	14.66 b	15.64 a	1.45 a	22.7 a
NT	4.24 c	38.21 a	15.64 a	1.47 a	14.3 b
MP	4.65 b	8.44 b	7.82 b	1.50 a	12.7 b
NV	4.11 c	2.89 b	3.91 b	1.38 b	15.1 b
	20–30 cm				
ICL	4.41 a	10.40 b	7.82 b	1.42 b	12.8 b
ILF	4.45 a	13.66 a	11.73 a	1.43 b	21.9 a
NT	4.21 b	21.11 a	11.73 a	1.45 b	13.8 b
MP	4.49 a	6.67 b	3.91 b	1.52 a	16.0 b
NV	4.0 b	3.7 b	3.12 b	1.36 b	11.4 b

Within each soil depth, means followed by the same letter within a column do not differ significantly according to Tukey's honestly significant difference (HSD) test ($p < 0.05$)

Soil pH varied significantly among management systems and soil depths (Table 4). In the 0–10 cm layer, the highest pH was observed under ICL (5.42), followed by ILF (4.89), MP (4.81), and NT (4.57), whereas

NV exhibited the lowest value (4.28). A similar pattern was observed in the 10–20 cm depth, ICL exhibited the highest pH (4.88), followed by MP (4.65) and ILF (4.63), whereas NT (4.24) and NV (4.11) showed the lowest values. In the 20–30 cm depth, soil pH ranged from 4.00 under NV to 4.49, under MP.

Available phosphorus (P) concentrations were consistently higher in the managed systems than in NV. In the 0–10 cm layer, NT (46.94 mg dm⁻³) and ICL (42.29 mg dm⁻³) exhibited the highest P concentrations, followed by ILF (30.28 mg dm⁻³) and MP (28.20 mg dm⁻³), whereas NV contained only 3.45 mg dm⁻³. At 10–20 cm, NT maintained the highest P concentration (38.21 mg dm⁻³), while the remaining systems ranged from 2.89 to 20.26 mg dm⁻³. In the 20–30 cm layer, NT (21.11 mg dm⁻³) and ILF (13.66 mg dm⁻³) again presented the highest values, whereas NV and MP exhibited the lowest concentrations.

Exchangeable K followed a pattern similar to that of P. In the 0–10 cm layer, NT showed the highest K concentration (31.28 mg dm⁻³), followed by ILF (27.37 mg dm⁻³) and ICL (23.46 mg dm⁻³), while NV exhibited the lowest concentration (7.82 mg dm⁻³). At the deeper layers, ILF and NT consistently maintained the highest K concentrations.

Soil bulk density (D_b) was highest under MP in the 0–10 cm layer (1.50 Mg m⁻³). Lower values were observed under ICL and NT (1.37 Mg m⁻³), whereas ILF presented an intermediate value (1.42 Mg m⁻³) and NV the lowest value (1.31 Mg m⁻³). In the 10–20 and 20–30 cm layers, D_b ranged from 1.36 to 1.52 Mg m⁻³, with MP consistently exhibiting the highest values.

Total organic carbon (TOC) was greatest under ILF at all evaluated depths, reaching 24.3, 22.7, and 21.9 g kg⁻¹ in the 0–10, 10–20, and 20–30 cm layers, respectively. In contrast, TOC in the remaining management systems ranged from 12.2 to 16.9 g kg⁻¹ in the surface layer, indicating lower carbon accumulation than under ILF.

3.2 Soil organic carbon stocks

Total organic carbon (TOC) stocks in the 0–30 cm soil profile differed significantly among the evaluated management systems (Fig. 2). The ILF system exhibited the highest TOC stock (98.86 Mg ha⁻¹), significantly exceeding those of the other management systems ($p < 0.05$). In contrast, NT (64.56 Mg ha⁻¹), MP (62.15 Mg ha⁻¹), ICL (56.24 Mg ha⁻¹), and NV (52.60 Mg ha⁻¹) did not differ significantly from one another, although all exhibited numerically lower TOC stocks than ILF.

3.3 Soil Health Index

The Soil Health Index (SHI), integrating biological, chemical, and physical components, was evaluated at the 0–10, 10–20, and 20–30 cm soil depths (Fig. 3).

The chemical component of the SHI varied among management systems across all soil depths (Fig. 3). In the 0–10 cm layer, the highest scores were observed under NT, whereas ICL, ILF, and MP exhibited lower values (Fig. 3a). A similar pattern was observed in the 10–20 cm layer, where NT (0.81) and NV (0.72) showed the highest chemical scores and did not differ significantly from one another (Fig. 3b). In the 20–30 cm layer, NT and NV again presented the highest chemical scores (0.85), while the remaining management systems exhibited lower values (Fig. 3c). The physical component showed a contrasting pattern, with MP consistently exhibiting the lowest scores across all soil depths, whereas NV maintained the highest values (Fig. 3).

3.4 Overall Soil Health Index

The overall SHI differed significantly among the evaluated management systems across the three soil depths (Fig. 4).

In the 0–10 cm layer, NT exhibited the highest overall SHI (0.80), although it did not differ significantly from ICL (0.74), ILF (0.73), or NV (0.71) (Fig. 4a). Managed pasture (MP) presented the lowest SHI (0.65), differing significantly from NT, ICL, and ILF, but not from NV. At the 10–20 cm depth, NT (0.73), NV (0.73), and ICL (0.72) exhibited the highest SHI values and did not differ significantly from one another. These systems showed significantly higher SHI values than ILF (0.66) and MP (0.65) (Fig. 4b). In the 20–30 cm layer, ICL (0.75) and NT (0.74) presented the highest SHI values and did not differ significantly from each other. Both systems exhibited significantly higher SHI than MP (0.67). Integrated livestock-forestry (ILF; 0.72) and native vegetation (NV; 0.72) showed intermediate values, not differing significantly from either the highest-scoring systems (ICL and NT) or MP (Fig. 4c).

3.5 Principal component analysis of soil attributes in different land use systems and depths.

Principal component analysis (PCA) revealed consistent associations between soil health indicators and land-use systems across the three soil depths (0–10, 10–20, and 20–30 cm) (Fig. 5).

In the 0–10 cm layer, the first two principal components explained 54.1% of the total variance (Dim1 = 31.9% and Dim2 = 22.2%). The PCA revealed a clear separation between native vegetation (NV) and the agricultural management systems (Fig. 5a). NV was associated with the negative side of Dim1, whereas the managed systems, particularly NT and ILF, were grouped on the positive side of this axis. Available phosphorus (P) and exchangeable potassium (K) showed strong positive loadings on Dim1 and were the main variables responsible for discriminating the agricultural systems. In contrast, D_b and pH were positively associated with Dim2, whereas total organic carbon (TOC) was negatively associated with this axis. ICL occupied an intermediate position, indicating transitional soil characteristics between the conservation-oriented and more intensively managed systems.

At the 10–20 cm depth, the first two principal components accounted for 61.4% of the total variance (Dim1 = 32.6% and Dim2 = 28.8%) (Fig. 5b). The pattern of association among the soil health indicators changed with depth. TOC showed a strong negative loading on Dim1 and was closely associated with

ILF, whereas available P and D_b were positively associated with this axis, primarily distinguishing NT. Exchangeable K contributed mainly to Dim2, while pH exhibited limited discriminatory power. Native vegetation remained clearly separated from the managed systems, reinforcing its distinct soil characteristics.

In the 20–30 cm layer, the first two principal components explained 61.3% of the total variance (Dim1 = 36.9% and Dim2 = 24.4%) (Fig. 5c). The greater dispersion of sample scores indicated increased heterogeneity at depth. TOC and pH showed strong positive associations with Dim1 and Dim2, respectively, and were closely related to ILF. Available P and exchangeable K remained positively associated with Dim1, although their contribution was weaker than in the upper soil layers. D_b was negatively associated with Dim2, suggesting greater soil compaction in some management systems. NT was associated with higher P concentrations, whereas NV remained clearly separated from the managed systems, reflecting its distinct chemical and physical soil characteristics.

Overall, Dim1 primarily represented a soil fertility gradient driven by available P and exchangeable K, whereas Dim2 was associated mainly with soil structural and acidity-related attributes, represented by D_b and pH. These relationships varied with soil depth, reflecting the influence of land-use and management practices on soil health.

4 DISCUSSION

Soil quality indicators

Different land-use and management systems significantly altered the chemical, physical, and biological attributes of the soil, with direct implications for soil fertility and overall soil health. In highly weathered soils, such as the Yellow Argisols of northeastern Brazil, native vegetation typically exhibits low soil pH (approximately 4.28) because of intense base leaching and the predominance of exchangeable aluminum (Lima et al. 2024). Under agricultural management, liming effectively increases soil pH, even when Ca^{2+} and Mg^{2+} concentrations remain below optimal levels.

In contrast to the present findings, Dias et al. (2019) reported that the conversion of native Cerrado to agricultural land reduced soil chemical fertility through declines in total organic carbon (TOC), labile carbon fractions, and base saturation. These contrasting results highlight that the effects of land-use change on soil health depend largely on management practices, reinforcing the importance of conservation-oriented systems for maintaining soil quality (Tahat et al. 2020).

The greater availability of P in the managed systems reflects both the legacy of phosphate fertilization and the low mobility of this nutrient in tropical soils. Under conservation practices such as NT and integrated systems, the absence of soil disturbance promotes P stratification through localized fertilizer application and the continuous deposition of crop residues. Consequently, surface P concentrations tend to increase over time, as reported by Soares et al. (2024). Nevertheless, the higher P concentrations observed throughout the soil profile in the managed systems indicate not only the residual effect of

fertilization but also the contribution of nutrient cycling by cultivated plants. These results suggest that long-term conservation practices, particularly NT and integrated production systems, are effective in maintaining soil P stocks and enhancing the long-term stability of soil fertility.

A similar pattern was observed for exchangeable K, whose concentrations were consistently higher in the managed systems than in native vegetation owing to fertilizer inputs and more efficient nutrient cycling. The decline in K concentration with soil depth agrees with its moderate mobility in tropical soils (Artuso et al. 2024). However, the relatively high K concentrations in the ILF system indicate enhanced nutrient cycling promoted by the tree component. Deep-rooted trees recover nutrients from subsurface layers and redistribute them to the soil surface through litter deposition, thereby improving nutrient availability throughout the soil profile (Friedel et al. 2021; Steinfeld et al. 2024; Nascimento et al. 2024). In addition, the presence of grazing animals accelerates nutrient recycling through manure deposition, further increasing K availability and contributing to the maintenance of soil fertility (Ferreira et al. 2011; Farias et al. 2020).

The higher D_b observed under MP across all soil depths is likely attributable to livestock trampling, which increases soil compaction and reduces pore space. Continuous grazing has been shown to increase soil bulk density by up to 20%, thereby decreasing water infiltration and restricting root growth (Trimarco et al. 2023; Henrique Dias Batista et al. 2024), supporting the results obtained in the present study. Moreover, the long-term absence of soil disturbance in this system may have intensified natural compaction processes, particularly because the cohesive Yellow Argisols of the region are inherently prone to soil densification (Corrêa et al. 2008; Lima Neto et al. 2009).

In contrast, conservation-oriented management systems, particularly ICL and ILF, exhibited lower soil bulk density, highlighting the beneficial effects of crop diversification, root system heterogeneity, and greater biological activity.

These systems promote biopore formation, improve soil aggregation, and mitigate compaction over time (Possamai et al. 2021; Nascimento Júnior et al. 2023). Likewise, the low bulk density observed under NV reflects the combined effects of high biological diversity, continuous organic matter inputs, and the absence of mechanical disturbance. In the ILF system, the presence of both tree and livestock components likely further enhanced soil structural quality by increasing root distribution and nutrient cycling. Collectively, these findings demonstrate that integrated and conservation-oriented management practices are effective in preserving soil physical quality and supporting the long-term sustainability of agricultural production (Bonetti et al. 2019).

The higher TOC stocks observed under ILF system throughout the soil profile highlight its strong potential for carbon sequestration and climate change mitigation. The inclusion of the tree component increases carbon inputs through litterfall, root turnover, and rhizodeposition, resulting in greater accumulation of organic matter both at the soil surface and in deeper layers (Cardinael et al. 2018). This mechanism is particularly important in sandy soils, where soil organic matter plays a critical role in maintaining soil structure, enhancing nutrient retention, and improving overall soil functioning (Matos et

al. 2025). In these soils, the stabilization of TOC depends largely on the interaction between pedogenic processes and conservation management practices that promote aggregate formation and the physical protection of organic matter within microaggregates (De Alencar et al. 2024). Previous studies conducted in tropical environments have shown that integrating trees into agricultural systems can increase TOC stocks by 30–50% compared with conventional production systems (Oliveira et al. 2024). Consequently, integrated livestock-forestry systems not only enhance carbon storage but also contribute to more sustainable agricultural production and climate change mitigation (Brewer et al. 2020; Silva et al. 2024).

Soil health assessment

The biological component, represented by TOC, consistently exhibited the highest scores across all soil depths, underscoring its fundamental role in maintaining soil health under tropical Cerrado conditions. Total organic carbon is among the soil health indicators most sensitive to changes in land use and management, responding rapidly to shifts in agricultural practices (Bhattacharya et al. 2020). Moreover, TOC strongly influences the chemical, physical, and biological functioning of soils (Liptzin et al. 2022; Lu et al. 2024), explaining its substantial contribution to the overall SHI. In contrast, the greater variability observed for the chemical component reflects differences in fertilizer inputs and nutrient management among production systems. As highlighted by Nath et al. (2024), the vertical distribution of nutrients in agricultural soils is strongly influenced by management practices and differs markedly between conventional and conservation systems.

The contrasting responses of the biological and chemical components emphasize that soil health in tropical agricultural systems depends on the integrated functioning of physical, chemical, and biological processes rather than on individual indicators alone. Consequently, the combined assessment of these components provides a more comprehensive evaluation of soil functionality and represents a robust framework for guiding sustainable soil management (Bünemann et al. 2018).

The overall SHI further demonstrated that conservation-based management systems, particularly NT and integrated production systems, maintained soil health at levels comparable to those observed under native vegetation. This finding highlights the capacity of conservation agriculture to preserve essential soil functions, including nutrient cycling, biological activity, carbon storage, and structural stability (Nunes et al. 2020a; Guo 2021; Agyei B et al. 2024). Collectively, these results demonstrate that conservation-oriented management is an effective strategy for enhancing the sustainability of agricultural production in tropical sandy soils by improving soil fertility, increasing carbon sequestration, and maintaining soil health over the long term.

Principal component analysis

Principal component analysis (PCA) revealed clear vertical stratification of soil attributes and a distinct separation between NV and the agricultural management systems. In the surface layer (0–10 cm), the strong association of available P and exchangeable K with the agricultural systems, particularly NT and

ILF, reflects the cumulative effects of fertilizer application and nutrient cycling promoted by conservation-oriented management practices that minimize soil disturbance and favor nutrient stratification (Stellacci et al. 2021; Rathore et al. 2023; Silva et al. 2025). In contrast, the weak association of these nutrients with NV reflects the greater reliance of natural ecosystems on nutrient cycling through soil organic matter and litter decomposition.

The negative association between TOC and the second principal component in the surface layer indicates contrasting patterns of carbon dynamics among the evaluated management systems, likely reflecting differences in organic matter inputs and decomposition rates (Stellacci et al. 2021; Bishi et al. 2023).

The intermediate position of the ICL system suggests a more balanced relationship between carbon inputs and decomposition, resulting from the integration of crops and pastures, which may promote greater carbon stabilization in the soil (Peter-Jerome et al. 2022; Rathore et al. 2023). Collectively, these results highlight the importance of conservation-based management for maintaining soil fertility and quality, particularly in surface soil layers where biological activity, residue accumulation, and nutrient cycling are most intense.

In the 10–20 cm layer, TOC emerged as the primary variable discriminating the management systems, highlighting the increasing importance of carbon incorporation and stabilization processes with soil depth. Whereas carbon inputs in surface soils originate predominantly from aboveground residues, which decompose relatively rapidly, subsurface carbon is derived mainly from root biomass and rhizodeposition. Because these carbon inputs are deposited directly into deeper soil layers, where oxygen availability and microbial activity are generally lower, they are less susceptible to decomposition and contribute more effectively to the formation of stable organic matter and long-term carbon sequestration (Gale et al. 2000; Kätterer et al. 2011).

Root-derived carbon has been reported to be approximately 2.0–2.3 times more efficient at forming stable TOC than carbon derived from aboveground residues (Kätterer et al. 2011; Jackson et al. 2017). In the present study, two complementary mechanisms likely contributed to the greater differentiation of the management systems based on TOC in the subsurface. First, the long-term adoption of NT (approximately 20 years) minimized soil disturbance, promoting the stabilization of root-derived organic matter. Second, the ILF system provided continuous carbon inputs through the combined effects of trees, forage grasses, and livestock. Deep-rooted tree and grass species increased carbon deposition at depth (Cordeiro et al. 2015; Sarto et al. 2020), while grazing likely stimulated rhizodeposition by forage grasses, further enhancing carbon inputs to the subsurface soil (McSherry & Ritchie 2013).

In the 20–30 cm layer, the greater dispersion of sample scores indicates that the influence of management became more heterogeneous, reflecting the combined effects of soil texture, structural characteristics, and management history. Nevertheless, ILF remained closely associated with TOC and pH, indicating that the inclusion of trees promoted persistent improvements in subsurface soil quality through enhanced organic matter inputs, nutrient cycling, and root activity (Rosinger et al. 2023; Vogado

et al. 2024; Souza et al. 2024; Khosa et al. 2025). Likewise, the consistent separation of NV across all soil depths reinforces its role as an ecological reference for evaluating the effects of agricultural management on soil health.

Collectively, the results demonstrate that integrated production systems, particularly ICL and ILF, promote more pronounced improvements in soil chemical and physical attributes throughout the soil profile than the other evaluated management systems. These systems also enhance functional heterogeneity and favor carbon accumulation and stabilization in deeper soil layers, whereas management systems lacking a tree component tend to concentrate improvements primarily in the surface soil (Nicoloso et al. 2021; Morya et al. 2023; Villat et al. 2024). These findings highlight the potential of integrated production systems as a sustainable strategy for improving soil health and increasing long-term carbon sequestration in the Brazilian Cerrado.

5 CONCLUSION

Conservation-based management systems, particularly integrated livestock-forestry (ILF), integrated crop-livestock (ICL), and no-tillage (NT), improved the chemical, physical, and biological attributes of the soil, resulting in higher Soil Health Index (SHI) values than the other evaluated management systems. Across the soil profile, these systems maintained soil health at levels comparable to those of native vegetation, demonstrating that conservation-oriented management can preserve essential soil functions under agricultural production.

Among the evaluated systems, ILF exhibited the greatest total organic carbon (TOC) stocks throughout the soil profile, highlighting its potential to enhance carbon sequestration and improve soil quality. The integration of trees, forage species, and livestock increases aboveground and belowground biomass inputs, diversifies organic matter sources, and promotes greater carbon stabilization within the soil profile.

The long-term adoption of conservation practices further enhances these benefits by promoting the gradual accumulation of soil organic matter and improving soil chemical, physical, and biological quality. Therefore, for the sandy soils of the MATOPIBA region, integrated production systems, particularly those incorporating a tree component, represent a promising strategy for increasing carbon sequestration, while no-tillage and integrated crop-livestock systems effectively maintain soil health. Together, these systems provide sustainable alternatives for reconciling agricultural productivity with long-term soil conservation.

DECLARATIONS

Competing interests

The authors declare that they have no competing interests.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

All authors have read and approved the final version of the manuscript and consent to its publication.

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Data Availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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Figures

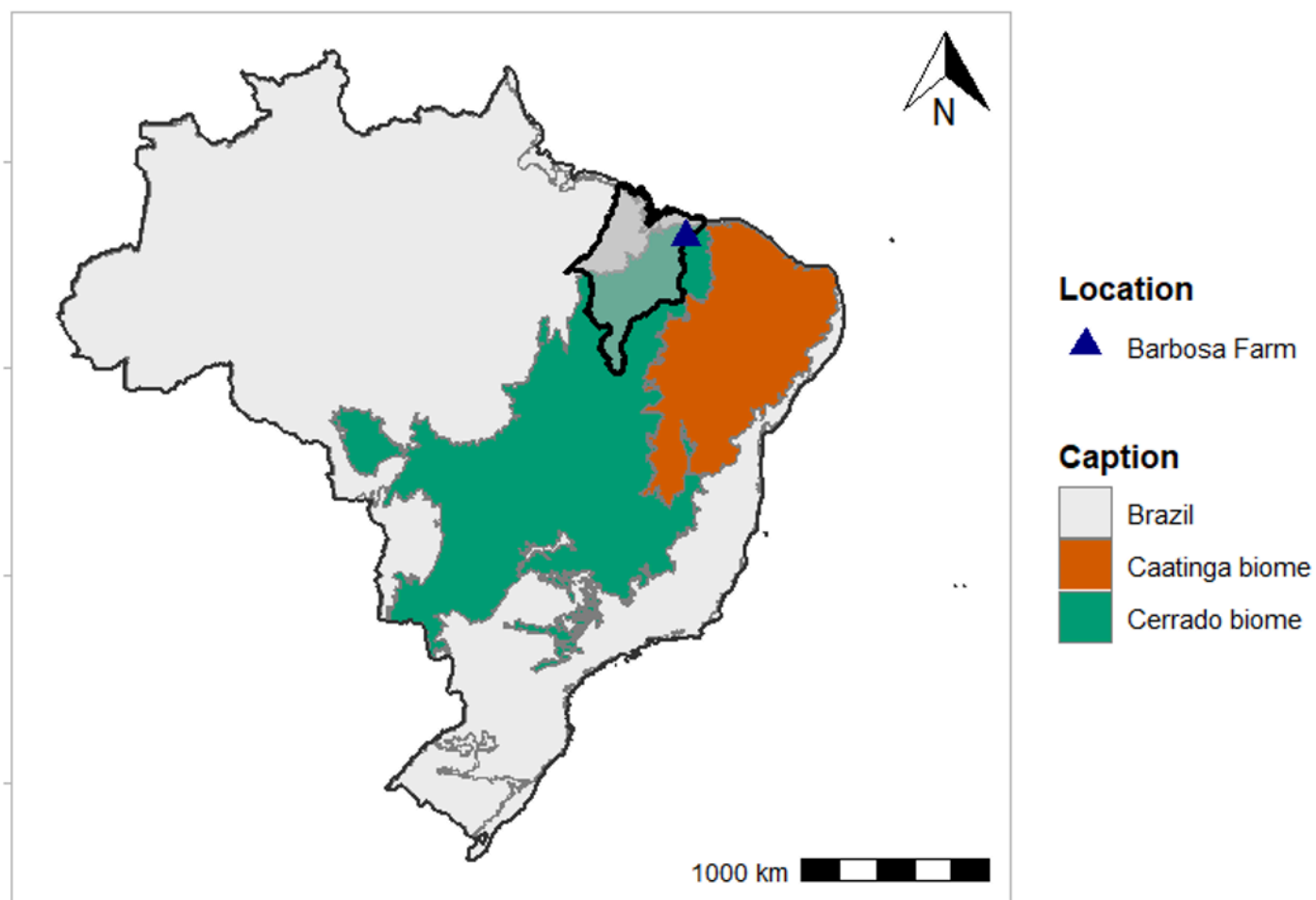


Figure 1

Location of the study area at Fazenda Barbosa, municipality of Brejo, eastern Maranhão state (Cerrado biome)

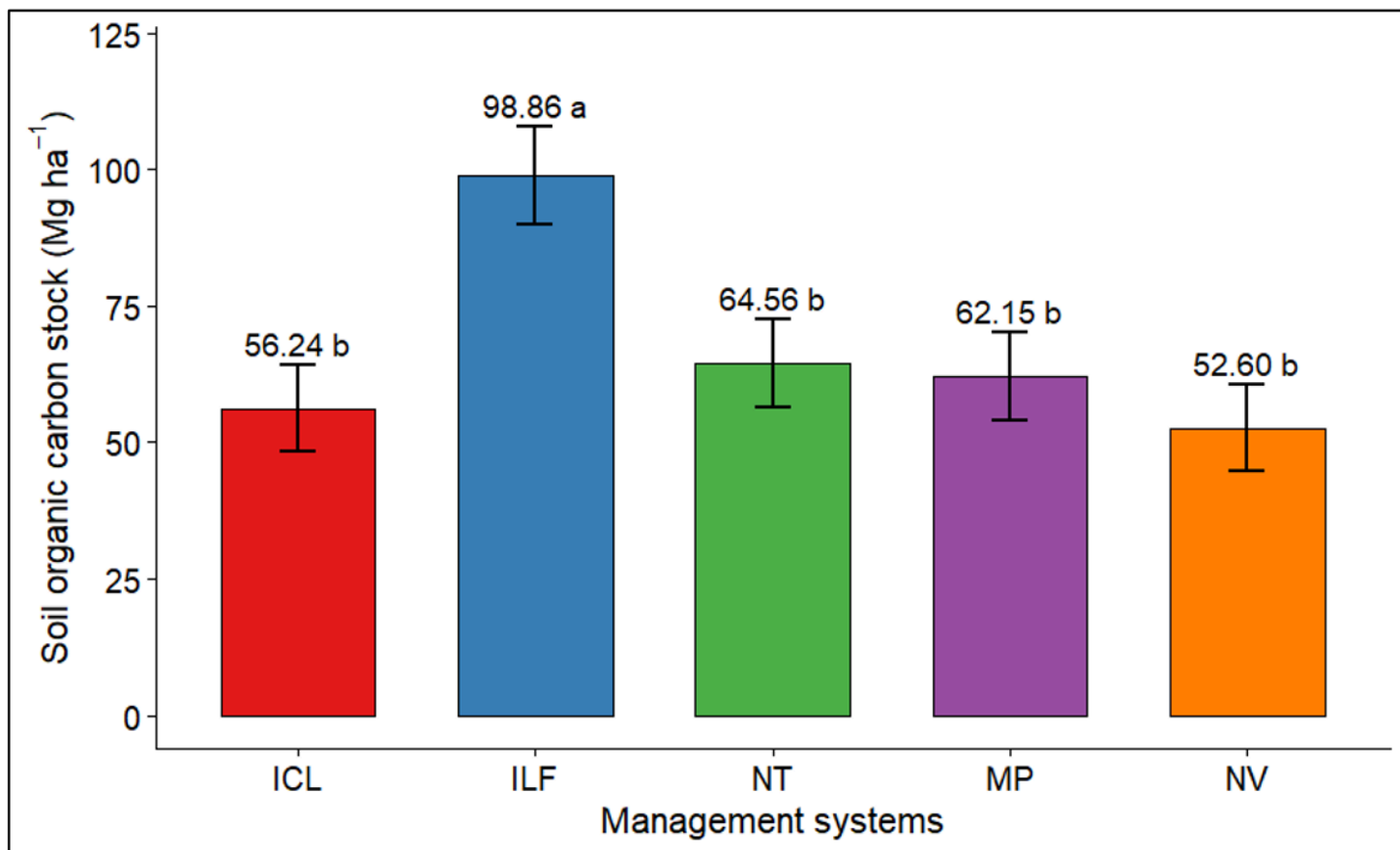


Figure 2

Total organic carbon (TOC) stocks (Mg ha⁻¹) in the 0–30 cm soil profile of a Yellow Argisol under integrated crop-livestock (ICL), integrated livestock-forestry (ILF), no-tillage (NT), managed pasture (MP), and native vegetation (NV) in Brejo, Maranhão, Brazil. Error bars represent the standard error of the mean (SE). Different letters indicate significant differences among management systems according to Tukey's honestly significant difference (HSD) test ($p < 0.05$)

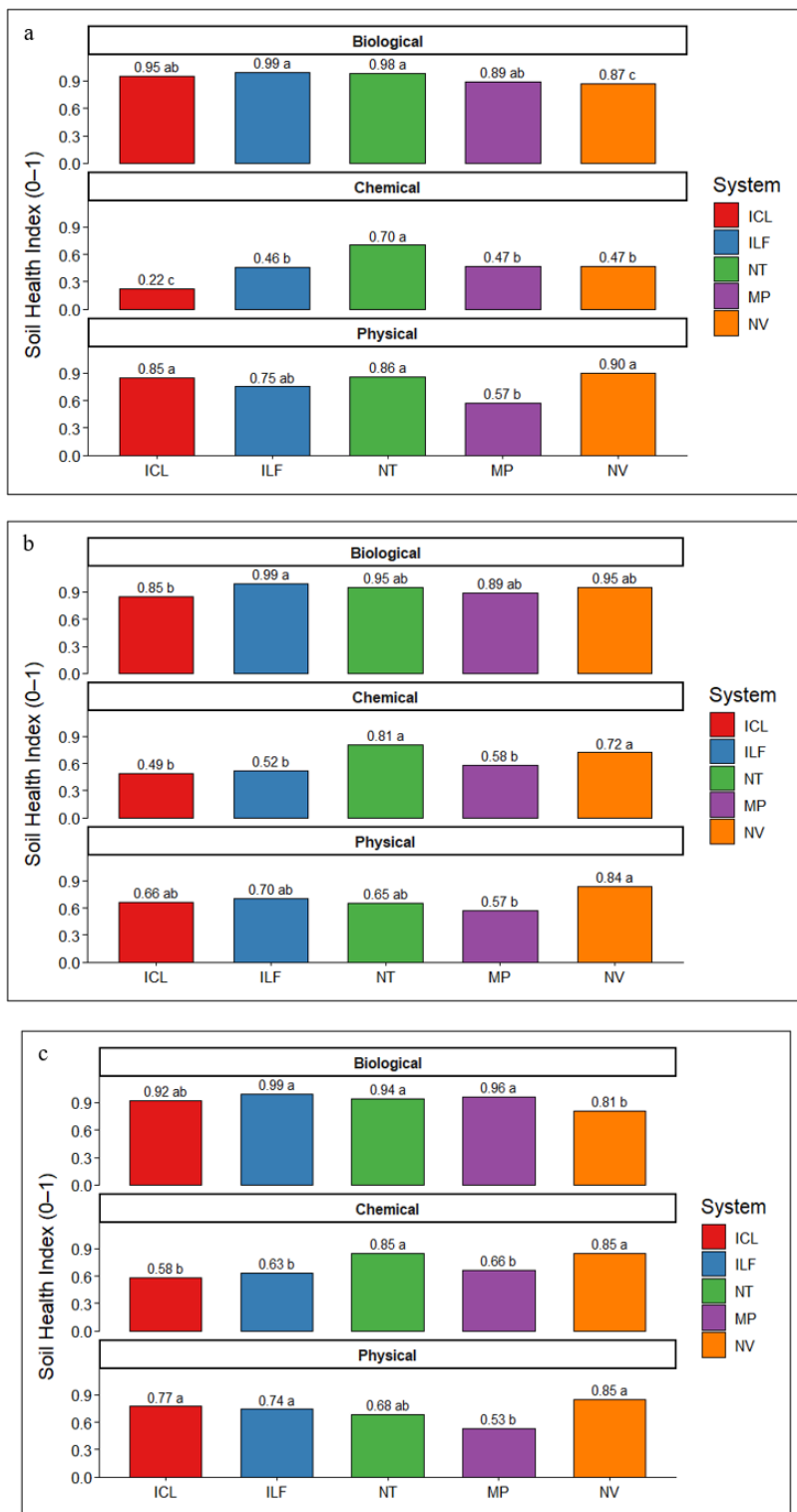


Figure 3

Soil Health Index (SHI) scores for the biological, physical, and chemical components at the 0–10 (a), 10–20 (b), and 20–30 cm (c) soil depths in a Yellow Argisol under integrated crop-livestock (ICL), integrated livestock-forestry (ILF), no-tillage (NT), managed pasture (MP), and native vegetation (NV) in Brejo, Maranhão, Brazil. Within each soil depth and soil health component, means followed by the same letter do not differ significantly according to Tukey's honestly significant difference (HSD) test ($p < 0.05$)

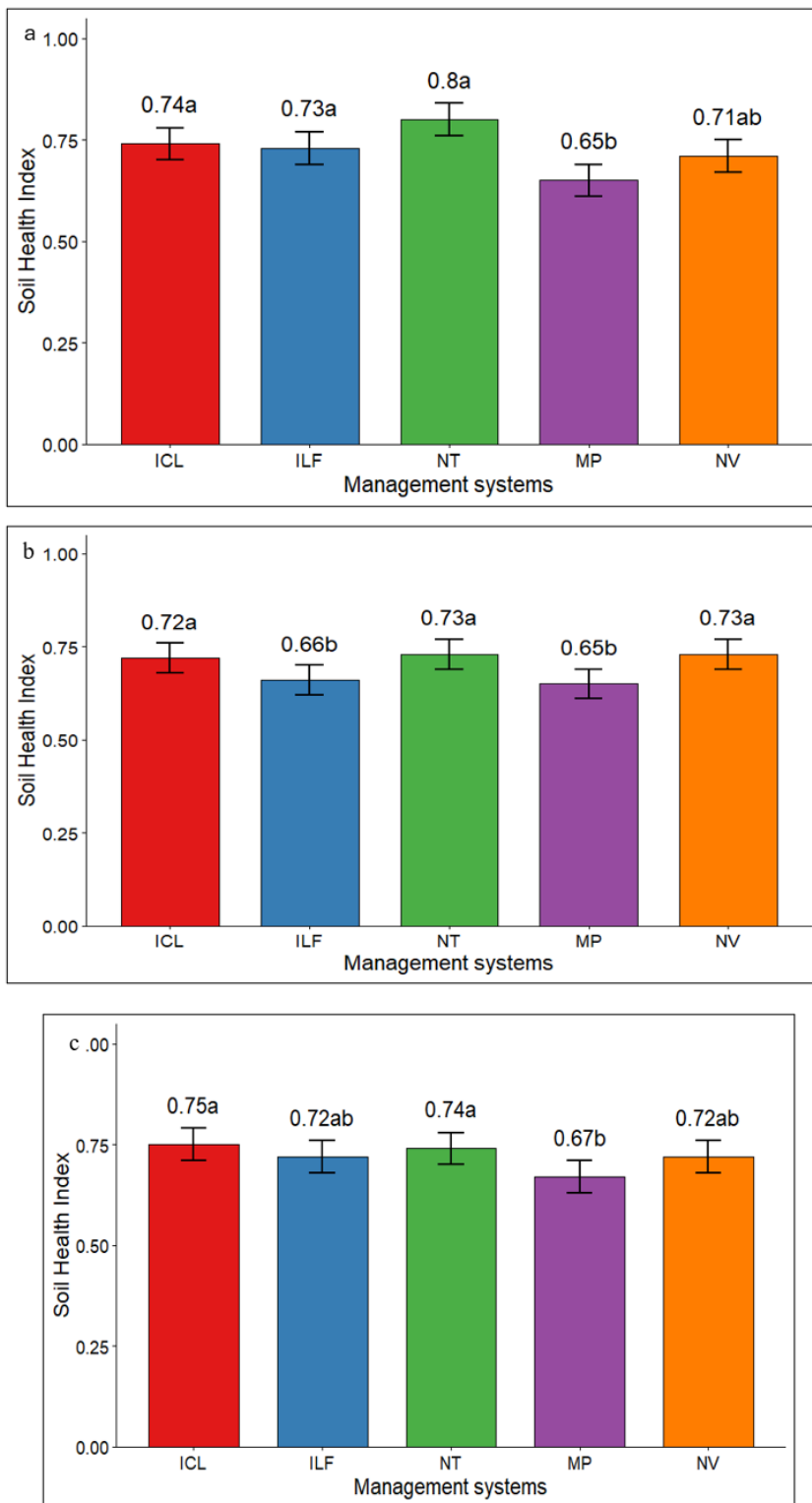


Figure 4

Overall Soil Health Index (SHI) at the 0–10 (a), 10–20 (b), and 20–30 cm (c) soil depths in a Yellow Argisol under integrated crop-livestock (ICL), integrated livestock-forestry (ILF), no-tillage (NT), managed pasture (MP), and native vegetation (NV) in Brejo, Maranhão, Brazil. Error bars represent the standard error of the mean (SE). Means followed by the same letter do not differ significantly according to Tukey's honestly significant difference (HSD) test ($p < 0.05$)

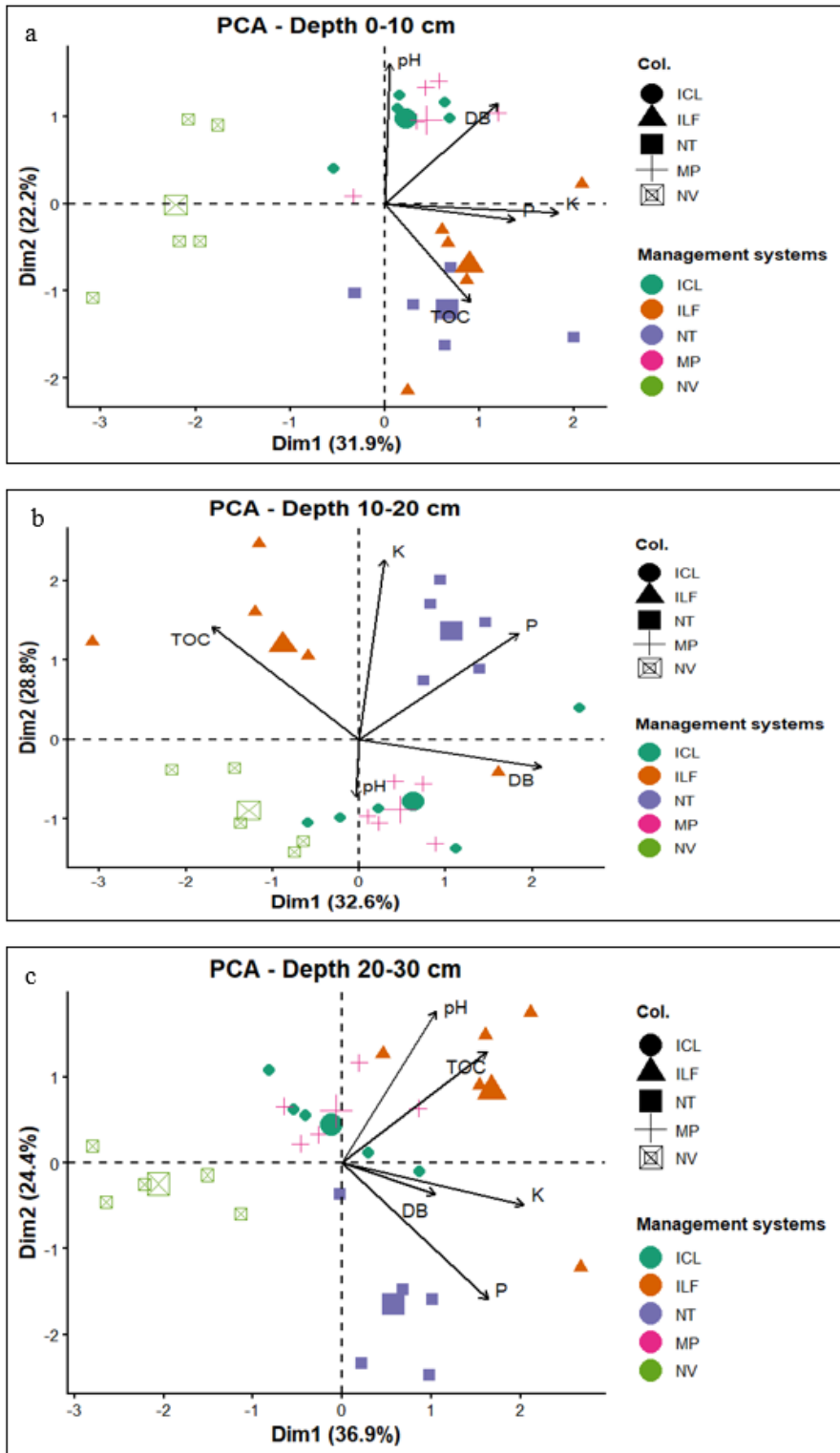


Figure 5

Principal component analysis (PCA) of soil health indicators at the 0–10 (a), 10–20 (b), and 20–30 cm (c) soil depths under integrated crop-livestock (ICL), integrated livestock-forestry (ILF), no-tillage (NT), managed pasture (MP), and native vegetation (NV) in Brejo, Maranhão, Brazil. Dim1 and Dim2 indicate the percentage of variance explained by the first and second principal components, respectively. Arrows

represent the soil health indicators pH, total organic carbon (TOC), available phosphorus (P), exchangeable potassium (K), and soil bulk density (D_B)