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Crop–Livestock Integrated Systems Improve Soil Health in Tropical Sandy Soils

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Abstract: The degradation of pastures in tropical regions, particularly in sandy soils, poses significant challenges to sustainable agricultural practices. Crop–livestock integration (CLI) systems have emerged as a promising strategy to restore these degraded soils. This study evaluated the impact of land-use transitions on soil health in Western São Paulo, Brazil, focusing on the conversion from pasture (*Urochloa brizantha*) to CLI systems with *U. brizantha* (CLI-u) and *M. maximum* (CLI-m). A comprehensive set of chemicals (pH, phosphorus, potassium), physical (aggregate stability, bulk density), and biological (β-glucosidase activity, soil organic carbon) indicators were assessed across four land-use types: native vegetation (NV), pasture (PA), CLI-u, and CLI-m. The Soil Management Assessment Framework (SMAF) was applied to calculate the Soil Health Index (SHI) across three soil depths (0–0.1 m, 0.1–0.2 m, 0.2–0.3 m). At the surface layer (0–0.1 m), PA and NV exhibited the highest SHI values (0.65 and 0.63, respectively), while CLI-m showed a lower SHI (0.56). In the subsurface layer (0.1–0.2 m), CLI-m and NV presented the highest SHI values (0.66 and 0.67, respectively), whereas PA and CLI-u had lower values (0.52 and 0.58). At the deepest layer (0.2–0.3 m), SHI values in CLI systems were comparable to NV (0.56), while PA recorded the lowest SHI (0.48). These results demonstrate that land-use transitions and management practices significantly affect soil health in sandy soils. The findings underscore the potential of CLI systems, particularly those incorporating *M. maximum*, to enhance biological and chemical soil health indicators in tropical agroecosystems. Further refinement of CLI management strategies is essential to optimize soil health recovery in sandy soil ecosystems.

Keywords: sustainable agriculture; soil carbon; agroecosystems; soil quality indicators; regenerative agriculture

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Academic Editor: Xufei Yang

Received: 30 December 2024
Revised: 24 January 2025
Accepted: 29 January 2025
Published: 31 January 2025

Citation: Vanolli, B.d.S.; Dias, H.B.; da Luz, F.B.; Lamparelli, R.A.C.; Magalhães, P.S.G.; Cherubin, M.R. Crop–Livestock Integrated Systems Improve Soil Health in Tropical Sandy Soils. *Agronomy* **2025**, *15*, 378. https://doi.org/10.3390/agronomy15020378

1. Introduction

Soil is crucial in ecosystem sustainability, acting as a key reservoir of carbon and a foundation for agricultural productivity. Globally, soils store approximately

2500 Pg of carbon in the top 0–1 m, highlighting their importance in regulating ecosystem functions [1–3]. Sustainable land management practices in tropical regions are critical for maintaining soil health, particularly in areas prone to degradation, such as sandy soils. Integrated agricultural systems, such as crop–livestock integration (CLI), have emerged as effective strategies for improving soil quality, restoring degraded areas, and enhancing agricultural resilience [4–7], as shown by studies that highlight the reduction in nitrous oxide and methane emissions in integrated systems [8–10]. The transition from low-productivity to high-productivity pastures through regenerative agricultural practices is crucial for enhancing soil health while providing additional economic value through sustainable land management [11]. For instance, the crop–livestock–forestry integrated (CLFI) systems in Brazil occupy over 17 million hectares, contributing significantly to both environmental sustainability and rural development [12,13]. These systems promote more efficient land use, reduce greenhouse gas emissions, and increase resilience in agricultural systems. In regions with sandy soils, where susceptibility to erosion and nutrient leaching is high, these benefits are crucial for mitigating soil degradation and promoting long-term sustainability.

Previous studies have demonstrated that crop–livestock integration (CLI) and crop–livestock–forestry integration (CLFI) systems are effective in improving soil health and reducing carbon emissions, especially in degraded areas [14,15]. In regions with sandy soils, these systems present unique challenges and opportunities. Integrated systems with forage species such as *U. brizantha* and *M. maximum* are increasingly used in these areas, given their adaptability to low-fertility soils and capacity to improve soil structure and nutrient cycling. The *U. brizantha* pasturage has been shown to enhance organic matter content and promote better water infiltration. In contrast, *M. maximum* pasturage is known for its deep rooting system, which helps reduce erosion and improve subsoil fertility. Additionally, studies have shown that such integrated systems can lead to significant improvements in soil quality and crop yields, particularly when combined with fertilization strategies and no-tillage practices [16]. These factors make integrated systems a valuable management strategy for improving the resilience of sandy soils in such regions.

The Soil Management Assessment Framework (SMAF) has been effectively applied to evaluate soil health under different land uses [17–21], revealing that conservation systems, such as no-tillage farming, can significantly enhance soil carbon content and chemical fertility [22]. Integrating biological indicators with physical and chemical assessments offers a more comprehensive understanding of impacts on soil health. For instance, including soil microbial diversity as a key indicator has proven essential to link CLI practices with improved nutrient cycling and enhanced soil resilience [23]. Ecological intensification practices within integrated systems have demonstrated positive impacts on multiple soil properties, such as soil structure, nutrient retention, and biological activity, especially in large-scale farmer experiments [24]. These findings highlight the potential of integrated systems to enhance soil health and sustainability, even in challenging environments such as sandy soils, which are less fertile and more prone to degradation [25,26]. Such conditions provide a unique opportunity to test the early-stage benefits of regenerative agricultural practices. This study evaluates the short-term effects of transitioning from degraded pastures to crop–livestock integrated (CLI) systems on soil health in sandy soils. Specifically, it aims to quantify improvements in biological, chemical, and physical soil health indicators across different land-use systems. The research focuses on regions highly vulnerable to erosion and nutrient leaching, addressing the gap in knowledge about the rapid effectiveness of CLI systems in restoring soil functionality. While long-term studies have shown the benefits of CLI systems in improving soil health and carbon sequestration [21–23], limited research has focused on their rapid effectiveness in these environments. We hypothesize that CLI systems lead to short-term improvements in soil health indicators (biological, chemical, and physical) in sandy soils. These improvements are expected due to the system's potential to enhance organic matter inputs, promote soil structure, and support nutrient cycling, thereby contributing to overall soil functionality and resilience.

2. Materials and Methods

2.1. Site Description and Experimental Design

This study was conducted on a commercial farm named "Campina", covering approximately 200 hectares, located in Cauiá, Western São Paulo state (21°38′15″ S; 51°54′57″ W, 310–380 m) (Figure 1). The farm is part of a private company that manages over 2000 hectares across various locations, with other farms employing different types and stages of CLI systems. The annual averages for rainfall and temperature during the monitoring period (October 2018 to April 2020) in this region were 2021.8 mm, with average minimum and maximum temperatures of 20.4 °C and 32.4 °C, respectively. These conditions classify the climate as tropical with a dry winter (Aw) according to the Köppen climate classification. Meteorological data were obtained from the Prediction of Worldwide Energy Resources (NASA/POWER; https://power.larc.nasa.gov/data-access-viewer/, accessed on 16 January 2024) [27].

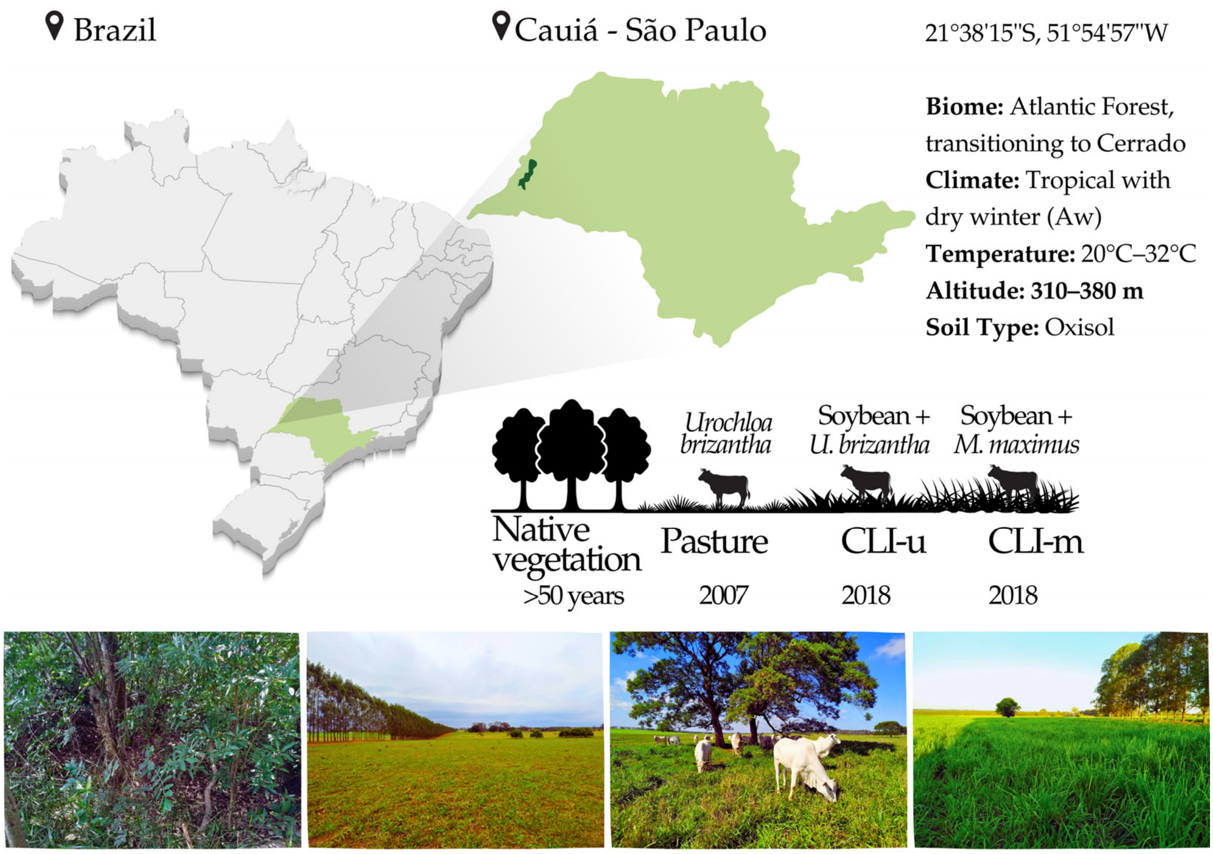

Figure 1. Geographical location and key characteristics of the study area in Cauiá, São Paulo, Brazil.

The soil in the study area derives from Bauru Group sandstone from the Cretaceous period [28] and is dominated by kaolinite in the clay fraction [29]. The slopes range from 3 to 7%, classified as "gently sloping" according to USDA guidelines [30]. The soil texture is predominantly sandy loam, with clay contents ranging from 22 to 241 g kg^{-1}. The soil is classified as an Oxisol with sandy texture, according to the USDA Soil Taxonomy system [31].

From 2007 to 2018, the area was primarily used for livestock farming with a monoculture of *Urochloa brizantha* (Marandu palisade grass). In October 2018, the area transitioned to a CLI system. The transition aimed to mitigate soil degradation and improve nutrient retention. Its effects were assessed through various soil health indicators, including physical, chemical, and biological properties, ensuring a comprehensive evaluation of the system's impact on soil health. Historical land-use details are provided in Table 1.

Table 1. History and description of management practices adopted in the study area.

Land Use	Description
Pasture	The pasture was established in 2007 with *Urochloa brizantha* (cv. Marandu). Soil correction included 0.5 t ha^{-1} of dolomitic limestone (56% $CaCO_3$, 42% $MgCO_3$), 400 kg ha^{-1} of reactive natural phosphate (35% P_2O_5, 12.5% citrate-soluble P_2O_5), and 200 kg ha^{-1} of N-P-K (4-21-15). From 2008 to 2018, maintenance fertilization comprised 300 kg ha^{-1} of N-P-K (20-10-10), applied when economically viable. Continuous grazing was maintained with heifers (~450 kg/animal) at a stocking rate of 1.6–1.8 AU ha^{-1}.
Crop–Livestock Integration Systems	From 2007 to 2018, the area was managed under a pasture monoculture system with *Urochloa brizantha* as the primary forage, exclusively used for livestock grazing. In 2018, the system transitioned to crop–livestock integration (CLI). To improve soil conditions, 1.5 t ha^{-1} of dolomitic limestone was applied in August, followed by 5 t ha^{-1} of chicken manure and organic compost in September (nutrient composition unknown). In November, the area was desiccated, mowed, and divided into four fields (R5–R8, ~50 ha each). Between November 18 and 22, 2018, soybean (*Glycine max*) cultivars (BRS 7380 RR, AS 3730 IPRO, NS 6700 IPRO) were sown using no-till management. Fertilization included 250 kg ha^{-1} of monoammonium phosphate (MAP, 11% N, 52% P_2O_5) and 150 kg ha^{-1} of potassium chloride (KCl, 60% K_2O). The first soybean harvest occurred in April 2019. Subsequently, the area was subdivided into 13 paddocks, and a mixed pasture of millet (*Pennisetum glaucum*) and *Urochloa ruziziensis* was established. Rotational grazing was implemented in three cycles during 2019, with stocking rates ranging from 57 to 205 AU ha^{-1}. Canopy uniformity was maintained by mowing fields R5 and R6 after the first grazing cycle. In November 2019, after the desiccation of the pasture, the second soybean crop was planted and harvested in April 2020. Post-harvest, the CLI system continued with mixed pastures incorporating millet and different forage species: *Urochloa brizantha* (cv. Marandu), *Megathyrsus maximus* (cv. Mombaça), and *U. brizantha* (cv. Piatã) combined with *Sorghum bicolor* (cv. Pódio) for silage. At the time of soil sampling, only permanent pastures (*U. brizantha* and *M. maximus*) remained, classified as CLI-u (with *U. brizantha*) and CLI-m (with *M. maximus*).
Native Vegetation	A fragment of Atlantic Forest (semi-deciduous submontane forest) was used as a reference site. The forest features a 20–30 m canopy with a mix of deciduous and evergreen species contributing organic matter through seasonal leaf shedding. The mid-layer hosts diverse epiphytes, such as orchids and bromeliads, which enhance nutrient cycling and microbial activity. The undisturbed site provided a baseline for soil health indicator comparisons.

Source: Original research data with information provided by the owner of the agricultural property.

A chronosequence approach was employed to evaluate the impacts of land-use changes under the following treatments: (i) A fragment of Atlantic forest, semi-deciduous sub-montane type, hereafter referred to as 'Native Vegetation' (NV), represents a natural and undisturbed baseline for soil health; (ii) conventional monoculture of *Urochloa brizantha* (Syn. *Brachiaria brizantha*), referred to as 'Pasture' (PA), representing low-intensity management and minimal soil restoration practices; (iii) crop–livestock integration with *Urochloa brizantha* cv. Marandu (CLI-u), and (iv) crop–livestock integration with *Megathyrsus max-*

imus (Syn. *Panicum maximum*) cv. Mombaça, referred to as '*Panicum*' (CLI-m) adopted to improve soil health in tropical regions.

2.2. Soil Sampling and Laboratory Analyses

Soil sampling was conducted at the end of October 2021 across the four different land uses, each with nine sampling points at a depth of 0.3 m, divided into three strata of 10 cm (0–0.1, 0.1–0.2, and 0.2–0.3 m), totaling 36 sampling points. At each point, disturbed, semi-disturbed, and undisturbed samples were collected for the analysis of various soil health indicators, including extracellular enzyme activity (β-glucosidase), organic carbon, soil bulk density, acidity, and soil nutrient content (Table 2).

Table 2. Soil health indicators, components, and functions.

Index	Component	Weight	Soil Functions	Soil Health Indicators
ISS	Physical	0.33	Root Growth and Architecture Habitat for Soil Organisms Water Purification and Regulation	BD AGG
	Chemical	0.33	Soil Acidity Regulation Nutrient Cycling	pH P K
	Biological	0.33	Carbon Sequestration Climate Regulation Habitat for Soil Organisms	SOC β-G

Note: BD: Bulk Density; AGG: Aggregate Stability; pH: pH ($CaCl_2$); P: Phosphorus; K: Potassium; β-G: β-Glucosidase; SOC: Soil Organic Carbon.

Extracellular enzyme activity was measured using the colorimetric method for β-glucosidase (β-G), as described by Tabatabai [32]. Potassium and phosphorus, essential chemical indicators of nutrient availability, were quantified using ion exchange techniques and spectrometric methods. Phosphorus was measured as available P through the resin extraction method, whereas potassium was determined as available K using ammonium acetate extraction. These procedures are consistent with standard protocols for evaluating nutrient availability in tropical soils, as established by [33]. Soil organic carbon (SOC) was quantified using the dry combustion method in a LECO® CN-2000 elemental analyzer, manufactured by LECO Corporation, located in St. Joseph, Michigan, USA, operating at furnace temperatures of 1100–1500 °C under pure oxygen conditions [34].

Bulk density (BD) was measured by drying the undisturbed soil samples at 105 °C and dividing the dry soil mass by the ring volume, following the method of Grossman [35]. Aggregate stability (AGG) was determined through an adapted method from Elliott [36]. Field-moist soil was passed through an 8 mm sieve by manually breaking up the soil along natural planes of weakness and then air-dried. The air-dried samples were rewetted for sixteen hours and wet-sieved using a vertical Yoder-type sieve column at 30 cycles per minute for 10 min. Soil was separated into three fractions: (i) large macroaggregates (>2 mm), (ii) small macroaggregates (0.250–2 mm), and (iii) microaggregates (0.053–0.250 mm). Aggregate stability was calculated as the percentage of macroaggregates. The measured values of soil health indicators are presented in Table 3.

Table 3. Soil health indicators and scores across various land uses and soil depths (0–0.1, 0.1–0.2, and 0.2–0.3 m).

Land Use	BD g cm^{-3}	BD Score	AGG	AGG Score	pH	pH Score	P mg dm^{-3}	P Score	K cmol$_c$ kg^{-1}	K Score	SOC g kg^{-1}	SOC Score	β-G µmol pNP g^{-1} h^{-1}	β-G Score
							0–0.1 m							
NV	1.3 ± 0	1	20.5 ± 1.9	0.7	4.6 ± 0.1	0.9	7.0 ± 0	0.9	75.0 ± 4.6	0.8	0.4 ± 0	0.1	36.6 ± 7.7	0.2
PA	1.7 ± 0	0.3	58.3 ± 3.4	1	5.1 ± 0.1	0.9	10.2 ± 1.2	0.9	63.5 ± 15.5	0.7	0.9 ± 0.1	0.7	29.1 ± 0.9	0.1
CLI-u	1.6 ± 0	0.5	37.3 ± 4.7	0.9	5.9 ± 0.1	0.9	16.2 ± 5.0	0.9	90.6 ± 15.1	0.8	0.5 ± 0.1	0.3	38.8 ± 3.9	0.2
CLI-m	1.6 ± 0	0.4	36.2 ± 4.4	0.9	6.0 ± 0.1	0.8	13.8 ± 2.2	1	70.2 ± 9.2	0.8	0.4 ± 0	0.2	31.4 ± 5.0	0.1
							0.1–0.2 m							
NV	1.3 ± 0	0.9	17.9 ± 3.4	0.7	4.2 ± 0	0.8	7.0 ± 0	0.9	38.8 ± 4.1	0.6	1.0 ± 0.1	0.7	39.1 ± 9.4	0.2
PA	1.7 ± 0	0.3	63.6 ± 2.5	1	4.9 ± 0.1	0.8	7.0 ± 0	0.9	43.1 ± 20.9	0.4	0.6 ± 0	0.3	17.5 ± 0.8	0
CLI-u	1.6 ± 0	0.5	37.6 ± 6.8	0.9	5.1 ± 0.1	0.8	9.4 ± 1.2	0.9	60.1 ± 6.7	0.7	0.7 ± 0.1	0.4	20.8 ± 2.6	0.1
CLU-m	1.6 ± 0	0.4	44.0 ± 2.8	1	5.0 ± 0.1	0.8	8.6 ± 0.5	0.9	71.8 ± 12.7	0.8	0.8 ± 0.1	0.6	55.2 ± 9.7	0.3
							0.2–0.3 m							
NV	1.4 ± 0	0.8	17.9 ± 3.5	0.7	4.2 ± 0.1	0.8	7.0 ± 0	0.9	32.1 ± 5.1	0.5	0.5 ± 0	0.3	33.3 ± 9.9	0.2
PA	1.7 ± 0	0.3	58.5 ± 3.9	1	4.7 ± 0.1	0.7	7.0 ± 0	0.9	21.3 ± 8.2	0.3	0.5 ± 0	0.2	12.8 ± 1.4	0
CLI-u	1.6 ± 0	0.4	20.2 ± 4.3	0.7	4.9 ± 0.1	0.8	7.0 ± 0	0.9	44.1 ± 8.7	0.6	0.4 ± 0	0.2	43.3 ± 8.6	0.2
CLI-m	1.5 ± 0	0.6	30.8 ± 4.6	0.8	4.8 ± 0.1	0.8	7.6 ± 0.5	0.9	56.7 ± 12.9	0.7	0.4 ± 0	0.2	46.3 ± 5.5	0.2

Note: NV: Native Vegetation; PA: Pasture; CLI-u: crop–livestock integration with *U. brizantha*; CLI-m: crop–livestock integration with *M. maximum*. Scores range from 0 to 1, where higher values indicate better soil health.

2.3. Soil Health Assessment

Soil health was assessed using the Soil Management Assessment Framework (SMAF) approach [37], which follows a three-step procedure: (1) selecting a minimum dataset; (2) interpreting measured indicators; and (3) integrating indicators into an overall index. In the first step, seven soil health indicators were selected: pH, phosphorus (P), and potassium (K) to represent chemical quality; AGG and BD to represent physical quality; and SOC and β-G to represent biological quality. These indicators are commonly used in soil health assessments worldwide [17–21,38].

In the second step, each indicator was scored by converting the measured values into scores ranging from 0 to 1, using non-linear scoring curves. The scoring curves were developed based on site-specific class factors, which included soil taxonomy, mineralogy, texture, climate, slope, and the analytical method used for measuring P [38,39]. The texture class (used for scoring AGG, BD, SOC, and β-G) was assigned a factor of 2. The mineralogy class (used for scoring AGG and BD) had a factor of 3, accounting for the dominance of 1:1 clays and Fe/Al oxides. The climate class (used for scoring SOC and β-G) was assigned a factor of 1, reflecting ≥170-degree days and ≥550 mm mean annual rainfall. The organic matter class (used for scoring AGG, SOC, and β-G) had a factor of 4, indicating low organic matter. The slope and weathering class (used for scoring P) had factors of 2 (for a slope of 2–5%) and 2 (for tropical soils), respectively. The Resin method (class 5) was used for scoring extractable P.

In the third step, all indicator scores were integrated into an overall Soil Health Index (*SHI*) using a weighted additive approach (Equation (1)):

$$SHI = \sum SiWi \tag{1}$$

Si represents the indicator score, and *Wi* represents the weighted value of the indicators. The indicators were weighted based on their chemical (pH, P, and K), biological (SOC and β-G), and physical (AGG and BD) components. Each component was assigned an equal weight (33.33%) in the final index, regardless of the number of indicators, following Cherubin et al. [40].

2.4. Data Analysis

The SMAF framework was further customized to reflect the unique conditions of the study region, including the sandy loam texture and low organic matter typical of tropical soils. Adjustments to scoring parameters, such as assigning texture and organic matter factors of 2 and 4, respectively, ensured an accurate reflection of local soil properties. This adaptability of SMAF makes it particularly suitable for evaluating soils prone to degradation, such as those in tropical environments.

Normalized scores (0–1) were calculated using SMAF's non-linear scoring curves for each indicator. Statistical analyses were performed to evaluate the effects of land management practices on soil health indicators. Analysis of variance (ANOVA) and Tukey's test were employed for mean comparisons. All data processing and visualization were conducted using R (version 3.5.2) with the ExpDes and tidy verse packages [41,42], and visualizations were created in Microsoft Excel 2019 [43].

3. Results

3.1. Soil Health Index in the 0–0.1 m Layer

The Soil Health Index (SHI) for native vegetation (NV) was 0.63, serving as the reference (Figure 2a). Conversion to pasture (PA) did not result in a statistically significant change, with PA showing an SHI of 0.65, likely due to an increase in soil organic carbon (SOC) in this layer (Figure 3a). However, the transition from PA to crop–livestock integration systems (CLI) resulted in a decline in SHI values. CLI-u and CLI-m recorded SHIs of 0.60 and 0.56, respectively, with the reduction in CLI-m being statistically significant ($p < 0.05$). The decline was attributed to reductions in biological components, particularly SOC.

Among biological indicators, PA exhibited the highest contribution to SHI (0.13), followed by CLI-u (0.08), CLI-m (0.05), and NV (0.05) ($p < 0.05$) (Figure 2a). This highlights an initial increase in biological contributions following the conversion from NV to PA, likely associated with SOC accumulation (Figure 3a).

3.2. Soil Health Index in the 0.1–0.2 m Layer

At this depth, NV recorded the highest SHI (0.67) across all systems (Figure 2b). Conversion to PA resulted in a sharp decline, with SHI dropping to 0.52. This reduction was driven by decreases in biological components such as SOC and β-glucosidase activity and physical indicators like aggregate stability (AGG) (Figure 3b).

Transitioning from PA to CLI systems led to partial recovery. CLI-m achieved an SHI of 0.66, nearly matching NV levels, while CLI-u showed a moderate recovery (0.58). CLI-m's superior performance was attributed to higher biological contributions (0.14), surpassing CLI-u (0.07) and PA (0.08). This indicates that CLI-m promotes improved soil biological properties, driven primarily by SOC and β-glucosidase activity (Figure 3b).

3.3. Soil Health Index in the 0.2–0.3 m Layer

In this deeper layer, NV exhibited an SHI of 0.56, which served as the baseline (Figure 2c). Conversion to PA resulted in a significant decline, with SHI dropping to 0.48, the lowest value across all systems and depths. This decrease was primarily associated with reduced potassium (K) availability in PA compared to NV (Figure 3c).

The shift from PA to CLI systems improved SHI values. CLI-m restored the SHI to 0.56, matching NV levels, while CLI-u recorded 0.51. Improvements in chemical and physical components, particularly bulk density (BD), contributed to this recovery. However, the physical component in CLI-u (0.18) remained lower than in CLI-m and NV (Figure 3c).

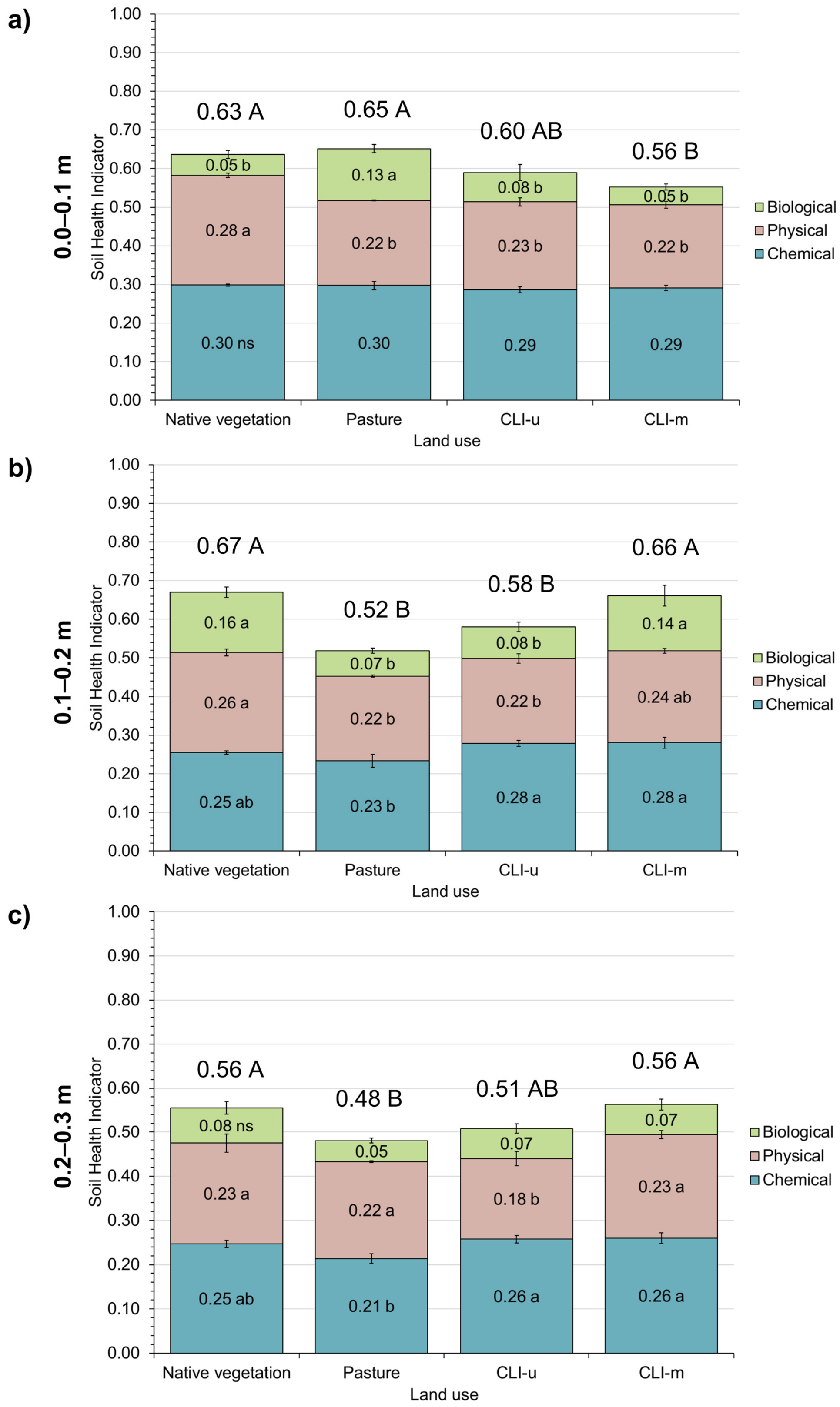

Figure 2. Soil Health Index with the weighted contribution of biological, physical, and chemical components at the 0–0.1 m (**a**), 0.1–0.2 m (**b**), and 0.2–0.3 m (**c**) soil layers in sandy soils under pasture (PA), crop–livestock integration with *U. brizantha* (CLI-u), crop–livestock integration with *M. maximum* (CLI-m), and native vegetation (NV). Mean values within each soil health component in the same soil layer followed by the same letter do not differ according to Tukey's test ($p < 0.05$). ns = not significant. Horizontal bars denote the mean standard error.

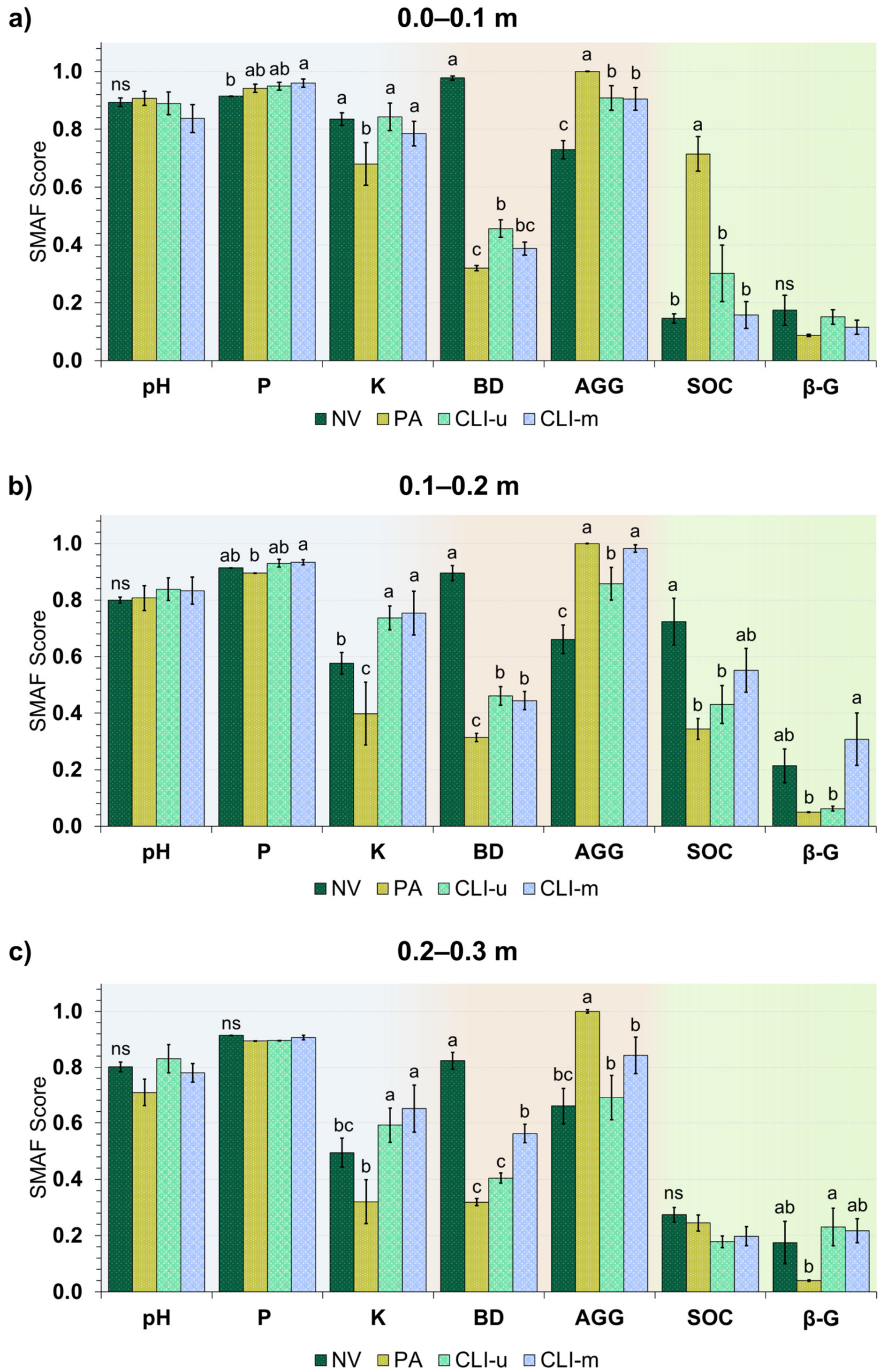

Figure 3. SMAF scores of pH (measured in $CaCl_2$), available phosphorus (P, mg dm^{-3}), available potassium (K, $cmol_c$ kg^{-1}), aggregate stability (AGG), bulk density (BD, g cm^{-3}), soil organic carbon (SOC, g kg^{-1}), and β-glucosidase (β-G) at the 0–0.1 m (**a**), 0.1–0.2 m (**b**), and 0.2–0.3 m (**c**) soil layers in sandy soils under pasture (PA), crop–livestock integration with *U. brizantha* (CLI-u), crop–livestock integration with *M. maximum* (CLI-m), and native vegetation (NV). Mean values within each soil health component in the same soil layer followed by the same letter do not differ according to Tukey's test ($p < 0.05$). ns = not significant. Horizontal bars denote the mean standard error.

3.4. Overall Soil Health Index (0–0.3 m Profile)

Across the soil profile, conversion from NV to PA resulted in an overall decline in SHI, from 0.62 to 0.54 (Figure 4). This reduction was most pronounced at the 0.2–0.3 m layer, where PA showed the lowest SHI values. Transitioning to CLI systems partially restored soil health. CLI-m increased SHI to 0.59, approaching NV levels, while CLI-u remained similar to PA (0.56, $p > 0.05$). Among the systems, only CLI-m approached NV's soil health, highlighting its potential for long-term soil restoration. Native vegetation (NV) soils operated at 62% of their full capacity. CLI-m and CLI-u operated at 59% and 56%, respectively. While CLI-m did not significantly outperform PA, it achieved soil health levels comparable to NV, indicating potential long-term benefits of *M. maximum*-based integration systems (Figure 4).

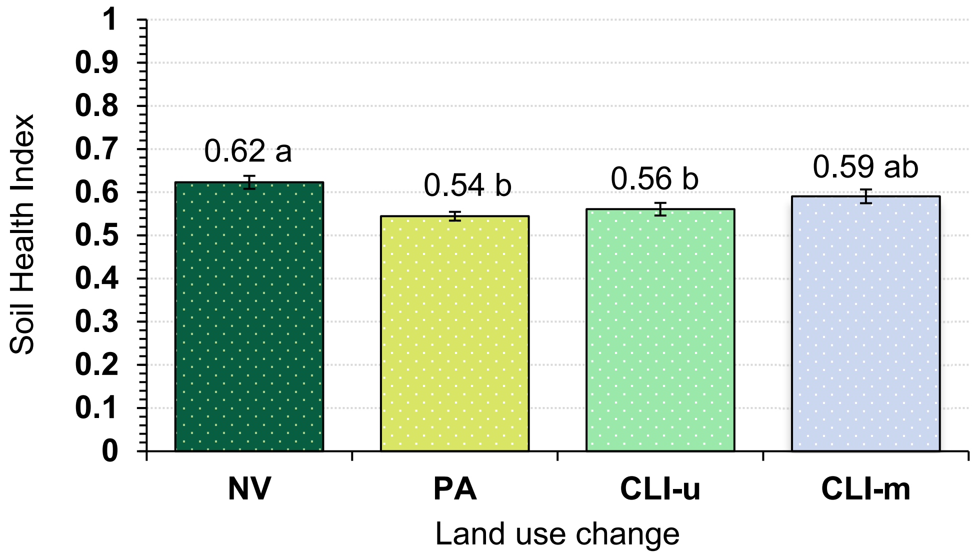

Figure 4. Overall Soil Health Index (0–0.3 m) in sandy soils under native vegetation (NV), pasture with *Urochloa brizantha* (PA), crop–livestock integration with *M. maximum* (CLI-m), and crop–livestock integration with *U. brizantha* (CLI-u). Mean values followed by the same letter do not differ according to Tukey's test ($p < 0.05$). ns = not significant. Horizontal bars denote the mean standard error.

4. Discussion

4.1. Impact of Land-Use Change on Soil Health

At the 0–0.1 m depth, the conversion of NV to PA did not significantly affect the SHI. However, PA systems demonstrated improved soil aggregation and higher SOC levels compared to both NV and CLI systems. These improvements are likely due to the accumulation of *U. brizantha* roots and organic matter at the surface, which enhance aggregation and carbon retention [15]. Despite these benefits, the increased bulk density observed in PA indicates a compaction process, potentially restricting root penetration and concentrating biomass near the surface [44]. While surface-level aggregation and SOC protection are advantageous, long-term risks such as compaction could impair soil functionality in pasture systems [40,45].

In contrast, CLI systems initially exhibited a slight reduction in SHI, primarily driven by declines in biological indicators such as SOC and β-G activity. This likely reflects the stress experienced by biological components during the early stages of system establishment, when soil structure and microbial communities are adapting to new land-use practices. However, long-term recovery is anticipated as these systems mature and stabilize, potentially fostering conditions that support biological activity and organic matter accumulation [46]. NV maintained higher SOC levels at the 0.1–0.2 m depth, whereas PA systems experienced a decline, likely due to soil compaction limiting root growth and reducing organic inputs. This trend aligns with previous studies, which report increased bulk density and reduced carbon inputs at depth as a consequence of intensive grazing [47–49].

Extracellular β-G activity was notably lower in the PA and CLI-u systems, both dominated by *U. brizantha* indicating limited microbial stimulation in compacted sandy soils [50]. This reduction is likely due to restricted root growth and reduced root exudation, which are essential for sustaining microbial processes and enzyme production [5,51]. In contrast, the CLI-m system, which included deep-rooted species such as *M. maximum*, exhibited SOC levels comparable to NV, particularly in deeper soil layers. The incorporation of *M. maximum* likely enhanced chemical and biological soil properties by improving root penetration, increasing carbon inputs, and fostering microbial activity, ultimately contributing to greater carbon sequestration.

At the 0.2–0.3 m depth, NV, characterized by deep-rooted vegetation, facilitated enhanced nutrient cycling and organic matter deposition, resulting in a higher SHI compared to other systems [52]. In contrast, PA exhibited the lowest SHI at this depth, primarily due to reduced potassium content and increased bulk density (BD), which restricted root growth and limited oxygen availability [47,49]. The absence of fertilization further exacerbated nutrient depletion at depth, hindering recovery.

The transition from PA to CLI systems led to a partial recovery in SHI, with CLI-m values approaching those of NV. This recovery is attributed to improvements in soil structure and nutrient cycling, driven by the inclusion of deep-rooted species and better fertilization practices [51–54]. Furthermore, integrating trees with pastures (i.e., crop–livestock–forestry integration) has been shown to increase organic carbon stocks in deeper soil layers, particularly in sandy soils [13,55–57]. Although our study did not evaluate crop–livestock–forestry integration, combining deep-rooted forages with tree species in integrated systems presents significant potential for enhancing soil carbon sequestration and improving soil health at greater depths. Future research focusing on the long-term impacts and potential intensification of such systems could provide valuable insights into their sustainability.

4.2. Short-Term Impacts of Integrated Management Practices on Soil Health in Sandy Soils

The effectiveness of integrated systems in improving soil health largely depends on the implementation of appropriate management practices that address critical challenges, such as soil compaction and nutrient cycling, thereby ensuring long-term sustainability. Soil chemical, physical, and biological attributes are particularly responsive to management in integrated systems [58]. In the CLI-m system, SHI levels significantly improved, approaching those observed under NV. This improvement was primarily attributed to enhancements in the biological component at a depth of 0.1–0.2 m, as well as in the physical and chemical components at a depth of 0.1–0.3 m. However, NV maintained superior physical health in the 0–0.1 m layer, where slightly higher BD in CLI-m constrained SHI performance. These findings are consistent with those of Salton et al. [47] who reported that integrated systems improve SOC and soil structure in sandy soils, echoing the patterns observed for CLI-m in this study. Similarly, [59] reported increases in SOC and nitrogen stocks in integrated systems, suggesting potential long-term benefits for sandy soils.

To optimize short-term impacts on soil health, management practices such as regulating cattle stocking rates and controlling grazing heights are critical [45]. The presence of *M. maximum* in the CLI-m system supports the hypothesis that CLI systems enhance soil health indicators in sandy soils in the short term. *M. maximum* outperformed *U. brizantha*, demonstrating higher SOC levels and increased β-glucosidase activity, likely due to its deeper root system and superior nutrient retention capacity. These findings, as shown in Table 3 and Figure 3, underscore the potential of CLI-m systems to improve soil health in sandy environments. Additionally, the implementation of no-till practices as part of the

CLI systems contributed to maintaining carbon stocks and enhancing biological activity, which are essential components of soil sustainability in these environments [46].

Our findings are consistent with previous studies highlighting the benefits of integrated systems on soil health. Vogado et al. [59] demonstrated that integrated crop-livestock systems significantly increase carbon and nitrogen stocks, particularly in deeper soil layers, aligning with our results. Similarly, Costa et al. [50] emphasized that these systems enhance microbial activity and biomass, thereby improving nutrient cycling. Additionally, Dias et al. [60] confirmed the effectiveness of crop–livestock integration in optimizing soil nutrient use and reducing environmental impacts, particularly with forages such as *Mombaça* and *Tamani* guinea grass. In our study, the use of *Megathyrsus maximus* in sandy soils under crop–livestock integration (CLI-m) systems significantly improved soil chemical properties, increased deep carbon stocks, and enhanced enzymatic activities, notably β-glucosidase. These results are in line with Soares et al. [61], who reported similar improvements in soil fertility and organic carbon fractions in Oxisols in the Brazilian Cerrado. Although Vogado et al. [59] focused on Oxisols, their observations on enhanced SOC and nitrogen stocks in integrated systems reinforce our findings regarding nutrient cycling and carbon stabilization in sandy soils.

Challenges such as soil compaction and nutrient leaching are well documented in sandy soils. However, our findings underscore the critical role of tropical forages, particularly *M. maximum*, in addressing these issues by enhancing soil structure (bulk density) and improving nutrient retention (organic carbon and potassium). Unlike prior studies that have primarily focused on clayey soils (e.g., [62]), our research demonstrates that *M. maximum* can significantly enhance porosity and water retention in sandy soils, addressing a key limitation in these environments. These findings suggest that the application of integrated systems extends beyond clay-rich soils, offering a promising approach to improving soil quality and sustainability under less favorable conditions.

The nutrient cycling observed in our study can be attributed to the efficient decomposition of plant residues, a process highlighted by Bortolli et al. [63]. Our data confirm that proper management of plant residues in integrated systems is crucial for sustaining long-term soil fertility, particularly in sandy soils where nutrient leaching is more pronounced.

Although an arboreal component was not included in this study, the observed improvements in carbon stabilization and nutrient cycling suggest that incorporating a forestry element could further enhance long-term soil resilience. This hypothesis aligns with findings from [51,64–66], which reported greater organic matter stabilization and deeper carbon sequestration in systems that integrate trees.

5. Conclusions

This study confirmed the hypothesis that CLI systems significantly enhance soil health in the short term, particularly in sandy soils. Crop diversification and regenerative practices demonstrated their ability to improve carbon retention, soil fertility, and biological activity. The inclusion of *Megathyrsus maximus* in CLI systems notably enhanced soil biological health by increasing carbon content and extracellular enzyme activity, contributing to carbon sequestration and supporting efforts to mitigate climate change.

While the short-term benefits are clear, sustained improvements will require ongoing management to address challenges such as soil compaction and nutrient leaching. Long-term studies are crucial to evaluate the durability of these impacts, especially in sandy soils, where soil structure and nutrient cycling are more susceptible to degradation. Additionally, integrating trees into CLI systems could offer further advantages, such as improved water retention and greater accumulation of soil organic matter.

To maximize the potential of CLI systems, continuous monitoring, and adaptive management practices will be essential. These strategies will help ensure the long-term sustainability of these systems while exploring their role in climate resilience and sustainable land management. Future research should investigate potential synergies between forages and arboreal species in sandy soils, particularly regarding carbon sequestration and nutrient retention.

Author Contributions: B.d.S.V.: Principal author, responsible for data processing, preparing graphs, tables, and figures, and writing the manuscript. H.B.D.: Data collection, data processing, and assistance in writing. F.B.d.L.: Contribution to the revision and writing of the manuscript. R.A.C.L.: Data collection and manuscript revision. P.S.G.M.: Data collection and manuscript revision. M.R.C.: Manuscript revision. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by multiple funding sources. We acknowledge the Center for Carbon Research in Tropical Agriculture (CCARBON), hosted by the University of São Paulo (USP) and supported by the São Paulo Research Foundation (FAPESP, grant no. 2021/10573-4). Additional funding was provided by the Research Centre for Greenhouse Gas Innovation (RCGI), also hosted by USP and sponsored by FAPESP (grant nos. 2014/50279-4 and 2020/15230-5). The study received further support from the Coordination for the Improvement of Higher Education Personnel (CAPES, Finance Code 001), and FAPESP grants awarded to Beatriz S. Vanolli (grant no. 2022/14212-9) and Henrique Dias (grant no. 2020/06775-8). Maurício R. Cherubin acknowledges funding from the National Council for Scientific and Technological Development (CNPq, Research Productivity Fellowship, grant no. 311787/2021-5), while Rubens Lamparelli acknowledges CNPq financial support (grant no. 305271/2020-2). Finally, this research was supported by FAPESP through the thematic project on integrated crop-livestock systems in Brazil (grant no. 2017/50205-9).

Data Availability Statement: The dataset used in this study, including the spreadsheet for calculating soil health indices using the Soil Management Assessment Framework (SMAF), is publicly available at [SMAF Soil Health Dataset, https://docs.google.com/spreadsheets/d/1cXH8mBwybPNyTXmxGhcRmd4L048Pf0vY/edit?gid=339837736#gid=339837736, accessed on 30 December 2024].

Acknowledgments: The authors are also grateful to Henrique Oldoni, Marcos André B. Pires, Matheus de Sá Altariugio, Gabriel Mateus M. Carneiro, and João Vitor A. Paixão for their invaluable assistance in the field and laboratory work.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

Acronym	**Description**
AGG	Aggregate Stability
ANOVA	Analysis of Variance
Aw	Tropical with dry winter (Köppen climate classification)
BD	Bulk Density
CAPES	Coordination for the Improvement of Higher Education Personnel
CCARBON	Center for Carbon Research in Tropical Agriculture
CLI	Crop–Livestock Integration
CLI-m	Crop–Livestock Integration with *Megathyrsus maximus*
CLI-u	Crop–Livestock Integration with *Urochloa brizantha*
CNPq	National Council for Scientific and Technological Development (Conselho Nacional de Desenvolvimento Científico e Tecnológico)
FAPESP	São Paulo Research Foundation (Fundação de Amparo à Pesquisa do Estado de São Paulo)

FL	Florida (University of Florida)
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
NDC	Nationally Determined Contribution
NV	Native Vegetation
PA	Pasture
P	Phosphorus
PR	Paraná
SHI	Soil Health Index
SMAF	Soil Management Assessment Framework
SOC	Soil Organic Carbon
SP	São Paulo
UNICAMP	University of Campinas
USDA	United States Department of Agriculture
USP	University of São Paulo
β-G	β-Glucosidase

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