RESEARCH ARTICLE

Landscape-scale assessment of the contribution of improved *Urochloa humidicola* pastures to soil organic carbon stocks enhancement in the Colombian Llanos

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Abstract

Tropical grasslands can sequester substantial soil organic carbon (SOC), yet the temporal dynamics of SOC across soil layers—particularly in deep horizons—remain poorly understood at landscape scale. This study presents the first large-scale, stratified assessment of SOC stocks under *Urochloa humidicola* pastures in the Colombian Llanos. We evaluated SOC stocks and related soil properties (soil texture and bulk density) across pasture age classes (Uh 1, Uh 2, Uh 3, and Uh > 3 years), and compared them to conventionally managed, regularly burned savanna areas (CBS). Soil samples were collected from 111 georeferenced field sites at four depths (0–10 cm, 10–30 cm, 30–50 cm, and 50–100 cm), and SOC stocks were calculated using the equivalent soil mass (ESM) approach. Results revealed a consistent increment in both SOC concentration and SOC stocks with increasing pasture age. Total SOC stocks (0–100 cm) were up to 35% higher in older pastures (Uh > 3 years) compared to CBS, corresponding to an average gain of ~27 Mg C ha^{-1}. These gains were observed in both soil layers, with ~8.5 Mg C ha^{-1} (19.5%) in the topsoil (0–30 cm) and ~14.8 Mg C ha^{-1} (39%) in the subsoil (30–100 cm). Accumulated SOC tends to be more stable in these deeper soil layers. SOC concentration patterns align with these trends, supporting its use as an early indicator of soil improvement. Soil texture and hydrological (drainage) conditions influenced SOC concentration and stock changes, with clay-rich and water-retentive soils accumulated significantly more SOC than sandy-texture soils. These results highlight the climate mitigation potential of improved tropical pastures and the importance of stratified, depth-resolved monitoring of SOC stocks. *U. humidicola* pastures show progressive, spatially heterogeneous SOC gains, supporting the strategy of sustainable intensification of tropical grazing systems and their integration into carbon crediting mechanisms.

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Data availability statement: All primary datasets generated and analyzed during this study are publicly available at Zenodo: https://doi.org/10.5281/zenodo.17923249. These files include soil organic carbon (SOC) concentration, bulk density, soil texture composition, SOC stocks by depth layer, SOC stocks for 0–100 cm, and sampling-site coordinates. Only original field and laboratory measurements are provided; no intermediate calculations or derived datasets are included.

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Introduction

Soils constitute the largest terrestrial carbon reservoir, storing approximately 1,500–1,600 gigatons of carbon (Gt C) within the top meter, more than the combined carbon stocks in global vegetation (~560 Gt C) and the atmosphere (~850 Gt C) [1,2]. Increasing soil organic carbon (SOC) stocks is a key climate mitigation strategy, particularly relevant for livestock-based production systems, which account for around 14% of anthropogenic greenhouse gas (GHG) emissions worldwide [3]. This challenge is especially acute in tropical regions, where rising demand for beef and the expansion of extensive grazing systems threaten to further increase the sector's carbon footprint [4].

In the Colombian Llanos, extensive grazing systems have traditionally relied on frequent burning of native savannas as a low-cost strategy to stimulate the regrowth of young, palatable shoots for livestock. While deeply rooted in local management practices, this approach has high ecological costs. Between 1997 and 2016, an estimated 1.68 ± 0.43 million hectares were burned annually in the Colombian Llanos, equivalent to 6.6% of the regional area per year. In Vichada, the department with the highest burned area, nearly 9% of the territory (~921,780 ha) was affected annually [5]. These recurrent fires contribute to GHG emissions, hinder natural regeneration of native savanna vegetation, and limit long-term SOC enhancement. In already degraded or frequently burned grazing areas, transitioning to improved pasture systems that eliminate the need for fire, represents a promising strategy for restoring ecosystem functions and enhancing SOC stocks.

Improved pasture systems based on deep-rooted genotypes such as *Urochloa humidicola* (Syn. *Brachiaria humidicola*) have demonstrated promising potential to enhance SOC accumulation in agricultural systems. These introduced pastures promote greater belowground carbon inputs and improve soil aggregation, thereby facilitating long-term SOC storage in deeper soil layers [4]. In the Colombian Llanos, for example, *Urochloa*-based systems have been associated with SOC increases of up to 1 Mg C ha^{-1} yr^{-1} in the topsoil and as much as 4 Mg C ha^{-1} yr^{-1} in deeper soil layers [6]. More recent long-term studies have reported net SOC gains of up to 15% after approximately 6.5 years of improved pasture management [7]. Conversion from frequently burned, fire-managed savanna to improved pastures in Colombia has also been associated with SOC increases ranging from 0.9 to 3.3 Mg C ha^{-1} yr^{-1} in the top 60 cm of soil, with soil texture and pasture age being the major influencing factors [8]. These values exceed the global median reported previously [9], who estimate SOC sequestration rates in grasslands between 0.6 and 2 Mg C ha^{-1} yr^{-1}.

The deep-rooting traits of *U. humidicola*, combined with its adaptation to low-fertility and acidic soils, make it particularly suitable for large-scale pasture improvement in the savannas of South America. Despite the growing body of evidence on the benefits of improved tropical forages, few studies have assessed SOC responses at large spatial scales or across diverse soil and landscape conditions. Existing studies have largely focused on experimental plots, small areas or small farms [10–13]. Variability in soil type, soil texture, climate, vegetation cover, and management practices can substantially influence SOC stock distribution and dynamics, highlighting the importance of landscape-scale assessments [10,14].

Understanding these spatial patterns is essential not only to quantify SOC baselines more accurately, but also to inform national GHG inventories and carbon finance mechanisms. Additionally, large-scale measurements are pivotal for the development and validation of monitoring, reporting, and verification (MRV) tools (particularly those based on remote sensing or predictive modeling) which are increasingly important for accessing carbon finance mechanisms and designing effective mitigation policies [15].

We aimed to quantify SOC stocks and related soil physical properties in *U. humidicola* pastures of different ages, compared to conventionally burned savannas, across a large heterogeneous landscape in the Colombian Llanos. This is the first large-scale assessment of SOC stocks across improved *U. humidicola* pastures of the region, accounting for key environmental covariates such as soil texture and topography that influence SOC accumulation but are rarely controlled in broad-scale studies.

Materials and methods

Study area

This research was conducted at Hacienda San José (HSJ) cattle farm, located in the municipality of La Primavera, Vichada department, Colombia (Fig 1). The study area covers 13,451 ha and extends between latitudes 6°01'21"N and 5°52'17"N and longitudes 69°22'9"W and 69°40'16"W. The farm experiences a warm, semi-humid climate, with annual precipitation ranging from 2,000–2,500 mm and an average temperature between 26°C and 28°C. Soils are predominantly Oxisols and Ultisols derived from silty and clayey alluvial deposits, well-drained, characterized by high acidity and aluminum saturation together with low natural fertility [16]. Land use includes a mix of introduced pastures, such as *U. humidicola,* with different years of age since establishment, as well as areas of native savannas and gallery forests.

Experimental design and sampling strategy

To assess the potential of improved *U. humidicola* pastures to enhance carbon sequestration, this study compared SOC stocks and associated soil properties (soil texture and bulk density) across sites representing different pasture ages (treatments). Improved pasture sites (treatments) consisted of areas planted with *Urochloa humidicola* CIAT 679 (cv. Tully) pastures of different ages: 1 year (Uh 1), 2 years (Uh 2), 3 years (Uh 3), and more than 3 years (Uh > 3). These were compared with control sites consisting of conventionally managed savanna under traditional management of burning (CBS). Pasture establishment and management practices followed regionally adapted protocols previously developed for the Colombian Llanos [17,18].

A total of 111 sampling sites were allocated using a stratified random strategy to ensure representative coverage of key environmental gradients. Stratification was developed based on geospatial covariates representing the soil type [16], topography landforms [19], soil texture (clay and sand content) [20], and vegetation and moisture indices (NDVI and NDMI) developed from Sentinel-2 images (January 2020 – October 2023). Improved pasture sampling sites were evenly distributed across the four pasture age classes (n = Uh 1: 30, Uh 2: 30, Uh 3: 28, and Uh > 3: 8), while reference sampling sites were allocated in adjacent farms where conventional savanna areas are subjected to traditional management of burning (n = CBS:15). Each sampling site was georeferenced and classified according to pasture age.

Stocking rates differed markedly between improved pastures and CBS. In the latter, rates were estimated at approximately 0.06 heads ha^{-1} based on regional livestock inventories and land use data [18]. These records include both small and large ruminants, preventing an accurate conversion into livestock units (UGG, from the Spanish *Unidad de Ganado Grande*, equivalent to one adult 450 kg animal). In contrast, *U. humidicola* pastures follow a progressive grazing strategy aligned with pasture age and establishment [17]. Grazing is typically avoided during the first 12

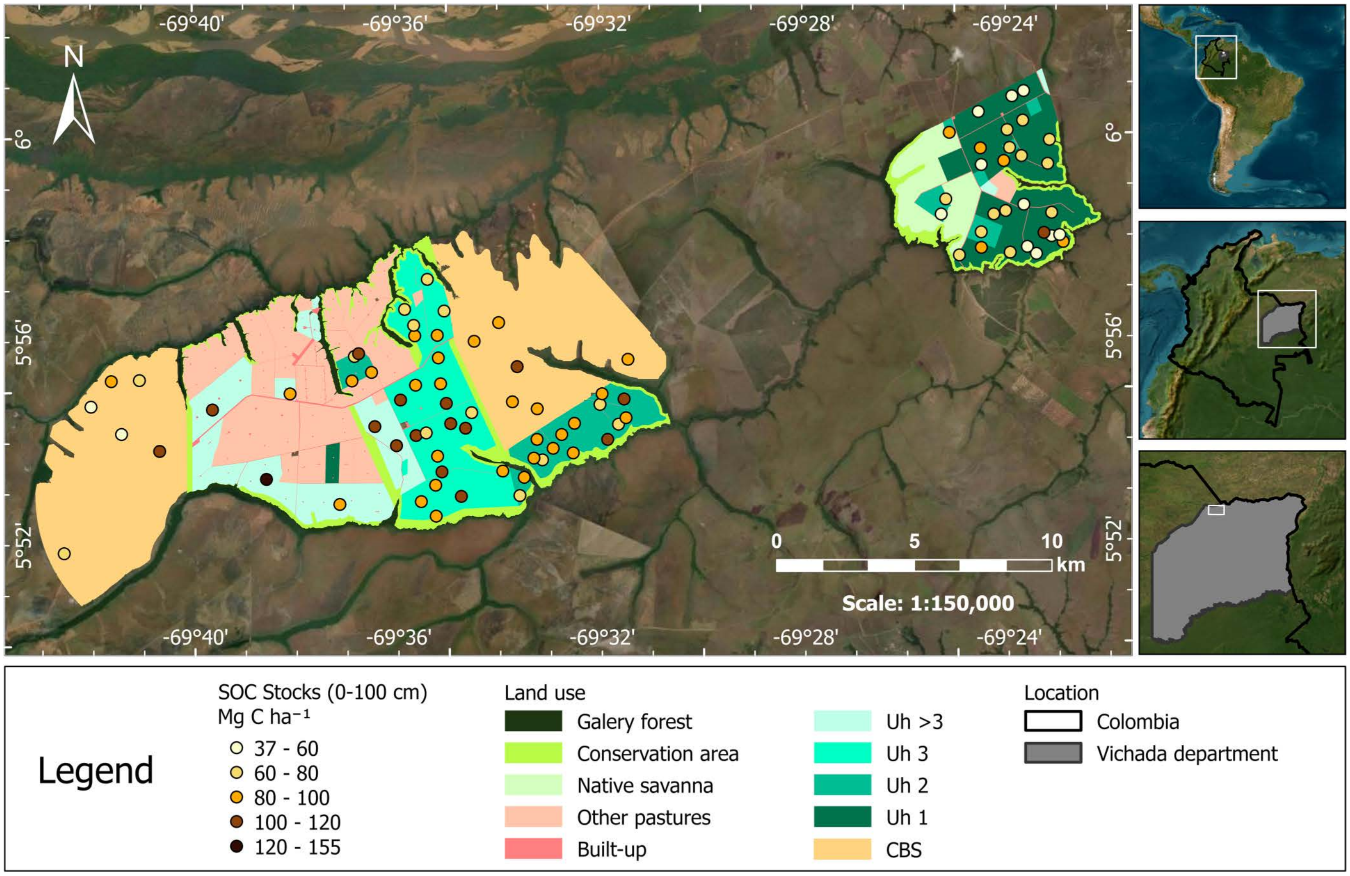

Fig 1. Location of the study area in the Colombian Llanos. The map shows Hacienda San José (HSJ) and neighboring farm areas, located in La Primavera, Vichada, Colombia. Points represent SOC stocks values at each sampling site distributed across *Urochloa humidicola* pastures of different ages: 1 year (Uh 1), 2 years (Uh 2), 3 years (Uh 3), and more than 3 years (Uh > 3) and conventionally managed, burned savanna areas (CBS) as reference, as part of a stratified design based on environmental covariates (soil type, texture, topography, Normalized Difference Vegetation Index (NDVI), and Normalized Difference Moisture Index NDMI). Administrative boundaries: Instituto Geográfico Agustín Codazzi (IGAC), public domain under CC BY 4.0. Obtained from *Colombia en Mapas*: https://www.colombiaenmapas.gov.co. Basemap: Esri, Maxar, Earthstar Geographics, and the GIS User Community. Accessed via ArcGIS Online World Imagery: https://server.arcgisonline.com/arcgis/rest/services/World_Imagery/MapServer. Terms of use for static maps in academic publications are available at https://doc.arcgis.com/en/arcgis-online/reference/static-maps.htm.

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months after sowing (Uh 1). From month 13 (Uh 2), stocking begins at 0.5 UGG ha^{-1}, increasing gradually to 0.6 UGG ha^{-1} (month 15), 0.7 UGG ha^{-1} (month 17), and 0.8 UGG ha^{-1} (month 19). This level is maintained until month 25 (Uh 3), when it raises to 0.9 UGG ha^{-1}, reaching 1.0 UGG ha^{-1} by month 26 and stabilizing thereafter (Uh > 3). These values reflect adaptive grazing practices based on pasture productivity and seasonal rainfall, and contrast sharply with extensive low-input systems [17].

Soil sampling and laboratory analysis

At each site, disturbed and undisturbed soil samples were collected at four depths: 0–10 cm, 10–30 cm, 30–50 cm, and 50–100 cm. Sampling took place between April and May 2024 during the wet season. Undisturbed cores (5 cm diameter × 10 cm height) were used to determine bulk density [21], while disturbed samples were collected for soil texture and SOC concentration analyses.

Disturbed soil samples were air-dried, sieved (<2 mm), and analyzed at the Analytical Services Laboratory of the International Center for Tropical Agriculture (CIAT). SOC concentration was determined via dry combustion using an Elementar Vario Macro Cube analyzer. Soil texture was determined using the hydrometer method [22], and bulk density was measured according to Blake and Hartge [23].

Soil organic carbon (SOC) stocks (Mg C ha^{-1}) were estimated using a mass-corrected approach based on differences in bulk density (BD) between land use systems. The correction was applied to ensure that SOC stocks were comparable across systems with varying soil compaction and management histories [24].

Initially, SOC stocks for each sampling layer were calculated using the following equation (Eq 1):

$$SOC\ stock\ \left(Mg\ C\ ha^{-1}\right) = SOC\ (\%) \times BD\ \left(g\ cm^{-3}\right) \times Depth\ (cm) \times 0.1 \tag{1}$$

Where the factor 0.1 accounts for unit conversions: SOC (%) to fraction (÷100), bulk density from g cm^{-3} to kg m^{-3} (×1,000), depth in cm to m (÷100), and area conversion from m² to ha (×10,000), yielding a combined factor of 0.1.

To account for differences in soil mass due to variation in bulk density between the CBS and the *U. humidicola*, a correction was applied to the SOC stock of the *U. humidicola* system using the following formula (Eq 2) [8]:

$$SOC\ stock_{corrected} = SOC\ stock \times \left(\frac{BD_{CBS}}{BD_{Uh}}\right) \tag{2}$$

Where SOC stock is the uncorrected SOC stock in the *U. humidicola* pasture (Mg C ha^{-1}), BD_{CBS} is the bulk density of the CBS, and BD_{Uh} is the bulk density of the *U. humidicola* pastures.

This correction was made because the comparison aims to evaluate the effect of land-use change and management on soil organic carbon (SOC) storage. The CBS and *U. humidicola* systems represent contrasting management conditions, with the conventionally burned savanna (CBS) as the reference system and the improved pasture (Uh) as the managed condition. The adjustment ensures that the comparison reflects differences in SOC stocks attributable to management rather than to inherent soil property variations unrelated to land use. Therefore, the correction was necessary to allow an appropriate interpretation of SOC change associated with the transition from conventionally burned savannas to improved pasture systems [8].

Statistical analysis

Soil organic carbon (SOC) content, bulk density, and SOC stocks were evaluated separately by soil depth intervals (0–10, 10–30, 30–50, and 50–100 cm), as well as cumulatively for the 0–100 cm profile. The total sample included 111 georeferenced points: 96 in improved pastures stratified by age classes (n = Uh 1: 30, Uh 2: 30, Uh 3: 28, and Uh > 3: 8) and 15 in adjacent savanna areas under traditional fire-based management (n = CBS: 15). Although sample sizes were unbalanced among treatments, particularly for the Uh > 3 pasture group and CBS reference sites, appropriate statistical procedures were applied to account for this limitation.

Assumptions of normality and homogeneity of variance were formally checked using the Shapiro–Wilk and Levene's tests, respectively. When both assumptions were met, one-way ANOVA was applied to evaluate differences among pasture age classes and CBS for each soil depth and for the cumulative profile. Post-hoc comparisons were conducted using Tukey's HSD test. If either assumption was violated, the non-parametric Kruskal–Wallis test was employed, followed by pairwise Dunn's tests with Bonferroni correction. Statistical significance was set at $\alpha = 0.05$.

Exploratory correlations between SOC, bulk density, and soil texture were also performed, but results are not reported in detail due to the absence of consistent or strong relationships. All statistical analyses were conducted in R version 4.5.0 (R Core Team, 2024) using the emmeans, car, FSA, and multcompView packages.

Results

Soil texture

Soil textural analysis revealed consistent patterns across treatments and depths (Tables 1 and 2), with most samples classifying as silty clay loam, clay loam, or silty clay according to the USDA soil texture triangle (Fig 2). Across all treatments and soil depths, silt was the predominant particle size fraction, followed by clay and sand. At 0–100 cm soil depth, Uh 1 and CBS exhibited higher values of silt proportion (53.3 ± 1.2% and 51.1 ± 1.8%, respectively), while Uh 3 showed the highest sand proportion (15.9 ± 2.7%), followed by CBS (13.7 ± 1.7%) and Uh 2 (14.4 ± 3.2%) (Table 2). Within this overall trend, Uh > 3 displayed the highest clay content (38.9 ± 0.6%) and the lowest sand proportion (7.7 ± 0.5%), highlighting subtle but consistent textural differences among pasture age classes.

At intermediate soil depths (10–30 cm and 30–50 cm), sand values showed greater variability, Uh 2 presented a slightly coarser texture compared to Uh > 3, which maintained a consistently fine-textured profile with higher values of clay. Silt content falls within a range of 48% to 53% across treatments. These differences persisted at deeper soil layers, where Uh > 3 consistently had the most clay-rich soils. Across treatments, clay content tended to increase with depth, while sand content decreased. For instance, in Uh > 3, clay values ranged from 37.6 ± 0.8% at 0–10 cm to 38.5 ± 0.6% at 50–100 cm, while sand decreased from 8.8 ± 0.4% to 6.3 ± 0.8%. A similar pattern was observed in the CBS, where clay content increased from 32.9 ± 1.5% to 38.1 ± 1.4% over the same depth range.

For the 0–100 cm profile, statistical analyses confirmed significant differences in sand (p = 0.031) and clay (p = 0.0107) values among treatments (Kruskal-Wallis test). Post-hoc Dunn's tests indicated that Uh > 3 had significantly lower sand

Table 1. Mean values (± standard error) of sand, silt, and clay content (%) across four soil depths (0–10, 10–30, 30–50, and 50–100 cm) under different land use treatments in the Colombian Llanos region. Treatments include *Urochloa humidicola* pastures of varying ages: one (Uh 1), two (Uh 2), three (Uh 3), and more than three years (Uh > 3) after establishment, and conventionally managed, regularly burned savanna areas (CBS).

Treatment	Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	clay	Sand	Silt	Clay
	0–10 cm			10–30 cm			30–50 cm			50–100 cm		
Uh 1	12.5 ± 1.1	55.8 ± 1.9	31.7 ± 2.1	11.2 ± 0.9	54.8 ± 1.9	34 ± 1.7	13.2 ± 1	51 ± 1.1	35.9 ± 1.2	10.3 ± 1.1	51.1 ± 0.8	38.6 ± 1.3
Uh 2	12.3 ± 1.2	53 ± 1.4	34.7 ± 1.4	13.2 ± 2.4	49.2 ± 2.8	37.6 ± 1.1	13.3 ± 2.8	47.2 ± 2.8	39.5 ± 1.1	9.4 ± 2	52.5 ± 2.9	38.2 ± 1.8
Uh 3	15.5 ± 3.6	50.5 ± 4	34.1 ± 1.1	14.7 ± 4.6	47.5 ± 5	37.8 ± 1.1	9.1 ± 1.2	51.2 ± 0.9	39.7 ± 0.9	8.4 ± 1	51.5 ± 1	40.1 ± 1.1
Uh > 3	8.8 ± 0.4	53.6 ± 0.4	37.6 ± 0.8	7.6 ± 0.9	52.5 ± 1.4	39.8 ± 0.5	8 ± 0.6	52.3 ± 2.5	39.7 ± 1.9	6.3 ± 0.8	55.2 ± 0.2	38.5 ± 0.6
CBS	11.1 ± 1.6	56 ± 1.9	32.9 ± 1.5	16.7 ± 3.5	48 ± 3.7	35.3 ± 1.1	12.3 ± 4.4	51.3 ± 3.9	36.4 ± 1.1	14.5 ± 3.6	47.4 ± 3.3	38.1 ± 1.4

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Table 2. Soil texture composition (% sand, silt, and clay) across the 0–100 cm profile under different pasture treatments. Values represent means ± standard error. Different letters within a column indicate statistically significant differences among treatments based on Kruskal-Wallis tests followed by Dunn's post-hoc comparisons (α = 0.05). Normality tests indicated that only some treatments met distributional assumptions; therefore, non-parametric analyses were used.

Treatment*	Sand (0–100 cm) (%)	Silt (0–100 cm) (%)	Clay (0–100 cm) (%)
Uh 1	11.8 ± 0.8 b	53.3 ± 1.2	34.8 ± 1.2
Uh 2	14.4 ± 3.2 ab	48.8 ± 3.6	36.8 ± 1.2
Uh 3	11.9 ± 2.7 ab	50.2 ± 2.8	37.9 ± 1.0
Uh > 3	7.7 ± 0.5 a	53.4 ± 1.2	38.9 ± 0.6
CBS	13.7 ± 1.7 ab	51.1 ± 1.8	35.2 ± 1.0

*Treatments include *Urochloa humidicola* pastures of varying ages: one (Uh 1), two (Uh 2), three (Uh 3), and more than three years (Uh > 3) after establishment, and conventionally managed, regularly burned savanna areas (CBS).

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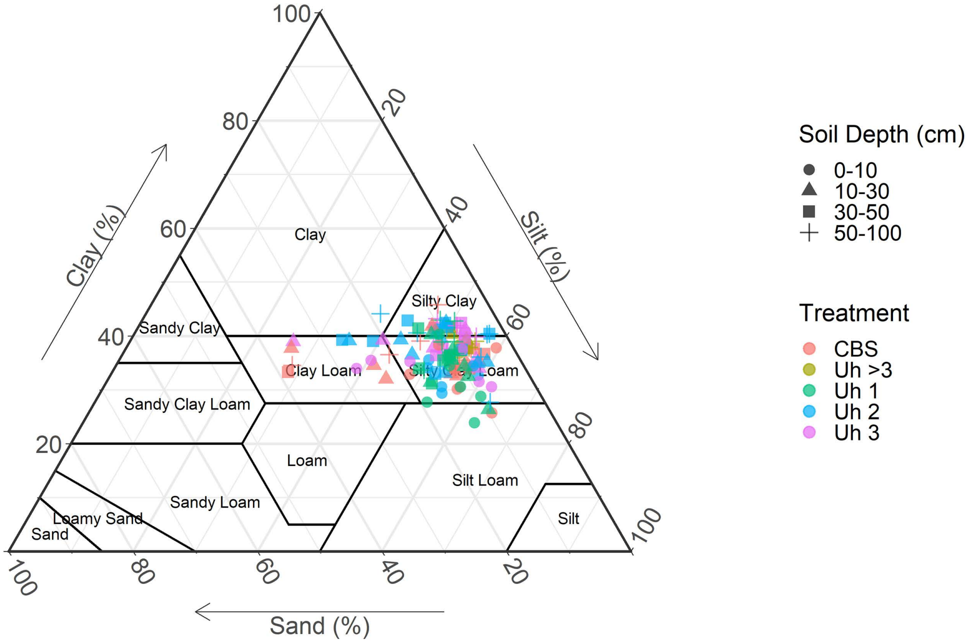

Fig 2. Distribution of soil samples across the USDA texture triangle. USDA soil texture triangle showing the distribution of all individual soil samples by treatment and depth. Points represent observations categorized by treatment (color) and soil depth (shape), overlaid on USDA textural classification boundaries.

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and higher clay proportions compared to CBS and Uh 2 ($p < 0.05$). No significant differences were observed for silt values ($p = 0.608$) (Table 2).

Soil bulk density

Significant differences in overall mean values of bulk density (BD) of different treatments were detected across soil depths (ANOVA, $p < 0.001$) (Fig 3). The mean BD value increased consistently with depth, starting at $1.324 \pm 0.011\ g\ cm^{-3}$ in the 0–10 cm layer, increasing to $1.406 \pm 0.011\ g\ cm^{-3}$ in the 10–30 cm layer, and reaching $1.437 \pm 0.011\ g\ cm^{-3}$ and $1.542 \pm 0.011\ g\ cm^{-3}$ at 30–50 cm and 50–100 cm, respectively. These increases correspond to relative gains of 6.2%, 2.2%, and 7.3% for each subsequent interval, highlighting a more pronounced compaction in the uppermost and deepest layers. According to Tukey's HSD test, the surface layer (0–10 cm) differed significantly from the deeper soil layers, while no significant differences were detected between the 10–30 cm and 30–50 cm layers. The 50–100 cm layer exhibited the higher BD values and differed statistically from all other depths.

In contrast, no statistically significant differences in BD were detected among treatments within any soil depth (ANOVA, $p > 0.05$) (Table 3 and S1 Fig). Nevertheless, consistent trends were observed across treatments. Soils under the CBS treatment generally exhibited slightly lower BD values compared to pastures established with *U. humidicola*, regardless of their age. Within the *U. humidicola* treatments, no consistent pattern in BD values was associated with pasture age, from 1 to more than 3 years of establishment.

Soil organic carbon concentration

Soil organic carbon (SOC) concentration showed a clear variation with depth, decreasing significantly from the surface to deeper layers (S1 Table). On average across treatments, SOC concentration was the highest in the 0–10 cm layer

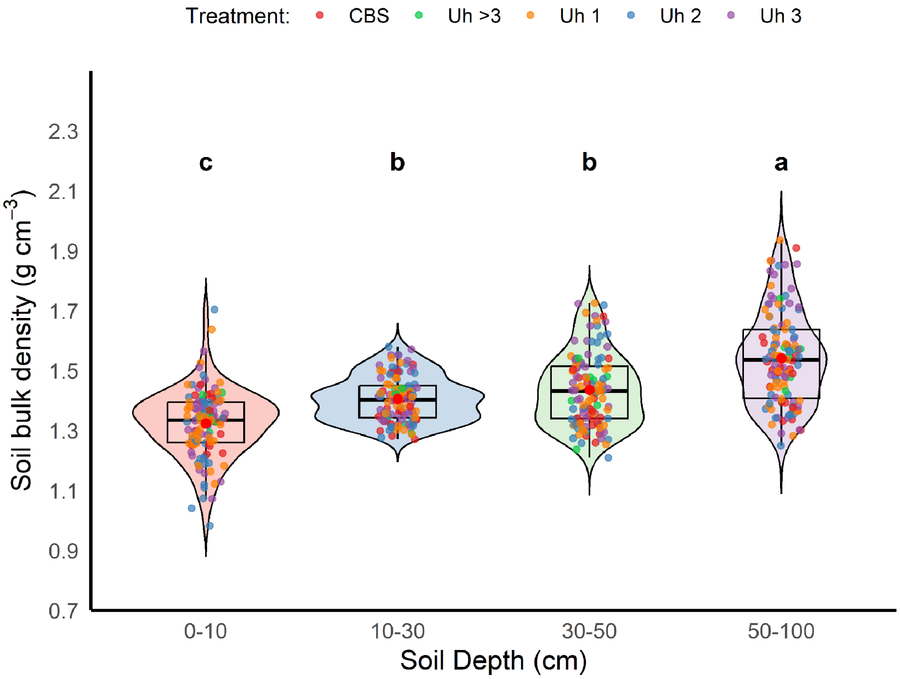

Fig 3. Soil bulk density across pasture treatments and depths. Mean values of soil bulk density (g cm^{-3}) ± standard error (SE) of different pasture treatments including *Urochloa humidicola* pastures of varying ages: one (Uh 1), two (Uh 2), three (Uh 3), and more than three years (Uh > 3) after establishment, and conventionally managed, regularly burned savanna areas (CBS) by soil depth. Different letters indicate statistically significant differences among depths according to Tukey's HSD test ($p < 0.05$).

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Table 3. Soil bulk density (g cm^{-3}) across four soil depths (0–10, 10–30, 30–50, and 50–100 cm) under different pasture treatments. Values represent mean ± standard error. Treatments sharing the same letter within each depth did not differ significantly (ANOVA, $p > 0.05$).

Treatment*	Soil bulk density (g cm^{-3})			
	0-10 cm	**10-30 cm**	**30-50 cm**	**50-100 cm**
Uh 1	1.327 ± 0.019	1.41 ± 0.012	1.434 ± 0.021	1.541 ± 0.029
Uh 2	1.286 ± 0.028	1.417 ± 0.015	1.435 ± 0.026	1.534 ± 0.028
Uh 3	1.339 ± 0.02	1.411 ± 0.015	1.472 ± 0.022	1.583 ± 0.032
Uh > 3	1.364 ± 0.015	1.392 ± 0.022	1.427 ± 0.032	1.54 ± 0.038
CBS	1.335 ± 0.016	1.38 ± 0.016	1.393 ± 0.023	1.489 ± 0.03

*Treatments include *Urochloa humidicola* pastures of varying ages: one (Uh 1), two (Uh 2), three (Uh 3), and more than three years (Uh > 3) after establishment, and conventionally managed, regularly burned savanna areas (CBS).

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(1.55 ± 0.03%) and declined progressively to 0.84 ± 0.02% at 10–30 cm, 0.52 ± 0.02% at 30–50 cm, and 0.31 ± 0.01% at 50–100 cm, representing an overall decrease of approximately 80% from the surface to the deepest layer. These differences were statistically significant ($p < 0.05$), highlighting the natural vertical gradient in organic matter content within the soil profile.

When comparing the pasture treatments (Table 4), differences in SOC concentration were evident across treatments at all depths. In the surface layer (0–10 cm), the recently established pasture (Uh 1) had the lowest SOC concentration (1.27 ± 0.04%), significantly lower than the control treatment of CBS (1.55 ± 0.10%). In contrast, Uh pastures with longer

Table 4. Soil organic carbon (SOC) concentration (%) (mean ± standard error) across soil depths (0–10, 10–30, 30–50, and 50–100 cm) under different pasture treatments and pasture ages. Different letters indicate statistically significant differences among treatments within each depth (p < 0.05). Statistical differences were assessed using one-way ANOVA followed by Tukey's HSD test for the 0–10 cm layer, and Kruskal-Wallis tests followed by Dunn-Bonferroni post-hoc comparisons for the deeper layers (10–30, 30–50, and 50–100 cm).

Treatment*	SOC (%)			
	0-10 cm	10-30 cm	30-50 cm	50-100 cm
Uh 1	1.27 ± 0.04b	0.7 ± 0.04c	0.44 ± 0.02b	0.26 ± 0.01c
Uh 2	1.62 ± 0.05a	0.85 ± 0.04abc	0.5 ± 0.02ab	0.31 ± 0.01bc
Uh 3	1.71 ± 0.05a	0.94 ± 0.04ab	0.56 ± 0.03a	0.34 ± 0.01b
Uh > 3	1.78 ± 0.06a	1.03 ± 0.02a	0.78 ± 0.15a	0.42 ± 0.04a
CBS	1.55 ± 0.1a	0.8 ± 0.07bc	0.5 ± 0.04ab	0.31 ± 0.02bc

*Treatments include *Urochloa humidicola* pastures of varying ages: one (Uh 1), two (Uh 2), three (Uh 3), and more than three years (Uh > 3) after establishment, and conventionally managed, regularly burned savanna areas (CBS).

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establishment periods Uh 2, Uh 3, and Uh > 3 reached higher SOC concentrations of 1.62 ± 0.05%, 1.71 ± 0.05%, and 1.78 ± 0.06%, respectively.

In the 10–30 cm layer, SOC concentrations ranged from 0.70 ± 0.04% in Uh 1 to 1.03 ± 0.02% in Uh > 3. All *U. humidicola* treatments surpassed the CBS baseline value (0.80 ± 0.07%) except for Uh 1, pointing to initial C loss in recently disturbed soils and its subsequent recovery and enhancement with pasture age [25].

At 30–50 cm soil depth, SOC concentration was lowest in Uh 1 (0.44 ± 0.02%) and increased gradually with pasture age, reaching 0.56 ± 0.03% in Uh 3 and 0.78 ± 0.15% in Uh > 3, both exceeding the CBS control treatment (0.50 ± 0.04%). A similar trend was observed at 50–100 cm, where SOC values increased from 0.26 ± 0.01% in Uh 1 to 0.42 ± 0.04% in Uh > 3, with the value of CBS control (0.31 ± 0.02%) situated in between.

Soil organic carbon stocks

The estimation of total soil organic carbon (SOC) stocks (0–100 cm) revealed consistent and significant differences across treatments, with a clear trend of increasing SOC associated with longer pasture establishment times. The control CBS, representing traditional management through recurrent burning, exhibited intermediate or low SOC values across all depths, underscoring its role as a baseline of soil health condition (degradation) against which improved pasture systems can be evaluated.

In the surface layer (0–10 cm), SOC stocks in the CBS treatment were 20.59 ± 1.24 Mg C ha^{-1} (Table 5). While pastures with only one year of establishment (Uh 1) showed lower values (17.00 ± 0.90), likely due to initial carbon losses associated with soil disturbance during pasture introduction [25]. However, SOC stocks increased progressively with pasture age: Uh 2 (21.65 ± 0.90), Uh 3 (22.91 ± 0.92), and Uh > 3 (23.79 ± 1.75 Mg C ha^{-1}), all of which exceeded the value observed in the CBS control. These results suggest early gains and sustained improvements in surface soil carbon following the establishment of *U. humidicola* pastures.

At 10–30 cm depth, the CBS presented the SOC stock value of 23.16 ± 1.16 Mg C ha^{-1}, exceeded by all pasture treatments except Uh 1 (19.24 ± 0.90) (Table 5). SOC stocks in Uh 2 (23.56 ± 0.90), Uh 3 (26.02 ± 0.92), and Uh > 3 (28.49 ± 1.75) showed gains of up to 23% relative to the control treatment (Table 5). These increases in SOC stock values reflect a progressive carbon accumulation in the subsoil, beginning as early as the second year of pasture establishment.

In the 30–50 cm layer, the control treatment exhibited 14.48 ± 1.20 Mg C ha^{-1} (Table 5). Uh 1 (12.26 ± 0.90) and Uh 2 (13.82 ± 0.90) values were similar or slightly lower, whereas Uh 3 (15.72 ± 0.92) and Uh > 3 (21.49 ± 1.75) surpassed the

Table 5. Soil organic carbon (SOC) stocks (Mg C ha^{-1}) in four soil layers (0–10, 10–30, 30–50, and 50–100 cm) and cumulatively (0–100 cm) across different pasture treatments of *Urochloa humidicola* and the CBS. Different letters indicate statistically significant differences between treatments within each depth (Tukey's HSD, α = 0.05). For cumulative SOC stocks, comparisons were performed using Kruskal–Wallis test followed by Bonferroni-adjusted Dunn's post-hoc tests.

Treatment*	**Soil Organic Carbon Stock (Mg C ha^{-1})**				
	0-10 cm	**10-30 cm**	**30-50 cm**	**50-100 cm**	**0-100 cm**
Uh 1	17.00 ± 0.90b	19.24 ± 0.90bc	12.26 ± 0.90b	19.37 ± 0.90b	67.85 ± 2.60b
Uh 2	21.65 ± 0.90a	23.56 ± 0.90a	13.82 ± 0.90b	23.32 ± 0.90ab	82.33 ± 2.62ab
Uh 3	22.91 ± 0.92a	26.02 ± 0.92a	15.72 ± 0.92ab	25.06 ± 0.92a	89.74 ± 2.56ab
Uh > 3	23.79 ± 1.75a	28.49 ± 1.75a	21.49 ± 1.75a	31.30 ± 1.75a	105.08 ± 7.39a
CBS	20.59 ± 1.24ab	23.16 ± 1.16ab	14.48 ± 1.20ab	23.51 ± 1.16ab	77.91 ± 5.21ab

*Treatments include *Urochloa humidicola* pastures of varying ages: one (Uh 1), two (Uh 2), three (Uh 3), and more than three years (Uh > 3) after establishment, and conventionally managed, regularly burned savanna areas (CBS).

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control, with the latter representing a 48% increase (Table 5). This marked improvement in the deeper layers further highlights the effect of pasture age on SOC restoration.

At 50–100 cm depth, the CBS treatment reached the SOC stock value of 23.51 ± 1.16 Mg C ha^{-1} (Table 5). Again, Uh 1 (19.37 ± 0.90) fell below, while Uh 2 (23.32 ± 0.90), Uh 3 (25.06 ± 0.92), and Uh > 3 (31.30 ± 1.75) equaled or exceeded the value of the CBS control treatment (Table 5). The deeper soil layer thus confirmed the long-term carbon accrual potential under well-established *U. humidicola* pastures. Across treatments, SOC stocks generally decreased at the 30–50 cm depth compared to the upper layers, followed by a subsequent increase in the 50–100 cm layer. This pattern was particularly evident in Uh 1 and Uh 2, where SOC dropped from 19.24 to 12.26 Mg C ha^{-1} and from 23.56 to 13.82 Mg C ha^{-1}, respectively, before increasing again in the deepest layer. In contrast, older pastures (Uh > 3) showed a more consistent SOC accumulation with depth, suggesting enhanced carbon stabilization at deeper soil layers over time.

Statistical analysis (Kruskal-Wallis $p < 0.001$) confirmed significant differences in total SOC stocks among treatments, particularly the comparison between Uh > 3 and both the CBS and Uh 1 treatment (Table 5). When aggregated across the full soil profile (0–100 cm), total SOC stocks reached 77.91 ± 5.21 Mg C ha^{-1} in the CBS. Uh 1 remained lower (67.85 ± 2.60), reflecting the early-stage losses mentioned above. In contrast, Uh 2 (82.33 ± 2.62), Uh 3 (89.74 ± 2.56), and Uh > 3 (105.08 ± 7.39 Mg C ha^{-1}) exhibited substantial gains, ranging from 6% to 35% above the control.

Discussion

This study provides the first large-scale, landscape-stratified assessment of SOC stocks under *Urochloa humidicola* pastures in the Colombian Llanos. By integrating soil texture, topography, and land-use history into the sampling framework, we minimized the influence of environmental heterogeneity—a persistent limitation in unstratified tropical pasture studies—and improved our ability to interpret changes in SOC stocks in relation to pasture age.

SOC stocks varied widely across the landscape, from <70 Mg C ha^{-1} in sandy, well-drained soils to >120 Mg C ha^{-1} in clay-rich, seasonally waterlogged zones. Mean SOC stock value across all stratified samples (90–100 Mg C ha^{-1}) was lower than earlier farm-level estimated value (~200 Mg C ha^{-1}) [7], which likely overrepresented high-SOC microenvironment. Earlier sampling efforts focused on more productive, low-lying areas with finer soil textures and favorable hydrology—conditions that inherently support higher SOC storage. In contrast, our stratified design ensured proportional representation of the full range of soil types, topographic positions, and land-use histories across the large farm. This reduced sampling bias, produced a more representative landscape mean, and allowed a clearer separation of pasture age effects from inherent site differences.

Spatial variability in SOC stocks was closely associated with soil texture and topographic features. Soils with low clay content and limited capacity for organo-mineral stabilization (e.g., sandy areas) exhibited SOC stocks below 70 Mg C ha^{-1} in the 0–100 cm profile. In contrast, clay-rich and seasonally waterlogged areas showed stocks exceeding 120 Mg C ha^{-1}, corroborating SOC stabilization mechanisms such as aggregate protection and microaggregate formation [26,27].

The contrast between this study and Costa Jr. et al. [7], who reported mean SOC stocks of ~200 Mg C ha^{-1} in specific zones of the same farm, highlights the importance of spatial resolution. Our stratified sampling identified localized areas with high SOC, suggesting that earlier estimates may have reflected favorable microenvironments rather than landscape averages. Around the same area sampled by Costa Jr. et al. [7], our study also recorded some of the higher SOC values (up to 130 Mg C ha^{-1} in the 0–100 cm layer), which may be explained by hydrological accumulation in low-lying sites, where periodic water saturation slows decomposition and enhances SOC stabilization. This refers to the tendency of SOC to accumulate in low-lying or poorly drained areas where poor drainage due to saturation of water filled pores reduces above and belowground litter decomposition rates and promotes organic matter stabilization, as reported in other tropical systems [28–31].

At the 0–100 cm soil depth, SOC stocks increased progressively with pasture age, with Uh 2, Uh 3, and Uh > 3 generally storing more carbon than CBS. However, variability across sites meant that these differences were not statistically significant at the whole-profile level. The clearest contrasts were between Uh 1—consistently the lowest across soil depths—and pastures with increasing age, suggesting that establishment of improved Uh pasture through cultivation results in a lower SOC stock baseline condition.

In the 0–30 cm layer, differences between CBS and Uh 2 or Uh 3 were modest, aligning with literature-reported SOC capture rates for improved tropical pastures (~1 Mg C ha^{-1} yr^{-1}) [12,25,32]. In contrast, when Uh 2 or Uh 3 were compared to Uh 1, apparent SOC capture rates reached 3–9 Mg C ha^{-1} yr^{-1}. Such higher values are unlikely to reflect true SOC sequestration and instead indicate that Uh 1 pastures may have begun from a lower initial SOC baseline, despite similar texture across strata. This difference is plausibly linked to prior land use, soil disturbance intensity due to cultivation, or vegetation history, underscoring a key limitation of synchronic chronosequences: they assume uniform starting conditions across age classes, an assumption rarely met in large, heterogeneous landscapes.

Even with these caveats, the pasture age-related trends in SOC gain are informative. SOC accumulation was evident across all depths in pastures with increased age, with gains in the subsoil (30–100 cm), particularly important for permanence due to slower turnover and stronger mineral protection of SOC [7,33,34]. Mechanistically, *U. humidicola*'s extensive root system delivers carbon inputs deep into the soil profile, where aggregation and organo-mineral interactions enhance SOC stabilization [6,25,35,36]. Surface-layer recovery is driven by litter inputs, root turnover, and microbial stabilization following the initial disturbance during pasture establishment [18,25,32,37].

The higher clay content and lower sand fraction observed in pastures older than three years (Uh > 3) compared to the treatments of CBS and younger pastures likely reflect pre-existing differences in soil texture rather than changes induced by land use or carbon accumulation. Since texture is an intrinsic soil property defined by the relative proportions of sand, silt, and clay, it is not expected to shift significantly over short timescales or due to organic matter inputs. However, these finer-textured soils in Uh > 3 sites may have facilitated greater SOC stabilization through enhanced organo-mineral interactions and improved aggregate formation. This aligns with the well-documented role of clay- and silt-rich soils in promoting physical protection and long-term retention of organic matter via microaggregation processes [27,38].

Although no statistically significant differences in BD among treatments were detected, the consistent increase in BD values with depth reflects natural compaction typically associated with greater overburden, lower organic matter content, reduced biological activity, fewer biopores and channels, and heavier soil textures in subsoil layers [12,34,39]. Slightly lower BD values in *U. humidicola* pastures compared to CBS suggest early improvements in soil structure, likely driven by increased root turnover and bioturbation, organic inputs, and the absence of recurrent burning [30].

SOC concentration declined consistently with depth across all pasture treatments, as expected in tropical soils with surface-driven organic inputs. Notably, all *U. humidicola* pastures older than one year exceeded the SOC concentrations of the CBS at every depth. Uh 1 had the lowest concentration (1.27 ± 0.04% at 0–10 cm), likely due to soil disturbance during pasture establishment [18], whereas Uh > 3 had the highest value (1.78 ± 0.06%).

These findings underscore two critical points. First, synchronic chronosequences have interpretive limits—when age classes do not share the same baseline, SOC stock change rates can be overstated or understated. Second, diachronic (re-measurement) monitoring within the same plots is essential for quantifying SOC capture rates credibly, refining estimates for MRV frameworks, and providing robust evidence for carbon finance. Reporting age-structured trends remains valuable, as they illustrate the trajectory of SOC stock change following implementation of land-use change.

From a broader perspective, these results confirm that improved tropical pastures can contribute meaningfully to climate mitigation, provided they are managed to sustain deep rooting and maintained beyond three years. In policy and carbon market contexts, the ability to document SOC gains across large, heterogeneous landscapes strengthens the case for including improved pastures in national greenhouse gas inventories and in results-based payment schemes [39]. A stratified, depth-resolved approach, as applied here, can be replicated in other tropical regions to ensure robust baselines, minimize uncertainty, and avoid over-crediting due to baseline bias. Coupling this approach with long-term monitoring will not only increase scientific confidence in SOC sequestration potential but also help align agricultural intensification strategies with climate goals, biodiversity conservation, and rural livelihoods.

Conclusions

This study provides strong evidence that, compared to conventionally managed, regularly burned savanna areas (CBS), improved *Urochloa humidicola* (Uh) pastures are associated with significantly higher soil organic carbon (SOC) stocks, particularly after three years of establishment. Despite high internal variability, total SOC stocks increased by 35% in pastures older than three years (Uh > 3) relative to CBS, with gains extending into subsoil layers (30–100 cm) where carbon is more stable. These results suggest that pasture age and soil depth are key factors influencing SOC accumulation, and that *U. humidicola* pastures with deep root architecture combined with adaptive grazing strategies can be viable alternatives to the land use as CBS for climate-smart livestock production.

No statistically significant differences in total SOC stocks were detected between intermediate-aged pastures (Uh 2 and Uh 3) and the CBS. However, the consistent upward trend and significantly higher SOC concentrations in surface layers across all *U. humidicola* sites support the hypothesis that pasture age contributes to cumulative SOC capture. The study's stratified design, which covered 111 sites across a large heterogeneous landscape, enabled a robust evaluation of spatial patterns in SOC. This evaluation confirmed the potential of *U. humidicola* pastures to capture carbon beyond localized estimates.

To our knowledge, this is the first large-scale field-based assessments of SOC stocks in *U. humidicola* pastures in Colombia. The methodology and results provide a foundation for future monitoring and scaling of these tropical pasture systems through carbon finance mechanisms. Long-term monitoring is necessary to assess the longevity and permanence of SOC gains, while integration with economic viability assessments is recommended to inform carbon credit programs, and to develop sustainable pasture intensification strategies that promote carbon sequestration, soil health, and resilience in tropical grazing landscapes.

Supporting information

S1 Table. Mean values of soil organic carbon (SOC) concentration (%) (mean ± standard error) by depth of different pasture treatments. Different letters indicate statistically significant differences among depths according to Dunn's post-hoc test with Bonferroni correction ($p < 0.05$).
(DOCX)

S1 Fig. Boxplot of soil bulk density (g cm^{-3}) across four depths (0–10, 10–30, 30–50, and 50–100 cm) under five pasture treatments: Uh 1, Uh 2, Uh 3, Uh > 3, and CBS. The boxplots illustrate the full distribution of values per group. Boxes represent the interquartile range (IQR), horizontal lines indicate the median, and whiskers extend to 1.5 × IQR. No statistically significant differences were detected among treatments within each depth (ANOVA, $p > 0.05$), although general trends were observed across treatments (see Table 5).
(TIF)

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