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Effects of pasture systems on soil compaction, aeration, and available water capacity

Efecto de los sistemas de pasturas sobre la compactación del suelo, aireación y capacidad de agua disponible

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ABSTRACT

This research is important to define which pasture systems are physically sustainable. This study assessed the effects of different pasture types on soil physical properties: degraded pastures (DP), improved pastures (IP), and silvopastoral systems (SPS) at two Llanero Piedmont locations. At location 1, the evaluated systems included an extensive DP of native grass (EDPNG), an extensive IP of Brachiaria decumbens (EIPB), and an extensive SPS of B. decumbens associated with Yopo (Anadenanthera peregrina) trees (ESPS + AP). At location 2, the evaluated systems included an extensive DP of B. decumbens (EDPB), an intensive IP of B. decumbens (IIPB), and an extensive SPS of B. decumbens associated with Acacia (Acacia mangium) trees (ESPS + A). A completely randomized factorial design (2 × 3 × 2; n=36) was used, considering location, pasture system, and soil depth (0–0.30 and 0.30–0.60 m). Soil texture, bulk density (ρb), total porosity (Tp), macroporosity and microporosity (MaP, MiP), gravimetric, volumetric (θg, θv), and available water capacity (AWC) were measured. Data were analyzed using ANOVA and Least Significant Difference (LSD) tests. At location 1, EDPNG exhibited higher ρb and lower Tp and MaP, throughout the soil profile, indicating greater soil compaction. At location 2, IP and SPS improved soil physical quality at two depths. At locations 1 and 2, θg differed significantly in DP, higher in EDPB, θv and AWC showed no significant differences. Overall, SPS at location 2 improved soil physical conditions and represent a viable strategy for enhancing soil quality in the Llanero Piedmont.

Keywords: bulk density; livestock systems; physical quality; porosity; silvopastoral systems; sustainability

RESUMEN

Esta investigación es importante para determinar qué sistemas de pasturas son físicamente sostenibles. En este estudio se evaluaron los efectos de diferentes tipos de pasturas sobre las propiedades físicas del suelo: pasturas degradadas (PD), pasturas mejoradas (PM) y sistemas silvopastoriles (SSP) en dos localidades del Piedemonte Llanero. En la localidad 1, los sistemas evaluados incluyeron una PD extensiva de pastos nativos (PDEPN), una PM extensiva de Brachiaria decumbens (PMEB) y un SSP extensivo de B. decumbens asociado a árboles de yopo (Anadenanthera peregrina) (SSPE + AP). En la localidad 2, los sistemas evaluados incluyeron una PD extensiva de B. decumbens (PDEB), una PM intensiva de B. decumbens (PMIB) y un SSP extensivo de B. decumbens asociado a árboles de Acacia (Acacia mangium) (SSPE + A). Se utilizó un diseño factorial completamente aleatorio (2 × 3 × 2; n = 36), teniendo en cuenta la localidad, el sistema de pastura y la profundidad del suelo (0–0,30 y 0,30–0,60 m). Se midieron la textura del suelo, la densidad aparente (ρb), la porosidad total (Pt), la macro y microporosidad (MaP, MiP), la capacidad de agua gravimétrica y volumétrica (θg, θv) y la capacidad de agua disponible (CAD). Los datos se analizaron mediante pruebas

ANOVA y LSD (Least Significant Difference). En la localidad 1, el PDEPN presentó una ρb más alta y una Pt y MaP más baja, a través de todo el perfil del suelo, lo que indica una mayor compactación del suelo. En la localidad 2, la PM y el SSP mejoraron la calidad física del suelo en las dos profundidades. En ambas localidades, la θg difirió significativamente en la PD, más alta en la PDEB; θv y CAD no mostraron diferencias significativas. En general, el SSP en la localidad 2 mejoró las condiciones físicas del suelo y representa una estrategia viable para mejorar la calidad del suelo en el Piedemonte Llanero.

Palabras clave: calidad física; densidad aparente; porosidad; sistemas ganaderos; sistemas silvopastoriles; sostenibilidad

INTRODUCTION

Colombia has an estimated cattle inventory of 22.6 million heads**,** producing 933 million kilograms of beef annually, distributed across approximately 39.2 million hectares**.** Within this context, the department of Meta, located in the Piedmont region, contributes about 7.7% of national production inventory (1.74 million heads) (Silva-Parra *et al*., 2023).

In these areas, livestock production is predominantly associated with extensive grazing systems, which include both degraded pastures (DP) and improved pastures (IP). Extensive livestock farming is a major driver of deforestation in Colombia, accounting for nearly 60% of forest loss (Fedegan, 2014). In tropical regions, extensive livestock systems typically occupy large areas and operate at low stocking rates, often leading to pasture degradation and soil compaction (Owuor *et al*., 2018). In contrast, intensive systems allow closer monitoring of pasture and animal management, incorporating practices such as pasture renovation, lime application, improved forages, and the integration of leguminous trees (Corbett *et al*., 2021; Fuentes *et al*., 2023). These practices enhance soil physicochemical and biological conditions, with additional benefits when trees are incorporated directly into pastures through silvopastoral systems (SPS) (Vázquez *et al*., 2020; Polanía-Hincapié *et al*., 2021; Silva-Parra *et al*., 2023). Soil degradation is a critical challenge in tropical pasturelands (Silva-Parra, 2018). Conventional cattle production practices—such as burning, extensive grazing, poor soil management, and low plant species diversity—negatively affect soil physical properties, reducing the soil's capacity to provide essential ecosystem services (Hossain et al., 2020; Lai & Kumar, 2020).

Livestock activity on degraded pastures promotes soil compaction, alters soil structure, reduces soil carbon stocks, increases bulk density, and decreases infiltration rates (Kumar *et al*., 2018; Parra *et al*., 2019). The extent of soil compaction depends on pasture type, livestock management, and the production system employed. Soil bulk density is a key indicator of compaction due to overgrazing, although its interpretation depends on soil texture and moisture content (Jaramillo, 2002). Common causes of soil compaction in pasture systems include livestock trampling due to inadequate stocking management, the formation of tillage pans from repeated machinery use at constant depths, and the development of subsurface hardpans from the accumulation of fine particles and leached minerals (Bondi *et al*., 2021; Emmet-Booth *et al*., 2020; Zhang *et al*., 2024).

In tropical regions, intense rainfall may promote surface crusting; however, well-managed silvopastoral systems with sufficient vegetative cover generally mitigate rainfall- induced compaction (Silva-Parra *et al*., 2020). Evaluating both bulk and particle density allows the estimation of total porosity**,** which is subdivided into microporosity and macroporosity to improve the understanding of water and air movement and retention (Shahrokh *et al*., 2025). Soil compaction reduces water-holding capacity, increases pasture vulnerability during droughts, and restricts drainage (Kumar *et al*., 2018). Severely compacted soils may exhibit total porosity below 35%, with up to 60% of compaction concentrated in the upper 0.10 m due to continuous livestock or machinery traffic (Bondi *et al*., 2021).

Optimal soil porosity is approximately 50%, with microporosity and macroporosity each around 25% (Jaramillo, 2002). Macroporosity below 10% significantly limits root growth, water and air movement, and water retention, highlighting the importance of distinguishing microporosity and macroporosity in pasture soils (Lopes *et al*., 2020). Silvopastoral systems are an effective ecological strategy for restoring degraded pastures in the Piedmont region by leveraging knowledge of soil aeration and water-holding capacity to improve physical soil quality (Silva-Parra *et al*., 2023; Paredes-Peralta *et al*., 2025). Global studies have shown that integrating trees into pastures increases soil organic matter and improves soil physical properties (Vázquez *et al*., 2020; Conant *et al*., 2017; Fuentes *et al*., 2023; Silva-Parra *et al*., 2023).

The objective of this study was to evaluate the effects of different types of pasture management systems (degraded pastures, improved pastures, and silvopastoral systems) at two depths on soil physical properties in two locations of the Piedmont region. This assessment aims to identify sustainable pasture systems that optimize soil physical properties for soil capacities and enhance the productivity and competitiveness of livestock systems.

MATERIALS AND METHODS

Study area

The present study was conducted in the Piedmont Llanero region of Colombia**,** located on the slopes of the Eastern Cordillera, where the mountains descend toward the Orinoquía savannas.

This subregion ranges from 300 to 700 m above sea level**,** with average temperatures between 23 and 30 °C, and a bi-seasonal rainfall regime providing 3,000 to 4,000 mm of annual precipitation. The Piedmont is characterized by high biodiversity and supports a variety of pasture systems. Two representative locations were selected for this study: Restrepo (location 1) and Cumaral (location 2)**.** Soils in both sites were classified as Oxisols with a loamy sand texture**,** typical of the region. At each location, three pasture management systems were evaluated: degraded pastures (DP)**,** improved pastures (IP)**,** and silvopastoral systems (SSP)**.**

At location 1 (Restrepo; 4°15′42″ N, 73°33′51″ W), the evaluated systems included an Extensive Degraded Pasture of native grass (EDPNG)**,** an Extensive Improved Pasture of *Brachiaria decumbens* grass (EIPB)**,** and an Extensive Silvopastoral System of *B. decumbens* grass in consortium with Yopo (*Anadenanthera peregrina*) trees (ESPS + AP)**.**

In location 2 (Cumaral, 4° 54′ N latitude and 73° 30′ W longitude), the systems included an Extensive Degraded Pasture of *Brachiaria decumbens* grass (EDPB)**,** an Intensive Improved Pasture of *B. decumbens* grass (IIPB)**,** and an Extensive Silvopastoral System of *B. decumbens* grass in consortium with Acacia (*Acacia mangium*) trees (ESPS + A)**.** One farm per location was selected, incorporating all three pasture systems, with their characteristics summarized in Table 1.

Table 1. *Characteristics of Pasture systems in each site and location*

Pasture systems	System type and stocking rate	Time use	Agronomic management
Restrepo (Location 1)			
Degraded pasture (DP)	Extensive, 0.5 AU/ha	>20 years	Extensive Degraded Pasture of native grass (EDPNG): unfertilized.
Improved Pasture (IP)	Extensive, 1.0 AU/ha		Extensive Improved Pasture of *Brachiaria decumbens grass* (EIPB): unfertilized, without rotational grazing.
Silvopastoral System (SPS)	Extensive, 1.0 AU/ha		Extensive silvopastoral system of *B. decumbens* grass with Yopo **(***Anadenanthera peregrina***)** trees (ESPS + AP): living fence, unfertilized, without rotational grazing.
Cumaral (Location 2)			
Degraded Pasture (DP)	Extensive, 0.8 AU/ha	10-20 years	Extensive Degraded Pasture of *Brachiaria decumbens* grass (EDPEB): unfertilized.
Improved Pasture (IP)	Intensive, 1.5 AU/ha		Intensive Improved Pasture of *B. decumbens* grass (IIPB): pasture renovation, fertilization, lime application, and rotational grazing.
Silvopastoral System (SPS)	Extensive, 1.5 AU/ha		Extensive silvopastoral system of *B. decumbens grass* with *Acacia mangium* trees (ESPS + A): living fence, pasture renovation, fertilization, lime application, and recovery of soil physical conditions through *Trifolium repens* establishment and rotational grazing.

Note. Silvopastoral systems (SPS) are a form of agroforestry that integrates woody components (trees and/or shrubs), pastures, and livestock either directly or indirectly, aiming to generate ecological, productive, and environmental synergies (Chará *et al*. 2019).

Experimental design

A completely randomized design with a 2 × 3 × 2 factorial arrangement was used, consisting of two Piedmont locations (Location 1: Restrepo; location 2: Cumaral), three pasture systems (Degraded pasture, improved pasture, and silvopastoral systems), and two soil depths ((0–0.30 m and 0.30–0.60 m), with three replicates per treatment, yielding a total of 36 samples.

Soil sampling

In each pasture system, three composite disturbed soil samples were collected from three randomly selected points at two depths (0–0.30 m and 0.30–0.60 m), resulting in a total of 18 samples per farm and 36 samples overall. All subsequent soil analyses were performed at the soil laboratory of the Faculty of Agricultural Sciences and Natural Resources at Universidad de los Llanos.

Determination of soil physical properties

Soil texture and bulk density. The physical analyses were performed in accordance with the procedures established by the Instituto Geográfico Agustín Codazzi (IGAC 2006). Soil texture fractions (sand, silt, and clay) were determined as percentages using the Bouyoucos hydrometer method.

Bulk density was calculated by the paraffin-coated clod method, that is a common technique for determining this propertie of undisturbed, irregularly shaped soil aggregates (clods) by calculating their volume through Archimedes' principle of water displacement. The paraffin seals the soil pores, preventing water absorption during immersion. The dry bulk density (ρb) is calculated as the ratio of the oven-dry mass of the soil sample (Mdry) to its total volume (Vt) (Equation 1):

$$(\rho b = Mdry/VT) \quad (1)$$

Where: ρb: bulk density (g cm^{-3}); VT: total volume of the sample (cm^3); and *Mdry*: mass of dry soil (g), at 105°C for 24 hours.

Particle density and total porosity. Soil particle density (Pd, g cm^{-3}) was alsomeasured using the pycnometer method.

Total soil porosity (Tp, %) was obtained using Equation (2):

$$(Tp = \ Pd - \rho b/Pd * 100) \quad (2)$$

Where: Pd: soil particle density (g cm^{-3}); ρb: bulk density (g/cm^3)

Micro- and macroporosity. Microporosity (MiP) (%) was determined as the volumetric moisture content at field capacity (VM_{fc}), using the tension tables (5 kPa).

The macroporosity (MaP) % was calculated as Equation 3:

$$(MaP = Tp - MiP) \quad (3)$$

Where: Tp: total porosity (%) and MiP: soil microporosity (%).

Available Water Capacity (AWC). Soil gravimetric water content (θg) (%) was determined using Equation (4):

$$(\Theta g = Mwet - Mdry/Mdry * 100) \quad (4)$$

Where: *Mwet*: mass of wet soil (g); and *Mdry*: mass of dry soil (g), at 105°C for 24 hours.

Soil volumetric water content (θv) (%) was calculated using Equation (5):

$$(\theta v = \Theta g * \rho b) \quad (5)$$

Where: θg: soil gravimetric water content (%); and ρb: bulk density (g cm^{-3}). Available water capacity (AWC) (mm) was determined using Equation (6):

$$(AWC = \theta v/100 * Depth) \quad (6)$$

Where: θv: volumetric water content (%); *Depth*: soil depth (mm)

RESULTS

Interaction effects on soil physical properties

The interaction between location, pasture system, and sampling depth (Table 2) showed significant effects on soil texture, bulk density (ρb), total porosity (Tp), macroporosity (MaP), and microporosity (MiP) ($p < 0.05$). In contrast, volumetric water content, as well as available water capacity, did not show significant differences among treatments ($p > 0.05$).

Table 2. *Mean values of soil physical properties at two soil depths under degraded, improved, and silvopastoral pasture systems at two locations (Restrepo and Cumaral) in the Piedmont region.*

Physical characteristics of the soil	**Depths (m)**	**Location 1 (Restrepo)**	**Location 2 (Cumaral)**	**Location 1 (Restrepo)**	**Location 2 (Cumaral)**	**Location 1 (Restrepo)**	**Location 2 (Cumaral)**
		Degraded pastures		Improved pastures		Silvopastoral systems	
		EDPNG	EDPB	EIPB	IIPB	ESPS+AP	ESPS + A
				Soil compaction			
Sa (%)	0 - 0.30	62^{bcd}	59.33^{bcde}	70^{ab}	65.33^{abc}	56.67^{bcde}	**78^{a}**
Sa (%)	0.30 - 0.60	54.67^{cde}	50.67^{de}	58.67^{bcde}	56.67^{bcde}	**46^{e}**	**76^{a}**
Si (%)	0 - 0.30	31.33^{ab}	34.00^{ab}	24.67^{bcd}	29.33^{abc}	31.33^{ab}	20.00^{cd}
Si (%)	0.30 - 0.60	27.33^{abcd}	33.33^{ab}	28.67^{abc}	26.00^{abc}	**35.33^{a}**	**18.67^{d}**
Cl (%)	0 - 0.30	6.67^{bc}	6.67^{bc}	5.33^{bc}	5.33^{bc}	12^{ab}	**2.00^{c}**
Cl (%)	0.30 - 0.60	**18.00^{a}**	**16.00^{a}**	12.67^{ab}	**17.33^{a}**	**18.67^{a}**	5.33^{bc}
ρb (g cm^{-3})	0 - 0.30	1.86^{ab}	**1.22^{d}**	1.66^{c}	**1.33^{d}**	1.73^{bc}	**1.24^{d}**
ρb (g cm^{-3})	0.30 - 0.60	**1.90^{a}**	**1.31^{d}**	**1.30^{d}**	**1.31^{d}**	1.70^{c}	**1.25^{d}**
Pd (g cm^{-3})	0 - 0.30	**2.29^{e}**	2.64^{de}	2.45^{cde}	2.34^{de}	2.43^{cde}	2.46^{cd}
Pd (g cm^{-3})	0.30 - 0.60	2.35^{de}	2.33^{de}	2.48^{bcd}	**2.68^{a}**	2.35^{de}	2.54^{abc}
Interpretation		Compacted	No compacted	Compacted 0 - 0 - 30m	No compacted	Compacted	No compacted
				Soil aeration			
Tp (%)	0 - 0.30	**18.46^{d}**	49.33^{ab}	32.40^{c}	**53.37^{a}**	29.00^{c}	44.10^{b}
Tp (%)	0.30 - 0.60	**18.84^{d}**	50.53^{ab}	27.10^{c}	49.77^{ab}	30.01^{c}	50.13^{ab}
MaP (%)	0 - 0.30	4.80^{bc}	10.08^{abc}	9.04^{abc}	17.97^{ab}	10.70^{abc}	14.29^{abc}
MaP (%)	0.30 - 0.60	**2.52^{c}**	**22.59^{a}**	9.27^{abc}	**20.64^{a}**	11.80^{abc}	11.50^{abc}
MiP (%)	0 - 0.30	**13.66^{d}**	**39.25^{a}**	23.36^{bcd}	35.40^{ab}	18.29^{cd}	29.81^{abc}
MiP (%)	0.30 - 0.60	16.33^{cd}	31.21^{abc}	17.82^{cd}	29.13^{abc}	18.21^{cd}	**38.63^{a}**
Interpretation		Low MaP, root restriction	MaP close to restriction	Low MaP, root restriction	MaP close to restriction		

Physical characteristics of the soil	**Depths (m)**	**Location 1 (Restrepo)**	**Location 2 (Cumaral)**	**Location 1 (Restrepo)**	**Location 2 (Cumaral)**	**Location 1 (Restrepo)**	**Location 2 (Cumaral)**
		Degraded pastures		Improved pastures		Silvopastoral systems	
		EDPNG	EDPB	EIPB	IIPB	ESPS+AP	ESPS + A
				Soil available water capacity			
Θg (%)	0 - 0.30	18.64^{bc}	**32.21^{a}**	28.19^{abc}	27.26^{abc}	21.31^{abc}	24.01^{abc}
Θg (%)	0.30 - 0.60	**17.40^{c}**	24.16^{abc}	23.53^{abc}	21.92^{abc}	21.40^{abc}	30.84^{ab}
θv (%)	0 - 0.30	33.99^{a}	39.25^{a}	46.72^{a}	35.40^{a}	36.59^{a}	29.81^{a}
θv (%)	0.30 - 0.60	35.65^{a}	32.67^{a}	35.65^{a}	29.13^{a}	36.63^{a}	36.43^{a}
AWC (mm)	0 - 0.30	140.16^{a}	117.76^{a}	101.97^{a}	106.19^{a}	109.78^{a}	89.42^{a}
AWC (mm)	0.30 - 0.60	116.96^{a}	93.64^{a}	98.00^{a}	87.29^{a}	109.24^{a}	115.89^{a}
Interpretation				Good available water capacity			

Note. In Location 1 (Restrepo): EDPNG: Extensive Degraded Pasture of Native grass; EIPB: Extensive Improved Pasture of Brachiaria decumbens grass; ESPS + AP: Extensive SPS of B. decumbens grass in consortium with Yopo Anadenanthera peregrina trees. In location 2 (Cumaral), EDPB: Extensive Degraded Pasture of Brachiaria decumbens grass, IIPB: Intensive Improved Pasture of B. decumbens grass, and ESPS + A: Extensive SPS of B. decumbens grass in consortium with Acacia, Acacia mangium trees (ESPS + A). Textural fraction (S: Sand; Si: Silt; Cl: Clay); ρb: bulk density, Pd: relative density, Tp: total porosity; MaP: macroporosity; MiP: microporosity; θg: Gravimetric water content; θv: volumetric water content; AWC: available water content. Interpretation: Restricts bulk density (BD) for root growth (g/cm3), for clay, sand, silt > 1.47, 1.80, 1.65 (Jaramillo, 2002). Interpretation Volumetric water at field capacity (θvfc) (%) for clay, sand, and silt; 30-70, 5-16, and 15-30, respectively (Jaramillo, 2002). Different letters between columns indicate differences at a 95% probability, LSD test.

Soil compaction

Interaction effects of location × pasture system × depth. Significant differences in sand, silt, and clay contents were observed among pasture systems ($p < 0.05$). Sand dominated across all treatments and depths, classifying soils as loamy sand. The highest sand contents were in the silvopastoral system ESPS + A at both depths in location 2 (78% and 76%), while lower sand and higher silt occurred in ESPS + AP at 0.30–0.60 m in location 1 ($p < 0.05$) (Table 2).

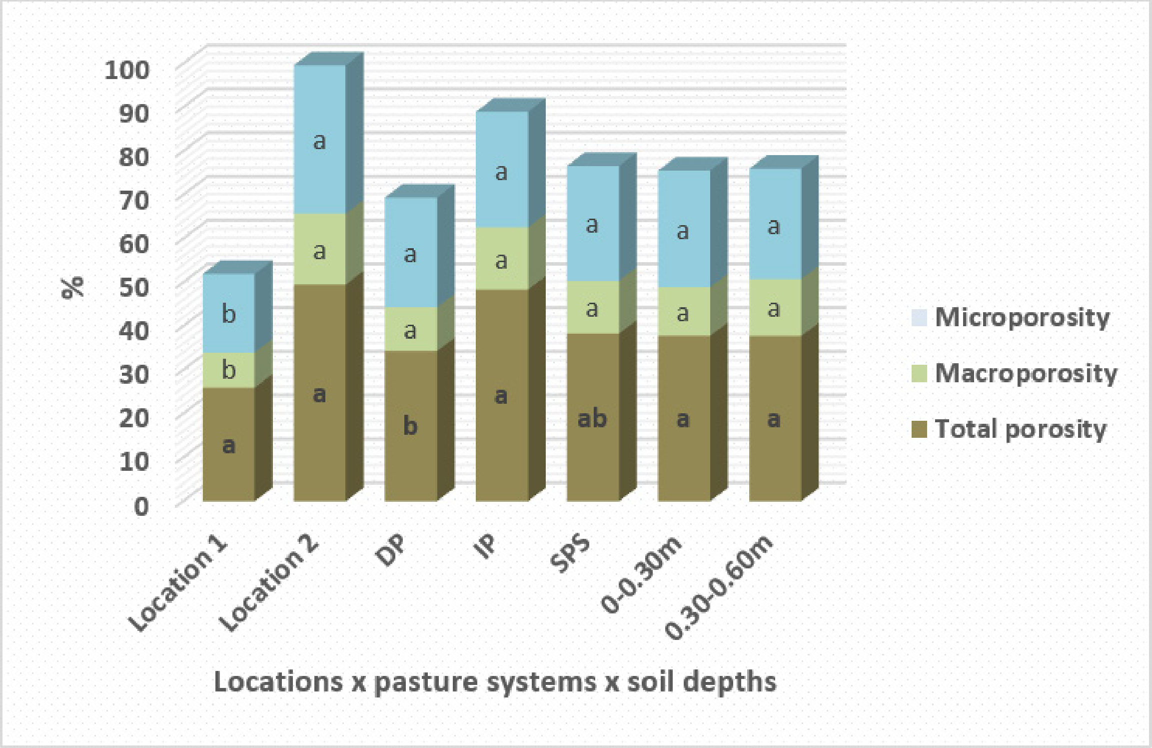
Higher clay contents occurred at 0.30–0.60 m in degraded pastures at both locations, in IIPB at location 2, and in ESPS + AP at location 1, although all remained in the same textural class (Table 2). Soil texture influenced bulk density (ρb), with the highest ρb (1.90 g cm^{-3}) in EDPNG at 0.30–0.60 m in location 1, indicating compaction.

Pasture systems at location 2 and the improved pasture EIPB at location 1 exhibited lower ρb values, with no significant differences among them ($p > 0.05$) (Table 2). Particle density values were within the typical range for mineral soils (Jaramillo, 2002), averaging 2.65 g cm^{-3}, with the highest values in IIPB at 0.60 m and the lowest in EDPNG at 0.30 m ($p < 0.05$) (Table 2).

Soil aeration

Simple effects of location, pasture system, and depth. Total porosity (Tp) differed significantly among locations and pasture systems ($p < 0.05$), while macroporosity (MaP) and microporosity (MiP) differed only between locations. Overall, Tp, MaP, and MiP were higher at location 2 (49.54%, 16.18%, and 33.91%) than at location 1 (25.97%, 8.02%, and 17.95%), with macroporosity at location 1 classified as critical (Jaramillo, 2002) (Figure 1).

Degraded pastures showed the lowest Tp values (34.29%), whereas improved pastures had the values (48.36%). Silvopastoral systems exhibited intermediate values (38.31%) ($p < 0.05$) (Figure 1).



Note. Location 1: Restrepo, Location 2: Cumaral. DP: degraded pastures, IP: improved pastures, SPS: silvopastoral systems (SPS). Different letters between columns indicate significant differences between the measurement locations, pasture systems, and depths according to the LSD test groupings (p ≤0.05)

Figure 1. *Partitioning of total soil porosity (Tp) into macroporosity (MaP) and microporosity (MiP), due to the simple effect of locations, pasture systems, and depths in the Piedmont region.*

Interaction effects of location × pasture system × depth. Total porosity (Tp) ranged from 53.37% at 0–0.30 m in IIPB at location 2 to 18.46–18.84% at both depths in the degraded pasture (EDPNG) at location 1 (Table 2). Pasture systems at location 2 showed significantly higher Tp throughout the profile ($p < 0.05$) (Table 2).

Macroporosity (MaP) was critically low in EDPNG at 0.30–0.60 m in location 1 (2.52%), below the 10% threshold for root development (Jaramillo, 2002), whereas EDPB and IIPB at location 2 exhibited the highest MaP values at the same depth (Table 2).

Microporosity (MiP) was consistently higher in pasture systems at location 2, reaching up to 39.25% in EDPB and ESPS + A, while the lowest value (13.66%) occurred in EDPNG at 0.30 m in location 1 (Table 2).

Soil water status

Gravimetric water content (θg). Gravimetric water content (θg) differed significantly among the evaluated treatments (location × pasture system × soil depth) ($p < 0.05$) (Table 2). Mean θg values ranged from 32.21% at 0–0.30 m in the degraded pasture of *B. decumbens* (EDPB) at location 2 to 17.40% at 0.30–0.60 m in the degraded native pasture (EDPNG) at location 1. The remaining treatments exhibited similar θg patterns across depths (Table 2).

Volumetric water content (θv) and AWC. Volumetric water content (θv) and available water capacity (AWC) did not differ significantly among treatments. In general, both variables decreased with increasing soil depth in pasture systems at both locations.

However, higher θv and AWC values were observed at 0–0.30 m in the improved pasture (EIPB) and degraded pasture (EDPNG) at location 1, which may be associated with soil compaction effects influencing water retention (Table 2).

DISCUSSION

The predominance of sandy textures across pasture systems at both locations and depths strongly influenced soil compaction, aeration, and available water capacity. Overall, the results confirm that pasture-based livestock management significantly affects soil physical properties across pasture systems and soil depths in the Piedmont region, in agreement with Polanía-Hincapié *et al*. (2021).

Soil texture plays a central role in regulating ecosystem services and soil physical functioning (Silva-Parra *et al*., 2020; Pent & Fike, 2021). Although differences in particle-size fractions were detected among treatments, both evaluated layers were classified as sandy loam, indicating that management practices rather than textural class alone largely explain the observed variability.

Pasture systems at location 1 consistently exhibited higher bulk density (ρb) and lower macroporosity (MaP) throughout the soil profile compared with systems at location 2. These conditions favored soil compaction and reduced water storage capacity, highlighting the importance of soil texture and structure in determining soil responses to management (Chará *et al*., 2019; Lopes *et al*., 2020). Accurate evaluation of soil compaction requires consideration of the interaction between intrinsic soil properties and external drivers such as climate, land use, and soil depth (Reichert *et al*., 2018).

At location 2, the silvopastoral system ESPS + A exhibited the highest sand content, lower clay content, and consistently lower ρb across depths, with no evidence of soil compaction. In contrast, the degraded pasture EDPNG at location 1 showed higher clay content and elevated ρb at 0.30–0.60 m, which was associated with compaction. These findings align with previous studies reporting that improved pasture management and silvopastoral systems reduce compaction and enhance soil physical quality (Corbett *et al*., 2021). Lower ρb in improved pastures and silvopastoral systems at location 2 can be attributed to intensive management practices—including fertilization, liming, and rotational grazing—combined with inherently better soil structure, which promoted improved soil aggregation and pore continuity. In contrast, extensive degraded pastures and silvopastoral systems at location 1 continued to exhibit compacted layers, likely due to naturally poor soil structure and low soil organic carbon (SOC) content (Parra *et al*., 2019), highlighting the persistence of compaction under unfavorable soil conditions, even with management improvements.

Comparisons between degraded pastures at location 1 and improved pastures and silvopastoral systems at location 2 indicate that the introduction of Brachiaria grasses significantly reduced ρb and soil compaction (Paredes-Peralta *et al*., 2025). Conversely, repeated burning, dominance of low-quality native pastures, and lack of mechanical interventions contributed to soil degradation at location 1 as supported by Nolberto

Coz (2025). Livestock trampling also exacerbated structural degradation through surface sealing and deformation, particularly under wet soil conditions (Drewry *et al*., 2008).

The improved pasture (IIPB) and silvopastoral system (ESPS + A) at location 2 showed no evidence of compaction throughout the soil profile, possibly linked to higher organic matter inputs and the formation of stable organic–mineral complexes that enhance aggregate stability, pore connectivity, and resistance to mechanical stress (Carrascosa *et al*., 2025). In silvopastoral systems, continuous organic residue inputs, root turnover, and litter deposition further improve SOC levels (Jose & Dollinger, 2019), water-holding capacity, and infiltration efficiency, supporting long-term soil physical functionality (Bento *et al*., 2025).

Grazing-induced compaction primarily affects the upper soil layers, especially the top 5 cm, due to soil poaching under high moisture conditions (Roesch *et al*., 2019; Bondi *et al*., 2021). Bulk density, which integrates soil texture and compaction intensity, remains a key indicator for assessing soil aeration and water storage capacity (Özdemir *et al*., 2022).

Differences in Tp, MaP, and MiP between simple factors (locations, systems) indicate that climate, soil management intensity, and vegetation cover strongly influence soil physical degradation and aeration (Lopes *et al*., 2020). Silvopastoral systems promote macropore networks through deep roots and biopores while higher organic matter inputs enhance overall porosity (Zaibon *et al*., 2017).

The elevated bulk density observed in EDPNG at location 1 across the soil profile substantially restricted macroporosity (MaP), reaching levels that can impede root growth and penetration (Jaramillo, 2002). In contrast, all pasture systems at location 2 exhibited better aeration conditions throughout the profile, reflecting improved physical, chemical, and biological soil conditions, favoring higher organic matter accumulation and enhanced structure (Silva-Parra *et al*., 2023; Conant *et al*., 2017).

Reduced MaP in degraded pastures is commonly associated with physical degradation and compaction (Chará *et al*., 2019). Degraded pastures at location 1 showed low total porosity (Tp) at both depths and critically low MaP at 0.30–0.60 m, indicating severe structural degradation. In contrast, IIPB at location 2 exhibited higher Tp at 0–0.30 m and greater MaP at 0.30–0.60 m, with silvopastoral systems showing similar but slightly less pronounced improvements. These results agree with Vallejo *et al*. (2010), who reported increased macroporosity and microporosity and reduced bulk density under improved silvopastoral systems.

Despite the benefits of improved pastures and silvopastoral systems at location 2, MaP values sometimes approached the critical threshold of 10% established by Jaramillo (2002), suggesting potential vulnerability to aeration limitations if management is not maintained. Soil compaction preferentially reduces macropores essential for air and water movement (Schulte *et al*., 2018; Frene *et al*., 2024; Özdemir *et al*., 2022), affecting soil ecological functions such as water transmission and storage (Lopes *et al*., 2020). Low microporosity (MiP) at location 1 reflects reduced total porosity and limited water retention, even under improved management.

Macroporosity is widely used as an indicator of structural quality because macropores are highly sensitive to mechanical disturbance (Six *et al*., 2004), with reductions increasing bulk density and penetration resistance, thereby limiting root growth and development (Roesch *et al*., 2019). Piedmont soils are characterized by inherently low organic matter content (Silva-Parra, 2018), and SOC strongly correlates with soil porosity (Zhang *et al*., 2024, enhancing aggregation, pore continuity, and gas exchange. Lower gravimetric water content was consistently observed in degraded pastures at location 1, whereas higher values occurred in degraded pastures at location 2, reflecting higher bulk density, reduced total porosity and macroporosity, and limited microporosity in degraded soils.

Pastures at location 2 exhibited better physical conditions and more favorable soil moisture dynamics related to Gravimetric water content (θg). Physical constraints at location 1 increased susceptibility to compaction, restricting root development and water movement, and intensifying water stress under drought or saturated conditions (Rabbi *et al*., 2024). Although volumetric water content and available water capacity did not differ significantly among locations, systems, or depths, it is recognized in the literature that silvopastoral systems improve soil water regulation by integrating trees, shrubs, and grasses, enhancing structure, organic matter inputs, infiltration, and water-holding capacity (Pent & Fike, 2021).

These attributes stabilize soil moisture and increase resilience to hydrological extremes (Vallejo et al., 2010). Woody components regulate the soil water cycle, reduce runoff, and improve storage through physical property and microclimatic improvements (Lopes *et al*., 2020; Jose & Dollinger, 2019). Organic matter further enhances water retention and stabilizes structure, reducing compaction under higher moisture availability (Liu *et al*., 2023). Consequently, silvopastoral systems should be prioritized in Piedmont landscapes to improve long-term soil physical quality, water regulation, and resilience.

CONCLUSIONS

Regarding pasture systems at location 2, these exhibited better soil physical quality than those at location 1 throughout the entire soil profile, despite both sites being characterized by a sandy loam texture. Total porosity (Tp), as well as macroporosity (MaP) and microporosity (MiP), were consistently higher in the pasture systems at location 2, while bulk density was lower. Degraded pastures (DP), particularly at location 1 (EDPNG), showed higher bulk density and reduced Tp across all depths, conditions that may restrict root growth and limit soil aeration. In contrast, improved pastures (IP) and silvopastoral systems (SPS) at location 2 (IIPB and ESPS + A, respectively) exhibited lower bulk density and greater Tp, indicating enhanced soil physical quality and reduced susceptibility to compaction. Both IP and SPS at location 2 also showed a tendency to increase available water capacity (AWC), reflecting more favorable soil physical conditions. Overall, silvopastoral systems represent a viable alternative for livestock production, as they improve soil physical properties and contribute to more sustainable farming systems. Future research should further explore the relationships between soil physical properties and productivity in silvopastoral systems.

AUTHOR CONTRIBUTIONS

Conceptualization, A.S.P., JM.T.G. and MA.T.M.; Methodology, A.S.P. and JM.T.G.; Investigation, A.S.P. and JM.T.G; Software, A.S.P.; Resources, MA.T.M.; Writing—Original Draft Preparation, A.S.P., JM.T.G. and MA.T.M.; Writing—Review & Editing, A.S.P., JM.T.G. and MA.T.M.; Visualization, A.S.P., JM.T.G. and MA.T.M.; Supervision, A.S.P., JM.T.G. and MA.T.M.; Project Administration, A.S.P., JM.T.G. and MA.T.M.; Funding Acquisition, A.S.P. and JM.T.G.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this article.

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