

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

Amanda Silva-Parra¹, Juan Manuel Trujillo-González²,
Marco Aurelio Torres-Mora²

¹ Facultad de Ciencias Agropecuarias y Recursos Naturales, Universidad de los Llanos, Villavicencio, Colombia, asilvap@unillanos.edu.co, <https://orcid.org/0000-0001-9872-790X> (Correspondence)

² Instituto de Ciencias Ambientales de la Orinoquia Colombiana - ICAOC, Universidad de los Llanos, Villavicencio, Colombia, jtrujillo@unillanos.edu.co, <https://orcid.org/0000-0001-9612-4080>; marcotorres@unillanos.edu.co, <https://orcid.org/0000-0002-3824-5412>

Cite: Silva-Parra, A., Trujillo-González, J., & Torres-Mora, M.A. (2026). Effects of pasture systems on soil compaction, aeration, and available water capacity. *Revista de Ciencias Agrícolas*, 43(1), e1292. <https://doi.org/10.22267/rcia.2026431.292>

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 ($2 \times 3 \times 2$; $n=36$) was used, considering location, pasture system, and soil depth (0–0.30 and 0.30–0.60 m). Soil texture, bulk density (pb), total porosity (Tp), macroporosity and microporosity (MaP, MiP), gravimetric, volumetric (θ_g , θ_v), and available water capacity (AWC) were measured. Data were analyzed using ANOVA and Least Significant Difference (LSD) tests. At location 1, EDPNG exhibited higher pb 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, θ_g differed significantly in DP, higher in EDPB, θ_v 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 ($2 \times 3 \times 2$; $n = 36$), 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 (pb), la porosidad total (Pt), la macro y microporosidad (MaP, MiP), la capacidad de agua gravimétrica y volumétrica (θ_g , θ_v) 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 pb 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 θ_g difirió significativamente en la PD, más alta en la PDEB; θ_v 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		Extensive Degraded Pasture of native grass (EDPNG): unfertilized.
Improved Pasture (IP)	Extensive, 1.0 AU/ha	>20 years	Extensive Improved Pasture of <i>Brachiaria decumbens</i> grass (EIPB): unfertilized, without rotational grazing.
Silvopastoral System (SPS)	Extensive, 1.0 AU/ha		Extensive silvopastoral system of <i>B. decumbens</i> grass with Yopo (<i>Anadenanthera peregrina</i>) trees (ESPS + AP): living fence, unfertilized, without rotational grazing.
Cumaral (Location 2)			
Degraded Pasture (DP)	Extensive, 0.8 AU/ha		Extensive Degraded Pasture of <i>Brachiaria decumbens</i> grass (EDPEB): unfertilized.
Improved Pasture (IP)	Intensive, 1.5 AU/ha	10-20 years	Intensive Improved Pasture of <i>B. decumbens</i> grass (IIPB): pasture renovation, fertilization, lime application, and rotational grazing.
Silvopastoral System (SPS)	Extensive, 1.5 AU/ha		Extensive silvopastoral system of <i>B. decumbens</i> grass with <i>Acacia mangium</i> trees (ESPS + A): living fence, pasture renovation, fertilization, lime application, and recovery of soil physical conditions through <i>Trifolium repens</i> 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 $2 \times 3 \times 2$ 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 (ρ_b) is calculated as the ratio of the oven-dry mass of the soil sample (M_{dry}) to its total volume (V_t) (Equation 1):

$$(\rho_b = M_{dry}/V_t) \quad (1)$$

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

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

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

$$(T_p = \rho_d - \rho_b / \rho_d * 100) \quad (2)$$

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

Micro- and macroporosity. Microporosity (M_iP) (%) 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:

$$(MaP = T_p - M_iP) \quad (3)$$

Where: T_p : total porosity (%) and M_iP : soil microporosity (%).

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

$$(\theta_g = M_{wet} - M_{dry} / M_{dry} * 100) \quad (4)$$

Where: M_{wet} : mass of wet soil (g); and M_{dry} : mass of dry soil (g), at 105°C for 24 hours.

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

$$(\theta_v = \theta_g * \rho_b) \quad (5)$$

Where: θ_g : soil gravimetric water content (%); and ρ_b : bulk density (g cm^{-3}). Available

water capacity (AWC) (mm) was determined using Equation (6):

$$(AWC = \theta_v/100 * \text{Depth}) \quad (6)$$

Where: θ_v : 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 (ρ_b), total porosity (T_p), 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
<i>Soil compaction</i>							
Sa (%)	0 - 0.30	62 ^{bcd}	59.33 ^{bcd}	70 ^{ab}	65.33 ^{abc}	56.67 ^{bcd}	78 ^a
Sa (%)	0.30 - 0.60	54.67 ^{cde}	50.67 ^{de}	58.67 ^{bcd}	56.67 ^{bcd}	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}
ρ_b (g cm ⁻³)	0 - 0.30	1.86 ^{ab}	1.22 ^d	1.66 ^c	1.33 ^d	1.73 ^{bc}	1.24 ^d
ρ_b (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
P_d (g cm ⁻³)	0 - 0.30	2.29 ^e	2.64 ^{de}	2.45 ^{cde}	2.34 ^{de}	2.43 ^{cde}	2.46 ^{cd}
P_d (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
<i>Soil aeration</i>							
T_p (%)	0 - 0.30	18.46 ^d	49.33 ^{ab}	32.40 ^c	53.37 ^a	29.00 ^c	44.10 ^b
T_p (%)	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
<i>Soil available water capacity</i>							
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); pb: 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).

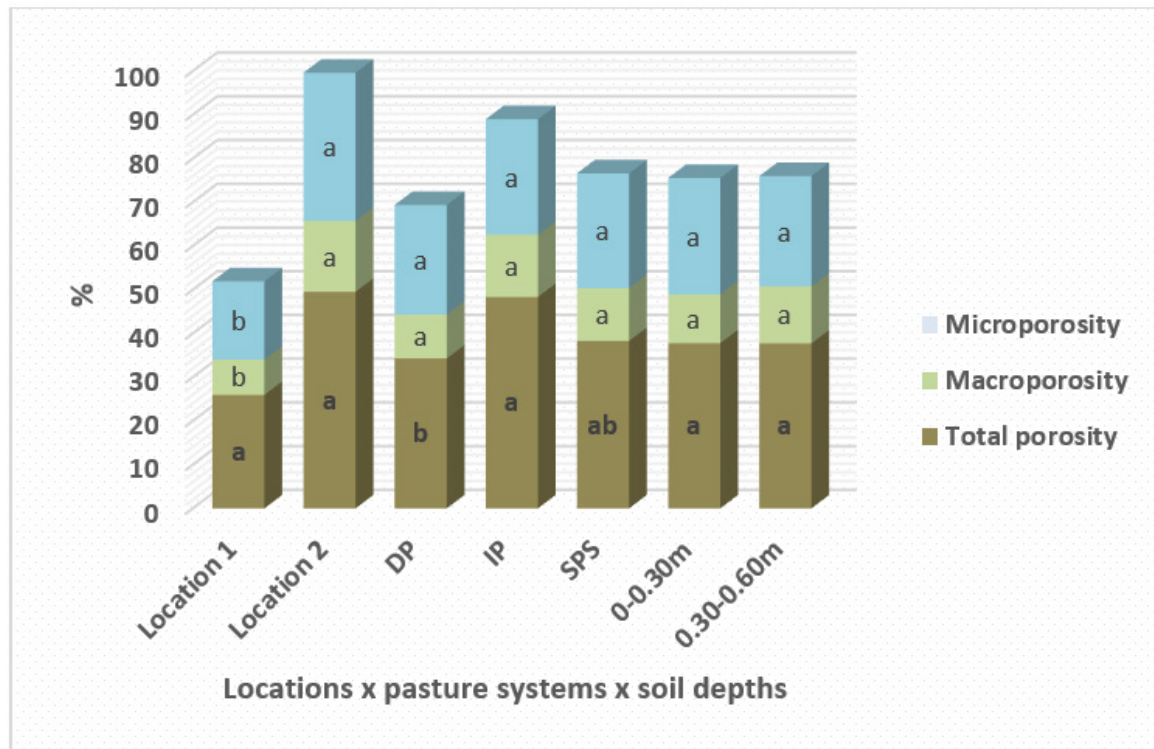
Higher clay contents occurred at 0.30–0.60 m in degraded pastures at both locations, in IIPB at location 2, and in ESPS + AP at location 1, although all remained in the same textural class (Table 2). Soil texture influenced bulk density (pb), with the highest pb (1.90 g cm⁻³) in EDPNG at 0.30–0.60 m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

Pasture systems at location 2 and the improved pasture EIPB at location 1 exhibited lower pb 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 ($p \leq 0.05$)

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 (θ_g). Gravimetric water content (θ_g) differed significantly among the evaluated treatments (location × pasture system × soil depth) ($p < 0.05$) (Table 2). Mean θ_g 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 θ_g patterns across depths (Table 2).

Volumetric water content (θ_v) and AWC. Volumetric water content (θ_v) 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 θ_v 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 (pb) 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 pb across depths, with no evidence of soil compaction. In contrast, the degraded pasture EDPNG at location 1 showed higher clay content and elevated pb 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 pb 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 pb 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 (θ_g). 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 (T_p), 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 T_p 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 T_p , 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.

ACKNOWLEDGMENTS

The authors extend their gratitude to The Direction General de Investigación's Universidad de los Llanos by Financial contribution and Instituto de Ciencias Ambientales de la Orinoquia Colombiana ICAOC and Research Group ISAF, by scientific and technical contributions.

CONFLICT OF INTEREST

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

REFERENCES

- Bento, L. R., dos Santos, J. V., Schweizer, S. A., de Moraes, C. P., Mitsuyuki, M. C., Oliveira, P. P. A.; Pezzopane, J. R. M., Bernardi, A. C., & Martin-Neto, L. (2025). Moderate pasture intensification enhances soil organic carbon stocks in a degraded Brazilian Ferralsol. *Soil and Tillage Research*, 251, 106534. <https://doi.org/10.1016/j.still.2025.106534>
- Bondi, G., O'Sullivan, L., Fenton, O., Creamer, R., Marongiu, I., & Wall, D. P. (2021). Trafficking intensity index for soil compaction management in grasslands. *Soil Use and Management*, 37(3), 504–518. <https://doi.org/10.1111/sum.12586>
- Carrascosa, A., Moreno, G., Cotrufo, M. F., Frade, C., Rodrigo, S., & Rolo, V. (2025). Improved management increases soil mineral-protected organic carbon storage via plant-microbial-nutrient mediation in semi-arid grasslands. *Soil*, 11(2), 911–937. <https://doi.org/10.5194/soil-11-911-2025>
- Chará, J., Reyes, E., Peri, P., Otte, J., Arce, E., & Schneider, F. (2019). *Silvopastoral systems and their contribution to improved resource use and sustainable development goals: evidence from Latin America*. FAO, CIPAV & Agri Benchmark.
- Conant, R. T., Cerri, C. E., Osborne, B. B., & Paustian, K. (2017). Grassland management impacts on soil carbon stocks: a new synthesis. *Ecological Applications*, 27(2), 662–668. <https://doi.org/10.1002/eap.1473>
- Corbett, D., Wall, D. P., Lynch, M. B., & Tuohy, P. (2021). The influence of lime application on the chemical and physical characteristics of acidic grassland soils with impeded drainage. *The Journal of Agricultural Science*, 159, 206–215, <https://doi.org/10.1017/S0021859621000381>
- Drewry, J. J., Cameron, K. C., & Buchan, G. D. (2008). Pasture yield and soil physical property responses to soil compaction from treading and grazing—A review. *Australian Journal of Soil Research*, 46(3), 237–256.
- Frene, J. P., Pandey, B. K., & Castrillo, G. (2024). Under pressure: elucidating soil compaction and its effect on soil functions. *Plant and Soil*, 502, 267–278. <https://doi.org/10.1007/s11104-024-06573-2>
- Fuentes, O., Guamán, S. A., Zacarías, F., & Paredes, V. (2023). Silvopastoral systems as a strategy for reconversion of livestock farming in Ecuadorian Amazon. *Advanced Composites Bulletin*, 37, 135–138.
- Emmet-Booth, J. P., Holden, N. M., Fenton, O., Bondi, G., & Forristal, P. D. (2020). Exploring the sensitivity of visual soil evaluation to traffic-induced soil compaction. *Geoderma Regional*, 20, e00243. <https://doi.org/10.1016/j.geodrs.2019.e00243>
- Federación Nacional de Ganaderos – Fedegan (2014). *Balance y perspectivas del sector ganadero colombiano*. FEDEGAN.
- Hossain, A., Krupnik, T. J., Timsina, J., Mahboob, M. G., Chaki, A. K., Farooq, M., Bhatt, R., Fahad, S., & Hasnuzzaman,

- M. (2020). Agricultural land degradation: processes and problems undermining future food security. In S. Fahad, M. Hasanuzzaman, M. Alam, H. Ullah, M. Saeed, I. Ali Khan, & M. Adnan (eds) *Environment, Climate, Plant and Vegetation Growth* (pp. 17-61). Cham: Springer. https://doi.org/10.1007/978-3-030-49732-3_2
- Instituto Geográfico Agustín Codazzi - IGAC (2006). *Métodos analíticos del laboratorio de suelos (6th ed)*. IGAC: National Printing Office of Colombia.
- Jaramillo, D. (2002). Introducción a la Ciencia del suelo. <https://repositorio.unal.edu.co/bitstream/handle/unal/70085/70060838.2002.pdf?sequence=1&isAllowed=yv>
- Jose, S., & Dollinger, J. (2019). Silvopasture: a sustainable livestock production system. *Agroforest System*, 93, 1–9. <https://doi.org/10.1007/s10457-019-00366-8>
- Kumar, V., Jain, M., Rani, V., Kumar, A., Kumar, S., & Naresh, J. (2018). A Review of soil compaction- concerns, causes and alleviation. *International Journal of Plant and Soil Science*, 22(4), 1–9. <https://doi.org/10.9734/IJPSS/2018/40351>
- Lai, L., & Kumar, S. (2020). A global meta-analysis of livestock grazing impacts on soil properties. *PloS One*, 15(8), e0236638. <https://doi.org/10.1371/JOURNAL.PONE.0236638>
- Liu, W., Huang, X., Feng, X., & Xie, Z. (2023). Compaction and bearing characteristics of untreated and treated lateritic soils with varying moisture content. *Construction and Building Materials*, 392, 131893. <https://doi.org/10.1016/j.conbuildmat.2023.131893>
- Lopes, V. S., Cardoso, I. M., Fernandes, O. R., Rocha, G. C., Simas, F. N. B., de Melo Moura, W., Santana, F., Veloso, G. V., & da Luz, J. M. (2020). The establishment of a secondary forest in a degraded pasture to improve hydraulic properties of the soil. *Soil and Tillage Research*, 198, 104538. <https://doi.org/10.1016/j.still.2019.104538>
- Nolberto Coz, R. A. (2025). Impacto de la quema de pastizales sobre la degradación de suelos en las zonas altoandinas de la región Huánuco. *Revista Científica Altoandina de Ciencias Agrarias*, 1(1), 65–72. <https://doi.org/10.54943/recialcia.685>
- Özdemir, N., Demir, Z., & Bülbül, E. (2022). Relationships between some soil properties and bulk density under different land use. *Soil Studies*, 11(2), 43-50. <http://doi.org/10.21657/soilst.1218353>
- Owuor, S. O., Butterbach-Bahl, K., Jacobs, A. C. G., Merbold, S. L., Rufino, M. C., Pelster, D. E., Pinés, E. D., & Breuer, L. (2018). Conversion of natural forest results in a significant degradation of soil hydraulic properties in the highlands of Kenya. *Soil and Tillage Research*, 176, 36–44. <https://doi.org/10.1016/j.still.2017.10.003>
- Paredes-Peralta, A. V., Guamán Rivera, S. A., Suárez Cedillo, S. E., Castañeda Caguana, S. I., Veloz-Veloz, D. M., Baquero-Tapia, M. F., Ruiz Salgado, M. V., & Maldonado Arias, D. F. (2025). Innovative improvements of silvopastoral systems applied to the *Brachiaria decumbens* yields in degraded areas – A case study in Orellana, Amazonian Ecuador. *Journal of Agriculture and Environment for International Development (JAEID)*, 119(1), 251–264. <https://doi.org/10.36253/jaeid-16729>
- Parra, A. S., de Figueiredo, E. B., de Bordonal, R. O., Moitinho, M. R., de Bortoli, D. T., & La Scala, N. (2019). Greenhouse gas emissions in conversion from extensive pasture to other agricultural systems in the Andean region of Colombia. *Environment, Development and Sustainability*, 21, 249–262. <https://doi.org/10.1007/s10668-017-0034-6>
- Pent, G. J., & Fike, J. H. (2021). Enhanced ecosystem services provided by silvopastures. In R. P. Udawatta, & S. Jose (eds) *Agroforestry and Ecosystem Services*. Cham: Springer. https://doi.org/10.1007/978-3-030-80060-4_7
- Polanía-Hincapié, K. L., Olaya-Montes, A., Cherubin, M. R., Herrera-Valencia, W., Ortiz-Morea, F. A., & Silva-Olaya, A. M. (2021). Soil physical quality responses to silvopastoral implementation in Colombian Amazon. *Geoderma*, 386, 11490
- Rabbi, S. M., Warren, C. R., Swarbrick, B., Minasny, B., McBratney, A. B., & Young, I. M. (2024). Microbial decomposition of organic matter and wetting–drying promotes aggregation in artificial soil but porosity increases only in wet-dry condition. *Geoderma*, 447, 116924. <https://doi.org/10.1016/j.geoderma.2024.116924>
- Reichert, J. M., Mentges, M. I., Rodrigues, M. F., Cavalli, J. P., Awe, G. O., & Mentges, L. R. (2018). Compressibility,

- and elasticity of subtropical no-till soil varying in granulometric organic matter, bulk density and moisture. *Catena*, 165, 345–357. <https://doi.org/10.1016/j.catena.2018.02.014>
- Roesch, A., Weisskopf, P., Oberholzer, H., Valsangiacomo, A., & Nemecek, T. (2019). An Approach for Describing the Effects of Grazing on Soil Quality in Life-Cycle Assessment. *Sustainability*, 11(8), 4870. <https://doi.org/10.3390/su11184870>
- Shahrokh, V., Bondi, G., Fahy, A., & O’Sullivan, L. (2025), Advancing soil compaction assessment: a comprehensive study in Ireland. *European Journal of Soil Science*, 76, e70122. <https://doi.org/10.1111/ejss.70122>
- Schulte, R., O’Sullivan, L., & Creamer, R. (2018). Soil Functions-An Introduction. In R. Creamer, & L. O’Sullivan (Eds.), *The Soils of Ireland* (pp. 201-208). (World Soils Book Series book series (WSBS)). Springer. https://doi.org/10.1007/978-3-319-71189-8_13
- Silva-Parra, A. (2018). Modelación de los stocks de carbono del suelo y las emisiones de dióxido de carbono (GEI) en sistemas productivos de la Altillanura Plana. *Orinoquia*, 22(2), 158–171. <https://doi.org/10.22579/20112629.525>
- Silva-Parra, A., Rodríguez-Rojas, B. A., & Vargas-Arrieta, N. (2020). Análisis textural en la regulación de funciones ecosistémicas en sistemas agroforestales de un oxisol de Piedemonte Llanero en época seca, Colombia. *Idesi*, 38(3), 43-51. <http://dx.doi.org/10.4067/S0718-34292020000300043>
- Silva-Parra, A., García-Ramírez, D. Y., & Martínez, E. A. (2023). Silvopastoral Systems ecological strategy for decreases c footprint in livestock systems of Piedmont (Meta), Colombia. *Brazilian archives of Biology and technology*, 66, e23220340. <https://doi.org/10.1590/1678-4324-2023220340>
- Six, J., Bossuyt, H., Degryze, S., & Denef, K. (2004). A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil & Tillage Research*, 79(1), 7–31. <https://doi.org/10.1016/j.still.2004.03.008>
- Vallejo, V. E., Roldán, F., & Dick, R. P. (2010). Soil enzymatic activities and microbial biomass in an integrated agroforestry chronosequence compared to monoculture and a native forest of Colombia. *Biology and Fertility of Soils*, 46, 577– 587. <https://doi.org/10.1007/s00374-010-0466-8>
- Vázquez, E., Teutscherova, N., Lojka, B., Arango, J., & Pulleman, M. (2020). Pasture diversification affects soil macrofauna and soil biophysical properties in tropical silvopastoral systems. *Agriculture, Ecosystems & Environment*, 302,107083. <https://doi.org/10.1016/j.agee.2020.107083>
- Zaibon, S., Anderson, S. H., Thompson, A. L., Kitchen, N. R., Gantzer, C. J., & Haruna, S. I. (2017). Soil water infiltration affected by topsoil thickness in row crop and switchgrass production systems. *Geoderma*, 286, 46–53. <https://doi.org/10.1016/j.geoderma.2016.10.016>
- Zhang, B., Jia, Y., Fan, H., Guo, C., Fu, J., Li, S., Li, M., Liu, B., & Ma, R. (2024). Soil Compaction due to agricultural machinery impact: a systematic review. *Land Degradation and Development*, 35(10), 3256–3273. <https://doi.org/10.1002/ldr.5144>