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Integrating Soil Compactness, Carbon Stocks, and Pieri-Index-Based Structural Vulnerability for Soil Quality Assessment Across Tropical Land-Use Systems

Juan David Mahecha-Pulido [1], Juan Manuel Trujillo-González [1,*], Marco Aurelio Torres-Mora [1] and Raimundo Jiménez-Ballesta [2]

[1] Instituto de Ciencias Ambientales de la Orinoquia Colombiana (ICAOC), Facultad de Ciencias Básicas e Ingeniería, Universidad de los Llanos, Campus Barcelona, Villavicencio 500001, Colombia; juan.mahecha@unillanos.edu.co (J.D.M.-P.); marcotorres@unillanos.edu.co (M.A.T.-M.)
[2] Department of Geology and Geochemistry, Autonomous University of Madrid, 28049 Madrid, Spain; profe.raimundojimenez@gmail.com
* Correspondence: jtrujillo@unillanos.edu.co

Abstract

Integrated assessments combining soil compactness, carbon storage, and structural vulnerability remain scarce in tropical soils of the Colombian Orinoquia. Soil physical condition was compared across natural forest (n = 21), secondary vegetation (n = 27), agricultural use (n = 12), and improved pastures (n = 67) in Arauca, Colombia, using stratified purposive sampling. The 127 samples from the 0–30 cm layer were analyzed for pH, soil organic carbon (SOC), bulk density, and particle-size distribution. Texture-adjusted packing density, fixed-depth SOC stock, and the Pieri index were calculated. Comparisons used Kruskal–Wallis and Dunn's tests with Holm adjustment and epsilon-squared (ε^2) effect sizes. Soil pH and texture did not differ among categories. SOC stock differed significantly (p = 0.001, ε^2 = 0.104), with a median of 56.5 Mg C ha^{-1} in natural forest and 30.0–35.3 Mg C ha^{-1} in the other categories. Higher SOC stock in natural forest coincided with higher SOC concentration despite lower bulk density, indicating that stock differences were associated with carbon concentration rather than texture. The Pieri index also differed (p = 0.002, ε^2 = 0.095), with lower inferred structural vulnerability in natural forest. Packing density showed a weaker association with land use (PD-R: p = 0.041, ε^2 = 0.043), with no significant pairwise differences after Holm adjustment. Because the study was cross-sectional and observational, these differences should not be interpreted as causal effects of land-use conversion. These findings indicate that management and restoration assessments should prioritize soil organic matter status while using compactness indicators to identify sites requiring further evaluation.

Keywords: packing density; soil compactness; soil organic carbon; soil physical condition; structural vulnerability; tropical land-use systems

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1. Introduction

Soil health has become a central framework for evaluating the capacity of soils to sustain agricultural productivity, regulate water and nutrient flows, store carbon, maintain biodiversity, and support ecosystem services under changing land-use conditions [1–3]. Although soil health is inherently multidimensional, involving physical, chemical, and biological attributes, its physical dimension is particularly relevant because it influences

root exploration, pore continuity, water infiltration, aeration, structural stability, and the capacity of soil to sustain productive and ecological functions [4–6]. Thus, assessing soil physical condition is essential in agricultural landscapes where land-use conversion, mechanization, grazing pressure, and management intensity may alter soil structure and functionality [7,8].

Soil physical degradation is commonly associated with compaction, loss of structural stability, reduced porosity, and changes in organic carbon storage [3]. Soil compaction involves the rearrangement of soil particles and the reduction in pore space, particularly functional macroporosity, thereby modifying bulk density, pore-size distribution, hydraulic conductivity, infiltration, water retention, and gas exchange [9–11]. These changes can restrict root growth, reduce oxygen diffusion, increase mechanical resistance, and modify the physical habitat of soil biota [5,6,12]. Under specific moisture and aeration conditions, compaction may also affect nitrogen transformations and increase the potential for nitrous oxide emissions, linking soil physical degradation with broader biogeochemical and environmental consequences [13,14].

The interpretation of soil compactness, however, cannot rely exclusively on bulk density because this property is strongly influenced by intrinsic soil characteristics such as texture, organic matter content, mineralogy, structure, coarse fragments, and soil-forming processes [15–17]. For this reason, texture-adjusted indicators such as packing density have been proposed to improve comparisons among soils with contrasting particle-size distributions. Packing density integrates bulk density with the proportion of fine particles and allows the identification of soils that exceed predefined compactness thresholds [17–19]. In this study, packing density was expressed as PD = BD + 0.005 × Clay + 0.001 × Silt, where PD is packing density (g cm^{-3}), BD is bulk density (g cm^{-3}), and clay and silt are expressed as percentages [18]. An alternative formulation, PDalt = BD + 0.009 × Clay, was also considered for sensitivity. This approach is particularly useful in heterogeneous tropical landscapes, where naturally dense horizons, textural contrasts, or high clay contents may generate elevated bulk density values even in the absence of direct anthropogenic pressure.

Soil organic carbon is not itself a physical soil property, but it is closely related to soil physical condition because it contributes to aggregate formation, pore organization, water retention, and resistance to erosion and crusting [20,21]. Soil organic carbon stocks also represent an important ecosystem function related to carbon storage and climate regulation [22,23]. Nevertheless, the interpretation of carbon stocks requires caution when bulk density differs among land-use systems, because fixed-depth stock calculations may be influenced by soil compaction or loosening. Therefore, carbon stocks should be interpreted jointly with physical indicators such as bulk density and packing density to distinguish genuine differences in carbon accumulation from changes associated with soil mass and compactness.

The balance between soil organic matter and fine mineral fractions also provides useful information on structural vulnerability. The Pieri index is an empirical indicator of potential structural vulnerability based on the ratio between organic matter and the silt-plus-clay fraction; it should not be interpreted as a direct measurement of aggregate stability [24]. It is calculated as SI = [OM/(Silt + Clay)] × 100, where SI is the Pieri stability index and OM, silt, and clay are expressed as percentages [24]. In this sense, low index values may indicate insufficient organic matter relative to the fine mineral fraction, suggesting greater vulnerability to surface sealing, crust formation, erosion, and compaction. These three indicators capture complementary, although partly overlapping, dimensions of soil physical condition. Packing density represents texture-adjusted compactness, SOC stock represents carbon storage within the sampled soil layer, and the Pieri index expresses potential structural vulnerability based on the balance between organic matter and the fine

mineral fraction. Their joint interpretation therefore allows compactness, carbon storage, and structural vulnerability to be assessed simultaneously without assuming that any single indicator represents overall soil physical health. Together, they provide an integrated assessment of selected dimensions of soil physical condition rather than a comprehensive soil health index.

In tropical agricultural regions, the assessment of soil physical condition is particularly relevant because land-use intensification often occurs on highly weathered, acidic, and texturally variable soils. In the Colombian Orinoquia and adjacent agricultural frontiers, soil physical degradation may interact with acidity, low natural fertility, rainfall seasonality, drainage constraints, and the expansion of cropping and livestock systems [25–27]. Recent studies in Colombian acidic pasturelands have also highlighted the importance of accurate bulk density measurements for regional soil assessment and carbon stock estimation [28]. Spatial variability is also an important consideration when evaluating soil properties across tropical landscapes. Differences in soil type, landscape position, parent material, drainage conditions, and land-use or management history can generate substantial spatial heterogeneity in soil physical and carbon-related properties. This variability is particularly relevant in the Colombian Orinoquia, where contrasting soil-forming environments and landforms occur across relatively short spatial distances [26,27]. Consequently, spatial analysis can complement comparisons among land-use categories by identifying the geographic heterogeneity of the evaluated soil indicators.

However, studies in the Colombian Orinoquia have generally evaluated soil compactness, carbon storage, or related soil properties separately, while comparative assessments that jointly integrate texture-adjusted compactness, fixed-depth SOC stocks, and empirical structural vulnerability across contrasting land-use systems remain limited.

Within this context, this study compares selected indicators of soil physical condition across contrasting land-use systems in Arauca, Colombia. Therefore, it remains unclear how these complementary indicators vary jointly across contrasting land-use categories in Arauca, integrating packing density, soil organic carbon stocks, and the Pieri stability index. These indicators represent complementary aspects of compactness, carbon storage, and potential structural vulnerability and do not constitute a direct assessment of all soil physical functions. The land-use categories represent current land-use conditions and broad disturbance status rather than standardized land-use histories. Information on the duration of each land use, previous land-use sequence, and the intensity or frequency of agricultural and grazing management was not available for all sampling sites. These factors were therefore not treated as explanatory variables, and differences among categories are interpreted as cross-sectional associations.

Specifically, the study aims to (i) quantify soil compactness using bulk density and texture-adjusted packing density; (ii) estimate soil organic carbon stocks in the upper soil layer; (iii) evaluate structural vulnerability using the Pieri index; and (iv) compare these indicators among natural forest, secondary vegetation, agricultural use, and improved pastures. We hypothesized that (i) managed or previously disturbed land-use categories would show lower fixed-depth SOC stocks and greater Pieri-index-based structural vulnerability than natural forest, and (ii) packing density would differ among land-use categories, although no uniform directional response was assumed a priori.

2. Materials and Methods

2.1. Study Area, Land-Use Systems and Soil Sampling

This study was conducted in the Department of Arauca, located in the Colombian Orinoquia, eastern Colombia. The region is characterized by humid tropical conditions, seasonal rainfall, acidic and highly weathered soils, and contrasting vegetation covers and

productive land-use systems (Figure 1). The climate shows a monomodal rainfall regime, with a rainy season generally extending from April to November and a drier period from December to March. These seasonal moisture conditions are relevant for soil physical condition because high soil water content can increase susceptibility to deformation, particularly when machinery traffic, grazing pressure or agricultural operations occur under wet conditions. Arauca soils include Cambisols, Leptosols, Acrisols, Arenosols, Ferralsols and Gleysols, with Ferralsols and Gleysols representing the largest soil mapping units. In the alluvial landscapes, soils are mainly of alluvial origin and commonly show variable textures, high acidity, low natural fertility and, in poorly drained areas, plinthic or gleyic horizons.

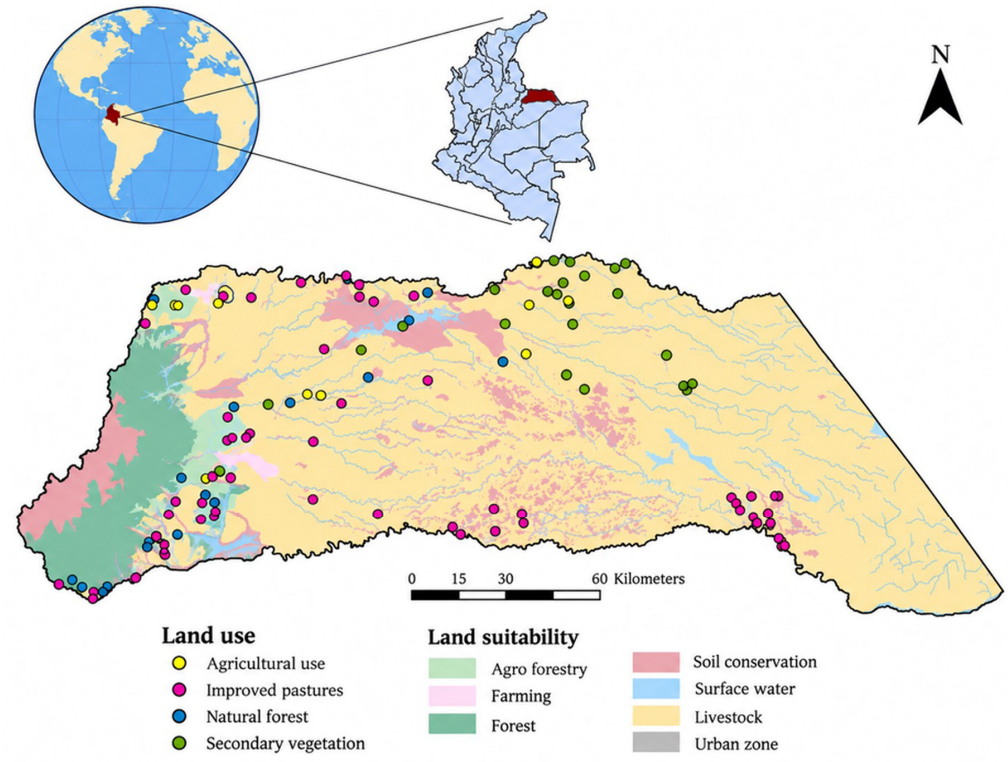


Figure 1. Geographic location of the study area and spatial distribution of land-use categories, land-suitability classes, and soil sampling points in Arauca, Colombia.

Soil sampling was conducted from October 2016 to November 2017 using a stratified purposive sampling approach, with land-use category as the stratification criterion. A total of 127 georeferenced sampling points were distributed among four land-use categories: natural forest (n = 21), secondary vegetation (n = 27), agricultural use (n = 12), and improved pastures (n = 67). Sampling locations within each land-use category were selected according to field accessibility and the possibility of verifying the corresponding land use in situ. The unequal sample sizes among categories reflected field accessibility and security constraints during the sampling period and were therefore not the result of an a priori balanced allocation. The sampling effort was intended to obtain observations from contrasting land-use conditions distributed across the study area rather than to achieve equal sample sizes among categories. Each georeferenced sampling point was sampled once and represented a separate observational unit. The imbalance was therefore a consequence of field feasibility rather than an a priori statistical allocation. Accordingly, comparisons among land-use categories were interpreted considering this unequal sampling representation.

Four land-use systems were evaluated: natural forest, secondary vegetation, agricultural use, and improved pastures. These categories were defined before data analysis to

represent contrasting levels of land-use disturbance and management. Natural forest was considered the reference condition with lower direct anthropogenic disturbance, whereas secondary vegetation represented areas undergoing natural regeneration after previous disturbance. Agricultural use and improved pastures represented managed systems subjected to crop production, pasture establishment, livestock trampling, or other forms of productive management.

The study followed a cross-sectional observational design. Land-use categories were compared at the time of sampling; therefore, the analysis identifies differences and associations among land-use systems but does not establish temporal changes or causal effects of land-use conversion.

Soil samples were collected from the 0–30 cm mineral soil layer, which represents the surface horizon most directly affected by land-use change, organic matter inputs, root activity, agricultural management, livestock trampling and soil structural modification. Each sampling point was assigned to one land-use system based on field verification and land-use information. The dataset included soil pH, soil organic carbon, organic matter, bulk density, sand, silt and clay contents.

Before calculating the derived indicators, the complete dataset was screened for missing values, transcription inconsistencies, and potentially implausible observations. Quality-control checks included pH, SOC, organic matter, bulk density, and particle-size distribution. pH and SOC values were examined for missing, negative, or anomalous observations and checked against the original laboratory records when necessary. Because organic matter was derived from SOC, its internal consistency was verified by recalculating OM as SOC $\times$ 1.724 for all samples. The sum of sand, silt, and clay was verified for each sample, and records with textural sums substantially different from 100% were flagged for review. Potentially atypical bulk-density values were also examined because bulk density directly affects both packing-density and SOC-stock estimates. The unusually high SOC-stock observations in the natural forest group were specifically rechecked against the original laboratory records and recalculated from the corresponding SOC concentration and bulk-density values. No transcription, unit-conversion, or calculation errors were identified for these SOC-stock observations, and they were therefore retained as valid data.

2.2. Soil Laboratory Analyses

Soil samples were air-dried, gently disaggregated, and sieved through a 2 mm mesh prior to laboratory analyses. Soil pH was determined in water using a 1:1 (w/v) soil-to-water suspension. Soil organic carbon (SOC) was determined directly by wet oxidation using the Walkley–Black method [29]. Organic matter (OM) content was subsequently calculated from the measured SOC values using a conversion factor of 1.724 (OM = SOC $\times$ 1.724). The same conversion procedure was applied to all samples. Particle-size distribution was determined using the Bouyoucos hydrometer method [30] and reported as sand, silt, and clay percentages. Bulk density (BD) was determined using the paraffin-coated clod method [25]. Two intact soil clods were analyzed per sample as technical replicates. The clods were oven-dried at 105 °C to constant mass, coated with paraffin, and their volume was determined by water displacement [31]. Bulk density was calculated as the ratio between dry soil mass and clod volume, and the mean of the two technical replicates was used as the representative BD value for each 0–30 cm field sample. The two clod measurements were technical laboratory replicates of the same field sample and were not treated as independent observational units in the statistical analyses.

2.3. Packing Density and Compaction Classification

Soil compactness was assessed using packing density, a texture-adjusted indicator that integrates bulk density with the fine mineral fraction. Packing density accounts for textural differences in bulk density and allows compactness to be compared among soils with contrasting particle-size distributions. The main packing density equation was calculated according to Renger et al. [18]:

$$PD = BD + 0.005 \times Clay + 0.001 \times Silt$$

where PD is packing density, expressed in g cm^{-3}; BD is bulk density, expressed in g cm^{-3}; and $Clay$ and $Silt$ are expressed as percentages. Samples were classified as compacted when $PD > 1.71$ g cm^{-3} and as non-compacted when $PD \leq 1.71$ g cm^{-3}.

For sensitivity analysis and comparability with previous packing-density studies, an alternative packing density equation was also applied following Renger [32], Huber et al. [33], and Panagos et al. [17]:

$$PD_{alt} = BD + 0.009 \times Clay$$

Under this approach, samples were classified as compacted when $PD_{alt} > 1.75$ g cm^{-3}. This alternative equation and threshold have been used for comparability with previous packing-density studies. The difference between the 1.71 and 1.75 g cm^{-3} thresholds reflects the fact that each threshold is associated with a different packing-density formulation and should not be interpreted as a simple change in the cutoff applied to the same equation. Because the equations generate different packing-density values, the selected equation–threshold combination can affect the proportion of samples classified as compacted. Accordingly, comparisons with tropical studies should consider both the equation and the threshold used rather than the threshold value alone.

Because these packing-density equations and thresholds were developed mainly from temperate soil datasets and have not been specifically calibrated for tropical Colombian soils, they were used here as comparative diagnostic criteria rather than as locally validated compaction thresholds. The two approaches were therefore evaluated as a sensitivity analysis to assess the dependence of the classification on the selected equation and threshold.

Soil organic carbon stocks were estimated for the 0–30 cm layer using soil organic carbon concentration, bulk density and layer thickness. This fixed-depth approach follows recent work on Colombian tropical soils, where SOC stocks were calculated from SOC concentration, bulk density and soil depth, and interpreted jointly with bulk density because changes in bulk density can affect stock estimates.

Because no additional depth increments below 30 cm were sampled, the soil mass required to adjust SOC stocks to a common equivalent soil mass could not be reconstructed. Consequently, an equivalent soil mass correction could not be applied retrospectively, and the reported SOC stocks should be interpreted strictly as fixed-depth estimates for the 0–30 cm layer. The general equation was:

$$SOC_{stock} = \left(\frac{SOC}{100}\right) \times BD \times z \times 10000$$

where SOC_{stock} is soil organic carbon stock, expressed as Mg C ha^{-1}; SOC is soil organic carbon concentration, expressed as percentage; BD is bulk density, expressed as Mg m^{-3}; z is soil layer thickness, expressed in m; and 10,000 is the conversion factor from m^2 to ha.

Since bulk density in g cm^{-3} is numerically equivalent to Mg m^{-3} and the sampled layer was 0.30 m, the operational equation was:

$$SOC_{stock\ 0–30} = SOC(\%) \times BD \times 30$$

No equivalent soil mass correction was applied because the available dataset corresponded to a single 0–30 cm soil layer. Consequently, SOC stocks were calculated and compared on a fixed-depth basis. Differences among land-use systems may therefore partly reflect differences in soil mass associated with variation in bulk density. For this reason, SOC-stock results were interpreted jointly with bulk density and packing density and should not be considered directly equivalent to stocks estimated using an equivalent soil mass approach [22,23].

Potential structural vulnerability was inferred using the Pieri stability index, which relates soil organic matter content to the fine mineral fraction. The index provides an empirical estimate of the potential risk of structural degradation by evaluating the amount of organic matter relative to the silt and clay fractions. It should therefore be interpreted as an indicator of structural vulnerability rather than as a direct measurement of aggregate stability, crusting, infiltration, pore-size distribution, hydraulic properties, or erosion resistance. The index was calculated according to Pieri [24]:

$$SI = \frac{OM}{Silt + Clay} \times 100$$

where SI is the stability index; OM is organic matter content, expressed as a percentage; and silt and clay are expressed as percentages. The Pieri index was interpreted in terms of potential structural vulnerability as follows: SI < 5, very high potential structural vulnerability; SI = 5–7, high potential structural vulnerability; SI = 7–9, low potential risk of structural degradation; and SI > 9, low potential structural vulnerability. These classes were used as empirical indicators of structural vulnerability and not as direct measurements of soil structural stability [24]. The physical dimension of soil health was assessed using three derived indicators representing related aspects of soil compactness, carbon storage, and potential structural vulnerability. Because these indicators share some underlying variables, they were not considered statistically independent.

2.4. Statistical Analysis

Statistical analyses were performed to compare measured soil properties and derived indicators of soil physical condition among land-use systems. The individual georeferenced sampling point was considered the observational unit for statistical comparisons. The analyzed variables were pH, soil organic carbon, organic matter, bulk density, sand, silt, clay, packing density, alternative packing density, SOC stock and the Pieri stability index. Descriptive statistics were calculated by land use and reported as medians, interquartile ranges, minimum and maximum values, and given the unbalanced sample size among land-use systems and the non-normal distribution observed for several variables.

Data distribution was inspected using boxplots and Q–Q plots, and normality was evaluated using the Shapiro–Wilk test. Differences among land-use systems were assessed using the Kruskal–Wallis test. When significant differences were detected, pairwise comparisons were performed using Dunn's post hoc test with Holm adjustment for multiple comparisons. Dunn's test is an appropriate non-parametric pairwise procedure after a significant Kruskal–Wallis test, and Holm adjustment controls the familywise error rate in multiple comparisons [34]. The Kruskal–Wallis analyses represent unadjusted comparisons among land-use categories and do not control for potential confounding factors. Because detailed information on management history, time since conversion, previous land use,

soil type, landscape position, and drainage was not consistently available for all sampling points, these variables could not be incorporated as covariates. Accordingly, the results were interpreted as cross-sectional associations rather than adjusted or causal effects of land use. Spearman's rank correlations were calculated among the measured soil properties and derived indicators to evaluate their degree of association and potential mathematical overlap. These correlations were interpreted descriptively and were not used to imply statistical independence among the indicators.

Compaction status was analyzed as a binary categorical variable based on the packing density threshold. The frequency and percentage of compacted and non-compacted samples were calculated for each land-use system, and differences among land uses were evaluated using Fisher's exact test. Agreement between the main and alternative packing-density classifications was assessed using Cohen's kappa coefficient. Because the number of discordant classifications was small, an exact McNemar test was used to determine whether the two equations differed in the proportion of samples classified as compacted.

2.5. Spatial Mapping

Spatial distribution maps of PD-R, PD-A, SOC stock and the Pieri stability index were generated using Empirical Bayesian Kriging (EBK) [35] in ArcGIS Desktop 10.8 (Esri, Redlands, CA, USA). Prediction performance was evaluated separately for each interpolated surface using cross-validation. Root mean square error (RMSE) and mean standardized error were calculated for PD-R, PD-A, SOC stock, and the Pieri index. Mean standardized error was used to evaluate overall prediction bias, with values closer to zero indicating lower systematic bias. Because the four indicators differ in units, numerical scale, and dispersion, RMSE values were interpreted separately for each variable rather than compared directly among indicators. The sampling points were projected to MAGNA-SIRGAS Origen Nacional (EPSG: 9377), and interpolation was performed using a Power semivariogram, 100 simulations and a circular search neighborhood of 23.92 km. The resulting raster surfaces were reprojected to WGS84 (EPSG: 4326) for final map composition. Because sampling locations were selected within land-use strata rather than through a spatially regular sampling design, the spatial distribution of observations was not independent of land-use category. Consequently, the interpolated surfaces may partly reflect the geographic distribution and unequal sampling representation of the land-use classes. The maps were therefore interpreted descriptively as representations of spatial variation in the measured indicators and not as evidence of independent spatial effects of land use.

3. Results and Discussion

3.1. Distributional Assessment and Soil Properties

The distributional assessment showed significant departures from normality for most measured and derived variables. Shapiro–Wilk tests rejected the null hypothesis of normality for 10 of the 11 evaluated variables (Table S3). Only alternative packing density did not show a significant departure from normality ($W = 0.985$, $p = 0.193$). The Q–Q plots particularly showed marked departures from the normal reference line for SOC, organic matter, SOC stock, and the Pieri index (Figure S1). These results, together with the unequal sample sizes among land-use categories, supported the use of non-parametric procedures for comparisons among land-use systems.

The evaluated soils showed an overall acidic condition across all land-use systems, with median pH values ranging from 4.35 in agricultural use to 4.60 in natural forest, secondary vegetation and improved pastures (Table 1). No significant differences in pH were detected among land uses, suggesting that soil acidity was a common background condition rather than a differentiating factor among the evaluated systems. This agrees with

previous reports for highly weathered tropical soils of the Colombian Orinoquia and Arauca region, where acidity, low base status and strong pedological control are recurrent features of agricultural and forest soils [26,27]. Similarly, sand, silt and clay contents did not differ significantly among land-use systems, indicating that the main differences in soil physical condition were not primarily explained by textural contrasts (Table 1). This is relevant because texture strongly constrains bulk density and compactness interpretation; therefore, the absence of significant textural differences strengthens the interpretation that observed differences in organic matter, SOC stocks, and Pieri-index-based structural vulnerability were associated with land-use category rather than with particle-size distribution alone.

Table 1. Measured soil chemical and physical properties in the 0–30 cm layer across natural forest, secondary vegetation, agricultural use, and improved pastures.

Variable	Natural Forest (n = 21)	Secondary Vegetation (n = 27)	Agricultural Use (n = 12)	Improved Pastures (n = 67)	Kruskal–Wallis p	ε^2
pH (H_2O 1:1)	4.60 [4.40–4.80] ^{a}	4.60 [4.50–5.15] ^{a}	4.35 [4.25–4.95] ^{a}	4.60 [4.40–4.80] ^{a}	0.466	0.000
Organic carbon (%)	1.60 [1.10–2.74] ^{a}	0.80 [0.46–1.35] ^{b}	0.73 [0.47–0.80] ^{b}	0.80 [0.59–1.31] ^{b}	<0.001	0.130
Organic matter (%)	3.10 [2.10–5.30] ^{a}	1.50 [0.90–2.60] ^{b}	1.40 [0.95–1.60] ^{b}	1.60 [1.10–2.55] ^{b}	<0.001	0.128
Bulk density (g cm^{-3})	1.25 [1.17–1.42] ^{b}	1.44 [1.27–1.56] ^{ab}	1.46 [1.38–1.58] ^{a}	1.42 [1.34–1.54] ^{a}	0.013	0.063
Sand (%)	61.3 [41.0–70.0] ^{a}	41.0 [29.0–66.0] ^{a}	56.5 [37.0–78.2] ^{a}	59.7 [34.6–75.6] ^{a}	0.308	0.005
Silt (%)	24.2 [20.1–32.0] ^{a}	0.5 [20.4–48.3] ^{a}	35.0 [17.3–42.5] ^{a}	24.1 [16.1–39.2] ^{a}	0.390	0.000
Clay (%)	16.1 [10.0–22.1] ^{a}	14.0 [10.9–24.2] ^{a}	5.4 [4.0–14.8] ^{a}	12.0 [8.0–22.4] ^{a}	0.098	0.027

Note. Values are medians [interquartile range]. Different letters within each row indicate significant differences among land uses according to Dunn's post hoc test with Holm adjustment ($p < 0.05$). ε^2 = epsilon-squared effect size for Kruskal–Wallis tests. The minimum and maximum values of the audited variables for each land-use system are reported in Table S1.

In contrast to pH and texture, soil organic carbon and organic matter showed clear and statistically significant differences among land-use systems (Table 1). Natural forest presented the highest median organic carbon content, 1.60%, and organic matter content, 3.10%, whereas secondary vegetation, agricultural use and improved pastures showed markedly lower values. The three managed or previously disturbed systems did not differ significantly from one another but showed lower organic carbon and organic matter values than the natural forest reference. This cross-sectional pattern indicates an association between land-use category and carbon-related soil properties but does not establish that land-use conversion caused the observed differences. This pattern is consistent with the soil health framework, in which organic carbon is a central attribute because it regulates aggregation, pore organization, water retention, nutrient cycling and biological activity [2]. It also agrees with global evidence showing that conversion of natural vegetation to agricultural land uses commonly reduces SOC stocks in tropical regions, particularly when organic inputs decrease or soil disturbance increases [22].

Bulk density differed significantly among land uses. Natural forest had the lowest median bulk density (1.25 g cm^{-3}), whereas secondary vegetation, agricultural use and improved pastures showed higher values of 1.44, 1.46 and 1.42 g cm^{-3}, respectively. Natural forest had significantly lower bulk density than agricultural use and improved pastures, whereas the difference between natural forest and secondary vegetation was not significant after Holm adjustment. However, bulk density alone should not be interpreted as direct evidence of compaction because it is influenced by texture, organic matter, mineralogy, structure and soil-forming factors [15,19].

3.2. Soil Compactness and Packing-Density Classification

Correlation analysis confirmed that the derived indicators were not independent. PD-R was strongly associated with bulk density (r_s = 0.91), while SOC stock was strongly associated with SOC concentration (r_s = 0.98). The Pieri index was moderately associated with organic matter (r_s = 0.64), and SOC stock and the Pieri index were also correlated (r_s = 0.63). In contrast, the association between PD-R and SOC stock was weaker (r_s = −0.23), indicating that packing density retained information more closely related to soil densification than to carbon content (Table S2).

In addition, land-use associations were larger for SOC stock (ε^2 = 0.104) and the Pieri index (ε^2 = 0.095) than for PD-R (ε^2 = 0.043) and PD-A (ε^2 = 0.026). Because pH and particle-size fractions did not differ significantly among land-use categories, the quantitative evidence indicates that the strongest measured differences among land-use systems were associated with carbon-related properties and organic-matter-related structural vulnerability rather than with textural variation or generalized compactness. These associations should be interpreted cautiously because the derived indicators share underlying variables and because management history and other potential drivers were not measured.

Packing density showed a significant overall land-use effect (p = 0.041), although no pairwise comparison remained significant after Holm adjustment (Table 2; Figure 2A). Median values were 1.44 g cm^{-3} in natural forest, 1.58 g cm^{-3} in secondary vegetation, 1.50 g cm^{-3} in agricultural use and 1.54 g cm^{-3} in improved pastures. This pattern indicates relatively small differences among land-use categories and considerable within-system variability. Some sampling points exceeded the compaction threshold, whereas others remained below it (Figure 3). However, because pairwise differences among land-use categories were not significant and compaction frequencies also did not differ significantly among categories, these observations should not be interpreted as evidence of a statistically demonstrated localized compaction pattern. The observed within-system variability is consistent with the heterogeneous distribution of packing-density values across the sampled locations. Factors such as soil moisture at the time of loading, machinery traffic, grazing pressure, initial soil structure, and intrinsic bearing capacity may contribute to this variability [4,6]. However, these factors were not measured in this study and cannot be identified as causes of the observed patterns.

Table 2. Packing density, soil organic carbon stock, and Pieri stability index in the 0–30 cm layer across land-use systems.

Variable	Natural Forest (n = 21)	Secondary Vegetation (n = 27)	Agricultural Use (n = 12)	Improved Pastures (n = 67)	Kruskal–Wallis p	ε^2
Packing density, Renger (g cm^{-3})	1.44 [1.21–1.54] ^{a}	1.58 [1.42–1.69] ^{a}	1.50 [1.43–1.73] ^{a}	1.54 [1.42–1.63] ^{a}	0.041	0.043
Packing density, alternative (g cm^{-3})	1.49 [1.24–1.55] ^{a}	1.59 [1.47–1.79] ^{a}	1.49 [1.42–1.77] ^{a}	1.56 [1.44–1.67] ^{a}	0.101	0.026
SOC stock 0–30 cm (Mg C ha^{-1})	56.5 [39.4–107.7] ^{a}	30.0 [20.2–59.1] ^{b}	31.2 [22.3–35.7] ^{b}	35.3 [24.1–53.4] ^{b}	0.001	0.104
Pieri stability index	9.71 [5.12–13.38] ^{a}	3.61 [1.92–5.86] ^{b}	3.10 [2.47–6.29] ^{b}	4.19 [2.70–6.37] ^{b}	0.002	0.095

Note. Values are medians [interquartile range]. Different letters within each row indicate significant differences among land uses according to Dunn's post hoc test with Holm adjustment ($p < 0.05$). ε^2 = epsilon-squared effect size for Kruskal–Wallis tests.

Cross-validation of the EBK models showed mean standardized errors close to zero for all four interpolated surfaces (−0.015 to 0.030), indicating limited overall prediction bias. RMSE values were 0.255 for PD-R, 0.272 for PD-A, 78.73 for SOC stock, and 9.80 for the

Pieri index (Table S4). Given the different units and numerical ranges of these indicators, RMSE values were interpreted separately for each surface.

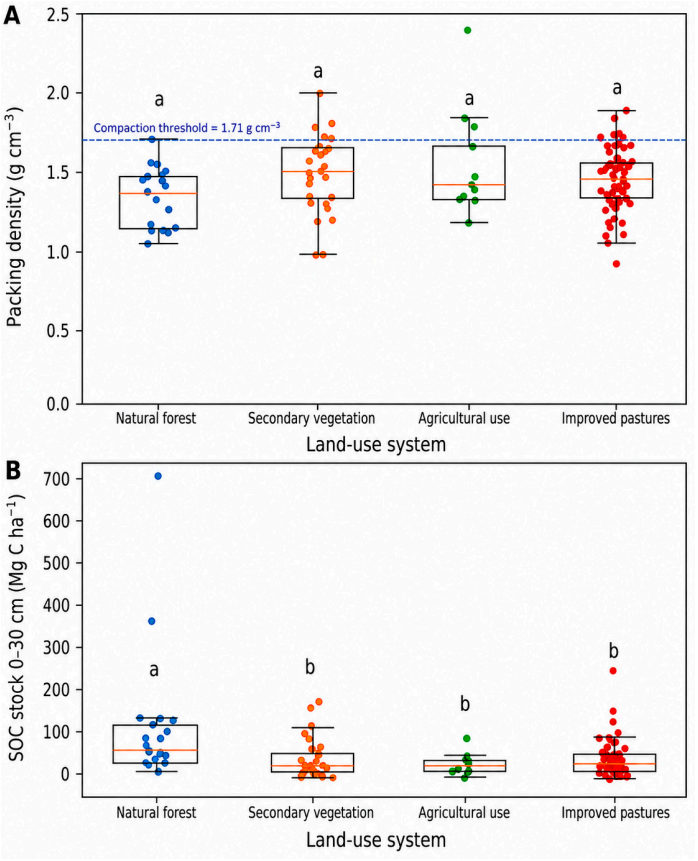


Figure 2. Soil compactness and organic carbon storage across land-use systems in Arauca, Colombia. (**A**) Packing density by land-use system. The dashed horizontal line indicates the compaction threshold of 1.71 g cm^{-3}. (**B**) Soil organic carbon stock in the 0–30 cm layer by land-use system. **Note.** Boxes represent the interquartile range, horizontal lines indicate medians, whiskers show the non-outlier range, and points represent individual observations. Different letters indicate significant differences among land-use systems according to the Kruskal–Wallis test followed by Dunn's post hoc test with Holm adjustment at $p < 0.05$.

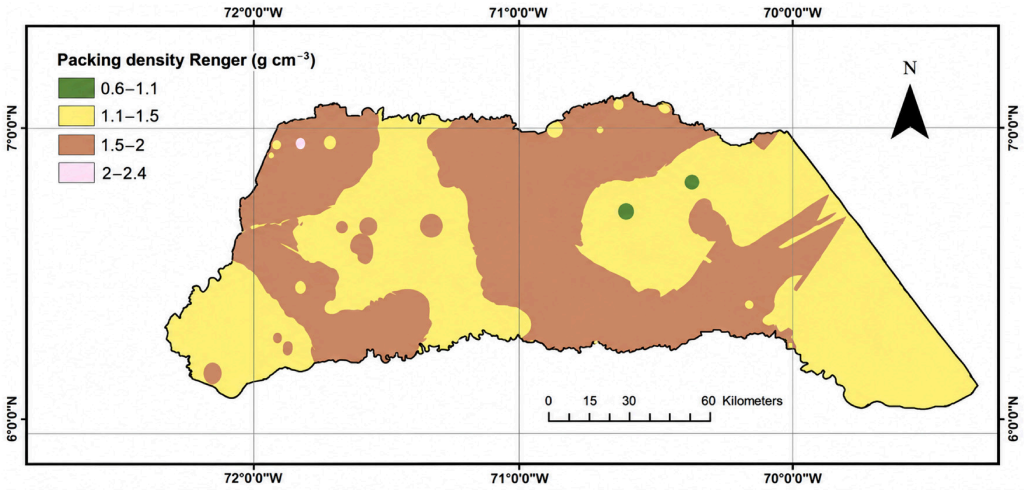


Figure 3. Spatial distribution of Renger packing density (PD-R) in the 0–30 cm soil layer in Arauca, Colombia.

The frequency analysis supports this interpretation. Using the main packing density threshold, only 14.2% of all samples were classified as compacted. Agricultural use showed the highest proportion of compacted samples, 25.0%, followed by secondary vegetation, 18.5%, improved pastures, 13.4%, and natural forest, 4.8% (Table 3). However, the frequency of compacted samples did not differ significantly among land-use systems. Therefore, while agricultural use and secondary vegetation showed a higher relative occurrence of compacted samples, the statistical evidence does not support a categorical separation of land uses based only on compaction frequency. This result is important for management interpretation: physical degradation in the study area should not be reduced to compaction alone, because other indicators revealed stronger land-use signals.

Table 3. Frequency of compacted samples and Pieri-index-based structural vulnerability classes by land-use system.

Land-Use System	*n*	Compacted by Main PD, *n* (%)	Compacted by Alternative PD, *n* (%)	Very High Structural Vulnerability, *n* (%)	High Structural Vulnerability, *n* (%)	Low Risk of Structural Degradation, *n* (%)	Low Structural Vulnerability, *n* (%)
Natural forest	21	1 (4.8)	2 (9.5)	5 (23.8)	3 (14.3)	2 (9.5)	11 (52.4)
Secondary vegetation	27	5 (18.5)	8 (29.6)	19 (70.4)	4 (14.8)	0 (0.0)	4 (14.8)
Agricultural use	12	3 (25.0)	4 (33.3)	9 (75.0)	0 (0.0)	0 (0.0)	3 (25.0)
Improved pastures	67	9 (13.4)	10 (14.9)	42 (62.7)	10 (14.9)	4 (6.0)	11 (16.4)
Fisher exact *p*-value		0.337	0.134	0.015			
Effect size		Cramer's V = 0.157	Cramer's V = 0.209	Cramer's V = 0.232			

Note. Fisher exact *p*-values are reported for categorical comparisons among land-use systems. For the Pieri index, the *p*-value refers to the overall distribution among the four Pieri-index-based structural vulnerability classes. Cramer's V is reported as the effect size. Pieri index classes were interpreted as empirical indicators of potential structural vulnerability and not as direct measurements of aggregate stability or soil structural stability.

The alternative packing-density equation classified 24 of 127 samples (18.9%) as compacted, compared with 18 of 127 (14.2%) using the Renger equation, particularly in secondary vegetation and agricultural use, where compacted samples increased to 29.6% and 33.3%, respectively (Table 3). Nevertheless, the general pattern remained similar to that obtained with the main equation. The spatial distribution of PD-A also showed a pattern broadly consistent with PD-R, although the alternative equation increased the relative extent of areas classified within higher packing density classes (Figure 4). This supports the sensitivity analysis based on the two threshold approaches and indicates that the diagnosis of compactness was reasonably robust, but still sensitive to the selected equation and threshold. Such sensitivity is expected because packing density thresholds were developed mainly from temperate soil datasets, and their transferability to humid tropical soils may be affected by differences in mineralogy, aggregation, organic matter dynamics and structural development. To our knowledge, these packing-density equations and thresholds have not been specifically validated for tropical soils in Colombia. Their application in the present study should therefore be regarded as a comparative diagnostic approach rather than as a locally calibrated criterion of compaction. This lack of local validation also identifies a methodological gap for Colombian tropical soils, where calibration against direct measurements of soil mechanical resistance, porosity, root restriction, or other physical responses would allow these thresholds to be evaluated under local pedological conditions. Recent applications of packing density have emphasized the need to distinguish compactness caused by intrinsic soil conditions from compaction attributable to land use or management [19]. Accordingly, the agreement between the two equations supports the

consistency of the observed classification pattern, but the absolute proportion of samples classified as compacted remains dependent on the selected equation and threshold.

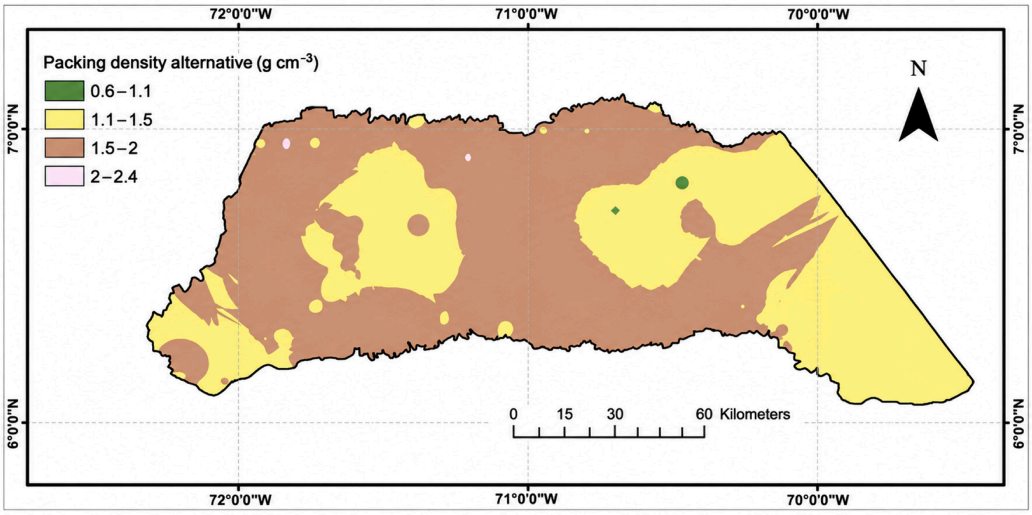


Figure 4. Spatial distribution of alternative packing density (PD-A) in the 0–30 cm soil layer in Arauca, Colombia.

The two packing-density classifications showed a high level of agreement. Of the 127 samples, 119 (93.7%) received the same classification under both approaches, resulting in a Cohen's kappa of $\kappa = 0.773$. Eight samples were classified differently: seven were classified as compacted only by the alternative equation, whereas one was classified as compacted only by the Renger equation. The exact McNemar test indicated that the difference in the proportion of samples classified as compacted was not statistically significant ($p = 0.070$). Thus, although the alternative equation classified more samples as compacted (24 of 127) than the Renger equation (18 of 127), the overall classification pattern was similar between approaches.

3.3. Soil Organic Carbon Stocks Across Land-Use Systems

Soil organic carbon stocks differed among land-use categories, with median fixed-depth stocks of 56.5 Mg C ha^{-1} in natural forest and 30.0–35.3 Mg C ha^{-1} in secondary vegetation, agricultural use, and improved pastures (Table 2; Figure 2B). These values can be placed in a regional context using recent measurements from the Colombian Llanos. Trujillo-González et al. [36] reported mean 0–30 cm SOC stocks of 52.3 ± 15.4 Mg C ha^{-1} in degraded pastures, 55.3 ± 11.6 Mg C ha^{-1} in improved pastures, and 60.8 ± 17.5 Mg C ha^{-1} in silvopastoral systems on Oxisols of the Colombian Llanos piedmont. Thus, the SOC stocks observed in the managed and secondary-vegetation categories of the present study were generally lower than those reported for these regional grazing systems, whereas the natural-forest median was within the same general range. However, these comparisons should be interpreted cautiously because the studies differ in soil type, land-use history, sampling design, and summary statistics, and the present estimates were calculated on a fixed-depth basis without equivalent soil mass correction.

The SOC stocks reported here represent total measured soil organic carbon and do not distinguish among fractions with contrasting turnover times. Therefore, differences among land-use categories cannot be interpreted directly as differences in carbon lability or recalcitrance. Current understanding indicates that SOC persistence is controlled not only by the molecular characteristics of organic compounds but also by mineral associations, aggregation, microbial accessibility, and environmental conditions [37,38]. In this context, the higher SOC stocks observed in natural forest, particularly at morichal sites, may

reflect differences in carbon inputs and preservation mechanisms; however, distinguishing labile from more persistent carbon pools would require specific fractionation or turnover measurements, which were not performed in this study.

The highest SOC-stock observations in natural forest were verified against the original laboratory records and recalculated from the corresponding SOC concentration and bulk density values. No analytical, transcription, unit-conversion, or calculation errors were identified, and these observations were therefore retained in the analysis. The highest values corresponded to sampling points associated with morichal (palm-swamp) environments. These sites are characterized by prolonged soil saturation and poor drainage, conditions that may reduce organic matter decomposition and contribute to greater carbon accumulation. Because decomposition rates were not measured in this study, this mechanism should be considered a plausible explanation rather than a direct finding. The spatial distribution of SOC stock showed a markedly heterogeneous pattern, indicating that carbon storage in the surface soil layer varied locally across the study area and was not uniformly distributed among land-use conditions (Figure 5). This distinction is essential because fixed-depth SOC stocks can be influenced by bulk density; therefore, stocks should be interpreted jointly with bulk density and compactness indicators [22,23]. Recent work in Colombian tropical soils has also emphasized the need to interpret SOC stocks together with bulk density when comparing land-use systems, particularly in landscapes where soil physical condition varies among productive systems [36].

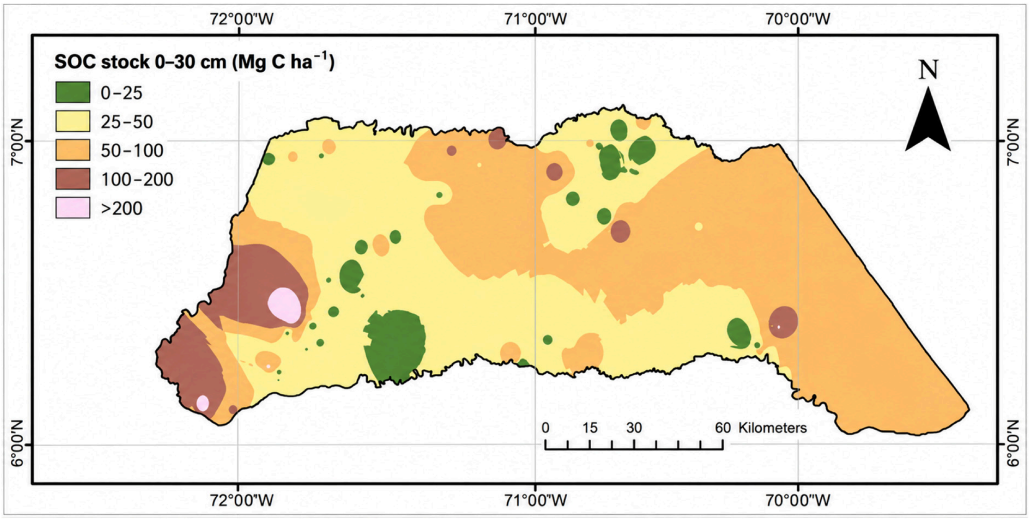


Figure 5. Spatial distribution of soil organic carbon stock (SOC stock) in the 0–30 cm soil layer in Arauca, Colombia.

The lowest median SOC stock was observed in agricultural use, which also showed the highest proportion of compacted samples according to both packing-density equations (Tables 2 and 3). Secondary vegetation also showed relatively low SOC stocks, whereas improved pastures showed intermediate values. Previous long-term restoration studies have similarly shown that vegetation recovery and soil-property recovery may not proceed synchronously, with improvements in vegetation characteristics not necessarily accompanied by equivalent recovery of soil properties [39]. Possible differences in root inputs, residue management, previous disturbance, or regeneration time could contribute to these patterns, but these variables were not measured. Therefore, the observed SOC-stock differences should be interpreted as associations with land-use category rather than as evidence of specific management or recovery mechanisms.

3.4. Pieri-Index-Based Structural Vulnerability

The Pieri index showed the clearest contrast in inferred structural vulnerability among land-use systems. Natural forest showed a median value of 9.71, indicating lower potential structural vulnerability, whereas secondary vegetation, agricultural use and improved pastures had median values of 3.61, 3.10 and 4.19, respectively, indicating a higher potential risk of structural degradation (Table 2). These differences were statistically significant and indicate that managed or previously disturbed systems had insufficient organic matter relative to their fine mineral fraction. The Pieri index is especially useful in this context because it does not only quantify organic matter content; it evaluates whether the amount of organic matter is adequate relative to the silt-plus-clay fraction involved in aggregation, aggregate protection and resistance to physical degradation [24]. Similar organic matter-to-fine-fraction approaches have been used to assess soil structural vulnerability, degradation risk and soil physical quality because the interaction between organic matter and fine mineral particles strongly influences aggregate stability, pore continuity and resistance to crusting or erosion [20,40]. Therefore, low Pieri index values indicate vulnerability to surface sealing, crust formation, runoff, erosion and further compaction. The association with land-use category was larger for the Pieri index ($\varepsilon^2 = 0.095$) than for PD-R ($\varepsilon^2 = 0.043$) and PD-A ($\varepsilon^2 = 0.026$). SOC stock showed a similarly larger effect size ($\varepsilon^2 = 0.104$), although these indicators differ in their mathematical structure and should not be interpreted as directly comparable measures of sensitivity.

The categorical distribution of the Pieri index reinforces this interpretation. In natural forest, 52.4% of samples fell within the Pieri class indicating low structural vulnerability, whereas classes associated with higher potential structural degradation predominated in secondary vegetation, agricultural use and improved pastures, with 70.4%, 75.0% and 62.7% of samples, respectively (Table 3). Unlike compaction frequency, the distribution of Pieri-index-based structural vulnerability classes differed significantly among land uses (Fisher exact $p = 0.015$), showing that Pieri-index-based structural vulnerability was a more consistent land-use signal than threshold-defined compaction (Figure 6). This result supports the central argument of the study: soil physical condition cannot be adequately assessed using compactness alone. A soil may remain below the packing density threshold and still be structurally vulnerable when organic matter is insufficient relative to the fine mineral fraction [41].

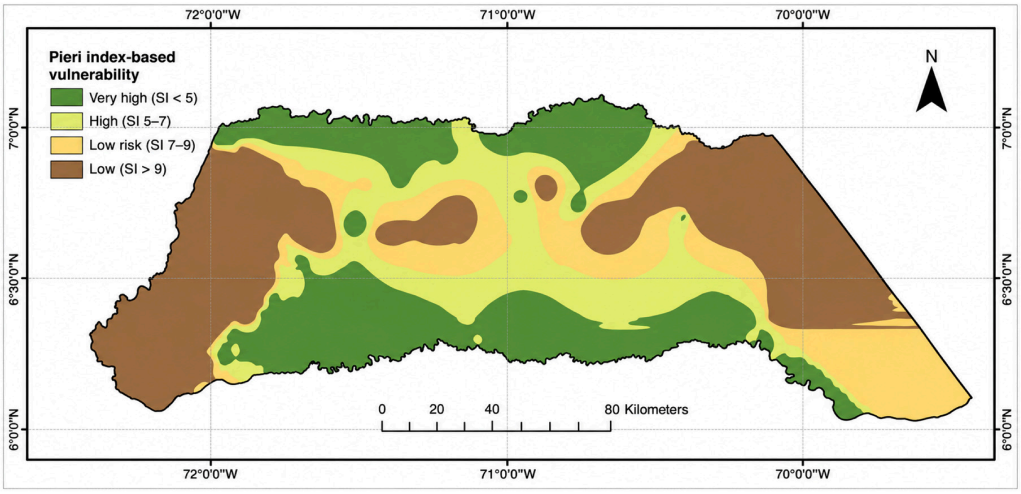


Figure 6. Spatial distribution of the Pieri stability index (SI) in the 0–30 cm soil layer in Arauca, Colombia. Note. Classes correspond to very high structural vulnerability (SI < 5), high structural vulnerability (SI = 5–7), low risk of structural degradation (SI = 7–9), and low structural vulnerability (SI > 9). The Pieri index is interpreted as an empirical indicator of potential structural vulnerability and not as a direct measurement of aggregate stability.

3.5. Integrated Interpretation of Soil Physical Condition

Overall, the results partially supported the initial hypothesis. Differences among land-use categories were more evident for carbon-related properties and Pieri-index-based structural vulnerability, whereas the response of packing density was weaker and more variable. In contrast, secondary vegetation, agricultural use and improved pastures showed a consistent decline in organic carbon, SOC stock and Pieri index values, although packing density showed only a weak overall land-use effect and no significant pairwise differences. This finding partially supports the initial hypothesis: managed or previously disturbed land-use categories were associated with greater Pieri-index-based structural vulnerability and lower SOC stocks. The unequal sampling representation among land-use categories should also be considered when interpreting the comparisons. In particular, the smaller number of agricultural-use observations (n = 12) relative to improved pastures (n = 67) may have reduced the precision and statistical power of some between-group comparisons. Although non-parametric procedures were used, they do not eliminate the limitations associated with unequal sample sizes.

From a management perspective, the results support prioritizing site-specific evaluation of soil organic matter status rather than broad interventions focused on compaction alone. Sites with elevated packing-density values should be evaluated individually using direct information on grazing intensity, machinery traffic, soil moisture, and other management factors before specific interventions are proposed. Instead, the results suggest a localized compaction pattern. The joint interpretation of packing density, SOC stock, and the Pieri index therefore provides complementary information on compactness, carbon storage, and potential structural vulnerability, but site-specific management recommendations require additional measurements that were beyond the scope of this study.

3.6. Study Limitations

This study has several limitations that should be considered when interpreting the results. First, the cross-sectional observational design allows differences and associations among land-use categories to be identified but does not support causal inference regarding land-use conversion. Detailed information on management history, time since conversion, previous land use, and other site-specific drivers was not consistently available. Second, sampling representation was unequal among land-use categories, particularly for agricultural use, which may have reduced the precision of some comparisons. Third, the 0–30 cm layer was evaluated as a single sampling interval, preventing assessment of vertical variation within the surface soil. SOC stocks were estimated on a fixed-depth basis because equivalent soil mass correction could not be applied. Fourth, the packing-density equations and thresholds were developed mainly from temperate soils and have not been locally calibrated against direct functional measurements in tropical Colombian soils. The Pieri index should likewise be interpreted as an empirical indicator of potential structural vulnerability rather than as a direct measurement of aggregate stability. Finally, the spatially interpolated surfaces may be influenced by the unequal and land-use-related spatial distribution of sampling points and should therefore be interpreted descriptively.

4. Conclusions

Natural forest showed the most favorable values among the evaluated indicators in the 0–30 cm layer, with lower bulk density (1.25 g cm^{-3}), higher SOC stock (56.5 Mg C ha^{-1}), and lower Pieri-index-based structural vulnerability (Pieri index = 9.71). Secondary vegetation, agricultural use, and improved pastures showed lower SOC stocks and lower Pieri index values. Soil pH and texture did not differ significantly among land-use categories. Packing density showed a weak overall land-use association without significant

pairwise differences, and compaction frequency did not differ significantly among land-use categories. These results identify cross-sectional differences among land-use categories in compactness, carbon storage, and Pieri-index-based structural vulnerability. Because management history, time since conversion, previous land use, soil type, landscape position, and drainage conditions were not fully characterized, the observed differences should not be interpreted as causal effects of land-use conversion.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land15091721/s1, Table S1: Minimum and maximum values of the variables audited by land-use system; Table S2: Spearman rank correlations among measured soil properties and derived indicators; Table S3: Shapiro–Wilk normality test results for measured soil properties and derived indicators (n = 127); Table S4: Cross-validation statistics for the Empirical Bayesian Kriging models used to generate the spatial distribution maps; Figure S1. Q–Q plots for the measured soil properties and derived indicators included in the statistical analyses (n = 127). Panels correspond to (A) pH, (B) soil organic carbon, (C) organic matter, (D) bulk density, (E) sand, (F) silt, (G) clay, (H) Renger packing density, (I) alternative packing density, (J) SOC stock at 0–30 cm, and (K) Pieri index. The reference line represents the expected distribution under normality. Departures from the reference line indicate deviations from a normal distribution.

Author Contributions: Conceptualization, J.D.M.-P., J.M.T.-G., M.A.T.-M. and R.J.-B.; methodology, J.D.M.-P., J.M.T.-G., M.A.T.-M. and R.J.-B.; formal analysis, J.D.M.-P.; data curation, J.D.M.-P.; visualization, J.D.M.-P.; supervision, J.M.T.-G., M.A.T.-M. and R.J.-B.; data interpretation, R.J.-B.; writing—original draft preparation, J.D.M.-P. and J.M.T.-G.; writing—review and editing, J.M.T.-G., M.A.T.-M. and R.J.-B. All authors have read and agreed to the published version of the manuscript.

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