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A Pedological Catenal Characterization along Steeply Sloped and Perhumid Regions: The Case Study of Piedemonte Llanero, Colombia

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Abstract: Owing to data scarcity, the soil properties of the Colombian “Piedemonte Llanero” are poorly quantified. To provide basic information about how pedogenic properties along a steeply sloped and perhumid landscape are related to its use (which can help lead toward better management and establishment of a sustainable crop production system), this work addresses the characterization of the morphogenetic and chemical features of selected Piedemonte Llanero soils. Research was conducted in a sequence of soils composed of four profiles located in a transect of 200–1800 m of altitude. After macromorphologically identifying, describing, and analyzing soils based on these data, soil weathering and general fertility were interpreted. Ultisols, Inceptisols, Entisols and Oxisols were fundamentally identified according to Soil Taxonomy; that is, Lixisols, Cambisols, Umbrisols, and Ferralsols, according to IUSS Working Group WRB (2015). The dominant effect of humidity attributes in soil formation, with slope and slope gradients, was the major controlling factor for the contrasting soil genesis and properties along the watershed sequence. The acid character, low cation exchange capacity, and degree of saturation stood out, and, including the inherent increase in Al³⁺ of change, were the most outstanding characters. The data obtained by this study present a substantial basis for good land use planning and will facilitate technology to be transferred from one area to another with a similar environmental picture.



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Keywords: landscape; pedon; slope; soil characteristics; soil fertility; aluminum saturation; soil classification

1. Introduction

To date, several research works have been carried out on land management impacts on soil properties, but results vary according to soil type, land use scenario (cropping systems, waste management), and climate in the area [1,2]. Soils of the tropics often have a low inherent fertility due to advanced stage of weathering, leaching of soil nutrients, and also rapid mineralization of organic matter [3].

It has probably not been recognized that site differences in processes can be attributed only to differences in cultivation practices if those sites were identical in soil quality, topography, land-use history, climate, and biota terms before cultivation began [4–6].

The conversion of forests into agricultural land is a common practice in Africa, Asia and America [7], and contributes to more than 50% of total deforestation [8]. Fragile ecosystems, land use change, and soil organic carbon (SOC) interaction, are significant for sustaining land productivity [9].

The perhumid intertropical zone constitutes a different extreme morpho-edaphic milieu because bioclimatic weathering mechanisms mostly develop on the earth's surface [10,11]. Despite notable agricultural development in equatorial or tropical countries, the study of soils has generally fallen behind that of temperate regions, especially as regards to the inclusion of the edaphic profile [12,13]. More recently, such studies have been treated more profusely, albeit generally. So, it is worth mentioning the critical soil genesis studies related to climate, rock, and vegetation by [14,15], which address selected aspects of tropical soils. However, the properties and potential of soils in tropics are poorly understood [16].

Of the greatest challenges of the tropical and subtropical Colombian, more crop production is necessary, as well as caring for and improving environmental quality. For this purpose, knowledge on soil resources and their agricultural potentials is important to define proper and appropriate land use and management. We, thus, investigated the status of soil quality in the Meta area to understand and monitor the impact of soil physico-chemical properties.

Indeed, in some regions of Colombia, soil fertility and soil quality management remain a major agricultural production problem. Hence, knowledge on soil resources and their agricultural potentials is required for proper and sustainable agricultural land use planning and management. The study of land resources in Colombia for agricultural activities has been limited, and is normally performed on large, exploratory and/or reconnaissance scales. Therefore, information on soil resources is required to manage soil fertility. Presently, soil surveys are being conducted in the Piedemonte Llanero of Colombia, in the central-east part of this country.

In rainy tropical regions, such as the Colombian Lowlands foothills, the nutrient loss rate due to leaching is expected. Natural ecosystems can become cultivated fields, in which case increases can be marked. If to this factor the fact that we expect to find acidic soils is added, then studies should focus the effect of this property on acidic soils subjected to crop production.

Therefore, Piedemonte Llanero of Colombia is a paradigmatic example of a steeply sloped and perhumid landscape (more than 6000 mm/year) about which hardly any studies on soils from the morphological point of view, and on their chemical and physico-chemical properties, are available. With these premises, the main objectives of this study are to seek the variance in explored soils related to soil uses in a perhumid climate, and to provide a baseline for future research about edaphic acidifying processes. To do so, we intend to: (i) characterize the macromorphological and physico-chemical properties of the soil profiles along the landscape; (ii) determine how soil properties vary as a result of complex interactions between altitude gradient and land use, in an attempt to identify the factors controlling soil weathering processes and properties in these tropical zone reliefs, characterized by steep environmental gradients; (iii) classify soils following major soil classification schemes.

2. Materials and Methods

2.1. Site Descriptions

Here we focus on distinctive shifting cultivation features in steeply sloping regions, such as Piedemonte Llanero, in Colombia (Figure 1). The present study was carried out in the Piedemonte Llanero of Colombia, located in the central-eastern part of Colombia. The highest elevation was 1800 m above sea level (m.a.s.l.) and the lowest was 200 m.a.s.l. [17]. There are mountain and Piedemonte landscapes in this area with heterogeneous geological features, which is why sandstones and shales are the dominant lithological materials in mountain areas. Clays, conglomerates, and mixed sediments are the dominant materials in Piedemonte areas [18]. This area encompasses an ecological transition zone between montane forests and savannas, supplied by drainage water networks of the mountain range's eastern slope, that generate sedimentary soils with superior fertility to that of those found in Orinoquía [18]. Geologically speaking, two regions are differentiated in the study area: (a) mountainous, made up of sedimentary rocks from the Cretaceous and Paleogene;

(b) plain, made up of recent sediments that cover Precambrian, Paleozoic, Mesozoic, and Paleogene rocks [19–21]. The Llanero piedmont is characterized by being an area of active deformation that is expressed by morphotectonic evidence, such as fault scarps, folding in alluvial terraces deposits of Quaternary age, and inversions of the drainage networks by tilting and thick fans. The Meta River is the main fluvial artery in the region, in which large and thick lateral, longitudinal, and transverse bars of fine-grained sand and mud–clay matrices form, with sloping stratification at a very low angle, and gray to brown in color.

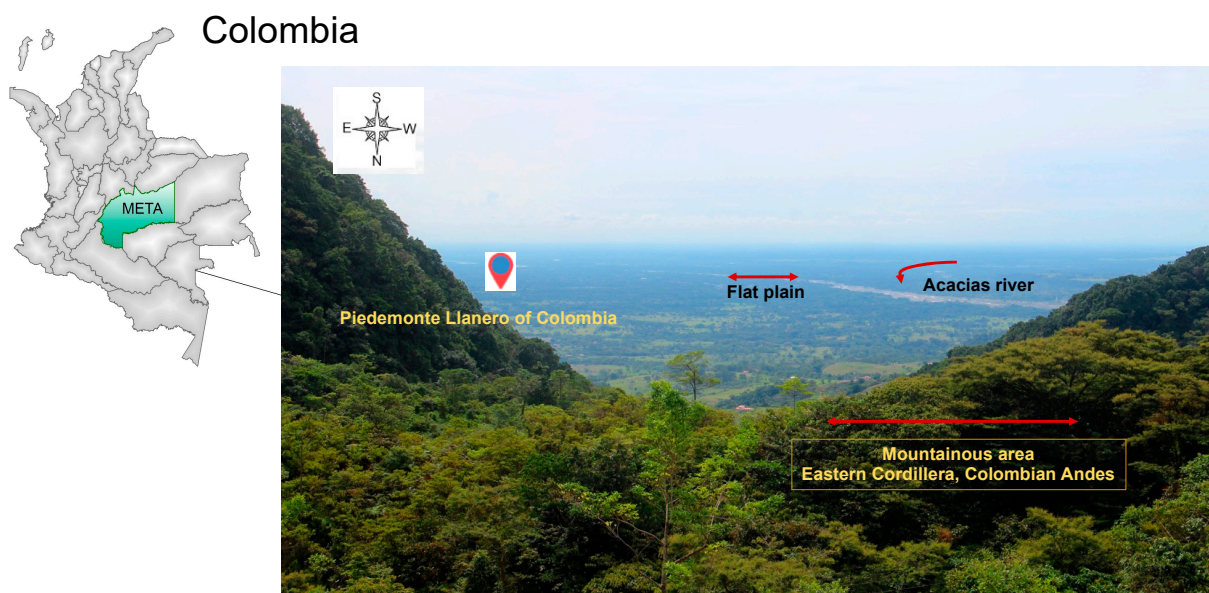


Figure 1. Study area. Note the dense vegetation layer (transition between the vegetation of the mountain and plain, or Piedemonte), and the strong escarpment, transverse to the N-S line, which acts as a screen against clouds. JMTG owns image.

The economy of this area is based on livestock and crops, specifically the pastures in the upper, middle, and lower areas of the basin, which cover an approximate area of 78,982.26 ha that corresponds to 84.8% of the total basin area. The distribution is as follows: areas with pasture for livestock comprise 39,977.32 hectares (42.9%), Palm oil systems occupy 22%, with approximately 20,470 ha, transitory rice crops stand out that cover 18,029.6 ha and correspond to 19.3% of the total area, and 0.6% corresponds to areas with production of minor species (poultry, fish, and pig) [17]. The monomodal rainfall pattern involves a wet season from April to November and a dry season from December to March, which is, at the same time, determined by the Intertropical Convergence Zone (ITCZ). Consequently, average annual precipitation is almost 6000 mm/year in the mountain areas and 2500 mm/year in the plain areas of Piedemonte. May and June are the months with the highest rainfall levels. Temperatures vary between 22.5 °C and 28.5 °C (Figure 2). According to the Caldas-Lang classifications, the study area contains the following topics: superhumid temperate, warm superhumid, warm humid, and warm midhumid [18].

Tropical mountain ecosystems make up an important gradient of ecological vegetation, as their structure is similar to tropical lowland forests [22,23] report the importance of these forests, mainly in the face of climate regulation, water flows, and the exchange of fauna species.

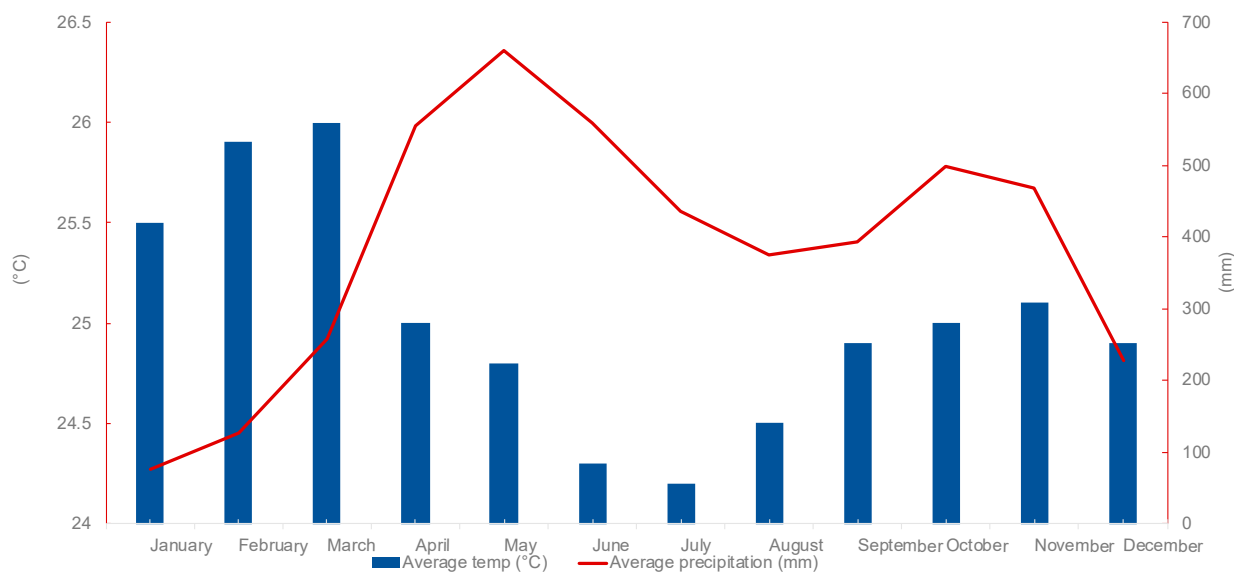


Figure 2. Climadiagram of the Acacias River Basin in the Piedemonte Llanero of Colombia.

2.2. Field Survey and Sampling

The recognition and sampling of soils and their mapping were carried out by an “inductive” method before moving to a “deductive” phase. Specifically, the study area was subdivided into the two major physiographic environments: plain and mountain. Subsequently, units were established based on the nature of the original materials, slope, erosion, landform, and land use.

Soil morphological properties were established in situ. Genetic horizons and check-points were established. The first profile is located at an altitude of 204 m and the highest at an altitude of 856 m. Samples were taken from each identified horizon.

2.3. Analytical Procedure

When soil samples arrived at the laboratory, they were air-dried and subsequently sieved (<2 mm) to exclude litter, roots, and coarse particles to analyze all the soil properties. For the organic matter determinations, the samples were passed through a 0.5 mm sieve. The selected soil properties were determined by the following methods: particle size distribution was established by the hydrometer method [24]; soil pH was measured at a soil: distilled water ratio of 1:2.5; electrical conductivity (EC) was measured with a conductivity meter at a soil: water ratio of 1:2.5 [25]; organic matter was analyzed by the wet digestion method [26]; phosphorus (P) was determined by the Olsen method [27].

Exchangeable aluminum (AlKCl) was extracted with a soil: potassium chloride (1.0 M KCl) ratio of 1:10 and analyzed by ICP spectrometry. To calculate Al saturation (Als_{at}), first, the Al extraction methodology proposed by [28] was employed to ascertain the effective cation exchange capacity (ECEC). For each sample, 2 g of the soil sample was placed inside a disposable 60 mL vessel. Next, 20 mL of 1.0 M KCl was added to each vessel. Vessels were then oscillated on a reciprocal shaker for 30 min. Using Whatman # 1 filter paper, extracts from samples were percolated in a 103 mL plastic cup. Finally, the total Al extracted with 1 M KCl was measured by ICP. Following the protocols described by [28], the following equation was used to calculate the ECEC of each ICP-analyzed soil extract: $ECEC \text{ (cmol/kg)} = [Na] + [K] + [Ca] + [Mg] + [AlKCl]$. All samples were analysed in duplicate.

Regarding metal oxides, determination it is obtained in this way: sub-boiling, double-distilled HNO₃ was added at 50% v/v to all samples and analytical targets, and the final determination was performed using an inductively coupled optical emission plasma spectrometer, Optima 2100DV (Perkin-Elmer), ICP-OES. For quality assurance and quality control (QA/QC), the accepted recoveries ranged from 70% and 130%. The analytical

method presents the evaluation of blanks ($n = 20$) and duplicated samples ($n = 25$) for each group. The relative deviation of the duplicated samples was $<15\%$ for all batch treatments.

2.4. Soil Index

Some soil properties are used to calculate soil fertility parameters, such as: sum of base cations (S); Soil Aggregate Stability Index (ISS); Forestier Index (IF); Soil Sealing Index (IB); Kamprath Index (m). S is obtained by summing the exchangeable cations, which were: Ca, Mg, K, and Na.

For computing soil fertility, several parametric indices were proposed and used. They included the so-called Soil Aggregate Stability Index (ISS) [29], which relates soil resistance to external disruption forces, and was assessed with the Pieri's formula in Equation (1) [29] below:

$$ISS = \frac{1.724 \times OC}{(L + A)} \times 100 \quad (1)$$

where OC is soil organic carbon; L is the silt fraction; A is the clay fraction.

The IB related to the soil erosion and compaction risks was estimated by Remy's formula in Equation (2) [30]:

$$IB = \frac{(1.5 \times Lf) + (0.75 \times Lg)}{(A - 10 \times OM)} - C \quad (2)$$

where C equals $0.2 \times (\text{pH } 7)$; Lf is fine silt; Lg is coarse silt; A is clay; OM is soil organic matter content.

The IF was assessed using the following formula in Equation (3) [31]:

$$IF = \frac{S^2}{(A + Lf)} \quad (3)$$

where S is the sum of base cations; A is the clay fraction; Lf is fine silt fractions.

Finally, it is worth mentioning aluminum toxicity (Al) as defined by the Kamprath Index (m), Equation (4) [32], to determine the degrees of toxicity of exchangeable aluminum. Calculations for Alsat were done with the following equation:

$$Al = \left(Al^{3+} \times \frac{100}{S + Al^{3+}} \right) \quad (4)$$

where Al^{3+} is exchangeable aluminum in cmol/kg of soil; S is the sum of exchangeable base cation in cmol/kg of soil. Table 1 shows the values and categories to interpret these indices: ISS, IF, IB, and m.

Table 1. Interpretation of soil categories according to the Soil Aggregate Stability Index (ISS), the Forestier Index (IF), the Soil Sealing Index (IB), and the Kamprath Index (m).

Soil Aggregate Stability Index (ISS)		Soil Sealing Index (IB)	
Value	Category	Value	Category
ISS > 9%	Stable structure	IB < 1.4	Soils with no thrust risk and with no erosion risk
7% < ISS ≤ 9	Low structural degradation risk	1.4 < IB ≤ 1.6	Soils with a low erosion risk
5% < ISS ≤ 7%	High degradation risk	1.6 < IB ≤ 1.8	Soils with a medium erosion riskf
ISS ≤ 5%	Structurally degraded soil	IB ≥ 1.8	Soils with high erosion risk

Table 1. Cont.

Soil Aggregate Stability Index (ISS)		Soil Sealing Index (IB)	
Forestier Index (IF)		Kamprath Index (m)	
Value	Category	Value	Category
IF < 1.5	Soils with low nutrient reserves	m < 20%	Soils with aluminium toxicity
IF > 1.5	Soils with good nutrient reserves.	20 < m (%) < 50	Soils with high aluminium toxicity
		m > 50%	Soils with very high aluminium toxicity

In addition to the other soil fertility parameters, the sum of exchangeable bases (S) and effective cation exchange capacity (ECEC) were grouped into classes to better represent these results. When $S < 2$ (cmol/kg), it indicates very low values; $2 < S$ (cmol/kg) < 5 denotes low values; $5 < S$ (cmol/kg) > 10 implies average values; $10 < S$ (cmol/kg) < 15 indicates high values; $S > 15$ (cmol/kg) denotes very high values [33]. When $ECEC < 5$ (cmol/kg), it implies very low values; $5 < ECEC$ (cmol/kg) < 10 indicates low values; $10 < ECEC$ (cmol/kg) < 25 suggests average values; $25 < ECEC$ (cmol/kg) < 40 represents high values; $ECEC > 40$ (cmol/kg) indicates very high values [33].

3. Results and Discussion

3.1. Soil Characteristics

The macromorphological characteristics of the four selected soil profiles appear in Table 2. The photos in Figure 3 are images of them.

Table 2. Essential macromorphological and diagnostic features of the studied soil profiles.

Profile	Altitude (m.a.s.l.)	Coordinates	Soil Use	Parent Material/Relief	Soil Type (Soil Taxonomy)	Morphology	Color
1	204	3°52'47.2" N 73°08'13.0" W	Palm oil cultivation	Alluvial sediments /Flat	Oxic Dystrudepts	Ap (0–25 cm) Bw (25–56 cm) C (56–100 cm)	5YR3/2 5YR5/3
2	369	3°54'51.5" N 73°36'06.3" W	Banana cultivation	Sandstone/Flat	Typic Hapludox	Ap (0–21 cm) Bw (21–54 cm) C (54–80 cm)	5YR3/2 5YR5/6
3	396	3°56'39.1" N 73°47'08.6" W	Pastures	Sandstone/Somewhat steep (>30%)	Oxic Dystrudepts	Ah (0–13 cm) Bw (13–43 cm) C (43–100 cm)	5YR4/4 7.5YR7/4
4	856	3°57'0.8" N 73°49'42.3" W	Pastures	Sandstone/Steep (>30%)	Typic Udorthent	A (0–25 cm) C (25–75 cm)	5YR3/2 5YR7/4

Table 2 shows the main soil types and their macromorphological properties, while Table 3 provides the analytical results. Pedon 1 was characterized by the initial stage of subsoil horizon differentiation, as evidenced by changes in color and structure. This soil has started to form as indicated by the modest development of structure, color, consistency, etc. It is a Bw horizon with a redder hue, moderately developed soil structure, and friable consistency. The horizon thickness met the cambic diagnostic horizon requirements. Therefore, they are younger than Ultisols and Oxisols. Then, there is Ochric epipedon and Cambic horizon as the diagnostic horizons, classified, therefore, as Inceptisol by USDA Soil Taxonomy [34], or Cambisol (IUSS Working Group WRB 2015) [35].

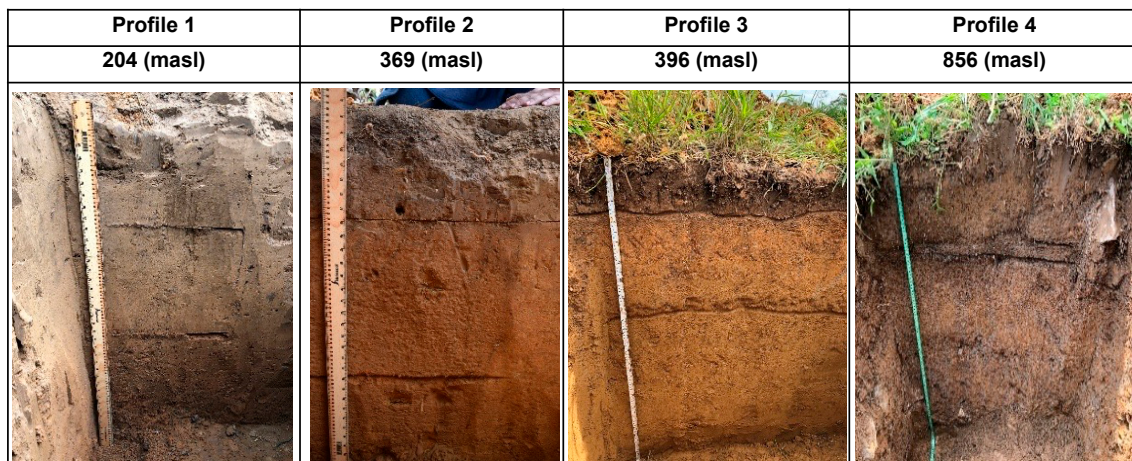


Figure 3. Detailed photographs of the analyzed soil profiles in Piedmonte Llanero of Colombia.

Table 3. Main soil chemical, physical, and physico-chemical properties in the Piedemonte Llanero of Colombia.

Altitude (m)	204		369		396		856	
	Profile 1 Oxic Dystrudepts		Profile 2 Typic Hapludox		Profile 3 Oxic Dystrudepts		Profile 4 Typic Udorthent	
	A _p	AB _w	A _p	B _w	A _h	AB _w	A _h	C
Depth (cm)	0–25	25–56	0–21	21–54	0–13	13–46	0–24	24–100
Sand (%)	31.96	29.83	56.28	38.02	70.43	54.11	51.57	90.74
Fine silt (%)	42.03	37.51	20.11	35.35	12.52	19.67	17.45	6.39
Coarse silt (%)	1.00	1.00	0.50	2.00	0.00	1.00	1.00	0.00
Clay (%)	25.01	31.66	23.11	24.63	17.05	25.22	29.98	2.87
Texture	Loam	Sandy loam	Sandy-Clay-Loam	Sandy-Clay-Loam	Sandy-Loam	Sandy-Clay-Loam	Sandy-Clay-Loam	Sandy
Organic Matter (%)	1.97	1.48	1.55	0.2	1.93	1.90	2.24	0.55
Soil Organic Carbon (%)	1.14	0.86	0.90	0.2	1.12	1.10	1.13	0.34
pH (distilled water 1:2.5)	4.74	4.94	4.64	4.77	4.94	4.11	5.00	4.09
Electrical conductivity (dS/m)	0.16	0.10	0.17	0.11	0.10	0.27	0.10	0.20
P (mg/kg)	8.36	7.90	5.76	<3.87	54.11	23.81	12.5	7.15
S (mg/kg)	12.57	6.11	4.23	2.37	1.82	0.76	3.01	2.11
ECEC (cmol/kg)	3.77	4.97	3.22	4.14	3.41	4.03	10.84	8.91
S (bases) (cmol/kg)	1.35	nd	2.80	nd	0.58	nd	2.05	nd
H + Al Int. (cmol/kg)	2.42	nd	2.23	nd	2.83	nd	8.79	nd
Al(KCl) (cmol/kg)	2.09	nd	1.60	nd	2.18	nd	8.59	nd
AlSat	55.0	nd	60.0	nd	64.0	nd	70.0	nd

Sand 2–0.05 mm; silt 0.05–0.002 mm; clay < 0.002 mm; P (mg/kg) = phosphorus; S (mg/kg) = sulfur; S (bases) = sum of base cations.

Pedon 2 has an Ochric epipedon and a relatively deep Oxic horizon (ferralic B) as the diagnostic horizons, classified, hence, as an Oxisol or Ferralsol according to the USDA Soil Taxonomy and the IUSS Working Group WRB (2015) classification, respectively. Oxic horizons characterize highly weathered soils.

Pedon 3 had Ochric epipedons and Cambic horizons as diagnostic horizons. The profile shows some Oxic horizon characteristics (highly weathered soils, but not genetically as old as Oxisols). Soil was classified as Inceptisol or Cambisol according to the USDA Soil Taxonomy and the the IUSS Working Group WRB (2015), respectively.

Pedon 4 (at a higher altitude) had fairly young soils with no diagnostic horizons other than an Ochric epipedon and were, hence, classified as Entisols (USDA Soil Taxonomy). As Pedons showed lithic contact, they were classified as Entisol (Soil Taxonomy) and Leptic Regosols (IUSS Working Group WRB (2015)). Some Pedons had fluvic material, as affirmed by stratification and irregular decreasing OC contents with depth, but with no diagnostic horizons other than an Ochric epipedon [34,35].

Regarding their color, soils (dry, humid) were found in a dark, reddish brown (5YR3/4) to a yellowish, red-color (7.5YR 5/6) environment (Table 2, Figure 3) due to the oxidation of iron oxides, responsible for the dark reddish brown color. Certain color and chroma nuances indicated the presence of soil moisture, and mottling was detected in the subsoil layers of certain pedons, which confirms poor drainage conditions. A moderate-to-high degree of structuring was observed on the surface horizons, which gives way to massive subsurface horizons. Some structural deterioration attributed to prolonged agricultural use was observed.

The granulometric analyses indicated that the soils are of sandy–clay–loamy, sandy–loam, and sandy texture (according to Soil Taxonomy). The electrical conductivity (EC) of the soils in all the pedons was well below unity and CaCO_3 was not detected on soil horizons. The obtained results about soil reaction (pH) generally showed acidic or very acidic values (Table 3). The acidic nature of soil through the transect was due to either considerable rainfall, which causes base cations to leach from soil colloids, or slow organic matter decomposition, with low-molecular acids being continuously released, which might be another reason for these soils' acidic nature. Soil pH (a measure of the concentration of protons in soil solution) is a very important parameter that directly influences the chemical reactions in soil and the availability of nutrients for plants [3]. Soil pH is closely related to the sum of the bases present in soil. So, the more acidic soil is, the fewer bases it contains. Soil pH reflects the saturation state in the bases of the absorbing complex [15]. The summation of processes results in soil cation exchange sites being dominated by Al^{3+} . As a result, base cations on the soil surface are replaced with Al^{3+} . Intrinsic variations between edaphic environments can markedly affect the amount of exchangeable Al that is present [36].

Kochian et al. [37], stated that approximately 50% of the world's suitable farmland is deemed acidic, for which a critical pH for most plant species grown in an acidic edaphic environment is <5.5 . According to Pålsson [38], for many crops, the onset of toxicity symptoms means that Al^{3+} must be present at concentrations of around $2\text{--}3 \text{ mg kg}^{-1}$.

For organic matter content, an apparent change was observed in the transit from the soils in the low topography to those of high topographies. This is attributed to the fact that lower parts are subjected to cultivation, while original plant covers still remain in higher parts. Organic matter content showed a limited difference between soil types, but an increase was observed that could be due to the altitude effect or to more pronounced human activities at lower altitudes. Perhaps it could also be explained by the double protection found between the latter and free aluminum. Upper layers are characterized by moderate humus accumulation.

The results showed that the ECC were very low $<5 \text{ cmol/kg}$ (Table 3). The sum of base cations was also very low, as was the base saturation. Lower base saturation (BS) values could be due to the depletion of base cations by intense rain. It can be interpreted that BS indicates the degree of leaching of base cations, and that, therefore, this meant that the

studied pedons were weakly leached soils (60–80%) according to the ratings set by Hazelton, P.; Murphy [39]. The variation observed in ECEC, base cations and sum of bases BS in the studied districts could be attributed to a combination of intrinsic (weathering, erosion, deposition, and soil-forming processes) or local extrinsic (anthropogenic practices) factors.

Phosphorus is an important primary nutrient required by plants in large quantities. In tropical soils, phosphorus adsorption is a major process that controls its availability to crops. The results obtained (Table 3) show that there are low contents. Fertilization practices such as the addition of organic manure, crop residues, rock phosphate, water-soluble P fertilizers, and incorporation of a phosphorus solubilizing organism are highly recommended to increase P solubility and availability in highly weathered soil. According to Wang [40] and Guedes [41], adding organic matter to tropical soils can be an efficient strategy to optimize P fertilization by reducing P sorption, and enhancing sorbed P reversibility in soils. P adsorption is likely to increase in tropical soil with a low pH and prevalence of kaolinite and Fe and Al oxides in the clay fraction [42].

The studied soils are subject to leaching and showed low organic matter content. Therefore, it is not strange that they present low contents in total sulfur (Table 3); The highest value is 12.57 (mg/kg). Olson [43] provided the following average topsoil values for total sulfur (in the temperate region): 500 mg/kg for Mollisols, 400 mg/kg for Alfisols, and 200 mg/kg for Ultisols. Following this reasoning, they assumed that most tropical soils would average about 100 mg/kg. Abounding in this matter, clayey Oxisol under native savanna contained 251 mg/kg S and sandy Ultisol only 40 mg/kg S, the latter of the two from Brazil [44].

3.2. Application of the Soil Index

An analysis of each soil type's fertility showed these soils' poor fertility statuses, which is related to the physico-chemical parameters (Table 4). The soils with a lower ECEC had a marked deficit nutrient reserve. This limited nutrient reserve and the low CEC are associated with low levels of organic matter of OM in these soils, and, fundamentally, with extremely high rainfall, which is one of the highest in the world (>6000 mm/year). The ISS showed a slight difference between soil types, although most were prone to degradation. From Table 4, $ISS \leq 5\%$ indicates structurally degraded soil in profiles one, two, and four. Only profile three had a high degradation risk value.

Table 4. Application of soil indices (surface horizons) to the Piedemonte Llanero of Colombia.

Soil Profile	Soil Index				
	ISS	IF	Al	Soil Fertility (CEC)	S
1 Oxic Dystrudepts	2.89	0.03	55	Very low value	Very low value
2 Typic Hapludox	3.54	0.18	60	Very low value	Low value
3 Oxic Dystrudepts	6.52	0.01	64	Very low value	Very low value
4 Typic Udorthent	4.62	0.08	70	Average value	High value

Since the percentage of coarse silt is negligible, in the calculation of the IF parameter, the value of the percentage of total silt has been introduced. In all cases, the IF values were <1.5, which denotes soils with low nutrient reserves. Similarly, Al always obtained values over 50%, which means that all the soils had very high Al.

The balance between the saturation rate and acidity highlights the impact of pH on the evolution of exchangeable aluminium and bases in soils. By way of conclusion, it can be stated that most soils can be included as poor fertility soils detrimental to crop production. Therefore, it is essential to encourage farmers to practice fallow systems after cultivation to maintain soil fertility and to alternate culture types, and to especially promulgate new soil nutrient supply mechanisms from inputs (composts, chemical fertilizers, and mineral fertilizers).

The large amount of rainwater that falls on the landform's surface in this perhumid region (more than 6000 mm/year in some places) determines deterioration rates. Therefore, water largely dominates weathering, favoring formation of deeply weathered profiles, [45,46] especially if, as is the case, temperature influences dominant types and weathering rates. Topography, altitude, rainfall, and temperature come over as the main factors responsible for soil spatial variation.

On chemical weathering indices, we should remember that climate is a major influence on the weathering processes that affect soil parent materials. Therefore, a climate that is as pluviometrically exacerbated as that on the foothills of Colombian plains should have a clear influence. According to Duzgoren-Aydin et al., Price and Velbel, and Dengiz et al. [47–49], chemical weathering indices estimate soil chemical weathering intensity by comparing changes in major and trace metal concentrations as mobile-to-immobile elements ratios in soil and rock or parent material. Although the pedological evaluation of the four soil profiles initially indicates pronounced weathering, the truth is that the applied indices (Chemical Index of Alteration, CIA; Chemical Index of Weathering, CIW; Plagioclase Index of Alteration, PIA) reveal progressive weathering.

(a) Chemical Index of Alteration, CIA 44 (Nesbitt and Young [50])

$$CIA = \left[\frac{Al_2O_3}{Al_2O_3 + CaO + Na_2O + K_2O} \right] * 100 \quad (5)$$

The CIA can vary from around 35–55 (for unweathered rocks) to 100 (highly weathered). Nesbitt and Young [50] classified the CIA values as very slightly weathered (50 to 60), slightly weathered (60 to 70), moderately weathered (70 to 80), highly weathered (80 to 90), and extremely weathered (90 to 100).

(b) Chemical Index of Weathering, CIW (Harnois) [51]:

$$CIW = \left[\frac{Al_2O_3}{Al_2O_3 + CaO + Na_2O} \right] * 100 \quad (6)$$

This index modifies CIA by excluding K_2O from assessments and

(c) Plagioclase Index of Alteration, PIA [52].

$$PIA = \left[\frac{Al_2O_3 - K_2O}{Al_2O_3 + CaO + Na_2O - K_2O} \right] * 100 \quad (7)$$

This index was proposed by Fedo et al. [52], as an alternative to the CIW.

Thus, soil formation in this region is a dynamic rather than a static process. Based on the literature [53,54], rocks from the upper crust and unweathered igneous rocks generally have CIA values of about 50, whereas the soils and sediments that derive from intensely weathered rocks and contain residual clay minerals have CIA values that approach 100. This is the case of the four studied soil profiles (Table 5), where the CIA values varied from 94.0 to 98.8. The CIW, PIA, and CIA display similar behavior, which means that the weathering process is very intense and is due to the heavy rainfall in this place.

Table 5. Evaluation of the geochemical weathering indices in surface horizons.

Profile	Oxides (mg/kg)				Weathering Index			
	Al_2O_3	CaO	Na_2O	K_2O	CIA	CIW	PIA	SOC/Clay Ratio
1	25,640	209.4	139.0	928.3	96.8	99.0	94.6	0.045
2	45,040	192.6	70.42	498.7	98.9	100	98.2	0.038
3	13,330	121.8	77.33	1121	94.0	98.9	89.0	0.065
4	30,260	552.1	130	28.77	98.3	98	98.3	0.037

CIA = Chemical Index of Alteration; CIW = Chemical Index of Weathering; PIA = Plagioclase Index of Alteration.

Finally, the SOC/clay ratio thresholds of [55] were calculated for each soil profile. The SOC/clay index is a simple measure to evaluate the SOC status, and it allows the soils to be evaluated on a scale from degraded-to-good soil conditions.

The literature contains physical soil properties (bulk density, water retention characteristics, and clay dispersibility), which can be better explained by the amounts of SOC and clay content in relation to one another than by their total contents [56,57].

SOC/clay ratio thresholds of $1/8 = 0.125$, $1/10 = 0.1$ and $1/13 = 0.076$, respectively, indicated that boundaries between them had “very good”, “good”, “moderate” and “degraded” levels of structural condition. The obtained values were 0.045, 0.038, 0.065, and 0.037 of the surface horizons of profiles one, two, three, and four, respectively, and were 0.027, 0.008, 0.04 and 0.118 for the subsurface horizons of profiles one, two, three, and four, respectively. On the above-cited scale, all these values (except the subsurface horizon of profile four, located at a higher altitude) clearly fell short of $1/13$ and were, therefore, degraded, which means that their SOC contents are unable to protect SOC by interacting with clay particles.

4. Conclusions

This paper is the first to provide chemical and morphological properties of the soils in the perhumid Piedemonte Llanero region of Colombia, and to demonstrate the dominant effect of humidity attributes on soil formation. The following conclusions can be drawn from the study results. Differences in slope gradient and land management across the landscape influence the characteristics of the soils at the studied site. Slope and slope gradient also contribute to verify soil genesis and properties along the sequence in the watershed. These results revealed a significant effect of slope positions, mainly on thickness of the soil profile and solum, clay, and organic carbon, which lead to change of type, depth, and sequence of soil horizons along the altitudinal transect. The four studied Pedons across the landscape are variable in terms of their profile depth, horizon features, and some physico-chemical properties. Soils are slightly acidic to acidic, with low-to-very-poor cation exchange capacity, and base cations that could have implications for nutrient uptake and, consequently, nutrient imbalances. Some soils are weathered with profiles showing advanced weathering stages (Oxic character as a diagnostic feature). Finally, the study results indicate that the soils from Piedemonte Llanero area are classified as Ultisols, Oxisols, Inceptisols, and Entisols (Soil Taxonomy); that is, Cambisols, Lixisols, Ferralsols and Umbrisols (IUSS Working Group WRB). From the obtained data, the adoption and promotion of the best management options may be required for different land uses and erosion control, with the aim to increase SOC stocks and overall soil quality.

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