SOIL SCIENCE ANNUAL
2025, 76(1), 203719

https://doi.org/10.37501/soilsa/203719

Soil physicochemical properties and aggregate stability in tropical soils

Juan Carlos Loaiza-Usuga[1,2]*, Tatiana Camila Zamora-Forero[3], Guillermo Antonio Correa-Londońo[4], Yolanda Rubiano-Sanabria[5], Magdalena Ryżak[6], Tomasz Zaleski[2]

[1] Universidad Nacional de Colombia, Sede Medellin, Facultad de Minas, Departamento de Geociencias y Medio Ambiente, Av. 80 #65 - 223, Robledo Villa Flora, 050041 Medellín, Colombia
[2] University of Agriculture in Krakow, Faculty of Agriculture and Economics, Department of Soil Science and Agrophysics, Al. Mickiewicza 21, 31120, Kraków, Poland
[3] Scientific Staff Institute of Soil Science and Site Ecology, Department of Forest Sciences, TUD Dresden University of Technology, Fachrichtung Forstwissenschaften, 01062 Dresden, Germany
[4] Universidad Nacional de Colombia, Sede Medellin, Facultad de Ciencias Agrarias, Departamento de Ciencias Agronómicas, Building 11, Carrera 65 Nro. 59A - 110, 050034 Medellín, Colombia
[5] Universidad Nacional de Colombia, Sede Bogota, Facultad de Ciencias Agrarias, Departamento de Agronomía, building 500, Cra 30 # 45 – 03, 16486 Bogotá, Colombia
[6] Institute of Agrophysics, Polish Academy of Sciences, ul. Doświadczalna 4, 20290 Lublin, Poland

* Corresponding author: Full Professor, Juan Carlos Loaiza-Usuga, jcloaiza@unal.edu.co, ORCID iD: https://orcid.org/0000-0002-3821-7518

Received: 2024-06-22
Accepted: 2025-04-04
Published online: 2025-04-04
Associated editor: Piotr Gajewski

Keywords:

Tropical soils
Soil genesis
Aggregate stability
Tropical weathering

Abstract

Several authors have suggested a relationship between soil physicochemical properties and the mineral composition of tropical soils concerning the development of soil structure and aggregate stability. This study analyzed soil samples from different climatical conditions, from Bt, Bss, Bo, and Bw (endopedons) soil diagnostic horizons, typical of tropical soils in Andean, Caribbean, and Orinoco regions in Colombia. The stability of soil macroaggregates was determined by the wet sieving method, and the stability of microaggregates was determined by the laser diffraction method. The results showed the predominance of silt and clay fractions and high variability of grain size distribution, which translates into low soil structure stability and high susceptibility to their dispersion (making them susceptible to degradation by erosion), except in Andisols. Wet sieving (KR) results and laser diffraction-based aggregate stability index (ASI_{LD}) showed good levels of microaggregate stability only in Andisols. The soil organic carbon (SOC) content was medium to low in dry climates and high in cold, humid conditions. Andisols were characterized by the high SOC content and Water Resistance Index (WRI). This study provided knowledge of the differences in the physicochemical properties of tropical soils as a tool for assessing the aggregation of soils under different management practices and environmental change scenarios.

1. Introduction

The change of land use in the tropics can affect soil properties and ecosystem services it can offer (Machado et al., 2019), which influences the impact of further remediation processes intended in soil functions recovery (Xu et al., 2022). The aggregate stability in relation to soil use, management, and degradation susceptibility among others factors have been widely used as indicators of soil quality (Boruvka et al., 2002; Rieke et al., 2022). The persistence or destruction of soil aggregates have been presented as soil structure indicators in agriculture systems and remediation programs (Wuddivira et al., 2009; Carrizo et al., 2015; Xu et al., 2022). Soil structure is directly related to many physical and chemical processes such as hydropedological behavior (water movement and retention), compaction and crusting processes, soil nutrient recycling, soil erosion, root penetration, and crop yield (Bronick and Lal, 2005; Statescu et al., 2013; Ye et al., 2019). Multiple factors are associated with the aggregates stability, including heterogeneity of edaphic conditions, soil water dynamics, flocculation of clay and soil organic matter (SOM), and cementation of dispersed clay (Boruvka et al., 2002; Ontl et al., 2015). Soil aggregation is a consequence of particles flocculation, rearrangement, cementation, formation of organometallic compounds, and cations activity, which form bonds between aggregates (Bronick and Lal, 2005). Plants, soil fauna, and microbial activity are reported as key biotic elements in soil agregate (Boruvka et al., 2002; Ontl et al., 2015; Xu et al., 2022). For tropical rain forests Sun et al. (2023) reported high sensitivity to seasonal changes of biological and chemical soil quality indicators; in these soils the presence of Al^{3+} and Fe^{3+} favors the precipitation of compounds and particle assembly (Bronick and Lal 2005).

Aggregate stability has been used as an indicator of the structural condition of the soil for assessing soil vulnerability to degradation (Carrizo et al., 2015; Ye et al., 2019). Several studies have focused on the importance of SOC and texture on soil structure formation and stabilization, improving nutrient and soil physical processes and properties (Carrizo et al., 2015; Zhou et al., 2020). SOC response to different cropping systems, tillage, fertilization, and vegetation restoration were studied by Sîmansky et al. (2008), Zhou et al. (2020), and Rieke et al. (2022). The interaction between geomorphological conditions, soil properties, ecological processes, anthropic activities, land uses, and cover directly influences soil structure variability (Ye et al., 2019). However, SOC varies through geomorphological positions, being the soil texture of primary influence (Ontl et al., 2015). Numerous studies have compared trends in soil organic matter and land uses in relation to soil structural stability, although soil genesis and type are not extensively considered.

Bronick and Lal (2005) underlined that soil genesis processes and anthropic activities affect soil structure development and aggregate formation. In temperate regions, several authors have focused on soil aggregate stability as an indicator of soil structure development in Inceptisols, Spodosols, Vertisols, Andisols, Ultisols (Statescu et al., 2013), Mollisols (Ontl et al., 2015; Zhou et al., 2020), and Alfisols (Boruvka et al., 2002; Sîmansky et al., 2008; Statescu et al., 2013). In tropical zones these studies were focused on land use and soil structure in Alfisols, Vertisols, Entisols, Inceptisols, Andisols, Oxisols, Ultisols, and Mollisols (Alekseeva et al., 2009; Pulido et al., 2009; Wuddivira et al., 2009; Vial and Sandoval, 2015; Novak et al., 2019). Unfortunately, none of these studies were focused on the loss of soil structure in the genetic horizons. However, few studies have explored the relationship between soil development under different ecological zones for tropical soils with regard to soil aggregate stability in endopedons. The diagnostic horizons of the most representative soil orders for each natural region have been selected, seeking a basic understanding of the driving mechanisms responsible for soil characteristics over different pedogenetic conditions. The aim of this study was (1) to determine the mechanical stability of water-stable aggregates in tropical soils by comparing different methods, and (2) to evaluate soil development impact on soil organic matter content and water-stable aggregates.

2. Materials and methods

2.1. Study area

The soils considered in this study were Alfisol (ALF), Andisol (AND), Oxisol (OX), and Vertisol (ERT) (Soil Survey Staff, 2022a) or as appropriate Luvisols (ALF), Andosols (AND), Ferrasols (OX), and Vertisols (ERT) (IUSS Working Group WRB, 2022). Soils are under different edaphoclimatic conditions, located in Colombia's Caribbean, Andean, and Orinoquia natural regions of the equatorial and subequatorial zones (Fig. 1). The soil forming factors, such as geomorphological position, parent material, environmental and climatic conditions, as well as the land uses are shown in Table 1. Representative soil types for the three natural regions were selected for this study. The chosen profiles have been extensively studied by the IGAC (2013). The predominant vegetation was shrub and natural forest in the lower montane moist forest, tropical, and subtropical dry and moist forests. Nevertheless, the study areas were severely deforested and A-horizons were degraded by deforestation, agriculture, and grassland for cattle, and in some cases lost by erosion; this dynamic has been associated with the colonization process from 100 years ago to the present day.

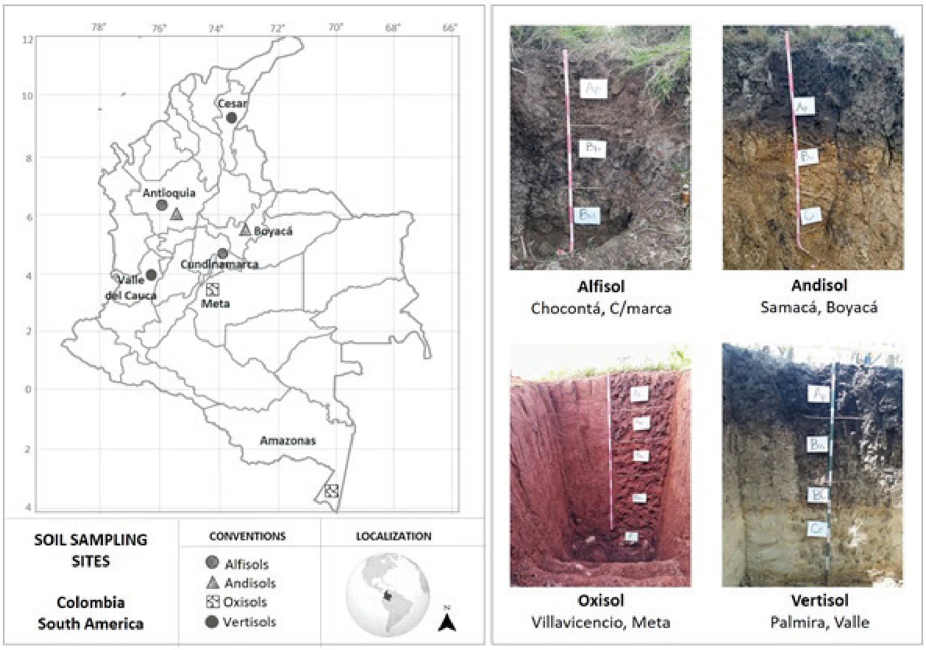

Fig. 1. Location of sampling sites and soils profiles. Explanations: Alfisol (ALF_2) Chocontá – Ventaquemada way, Cundinamarca; Andisol (AND_2) Samacá – Puente Boyacá Way, Boyacá; Oxisol (OX_1) Agrosavia "La Libertad" – Villavicencio, Meta; Vertisol (ERT_2) Agrosavia – Palmira, Valle del Cauca

Table 1
Study sites and soils characteristics

Sample	Sample site (Town and Region)	Elevationm a.s.l.	Pp (mm/yr)	T_m (°C)	RH (%)	Horizon	Depth (cm)	Geomor-phology position	Parental Material	Classification (Soil Survey Staff 2022a)	Classification (IUSS Working Group WRB, 2022)	Life zones (Holdridge, 1967)	Soil uses	Soil Temperature Regime
ALF_1	San Jerónimo, Antioquia	800	1453	25	77	Bt	20–35	Terrace fan	Alluvial coluvial deposit	Typic Haplustalfs	Haplic Luvisol (Clayic, Aric, Cutanic, Humic, Profondic)	Tropical dry forest	Shrubs, pasture	Isohyperthermic
ALF_2	Chocontá, Cundinamarca	2580	1003	12	87	Bt	22–40	Terrace	Clastic Deposit	Typic Haplustalfs	Haplic Luvisol (Loamic, Aric, Cutanic, Epidystric, Ochric)	Lower montane moist forest	Extensive livestock	Isomesic
AND_1	Guarne, Antioquia	2200	1716	16	75	Bw	32–60	Hilltop	Volcanic ashes	Ultic Hapludands	Aluandic Vitric Umbric Dystric Andosol (Loamic, Humic, Thixotropic)	Lower montane moist forest	Shrubs, forest	Isothermic
AND_2	Samacá, Boyacá	2879	695	14	80	Bw	22–68	Hilltop	Volcanic ashes	Typic Hapludands		Lower montane moist forest	Extensive livestock	Isomesic
OX_1	Villavicencio, Meta	330	2591	26	80	Bo	34–50	Terrace fan	Alluvial deposit	Typic Hapludox	Ferritic Rhodic Geric Ferrasol (Clayic, Activic, Dystric, Ochric)	Tropical moist forest	Extensive livestock	Isomesic
OX_2	Leticia, Amazonas	310	3533	26	87	Bo	30–46	Hilltop	Sand and clay stones	Typic Haploperox		Tropical moist forest	Agroforestry	Isohyperthermic
ERT_1	Valledupar, Cesar	100	1278	28	69	Bss	15–35	Deposit	Alluvial deposit	Typic Haplusterts	Salic Hydragric Vertisol (Aric, Drainic, Hypereutric, Pelocrustic, Ochric)	Tropical dry forest	Shrubs, forest	Isohyperthermic
ERT_2	Palmira, Valle del Cauca	1000	1507	24	77	Bss	18–40	Terrace	Alluvial deposit	Typic Haplusterts	Irragric Pellic Vertisol (Aric, Mollic, Endic, Gilgaic, Humic)	Tropical dry forest	Forest	Isohyperthermic

Explanations: Pp: mean precipitation. T_m: mean temperature. RH: Relative humidity. Hz: Horizon.

2.2. Soil sampling, chemical and physical

Soil samples were collected in February 2019. At each location 0.3 x 0.3 x 0.5 m holds have been dug, subsequently a composite soil sample was randomly taken from diagnostic horizons from sites where the soil had retained its natural state from previous years according to the Soil Survey Staff (2022b) and IGAC (2013) criteria. Moist soil blocks weighing around 0.5 kg were carefully retrieved from the B horizon (diagnostic endopedon) using a spade, to ensure sample integrity they were stored in polystyrene boxes. Then, soil chemical properties were measured using standard methods for soil analysis according to the Soil survey Staff (2022b). Soil texture was determined by the pipette method NEN 5753 and PN–ISO 11277 standards (Taubner et al., 2009). Chemical analyses were done in the Soil Science Laboratory at the Universidad Nacional de Colombia (Campus Bogotá), the University of Agriculture in Krakow, and the Institute of Agrophysics, Polish Academy of Sciences, Lublin, Poland, according to Soil Survey Staff methodologies (2022b).

2.3. Aggregate stability analysis

The agregate stability was measured using the wet-sieving method (Kemper and Rosenau, 1986). Briefly, four grams of air dried soil having aggregates of 1–2 mm were placed on a sieve of 0.25 mm, then they were slowly immersed in distilled water and sieved in an Eijelkamp® Agriresearch Equipment; the fraction retained on the sieve after 3 minutes corresponded to the unstable fraction; next the sieving procedure is repeated with a dispersing solution of NaOH (2 g/L), this fraction was taken as a stable fraction. Both fractions were dried at 105°C for 24 hours and weighed. Three replicates were made for each soil sample. The Water Resistance Index (WRI) by KR was used as a measure of the soils structural stability. The soils with a WRI > 70% (in fractions greater than 0.25 mm) were considered stable soils, while those with a WRI (same fraction) <50% were considered unstable soils. The percentage of WRI was calculated as suggested by Bieganowski et al. (2018).

$$\mathrm{WRI} = \frac{\mathrm{MDS}}{\mathrm{M_{H_2O}} + \mathrm{MDS}} \tag{1}$$

Where: WRI = water resistance index, MDS = the weight of soil obtained using dispersing solution (stable fraction), M_{H2O} = the weight of soil obtained using water (unstable fraction).

The wet sieving with multiple sieves developed by Yoder (1936) and modified by Pojasok and Kay (1990) was used to characterize structural stability. The soils analyzed were stored in a humidity chamber Hcp (Memmert®) at field moisture conditions before the analysis. Another 100 g of undisturbed soil sample was sifted through an 8 mm sieve, after wich the soil sample was passed through a series of five sieves: opening sieves 6.3, 4.0, 2.0, 1.0, and 0.5 mm in the Wet Sieve Shaker Yoder Type (Wet Sieving Machine Bionics Scientific Technologies, Delhi, India). The soil sample was exposed to vertical oscillations of 32 mm at a rate of 30 cycles/min for 30 minutes. To determine the aggregation index, the fractions obtained in each sieve were dried (105°C, 24 h) and weighed. The Weighted Average Diameter (WAD) was used as a measure of structural stability. The WAD values in fractions above 0.5 mm > 70% are associated with high aggregate stability, while if WAD <50%, the soil in considered unstable. The Weighted Average Diameter (WAD) was calculated according to Yoder (1936).

$$\mathrm{WAD} = \frac{\sum_{i=1}^{n} m_i * d_i}{m_i} \tag{2}$$

Where: m_i = aggregate mass, d_i = mean sieve opening diameter in mm. The measurements were recorded over one replication per site.

2.4. Microscopy, image processing, and analysis

This analysis was done according to the method reported by Sochan et al. (2015) and Bieganowski et al. (2018), using air-dried aggregates between 1–2 mm. The optical microscope (Morphologi G3, automated particle size, and particle shape analysis, Malvern, UK) was used to quantify aggregates Particle Size Distribution (PSD). A high-resolution microscope ensures quality particle images for image analysis data using a Nikon Plan UW 1x/0.04 objective, which captured the images at a 123x magnification objective and a pixel size of 1.08 µm. The software for imagen treatment was used to determine aggregates PSD measuring an average of 250 aggregates per sample in an approximate time of 10 minutes for each one. The images were subjected to a Morfologi G3, Circle Equivalent (CE) Diameter software treatment to measure particles with diameters (d_{CE}) of 0.5 mm, removing dust particles from image analysis (Bieganowski et al., 2011).

2.5. Soil particle-size distribution – laser diffraction method

A Laser Diffraction Analysis of air-dried soil aggregates was done using Malvern Mastersizer 2000 (Malvern®) following the method of Bieganowski et al. (2011, 2018). The samples were measured in the Hydro G dispersion unit (Malvern®). The stirring tank at 700 rpm was used; the sample was recirculated using a centrifugal pump (1750 rpm), which performed the work of retaining and homogenizing suspended solids. This equipment is designed for standard determination of grain size distribution of particles within the size range of 0.02–2000 µm. It uses scattered laser light and converts it into particle size distribution. Each single diffractometer measurement was adjusted in a time of 60 s (30 s for red light and 30 s for blue light) with an obscuration range between 10% and 20%; ten single measurements were taken. The aim of the measurements was to determine the change in median particles distribution during the measurements in order to determine the water stability of aggregates. The measurements were done in three replicates for each sample. To measure water aggregate stability the aggregates stability index based on laser diffraction ASI_{LD} was used. This index corresponds to the calculated slope between two points: the higher value is obtained by light microscopy, and the lower value is the median of the laser diffractometer measurement after 60 s. The

ASI_{LD} index using microscopy analysis was calculated according to Bieganowski et al. (2011).

2.6. Statistical analysis

The PROC NLIN (SAS®) procedure was used to analyze the data so that gives us estimate of least squares for the nonlinear model parameters and thus obtains the model that offers the best fit. The agreement between stability orders can be assessed using Spearman's rank correlation coefficient (r = 0.2381). The concordance between the three stability indexes was evaluated with the Spearman rank correlation coefficient. The SAS software (version 9.2; SAS Institute, Inc.) was used to analyze the statistical parameters.

3. Results and discussion

3.1. Soil physico-chemical analysis

The highest clay content was observed in the Vertisol 2 (ERT_2) and in the Oxisol 1 (OX_1), and the highest values for silt fraction were detected in the Andisol 1 (AND_1), Alfisol 2 (ALF_2), Andisol 2 (AND_2), and Vertisol 1 (ERT_1) (Table 2), silt content in the other studied soils was smaller than 19%. The OX_2, ALF_1 and OX_1 had the highest sand conten; the other soils were lower than 26%. All studied soils showed a predominance of fine particles (Table 2). Poesen (1986) and Pulido et al. (2009) showed that the predominance of particles between 2 to 100 µm confers low structural stability in soils, and high susceptibility of separation against the raindrop impact because less energy is required to separate the aggregates (Table 2).

The grain size distribution for ALF_2 showed high silt content that increased the proportion of less stable aggregates. Studies conducted by Boruvka et al. (2002) in Alfisols showed the strongest influence of fine silt and clay particles in the aggregate stability coefficient. Pulido et al. (2009) reported low soil structure stability associated with the predominance of particles between 2–100 µm (fine sand and silt) in Alfisols. Particles <2 µm (clay) were dominant in Vertisols conferring high structure stability even under wetting conditions. Pulido et al. (2009) find a relationship between fine particles percentage in tropical Vertisols with high aggregate stability; water-stable aggregates were concentrated in the range of 2–4 mm diameter. The results for Vertisols of Wuddivira et al. (2009) showed similar clay content and water-stable aggregation values to those found in this study. The studied Andisols showed higher aggregate stability values, these results coincide with Vial and Sandoval (2015), who reported a high percentage of aggregation (77.8 ±9.7% to 85.4 ±11.1%) and a predominance of macroaggregates in Andisols. The OX_1 and OX_2 showed variable clay content and high aggregate stability. In Brazilian Oxisols Novak et al. (2019) reported high clay content and stable aggregation. In Oxisols, iron is a strong binding agent that favors physical stability to mechanical stress (Arias et al., 2001).

The biplot representation showed the relationship between physical and chemical variables for the studied soils. The results

Table 2
Soil texture and chemical properties

Sample	Diameter milimeters 2–1 (%)	1–0.5	0.5–0.25	0.25–0.1	0.1–0.05	0.05–0.02	0.02–0.002	<0.002	Texture Soil Survey Staff (2022b)	TN (%)	SOC	pH (1:1) H_2O	KCl	Ca (cmol(+) kg⁻¹)	K	Mg	Na	Fe* (mg kg⁻¹)	SBs (cmol kg⁻¹)
ALF_1	8.6	9.7	14	13.1	2.5	4.3	10.4	37.4	Sandy clay	0.18	1.1	6.2	5.3	14.6	5.3	3.1	0.15	4.7	23.2
ALF_2	0.1	0.6	3.3	8.7	2.5	12.2	43.2	29.4	Silty clay loam	0.50	6.6	4.6	4.0	1.5	0.60	0.13	0.49	2.1	2.7
AND_1	0.5	3.6	5.4	4.0	1.5	13.7	62.7	8.7	Silt loam	0.96	12.4	4.7	4.2	2.1	2.1	0.42	0.19	1.6	4.7
AND_2	0.3	0.5	1.8	6.6	2.5	11.6	40.9	35.8	Silty clay loam	0.46	5.6	4.5	4.0	0.82	0.69	0.13	0.45	1.5	2.1
OX_1	1.1	5.2	11.1	11.8	2.9	8.0	9.4	50.5	Clay	0.10	0.7	4.7	3.9	1.2	0.28	0.10	0.09	72.8	1.6
OX_2	0.3	4.6	26.5	17.7	3.1	7.3	11.6	28.9	Sandy clay loam	0.08	0.26	4.8	3.7	0.90	0.42	0.07	0.14	149.3	1.5
ERT_1	0.2	0.9	8.6	13.4	2.8	16.9	26.1	31.1	Clay loam	0.22	0.55	7.5	5.5	53.1	3.4	15.7	0.66	23.2	72.8
ERT_2	0.01	0.1	0.1	0.4	0.6	3.7	11.9	83.2	Clay	0.52	2.2	5.6	4.6	121.6	10.3	16.1	1.4	2.7	149.3

Explanations: (SBs) sum of extractable bases,(TN) total nitrogen, (SOC) soil organic carbon, *non-crystallized, amorphous, chelated iron in the form of hydroxides and gels show contrasting values between the soil profiles of each soil type. The similarity between the main components for physical-chemical variables (closeness between points), especially for some properties related to the type of clay, is illustrated in Fig. 2. The groups of correlated variables showed a direct relationship between the finest fraction (size 0.002 mm) and Na, Fe, Cu, Ca, K, and Mg contents; while the fractions between 0.05 to 0.02 mm were directly related to N, SOC, and C:N ratio, with an inverse relationship with pH (H_2O) and pH (KCl). The sand fractions were related to each other, without exhibiting noticeable relationships with the other measured variables. The results were consistent with Boruvka et al. (2002), who reported that the sand content did not show any significant correlation with aggregate stability. The pH was very strongly acidic, except for ALF_1 and ERT_1 (neutral), located in tropical dry forest conditions (Table 2). Studies in Alfisols, Vertisols, and Andisols by Stătescu et al. (2013) reported negative impact of soil acidity in soil aggregation due to loss of stable connection of cement particles in aggregates.

The contents of Ca and Mg were high in ALF_1 and ERT, in the other soil orders these were low to very low. The K content was high in all soils, except in OX (low). The Na content was medium for the studied soil orders, except for the ERT in which the Na value was high. The Ca^{+2}, Mg^{+2}, Na^{+} ions ratio influences soil aggregation and stability under field conditions (Mamedov et al., 2010, Stătescu et al., 2013). The chemical results were consistent with Agegnehu and Anede (2017) and Chang et al. (2019), that showed progressive soil acidification processes, a decrease of exchangeable cations, and low soil fertility in tropical soils. The interactionships among clay, organic matter, and aggregates formation are closely related to the soil chemical composition (pH, CEC, Na^{+}, Ca^{+2}, Mg^{+2}) and clay amount and type (Amezketa et al., 2003; Stătescu et al., 2013). In tropical soils, Jiang et al. (2011) found that Fe oxide content increased with the degree of soil development; in this research different pattern was observed (low iron content). The chemical behavior for sandy clay, sandy clay loam, and clay soils was similar; the same happens for silty clay loam and silt loam soils. The ERT_2 (clay texture) showed an atypical behavior, characterized by high contents of all variables to the right and low contents of those that point to the left (Fig. 2). It was found greater similarity between soil variables in the OX, it is worth noting the proximity with the ALF_1. In the case of AND, it was clear the importance of factors that favor aggregation that were associated with andic properties as bulk density (BD) and soil organic carbon (SOC) (Fig. 2).

3.2. Effect of soil organic carbon

The Soil Organic Carbon (SOC) content was different among the studied soil orders. The soils located below 1000 m a.s.l. (seasonal drier climates) have medium and low SOC content; soils above 2000 m a.s.l. had high SOC content. According to Loaiza-Usuga et al. (2013) SOC content is associated with soil microclimate (Udic soil moisture regimes) and weather conditions. The AND1, AND2, and ALF_2 had 46% to 95% more SOC contents than the other studied soil orders. Andisols showed WRI values of 99.2% and 98.6%, being the most stable soils in this regard. To Rieke et al. (2022) and Sun et al. (2023), soil properties were influenced by inherent soil properties and climate. Some Alfisols (ALF), Oxisols (OX), and Vertisols (ERT) are stable soils with WRI values around 89% (Tables 2 and 3); these soils despite being in dry ecosystems with low SOC contents had high WRI values associated with the clay content; in the case of OX the presence of iron oxides played an important stabilizing role on the soil structure. Denef et al. (2002) concluded that soils dominated by variable charge clay minerals (1:1 clays and Fe and Al oxides) have higher potential to form stable aggregates under low OC concentrations. The results showed a close relation between SOC content and agregate stability, especially for Andisols, where high organic matter content and kind of colloids plays an important role in soil structure. The results agree with those of Calero et al. (2023), who find the Pearson's correlation matrix for clay content, giving a high weight to the SOC content, which had a high effect on the reduction of the partial R and the statistical significance. The C/N ratios were extremely low respect to the values reported for tropical soils by Loaiza-Usuga et al. (2013) and Martinez et al. (2020). Soil structure and SOC are associated with environmental conditions and land use in the study sites. Boruvka et al. (2002), Ontl et al. (2015), and Xu et al. (2022) underlined the importance of environmental factors in the soil structure development, Denef et al. (2002) highlight the importance of type clays in the structure development. Although AND_1, AND_2, and

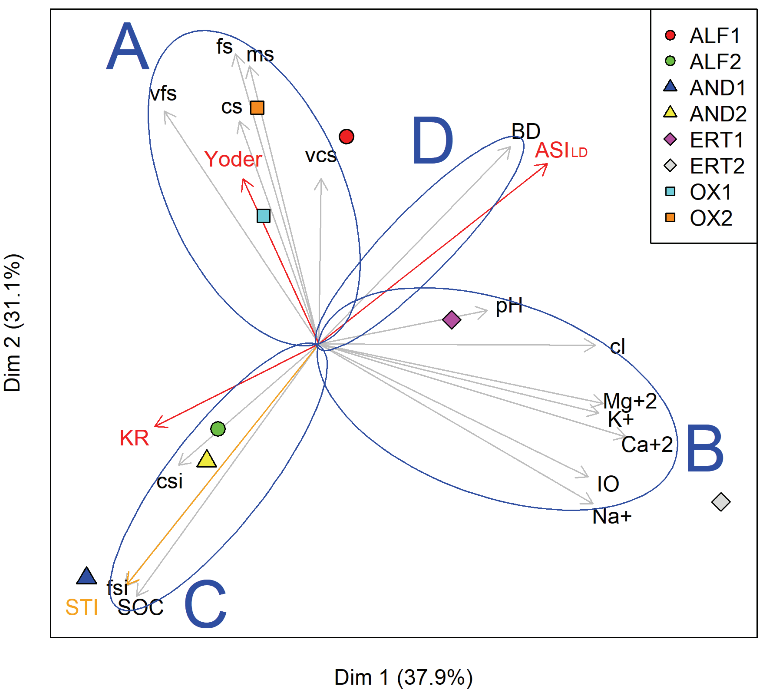

Fig. 2. Correlation coefficient by Sperman class for Particles size, soil chemical properties and aggregate stability for the study soil orders

ALF_2 showed a larger SOC input and high levels of stable macroaggregate formation with respect to the other studied soils, it cannot be stated that the organic matter content is the only factor responsible for the stability of soil aggregates in tropical soils. It is clear that the readily available SOC becomes depleted over time due to microbial decomposition and, subsequently, microbial activity and production of binding agents decrease (Table 2). The composition and concentration of soil organic carbon depends on the SOC source, affecting soil aggregation due to the influence of the association of cations with soil particles (Bronick and Lal, 2005). On the other hand, the high SOC content in tropical soils is related to environmental conditions and land uses (Loaiza-Usuga et al., 2013, Martinez et al., 2020). Zhou et al. (2020) reported the dominant effect of SOC concentration in water-stable aggregates (WSA) $WSA_{0.106–0.25\ mm}$, $WSA_{2–5\ mm}$, and $WSA_{0.5–1\ mm}$ on soil aggregate stability.

3.3. Comparison between methodologies

The values of WRI in the KR test were higher in all studied soils (> 89.5%) especially in Andisols, it has a direct relationship with the presence of high organic matter content, fine and coarse silt content. The presence of noncrystalline materials and humus has a strong effect on aggregate formation in Andisols (Shoji et al., 1993). The Yoder method had a good performance in Oxisols where the presence of sands and soil colloids confers high soil stability; the results were coincident with Mamedov et al. (2010) for oxisols. The type of colloids and granulometry are the key factors in the soil stability behavior (Powers and Schlesinger 2002, Bronick and Lal 2005, Pulido et al., 2009). The KR method had a better performance in soils with higher aggregation, high organic matter content and the presence of fine granulometry materials. The other studied soil orders showed dissimilar tendencies among samples, from rapid disaggregation to a greater stability of aggregates in the remaining samples. This result may be explained by the precision of the structural stability measurements based on particle size, underlined by Bieganowski et al. (2018). The ASI_{LD} method presented a good precision in the measurement of structural stability by particle size, being easily applicable to soils with low stability of aggregates; where it was difficult to measure under conventional methods. Alekseeva et al. (2009) reported contrasting behavior in Vertisols, characterized by the lowest and highest water stability. Andisols showed fewer differences between samples and Vertisols showed greater disparity. In the acidic tropical and subtropical soils, the theory of soil structure hierarchy is inapplicable due to the high soil mineral variability and organic matter content that can lead to aggregate stabilization by different means (Alekseeva et al., 2009). High values of KR and Yoder indices indicated high stability, while the values for ASI_{LD} were inversely proportional (Table 3).

Table 3
Macroaggregate stability according to “Kemper and Rosenau” method (KR). and Aggregate Stability Index by Laser Difractometry (ASI_{LD}), and wet sieving with multiple sieves (YODER)

Sample	KR*	ASI_{LD}	YODER**
ALF_1	0.895 (3)	–0.769 (4)	0.818 (7)
ALF_2	0.975 (5)	–0.831 (6)	0.719 (3)
AND_1	0.993 (8)	–1.147 (8)	0.745 (4)
AND_2	0.986 (7)	–0.914 (7)	0.685 (2)
OX_1	0.984 (6)	–0.828 (5)	0.759 (5)
OX_2	0.759 (2)	–0.645 (2)	0.889 (8)
ERT_1	0.626 (1)	–0.624 (1)	0.304 (1)
ERT_2	0.898 (4)	–0.727 (3)	0.788 (6)

Explanations: * percentage of aggregates retained in fractions 2–0.250 mm; ** percentage stable aggregates retained in fractions 8–0.5 mm and classification by stability ranges in brackets (1 low stability to 8 high stability).

The correlation between methods showed agreement between stability values, using Spearman’s rank the correlation coefficient was −0.952381 (P = 0.001141). The KR and ASI_{LD} methods had a significant negative correlation that reflects a high similarity between the structural stability values measured by both methods. The behavior of similarities/dissimilarities has the same tendencies between soil orders as well as the groupings between variables, it is worth highlighting the way in which the indices were configured around the evaluated variables. The Fig. 2 shows scarse correlations for the studied soil orders. The differences between these methods suggest that they measure different aspects of soil aggregation, in the case of Yoder index is correlated with the first group of variables, while KR is associated with variables associated with the soil chemical behavior and type of clay. The Sperman rank correlation coefficient (r = –0.2143) for Yoder and KR methodologies showed inconsistencies in the aggregate stability values for most of the soils except to ERT_1, which presented the lowest aggregate stability in both methods. This tendency was evidenced in a negative correlation between these methods, reflected in the contrasting values for aggregates stability (Fig. 2). The Sperman rank correlation coefficient (r = 0.2381) results for Yoder and ASI_{LD}. However, with the exception of AND_1 and ERT_1, a negative correlation would be expected. The other six soils had a positive correlation that reflected the inconsistencies for structural stability measurements between methods (Fig. 2). The classification of aggregate stability range was based on the three methods and the contrast between them (Table 3). It was found that this is consistent with contrasting results obtained by Amezketa et al. (2003), using different methods in tropical soils. The results are agree with Bieganowski et al. (2018), who report low change in particle size after dispersion and low ASI_{LD} values, for soils with high aggregate stability.

4. Conclusions

The soil aggregation formation processes are soil dependent, they cannot be easily generalized, an emphasis should be placed on developing simple and reproducible methods.

(1) The KR and ASI_{LD} methods showed similar results, in contrast with the results obtained using the Yoder method. Soils with low structural stability, KR and ASI_{LD} had better performance under high soil organic matter content conditions (Andisols) whose stability depends on soil microaggregates. The Yoder method had a better performance in soils where stability depends on the macroaggregates (Oxisols) that result from the presence of iron and aluminum oxyhydroxides complexes. The disparities in the results suggest that the breakdown processes of soil aggregates subjected to wet sieving treatments were affected by different factors influencing soil agregate stability, physical and/or chemical soil properties. Notwithstanding their precision, KR and ASI_{LD} did not have a significant correlation factor with other estructural stability indices and reference values.

(2) The high weathering and pedogenesis in the soils of the equatorial region do not necessarily imply a high soil agregate stability. The pedogenic development in the studied soils was inversely proportional to the durability of structural peds. The soil aggregate stability was different even inside similar soil orders, despite similar pedogenesis. The chemical characteristics of Andisols and Oxisols have a relation with soil aggregation and particles size, while Vertisols and Alfisols showed a high disparity relation. Despite the relative proximity of the values for chemical properties of the soil as a function of the texture, the results found were not conclusive.

Acknowledgements

In memory of Dr. Jorge Alberto Sánchez-Espinosa friend and devoted pedologist. We thank Dr.Andrzej Bieganowski from the Institute of Agrophysics of the Polish Academy of Sciences, the Corporación Colombiana de Investigación Agropecuaría (AGROSAVIA), Maria Casamitjana-Causa, Diana Lucía Correa-Moreno, and Judith Martínez-Atencia.

References

Agegnehu, G., Amede, T., 2017. Integrated Soil Fertility and Plant Nutrient Management in Tropical Agro-Ecosystems: A Review. Pedosphere 27(4), 662–680. https://doi.org/10.1016/S1002-0160(17)60382-5

Alekseeva, T.V., Sokolowskab, Z., Hajnosb, M., Alekseeva, A.O., Kalinina, P.I., 2009. Water Stability of Aggregates in Subtropical and Tropical Soils (Georgia and China) and Its Relationships with the Mineralogy and Chemical Properties. Eurasian Soil Science 42(4), 415–425. https://doi.org/10.1134/S1064229309040085

Amezketa, E., Ramón, A., Urgel, B., 2003. Macro-and micro-aggregate stability of soils determined by a combination of wet-sieving and laser-ray diffraction. Spanish Journal of Agricultural Research 1(4), 83–94. https://doi.org/10.5424/sjar/2003014-50

Arias, D., Madero, E., Amézquita, E., 2001. Susceptibilidad al encostramiento en algunos suelos álicos colombianos. Suelos Ecuatoriales 31(2), 220–225 (In Spanish)

Bieganowski, A., Zaleski, T., Kajdas, B., Sochan, A., Józefowska, A., Beczek, M., Lipiec, J., Turski, M., Ryżak, M., 2018. An improved method for determination of aggregate stability using laser diffraction. Land Degradation and Development 29(5), 1376–1384. https://doi.org/10.1002/ldr.2941

Bieganowski, A., Krusińska, A., Ryżak, M., 2011. Elimination of measurement error in light microscopy investigations of starch granules geometry. International Agrophysysics 25, 193–196.

Boruvka, L., Valla, M., Donátová, H., Nemecek, K., 2002. Vulneravility of soil aggregates in relation to soil properties. Rostlinná Vyroba 48(8), 329–334. https://doi.org/10.17221/4376-PSE

Bronick, C.J., Lal, R., 2005. Soil structure and management: a review. Geoderma 124, 3–22. https://doi.org/10.1016/j.geoderma.2004.03.005

Calero, J., García-Ruiz, R., Torrús-Castillo, M., Vicente-Vicente, J.L., Martín-García, J.M., 2023. Role of Clay Mineralogy in the Stabilization of Soil Organic Carbon in Olive Groves under Contrasted Soil Management. Minerals 13, 60. https://doi.org/10.3390/min13010060

Carrizo, M., Alesso A., Cosentino, D., Imhoff, S., 2015. Aggregation agents and structural stability in soils with different texture and organic carbon contents. Scientia Agricola 72, 75–82. https://doi.org/10.1590/0103-9016-2014-0026.

Chang, A.L., Liang, M.Y., Nie, Y., Tang, J.W., Siddique, K.H.M., 2019. The conversion of tropical forests to rubber plantations accelerates soil acidification and changes the distribution of soil metal ions in topsoil layers. Science of the Total Environment 696, 134082. https://doi.org/10.1016/j.scitotenv.2019.134082

Denef, K., Six, J., Merck, R., Paustian, K., 2002. Short-term effects of biological and physical forces on aggregate formation in soils with different clay mineralogy. Plant and Soil 246, 185–200. https://doi.org/10.1023/A:1020668013524

Holdridge L.R., 1967. Life Zone Ecology. San José, CR, Tropical Science Center. 206 p

IGAC., 2013. Estudio de suelos del territorio colombiano. Instituto Geográfico Agustín Codazzi (IGAC). Sistema de Información Geográfica Agrologica (SIGA). Bogotá. (In Spanish)

IUSS Working Group WRB., 2022. World Reference Base for Resources. International soil classification system for naming soils and creating legends for soil maps. 4th edition. International Union of Soil Sciences (IUSS), Vienna, Austria.

Jiang, J., Xu, R.K., Zhao, A.Z., 2011. Surface chemical properties and pedogenesis of tropical soils derived from basalts with different ages in Hainan, China. Catena 87, 334–340. https://doi.org/10.1016/j.catena.2011.06.016

Kemper, W.D., Rosenau, R.C., 1986. Aggregate Stability and Size Distribution. In: Klute, A., Ed. Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods, 2nd Edition, Soil Science Society of America Agronomy Monograph No. 9, 425–442.

Loaiza-Usuga, J.C., León-Peláez, J.D., González-Hernández, M.I., Gallardo-Lancho, J.F., Osorio-Vega, W., Correa-Londońo, G., 2013. Alteration in Litter decomposition pattern in tropical montane forest of Colombia: Oak forests contrasted with coniferous plantations. Canadian Journal of Forest Research 43(6), 528–533. https://doi.org/10.1139/cjfr-2012-0438

Machado, J., Villegas-Palacio, C., Loaiza-Usuga, J.C., Castańeda, D., 2019. Soil natural capital vulnerability to environmental Change. A regional scale approach for tropical soils in the Colombian Andes. Ecological Indicators 96(1), 116–126. https://doi.org/10.1016/j.ecolind.2018.08.060

Mamedov, A.I., Wagner, L.E., Huang, C., Norton, L.D., Levy, G.J., 2010. Polyacrylamide Effects on Aggregate and Structure Stability of Soils with Different Clay Mineralogy. Soil Science Society of Americ Journal 74, 1720–1732. https://doi.org/10.2136/sssaj2009.0279

Martinez, J.A., Loaiza-Usuga, J.C., Osorio N.W., Correa, G., Casamitjana-Causa, M., 2020. Leaflitter decomposition on diverse silvopastoral systems in a neotropical environment. Journal of Sustainable Forestry 39(7), 710–729. https://doi.org/10.1080/10549811.2020.1723112

Novak, E., Carvalho, L.A., Santiago, E.F., Tomazi, M., 2019. Changes in the soil structure and organic matter dynamics under different plant covers. CERNE 25(2), 230–239. https://doi.org/10.1590/010477602019 25022618

Ontl, T., Cambardella, C., Schulte, L., Kolka, R., 2015. Factors influencing soil aggregation and particulate organic matter responses to bioenergy crops across a topographic gradient. Geoderma 255–256, 1–11. https://doi.org/10.1016/j.geoderma.2015.04.016

Poesen, J., 1986. Surface sealing on loose sediments: the role of texture, slope and position of stones in the top layer. In: Callebaut, F.D., Gabriels., Ed. Assessment of Soil Surface Sealing and Crusting. Proc. of Symposium, Gent, Belgium. 354–362.

Pojasok, T., Kay, B.D., 1990. Assessment of a combination of wet sieving and turbidimetry to characterize the structural stability of moist aggregates. Canadian Journal of Soil Science 70, 33–42. https://doi.org/10.4141/cjss90-004

Powers, J.S., Schlesinger, W.H., 2002. Relationships among soil carbon distributions and biophysical factors at nested spatial scales in rain forests of northeastern Costa Rica. Geoderma 109, 165–190. https://doi.org/10.1016/S0016-7061(02)00147-7

Pulido, M., Lobo, D., Lozano, Z., 2009. Association between soil structure stability indicators and organic matter in Venezuelan agricultural soils. AGROCIENCIA 43(3), 221–230.

Rieke, E.L., Bagnall, D., Morgan, C.l.S., et al., 2022. Evaluation of aggregate stability methods for soil health. Geoderma 428, 116156. https://doi.org/10.1016/j.geoderma.2022.116156

Shoji, S., Nanzyo, M., Dahlgren, R.A., 1993. Volcanic ash soils: genesis, properties and utilization. Developments in Soil Science 21. Elsevier Science Publishers B.V.

Sîmansky, V., Tobiasova, E., Chlpýk, J., 2008. Soil tillage and fertilization of Orthic Luvisol and their influence on chemical properties, soil structure stability and carbon distribution in water-stable macroaggregates. Soil and Tillage Research 100, 125–132. https://doi.org/10.1016/j.still.2008.05.008

Sochan, A., Zieliński, P., Bieganowski, A., 2015. Selection of shape parameters that differentiate sand grains, based on the automatic analysis of two-dimensional images. Sedimentary Geology 327, 14–20. https://doi.org/10.1016/j.sedgeo.2015.07.007

Soil Survey Staff., 2022a. Keys to Soil Taxonomy, 13th edition. USDA Natural Resources Conservation Service.

Soil Survey Staff., 2022b. Kellogg Soil Survey Laboratory methods manual. Soil Survey Investigations Report No. 42, Version 6.0. U.S. Department of Agriculture, Natural Resources Conservation Service.

Środoń, J., 2013. Chapter 2.2 – Identification and Quantitative Analysis of Clay Minerals, [In:] Bergaya, F., Lagaly, G. (Editors) Developments in Clay Science, Elsevier, Vol 5, 25–49. https://doi.org/10.1016/B978-0-08-098259-5.00004-4

Sun, R., Lan, G., Yang, C., Wu, Z., Chen, B., Fraedrich, K., 2023. Soil quality variation and its driving factors within tropical forests on Hainan Island, China. Land Degradation and Development 34(11), 3418–3432. https://doi.org/10.1002/ldr.4693

Stătescu, F., Zaucă, D., Pavel, L., 2013. Soil structure and water-stable aggregates. Environmental Engineering and Management Journal 12(4), 741–746. https://doi.org/10.30638/eemj.2013.091

Taubner, H., Roth, B., Tippkötter, R., 2009. Determination of soil texture: Comparison of the sedimentation method and the laser-diffraction analysis. Journal of Plant Nutrition and Soil Sciences 172(2), 161–171. https://doi.org/10.1002/jpln.200800085

Vial, M., Sandoval, M., 2015. Soil structural condition and its relationship with pastures under different conditions in the Simpson Valley (Humid western Patagonia, Chile). IDESIA 33(4), 31–40. https://doi.org/10.4067/S0718-34292015000400005

Wuddivira, M., Stone, R., Ekwue, E., 2009. Structural Stability of Humid Tropical Soils as Influenced by Manure Incorporation and Incubation Duration. Soil Science Society of America Journal 73(4), 1353–1360. https://doi.org/10.2136/sssaj2008.0080

Xu, L., Xing, X., Bai, J., Li, D., 2022. Soil aggregate structure, stability, and stoichiometric characteristics in a smelter-impacted soil under phytoremediation. Front. Environ. Sci 29(10), Sec. Toxicology, Pollution and the Environment. https://doi.org/10.3389/fenvs.2022.900147

Ye, L, Tan, W., Fang, L., Ji, L., 2019. Spatial analysis of soil aggregate stability in a small catchment of the Loess Plateau, China: II. Spatial prediction. Soil and Tillage Research 192, 1–11. https://doi.org/10.1016/j.still.2019.03.009

Yoder, R.E., 1936. A direct method of aggregate analysis of soils and a study of the physical nature of erosion losses. Journal of the American Society of Agronomy 28, 337–351. https://doi.org/10.2134/agronj1936.00021962002800050001x

Zhou, M., Liu, C., Wang, J., Meng, Q., Yuan, Y., Ma, X., Liu, X., Zhu, Y., Ding, G., Zhang, J., Zeng, X., Du, W., 2020. Soil aggregates stability and storage of soil organic carbon respond to cropping systems on Black Soils of Northeast China. Sci Rep 10, 265. https://doi.org/10.1038/s41598-019-57193-1

Właściwości fizykochemiczne gleby i stabilność agregatów w glebach tropikalnych

Słowa kluczowe

Gleby tropikalne
Geneza gleby
Stabilność agregatów
Wietrzenie tropikalne

Streszczenie

Wielu autorów badających gleby obszarów tropikalnych sugeruje związek między składem mineralnym tych gleb a właściwościami fizycznymi, szczególnie w odniesieniu do wykształcenia struktury gleby, stabilności agregatów glebowych i składy granulometrycznego. W przeprowadzonych badaniach analizowano próbki gleb pobrane z endopedonów – poziomów genetycznych (Bt, Bss, Bo i Bw) pochodzących z wybranych gleb stref klimatycznych obszaru tropikalnego Kolumbii, z rejonów Andów, Karaibów i dorzecza Orinoko. Określono stabilność agregatów glebowych metodą przesiewania na mokro i metodą dyfrakcji laserowej. Wyniki wykazały dużą zmienność składu granulometrycznego gleb, z dominującym udziałem frakcji pyłowych i iłowych. To przekłada się na niską stabilność agregatów glebowych, a tym samym dużą podatność na ich dyspersję z wyjątkiem Andisoli. Wyniki przesiewania na mokro (KR) i wskaźnik stabilności agregatów oparty na dyfrakcji laserowej (ASILD) wykazały dobry poziom trwałości mikroagregatów tylko w Andisolach. Zawartość węgla organicznego (OC) była średnia do niskiej w glebach pochodzących z klimatu suchego i wysoka w glebach klimatu zimnego i wilgotnego warunkach. Andisole charakteryzowały się najwyższą zawartością SOC. Wpływ wietrzenia został potwierdzony występowaniem kaolinitu jako dominującego minerału ilastego. Niniejsze badanie dostarczyły wiedzy na temat zróżnicowania właściwości fizykochemicznym i składu mineralogicznego gleb tropikalnych jako narzędzia do oceny agregacji gleby różnie użytkowanych w zróżnicowanych warunkach środowiskowych.