SOIL SCIENCE ANNUAL
2026, 77(1), 221664

https://doi.org/10.37501/soilsa/221664

Carbon sequestration and soil quality in different land uses in the Ramsar Wetland La Cocha, Colombia

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Received: 2025-06-19
Accepted: 2026-05-11
Published online: 2026-05-11
Associated editor: Stephan Glatzel

Keywords:

Volcanic ash soil
Soil quality
Paramo ecosystems
Carbon storage
Tropical Mountain soils

Abstract

Soil composition (in terms of mineral and organic materials) and its functions are conditioned by soil pedogenetic processes. Consequently, soil acts as a natural body that interacts with the environment, thereby determining the efficiency of physical, chemical, and biological processes. In Andisols, soil organic matter plays a crucial role in the soil composition and processes, directly affecting soil health and overall soil quality. To determine the dynamics of organic matter in a Hydric Pachic Melanudands (Soil Survey Staff, 2022) / Andosol (IUSS Working Group WRB, 2022) under grassland (*Pennisetum clandestinum*), potato (*Solanum tuberosum*), and Andean paramo (*Espeletia* sp.), soil physical, chemical, and biological properties were evaluated. The evaluated soil quality indicators were: bulk density (BD), total porosity (TP), aggregate stability (AS), soil organic matter (SOM), pH, available phosphorus (AP), total nitrogen (TN), cation exchange capacity (CEC), microbial biomass (MB), and basal respiration (BR). The proposed soil parameters were measured at three sampling depths (0–5, 5–15, and 15–30 cm) with three repetitions by land use. Under the studied soil conditions, non-organic amendments and fertilizers significantly influenced ($p \leq 0.01$) AP, TN, CEC, TP, MB, and BR. SOM was linked to the availability of nutrients ($p < 0.01$) as well as to the functioning of the pore space (TP $p<0.01$). Land use in La Cocha wetlands affects environmental conditions, which, in turn, influence the dynamics of SOM. The anthropic activities that should be maintained in the paramo ecosystems re-evaluate those that modify the physical processes in the soil; through implementation of management, conserve ecosystem services associated with soil quality.

1. Introduction

Agricultural development over the last 80 years has provided a foundation for economic and social development in tropical countries worldwide (Huerta et al., 2021). In South America, cultural diversity and abundant environmental resources have accentuated this dynamic. However, meeting food demand puts pressure on resources, such as soil, limiting the provision of ecosystem services. According to Dondini et al. (2023), improving soil health and fertility can help alleviate global hunger by ameliorating soil degradation and mitigating climate change. According to the IPCC (1997), food production has increased by 240 since 1961. Against this background, various researchers, including Józefowska et al. (2020) and Sheikn et al. (2009), have expressed concerns about soil quality, not only from an agricultural perspective but also from ecological and environmental ones.

High-altitude areas are considered important due to their biological diversity and their role in the productivity of local communities (Hasiotis et al., 2007). Although researchers differ in their conception of soil quality, some agree that it is a quantitative and qualitative indicator of the capacity of the soil to provide "biological production and environmental quality" (Moinet et al., 2022; Gonzalez et al., 2024). Soil quality should be evaluated using appropriate indicators, which are based on the analysis of properties that reflect the levels of soil degradation (Doran et al., 1996). The change in land use is the most significant factor driving the alteration in terrestrial carbon stocks. By analyzing degradation, it is possible to understand the behavior of the soil and expose the degree to which it is affected by anthropogenic activities associated with its use (Frąc et al., 2020; Wang et al., 2019; Yu and Song, 2023; Gonzalez et al., 2024). Eswaran et al. (1993) and Sheikn et al. (2009) have indicated that changes in land use are associated with significant losses of organic matter content and thus lower productivity. Moreover, Azizsoltani et al. (2019), Emami et al. (2012) and Filep et al. (2015) consider that SOM largely determines the quality of soil in relation to edaphic changes associated with physical attributes such as structural stability, porosity, and bulk density (BD), which in turn reflect soil manipulation and management. Studies have revealed that soils are increasingly subjected to chemical fertilization processes via the application of organic and inorganic fertilizers that modify the soil's nutritional status (Marinari et al., 2006), and directly affect the reserves of nitrogen, phosphorus, and cation exchange capacity (CEC). Regarding biological attributes, Wada (1985), Abera and Wolde (2013) and Dondini et al. (2023) highlighted the importance of the microbiota present in the soil and its behavior in catalytic "reactions associated with the degradation of organic" material and the production of carbon dioxide through respiration. Fauci and Dick (2015), Gweyi-Onyango et al. (2021) and Ren et al. (2023) reported the outstanding potential role of microbial biomass (MB) as an indicator of soil quality by reflecting the effects of management practices in the short term, due to its close relationship with organic matter. A large proportion of research on soil quality performed to date has focused on forest and crop soils (Guggenberger et al., 1994; Johnson et al., 2007; Anda and Dahlgren, 2020.

Gonzalez et al., 2024). However, high-altitude areas vulnerable to climate change, such as paramo ecosystems and Andean wetlands, have remained poorly understood. A study of high-altitude ecosystems by Bierman-Lytle (2015) clarified the importance of such ecosystems for understanding the dynamics of organic matter storage and its relationship with soil quality. Soil represents the most substantial "carbon reservoir in terrestrial ecosystems, and the consequences of land use change on soil carbon sequestration" are closely linked to crucial concerns like climate change and food security (Yu and Song, 2023). Against this background, the current study focuses on the physical, chemical, and biological properties of a Pachic Hydric Melanudand Ashy Mixed Semiactive Acid Isothermic (Soil Survey Staff, 2022), Aluandic Vitric Hydric Tephric Dystric Andosol (Siltic, Humic, Panpaic, Thixotropic) (IUSS Working Group WRB, 2022) under grassland (*Pennisetum clandestinum*), potato (*Solanum tuberosum*), and Andean paramo (*Espeletia* sp.), and the effect of land use dynamics on the concentration of organic matter. The obtained results were analyzed via an ecosystemic approach, allowing description of Andisol behavior and characteristics under different land use conditions in high-altitude ecosystems in the Andean plateau. This study seeks to know (1) The influence of land use on the metabolic efficiency of the pool of microorganisms in the soil, (2) The impact of land use changes on soil carbon sequestration (3) How carbon content influences the structural conditions of moorland soils, specifically in the stability of aggregates.

2. Materials and methods

2.1. Site description

This study was carried out in the Ramsar wetland La Cocha with an area of 39.000 ha, located 20 km from the urban area of Pasto at 2750 m a.s.l., between 0°50' N, 1°15' N, 77°05' W, and 77°20' W. The catchment is part of the Amazon basin, nestled in the north of the Andean Amazonia region on the eastern slope of the Andes Mountain range, southwest Colombia (Fig. 1). In terms of the climate at this site, precipitation is 1.632 mm/year (268 rainy days) with a monomodal regime, there is a rainy period between April and August and a dry period from October to March. The mean temperature is between 8 and 12°C, and the mean relative humidity is 86% (Corponariño, 2011). The Guamués River basin (tributary of the lagoon) belongs to the great Amazon basin as a tributary of the Putumayo River, which is influenced by the Amazon regime, causing high rainfall. The primary cause "of interannual climate extremes in Amazonia" is the El Niño-Southern Oscillation, characterized by unusual wetness, which is "attributed to the location of the maximum sea surface warming in the Central Equatorial Pacific" (Jimenez et al., 2016). According to IGAC (2004), geomorphologically, it is composed of hills, soils derived from volcanic ashes (Andisols) with low base saturation, deep and well drained soils, under udic moisture regimes, all belonging to the Tebaida consociation. For the fluviolacustrine formations composed of lacustrine organic deposits, some mixed with mineral sediments, they have flat to flat/concave surfaces, are floodable, under an aquic and udic soil moisture regime, and belong to the Corota association. The plant formations correspond to very humid lower montane forest and azonal Andean paramo, with endemic species of frailejon (*Espeletia cochensis* and *E. schultesiana*), straw, ferns, and mosses. The Ramsar wetland has a comprehensive environmental management plan, which establishes areas of different categories such as: preservation, conservation, protection, recovery, sustainable production under special environmental conditions; areas that are framed in uses defined as main, compatible, conditional, and prohibited (Corponariño, 2011). The soil uses are 9.8% paramo vegetation, 64% forest in different states of succession, 12.6% grasslands for cattle, 9.2% agroecosystems, 4% flooded areas, and 0.4% mixed uses (Corponariño, 2011). The selection of the study areas was made considering previous works, such as that of Portilla (2019), which indicates the main changes in land use suffered by the wetland in the last 30 years. The dynamics of land use change in the wetland range from natural forest, crops, to peas or grasslands. The rotation of pastures to potatoes is done every 4 years. The areas considered were natural forest, kikuyu grassland with a 10-year history of use in bovine exploitation with animal load 2 animal ha^{-1}. In potato monoculture >30 years the rotation of peas to potatoes is done every 4 years, the commercial seeds are treated with chemical protectants, starting with the soil preparation using disc plowing (affecting soil profile depth by erosion) approximately 20 cm deep, the fertilization includes the use of mineral fertilizers (urea, potassium chloride, K-Mag premium, Complex gr 13–26–10+3+3 and 120–20–30+1+1) at rate 90–150 kg ha^{-1} N, 60–65 kg ha^{-1} P, 120–203 kg ha^{-1} K, 10–20 kg ha^{-1} MgO and 20–30 kg ha^{-1} CaO, addition of organic matter and ground limestone, the pest control using chemical fungicides and pesticides depending on the weather. Peas are planted after the potato cycle using the fertilizer excess of potato crops; nitrogen fertilizers, herbicides, and pesticides are applied occasionally. The agricultural systems are characterized by a high use of inputs with a low technological level.

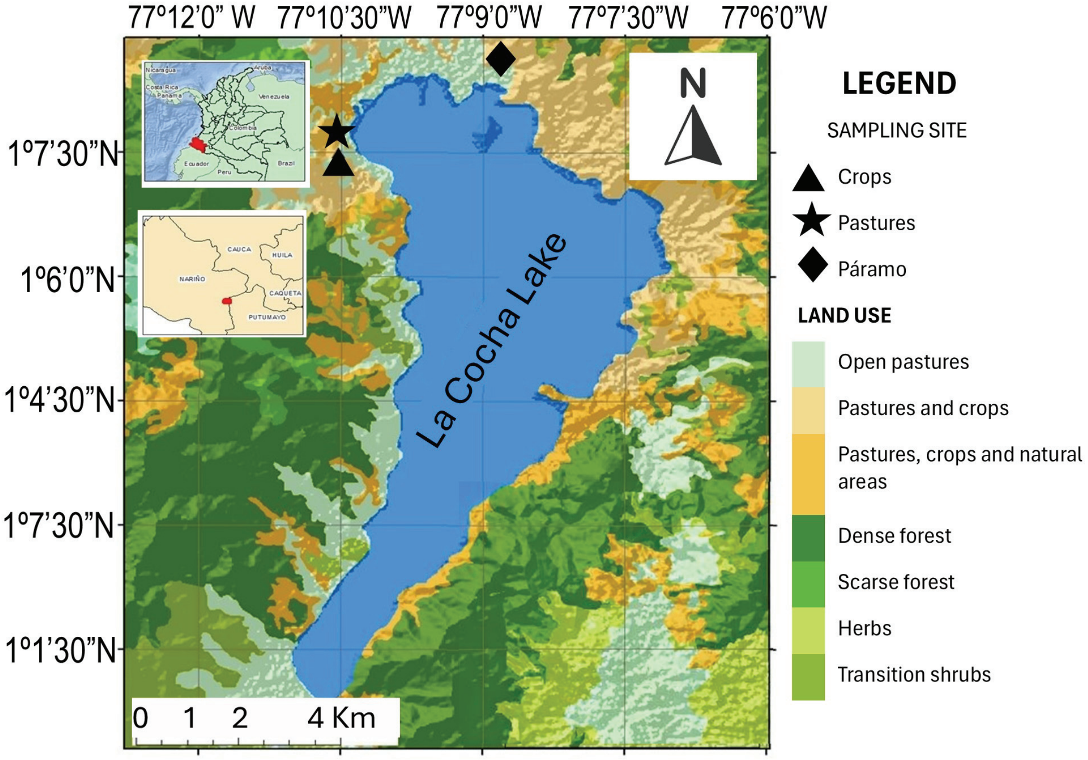

Fig. 1. Study zone, Laguna de la Cocha Ramsar Wetland- Colombia

2.2. Experimental design, statistical analysis, and laboratory study

The characterization of the areas was carried out contemplating a completely randomized experimental design, which was proposed under random sampling with three soil profiles for each land use, selected according to soil series criteria of SSS (2022). This study was based on three specific sampling areas, the first corresponding to the Andean paramo, made up of communities of "frailejon" species, the second having undergone 30 years of potato cultivation, and the third having kikuyu grassland with a 10–year history of use in cattle. In each land use, soil samples were extracted at depths of 0–5, 5–15, and 15–30 cm for physical (54 samples in total) and chemical (27 samples per soil use) soil analyses.

For physical parameters, two soil samples were taken for each depth, for a total of six samples per profile. Meanwhile, for the chemical parameter, one soil sample for each depth, for a total of three samples per profile.

For the biological analysis, soil samples were taken using a shovel up to a depth of 0–5 cm (9 samples per soil use) and stored in plastic bags (2 kg) in a portable fridge at a temperature of approximately ≤4°C; These samples were analyzed in duplicate and triplicate in the laboratory (between 18 and 72 replicated samples, respectively). Analysis of the soil properties, was carried out using the following methods: BD (Blake and Hartge, 1986), total porosity (TP) (Danielson and Sutherland, 1986), structural stability wet sieving method (Yoder, 1936 modified by Kemper and Rosenau, 1986), organic matter by the Walkley Black method (Nelson and Sommers, 1982), TN by the Kjeldahl digestion method (McGill and Figueredo, 1993), available phosphorus (AP) by the Bray II method (Bray and Kurtz, 2009), effective cation exchange capacity CECe using 1 M ammonium acetate, sum of exchange cations (Pansu and Gautheyrou, 2006), MB through fumigation with ethane free chloroform for 24 h (Sparling et al., 1990), and basal respiration (BR) using alkali NaOH traps, incubated at 25°C for 24 hours (Alef and Nannipieri, 1995).

The stock of soil carbon (AC) in each layer was calculated by Da Silva et al. (2004), equation (1)

$$AC = (Conc \times BD \times T)/10 \qquad (1)$$

Where:
AC = amount or stock of soil carbon (Mg C ha^{-1}) per layer
Conc = concentration of soil organic carbon (g C kg^{-1} soil)
BD = soil bulk density (g cm^{-3}) per layer
T = thickness of the considered soil layer (cm)

Carbon amounts in each layer (ACi) were added up to make the total amount of carbon in the soil profile down to a depth of 1m.

2.3. Statistical analyses

Statistical analysis was performed based on the methodology proposed by Webster and Oliver (2007). To establish the statistical significance of differences associated with the type of land use, sampling depth, and efficiency of accumulation of organic carbon. An analysis of variance was carried out, after verifying the assumption, and mean comparison by Tukey's was performed with a significance level of p-value<0.05. To determine the correlation between soil properties with Total organic carbon (TOC) and soil organic matter (SOM), a comparative analysis was made where the Spearman correlation coefficient was observed, to recognize variables associated with OC and SOM accumulation associated with land use, principal component analysis (PCA) was carried out. The Minitab 19 program® (Minitab, LLC, 2021) was utilized for all statistical analyses.

3. Results and discussion

3.1. Soil organic carbon and organic matter dynamics

The concentration of organic matter in the studied soils is shown in Fig. 2. Statistically significant differences ($p<0.05$) were found between land uses, with paramo soil having the highest SOM concentration (26%), followed by grasslands (15%) and potato cultivation (12%). In this sense, the concentration of carbon in the paramo was 11% higher than in the grasslands condition and 12% higher than in the soil cultivated with potatoes, respectively. These results indicate that land use has a major influence on the dynamics of SOM concentration and OC.

Poulenard et al. (2001), Dörner et al. (2022), González et al. (2024), and Lis-Gutierrez et al. (2019) point out that ecosystems of the Andean highlands have great potential for carbon and water storage, fulfilling an inherent function in the regulation of the carbon and water cycles, respectively. These characteristics are linked to the parent material (volcanic ash). Due to land use change, these ecosystems are at risk of degradation, which affects the quality of organic carbon on the soil surface; Despite their excellent physical properties and high organic matter content, Andisols are highly susceptible to degradation when subjected to intensive agricultural systems; rapid decline could be attributed to the use of unbalanced organic and chemical fertilizers, without the application of conservation techniques (Shoji et al., 1993, Machado et al., 2015, Lis–Gutierrez et al., 2019, Beckstrom et al., 2025, Mora-Mota et al., 2025).

The OC showed statistical differences ($p<0.05$) between the evaluated land uses. The highest carbon content was found under the paramo condition with 11.4%. The carbon content in paramo conditions is 50% higher than that found in grasslands and potatoes. The results coincide with those reported for paramo soils by Gutierrez et al. (2020) and Ayala et al. (2021), with values ranging between 11% and 17%. Fassbender and Bornemisza (1994) and Gonzalez et al. (2024) indicate that the intervention of soils under natural vegetation, such as in the paramos, due to crops, encourages the processes of mineralization of organic matter and carbon due to management practices such as fertilization and tillage.

Studies conducted by Ross et al. (2017 and Thompson et al., 2021 indicate a significant reduction in carbon storage capacity and the provision of ecosystem services in the paramos due to land use change when switching from a nonintervention condition to agricultural use.

The report points out that the paramos in Colombia, located in high mountain areas, in recent years have shown intensive degradation due to the partial or total loss of vegetation cover due to land use change, which leads to alterations in the capacity for water regulation. According to Dondini et al. (2023) and Mora-Motta et al. (2025), the highest soil organic carbon (SOC) stocks in South America are present under unimproved grasslands. Moreover, this occurrence was noted in a historical tillage system where intermittent trampling by cattle and sheep took place on a steep incline; SOM values in the soil profile were relatively high (Lis-Gutierrez et al., 2019).

This is primarily due to intensive mechanized tillage or the transformation of the land into pastures, which involves trampling. Machado et al. (2015), Tobiašová et al. (2013), Du et al. (2021), and Fang et al. (2023), reported the impact of land use change on the sequestration of carbon in the soil. The behavior of the SOM concentration reported in this paper is consistent with the findings reported by Rakshit et al. (2021), who established that the mineralization rate of SOM was higher in fertilized cultivated soils than in soils under natural vegetation cover, despite high exposure, and low quality and quantity of residues incorporated into soils under tillage. Enhanced biological activity in the upper soil layers facilitates the buildup of SOM (Sheikh et al., 2009). The reported values correspond to soils with high organic matter content (>10%). Despite the anthropic activities occurring in wetlands, the potential for SOM storage was high. This is associated with the impact of soil-forming fac-

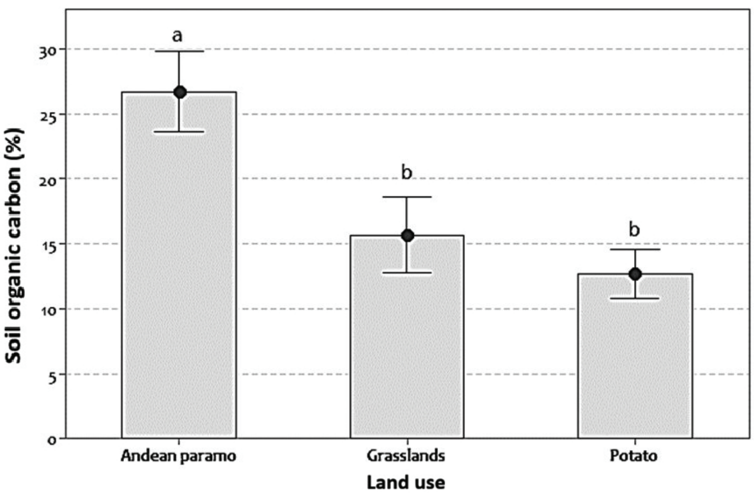

Fig. 2. Soil organic carbon (%) in the studied land uses

tors, including parent material, topography, climate, and the history of land use (Ibrahim et al., 2007), and the processes of SOM stabilization typical of soils with andic properties (Tonneijck et al., 2010). Lis-Gutierrez et al. (2019) in the Guerrero paramo Andisols observed changes in SOM stocks associated with land use change that mainly affect the upper 10 cm of soil where it's stored until 40% of total SOM in the studied soil catena. In addition, several research groups, including Zhang et al. (2015), Lis-Gutierrez et al. (2019), Fang et al. (2023), and Reyes-Rojas et al. (2025), reported that the vertical distribution of SOC shows a negative correlation with soil depth.

The percentage of SOM in soils under paramo conditions is higher than in cultivated soils and grasslands (Lis-Gutierrez et al., 2019). The ongoing influences of organic matter and climatic conditions (cold weather <6°C), high rainfall, and a udic soil moisture regime (humid) contribute to a slow organic matter decomposition rate. Similar behavior has been reported by Tonneijck et al. (2010) and Lis-Gutierrez et al. (2019). SOM content in grasslands is a driver of the volume of fine, deep, and branched roots throughout the soil profile, which is associated with perennial pastures (Ayala et al., 2021), as well as the presence of shoots and stolons (Guitian and Bardgett, 2000; Cardinael et al., 2017). At the same time, the transformation rate of SOM and the probability of erosion are increased. Similar patterns were reported by Anda and Dahlgren (2020), Dörner et al. (2022), González et al. (2024), and Reyes-Rojas et al. (2025).

In Andisols, the researchers found that converting native forest to pasture can lead to soil degradation connected with the increased intensity of land use.

3.2. Overall relationship between organic matter with physicochemical and biological properties of the soil

The physical and chemical properties of soil under different land uses are presented in Table 1. The results showed no significant differences in bulk density (BD) in relation to land uses ($p<0.05$). The average value for BD was 0.61 g·cm^3 in paramo, 0.60 g·cm^3 for potato crops, and 0.62 g·cm^3 under grasslands. The correlation for all uses was not significant; the relationship was negative for grasslands (c= –0.0516) and potato (c= –0.3274) conditions (but positive for the paramo (c=0.4326) condition.

Similar values were reported by Shoji et al. (1993), Beckstrom et al. (2025), and Mora-Motta et al. (2025) in Andisols, where low bulk density was found to be influenced by soil genesis, promoting increases in allophane and organic matter content. Similar results were reported by Shoji et al. (1993), Buytaert et al. (2005), and Astier et al. (2006) in Andisols in Japan, Ecuador, the United States, and Mexico, respectively. Low apparent densities are conferred to the rapid weathering of Andisols by favoring the formation of a unique colloidal assemblage and unique physical and chemical properties; the abundance of non-crystalline materials and organic materials contributes to low bulk density (Shoji et al., 1993; Beckstrom et al., 2025).The studied soils had high TP with values of 70%, 74%, and 80% in soils under crops, grasslands, and paramo, respectively, which differed significantly ($p < 0.05$). Anthropic activities, especially those related to tillage, influence the distribution of soil pore space. The sealing and crusting processes in paramo soils are influenced by the stability of the aggregates. This condition accentuates erosion, especially water erosion due to low infiltration (Poulenard et al., 2001). According to Mateo-Marin et al. (2021), tillage affects the physical and hydraulic properties of soil and increases topsoil porosity, pore size distribution, and water storage. The temporary alterations in pore shape resulting from tillage can be attributed to the soil's microstructure collapsing due to mechanical disturbance and compaction, followed by a partial restoration of porosity through faunal activity. The presence of significant pore volumes in Andisols is linked to distinct intra- and interaggregate porosity, which facilitates water movement and retention (Dörner et al., 2022). According to Nanzyo et al. (1993), the development of the porous structure and high SOM content are the main factors responsible for the low BD in Andisols under natural conditions. Similar results were reported by Podwojewski et al. (2006). Total porosity was in the range suggested by Shoji et al. (1993) for

Table 1
Physical properties of the studied soil

Land Use	Depth (cm)	BD (g.cm^{-3})	TP (%)	AS (%)	
				≥0.5 mm	≤0.5 mm
Potato	**0–5**	0.57 ^{a}	73.0 ^{b}	92.0	8.0
	5–15	0.60 ^{a}	70.2 ^{b}	94.0	6.0
	15–30	0.63 ^{a}	66.6 ^{b}	93.4	6.6
Grassland	**0–5**	0.64 ^{a}	79.4 ^{ab}	95.6	4.4
	5–15	0.63 ^{a}	72.9 ^{ab}	94.4	5.6
	15–30	0.59 ^{a}	69.5 ^{ab}	92.2	7.8
Andean Paramo	**0–5**	0.65 ^{a}	78.7 ^{a}	91.1	8.9
	5–15	0.64 ^{a}	75.2 ^{a}	95.7	4.3
	15–30	0.53 ^{a}	85.6 ^{a}	95.1	4.9

Explanations: BD – Bulk Density, TP – Total Porosity, AS – Aggregate Stability.

Andisols (60%–80%), while Fontes et al. (2011) and Beckstrom et al. (2025). The presence of allophane promote high porosity, low bulk density and soil structure developed.

Regarding the stability of aggregates in paramo soils, the results indicate that proportions of stable (>0.5 mm) and unstable (<0.5 mm) aggregates did not present statistically significant differences among the studied land uses. The proportions of stable aggregates were 93.1%, 93.9%, and 94.1% for crops, paramo, and grasslands, respectively. This indicates that paramo soils have good structural stability. Under grasslands and crops, the soil behavior was associated with the contribution of organic matter and a high density of roots, especially fine roots. In paramo soils, it has been suggested that the predominance of carbon associated with humic acids (CAH) linked with silt and fine sand particles is associated with the formation of a clay-humic complex (Ruiz et al., 1997). The correlation between carbon and aggregates (>0.5 mm) was negative and not significant in the paramo, potato, and grasslands use with (c = –0.4684), (c = 0.3174), and (c = –0.3617), respectively. For minor aggregates (<0.5 mm), it was positive for paramo and crop with (c = 0.4684) and (c = 0.3075) respectively, and negative and in grasslands (c = –0.317), not significant ($p<0.05$) in all land uses and aggregate sizes evaluated.

Under paramo conditions, CAH predominates, which does not contribute to soil aggregation since CAH is related to microaggregates (<0.25 mm). In Andisols under agricultural conditions in the Andean mountains, Mosquera et al. (2007) found that the molecules associated with the chemical structure of humic acids do not correspond to highly conjugated groups, which are equivalent to humus under incipient humification conditions. The studied soils in the Laguna de La Cocha wetlands present good aggregation and structural stability in a manner depending on the land use. In the study, Andisols parental material and pedogenetic conditions favor good soil physical performance.

The chemical variables, such as pH and EC, were statistically different between the land uses studied; the crop condition showed higher pH values between 5.3 and EC 0.3 dS m^{-1}, especially in the first horizons of the soil. This is possibly due to the recurrent fertilization carried out on the potato crop. All the uses evaluated do not present salinity problems (<2 dS m^{-1}) according to Rakshit et al. (2021).

The average pH values were 5.1, 5.3, and 5.3 for soils under crops, grasslands, and paramo, ranging from very strong to strongly acidic (Table 2), which did not differ significantly ($p< 0.05$. This low pH is a response to the high loss of calcium by leaching, and soil acidity has been reported to be directly related to soil genesis (Shoji et al., 1993; Dahlgren et al., 2004; Beckstrom et al., 2025; Reyes-Rojas et al., 2025). Mean values for available phosphorus (AP) were 30 mg·kg^{-1} (crops), 16 mg·kg^{-1} (paramo), and 7 mg·kg^{-1} (grasslands), which differed significantly among the land uses ($p<0.05$). Cultivated soils had higher AP values than paramo and grasslands; according to Estupińan et al. (2009) and Giraldo-Sanclemente et al. (2025), these differences were due to soil preparation and the development of agricultural practices, including fertilization. The requirements of phosphorus (P) in potatoes are due to it being an essential nutrient. Specifically, in the early vegetative development and throughout the tuber growth period, there is a rapid rise in total plant P uptake, which then stabilizes at a constant rate during the tuber bulking stage (Tindall et al., 1993). Several research groups, such as Montes et al. (2016), Bustos et al. (2022), Giraldo-Sanclemente et al. (2025), and Mora-Motta et al. (2025) have reported greater sensitivity of fertilizers in Andisol associated with crop cultivation, due to the productivity of the crop, short cycle, high yield, and relationship with an increase in exchangeable cations. In the cases of paramo and grasslands, AP is derived from humification processes (Estupińan et al., 2009).

The total nitrogen content (TN) showed significant differences among land uses ($p<0.05$), with mean values being 0.8% for land under cultivation, 0.7% for grasslands, and 0.3% for paramo soils. The variations among land uses can be attributed to the gradual decomposition of SOM under paramo con-

Table 2
Chemical properties of the studied soils

Land Use	Depth (cm)	pH	AP (mg·kg^{-1})	TOC (….)	TN (%)	C/N	EC (dS·m^{-1})
Potato	**0–5**	5.3 [a]	44.0 [a]	11.0 [a]	0.9 [a]	9.8 [b]	0.3 [a]
	5–15	4.9 [a]	28.0 [a]	10.4 [ab]	0.8 [a]	9.9 [b]	0.3 [a]
	15–30	5.1 [a]	18.3 [a]	9.0 [b]	0.8 [a]	7.7 [b]	0.2 [a]
Grassland	**0–5**	5.2 [a]	8.3 [a]	12.8 [a]	0.8 [a]	14.0 [b]	0.2 [b]
	5–15	5.3 [a]	6.3 [a]	11.1 [a]	0.8 [a]	11.0 [b]	0.1 [b]
	15–30	5.3 [a]	6.7 [a]	10.0 [a]	0.6 [a]	11.7 [b]	0.1 [b]
Andean paramo	**0–5**	5.4 [a]	15.3 [b]	19.5 [a]	0.3 [b]	60.0 [a]	0.1 [b]
	5–15	5.2 [a]	16.0 [b]	18.2 [a]	0.3 [b]	54.9 [a]	0.1 [b]
	15–30	5.3 [a]	17.0 [b]	14.3 [b]	0.4 [b]	33.4 [a]	0.1 [b]

Explanations: TOC – Total Organic Carbon, AP – Available Phosphorous, TN – Total Nitrogen, C – Carbon, N – Nitrogen, EC – Electric Conductivity.

ditions, which is linked to the limited availability of nitrogen in the soil. The anthropic activities occurring in soils under crop and grassland cultivation, such as the application of fertilizers, promote nitrogen mineralization processes (Powers, 2004., Giraldo-Sanclemente et al., 2025); which conditions plants N availability (Kusmierz et al., 2023) found that, in volcanic ash soils (Andisols) in the Andean mountains of Colombia, the influence of soil microclimate (Udic soil moisture regime) and weather conditions appeared to have a lesser effect on litter decomposition when compared to the type of species and the ratio of labile and recalcitrant compounds. The C/N ratios differed significantly among the studied land uses, being higher in paramo conditions (49.4), followed by grasslands (12.2) and then crops (9.1). According to Heuck et al. (2015), soils in paramo conditions have high N immobilization due to the competition of microorganisms, while soils under grasslands and crops show more N mineralization. It was demonstrated that the availability of a nitrogen pool for plants is influenced by the same factors that control SOM; regarding ammonia and nitrate, mineral fertilization was identified as the most significant factor impacting their concentrations (Kusmierz et al., 2023). The effective CEC (ECEe) was directly influenced by land uses ($p < 0.01$); specifically, soils under grasslands had the highest average value (5.1), followed by soils under crops (2.9) and then paramo (1.3). Similar physicochemical results were reported by Estupińan et al. (2009), Montes et al. (2016), and Lis-Gutierrez et al. (2019) for Andisols in Colombian paramo conditions.

The MB values differed significantly among the land uses ($p < 0.01$, see Table 3). The grassland soils reported 1.56 and 4.12 times more MB than the paramo and crops, respectively. This behavior was allied with the mobilization of substrates for microorganisms through root and rhizosphere activity in the grasslands (Haynes, 1999). Similar results were reported by Ordońez et al. (2022) in Colombian mountain Andisols; they found higher MB values in grasslands than in natural forests. Martínez-Atencia et al. (2020) find that grasslands have high litter decomposition rates with nutrient liberation increasing and activation of biogeochemical cycles, associated with high rise microorganisms under seasonal rise in soil moisture conditions. The microbial biomass carbon (MBC) was higher in paramo soils (446 $mg \cdot kg^{-1}$) than in grasslands (360 $mg \cdot kg^{-1}$) and crops (90.5 $mg \cdot Kg^{-1}$), which was statistically significant. There was a different trend regarding the microbial biomass nitrogen (MBN), for which crop and grassland soils did not differ significantly. The MBN values were in the following order: paramo (11.39 $mg \cdot kg^{-1}$) > crops (6.10 $mg \cdot kg^{-1}$) > grasslands (5.89 $mg \cdot kg^{-1}$). This behavior was due to the high faunal composition and diversity in the paramo ecosystems, which promote microbial activity in the soil. Researchers, including Creamer et al. (2014), Xu et al. (2014), Bolat (2019), and Gonzalez et al. (2024), reported similar results; specifically, higher nutrient/substrate availability and quality are associated with lower microbial activity, which in turn confers higher MBC and MBN values.

The variations in MBC and MBN among the evaluated land uses were due to the different inputs and outputs of carbon and nitrogen for each land use. Martínez-Atencia et al. (2020) and Gonzalez et al. (2024) highlighted the importance of the activity of soil microorganisms, species diversity, and ecosystem behavior rather than the control of C and nutrient recycling from plants to soil. Higher concentrations of MBC and MBN in soil under crops help to decrease the availability of carbon from organic matter, which is related to the mineralization of SOM (Gregorich et al., 1994). In Andisols under intensive cropping conditions, Durango et al. (2015) showed that MBC decreased in periods longer than 10 years. In addition, Smith and Conen (2006) reported that there was greater microbial activity in soils under natural vegetation than in cultivated soils because of the high quality of residues (substrates for C and N) in the absence of anthropogenic activity, which promoted microbial populations and increased MB. This explains the behavior of MB under grassland conditions, where higher root biomass stimulates the development of microbial populations. Regarding basal respiration (BR), paramo soils showed a significantly lower average value (202.3 mg CO_2 $kg^{-1} \cdot day^{-1}$) than soils under crops (294.6 mg CO_2 $kg^{-1} \cdot day^{-1}$) and grasslands (324.9 mg CO^2 $kg^{-1} \cdot day^{-1}$). The BR values in soils under paramo reflected a microbial community that was less active, as well as a lower CO_2 release, while the soils in land with crops and grassland, the average basal respiration was significant; this behavior was associated with high microbial activity. According to Maia et al. (2007), the addition of organic residues to soil and the amount of labile carbon reserve increase BR values. For Zagal and Córdova (2005), a lower BR value in paramo indicates lower microbial activity due to the conditions of temperature (<6°C) and humidity (82%).

The fig 3 and 4 showed the correlation and PCA between organic matter and soil characteristics for the diferents land uses in the study site.

Table 3

Characteristics of the biological properties of soil

Land Use	MB	MBC ($mg \cdot kg^{-1}$)	MBN ($mg \cdot kg^{-1}$)	BR ($mgCO_2 \cdot kg^{-1} day^{-1}$)
Potato	14.8 ^{b}	90.5 ^{b}	6.1 ^{b}	294.6 ^{a}
Grassland	61.1 ^{a}	360.1 ^{a}	5.9 ^{b}	324.,9 ^{a}
Andean paramo	39.1 ^{ab}	446.1 ^{a}	11.4 ^{a}	202.3 ^{b}

Explanations: MB – Microbial Biomass, MBC – Microbial Biomass Carbon, MBN – Microbial Biomass Nitrogen, BR – Basal Respiration.

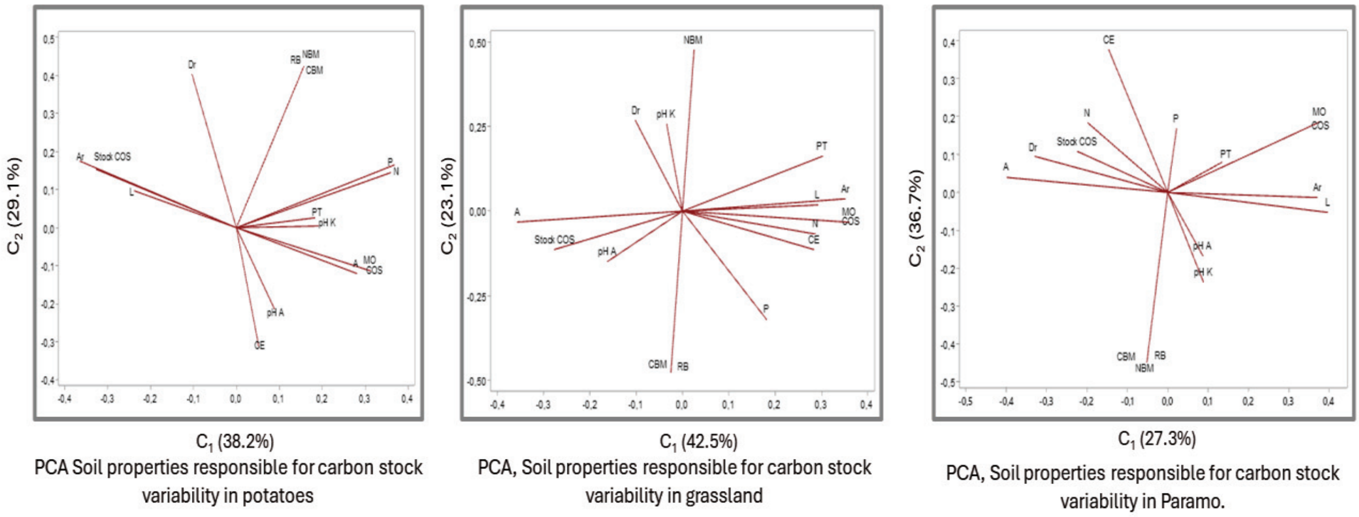

Fig. 3. Correlation between organic matter, physical and chemical properties at 0–15 cm depth

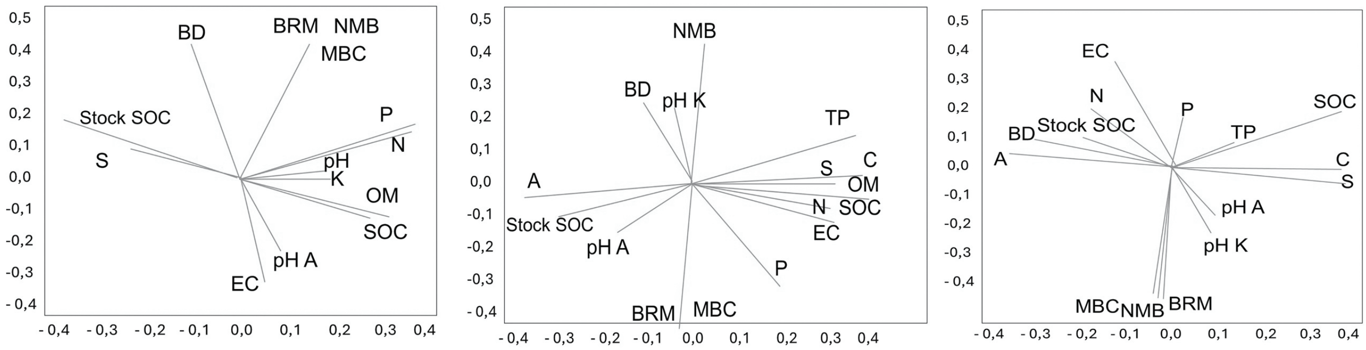

Fig. 4. Principal Components Analyses (PCA), soil properties responsible for the variability of the carbon stock in the study sites

3.3. Factors affecting the relationship between measured soil parameters

The SOM content for the measured land uses was significantly correlated ($p < 0.05$) with TP, TN, and CEC, while BD, AS, pH, and AP at a depth of 0 to 15 cm were not significantly associated with it (Table 4). The highest SOM content was found at 0–5 cm; meanwhile, SOM in the study profiles was found to decrease progressively with depth. In this study, land uses were not directly related to the correlations of CEC, BD, AS, AP, and pH with SOM. The content of CEC would be strongly connected to SOM since it acts as both a provider and receiver of nutrients for plants and microorganisms (Morris, 2004). Nevertheless, a direct correlation between SOM and TP has been reported by Meza and Geissert (2003) and Mora-Motta et al. (2025), Naveed et al. (2014), who found a relationship between SOM and soil porosity (large pores. This aids in the movement of air and water, as well as the accumulation of organic matter. Iwasaki et al. (2017) characterized SOM as a binding agent that stabilizes and promotes soil aggregation, reflected in an increase in porosity. Meanwhile, Mateo-Marin et al. (2022) reported that BD and the morphology of topsoil evolve under tillage, particularly its micro-structure and porosity doesn't show detectable changes in BD.

The inverse correlation between SOC and nitrogen (N), as reflected in the C: N ratio, indicates that nitrogen mineralization occurs due to microbial stimulation. The presence of such reserves of useful carbon would imply that microorganisms can more efficiently decompose SOM in the case of grasslands and crop soils. According to Fontes et al. (2011), N availability regulates plant growth and increases SOC fixation. These results coincide with the findings of Zagal and Córdova (2005) and Undurraga et al. (2009) on Chilean Andisols.

4. Conclusions

Land use had a significant influence on the evaluated physical, chemical, and biological soil properties, except for pH and soil aggregation. The SOM content is high in the first 10 cm, and its value decreases with increasing depth, highlighting the importance of soil conservation strategies in the protection of SOC storage and soil biodiversity, guaranteed soil quality, and health. Land use was found to have a direct effect on the soil porosity; however, the increased porosity under tillage and microbial activity in grasslands and crops was not directly related to SOM content. Nitrogen and AP in crops were found to be related to soil and crop cultural practices.

Table 4
Correlation between soil organic matter content, physical and chemical properties at 0–15 cm depth. Significant correlation (p<0.05).

	SOM							
≥0.5 mm	0.015	**≥0.5 mm**						
≤0.5 mm	–0.015	–1	**≤0.5 mm**					
BD	0.028	0.22	–0.22	**BD**				
TP	0.628	0.038	–0.038	–0.111	**TP**			
pH	0.162	–0.116	0.116	0.008	0.333	**pH**		
AP	0.013	–0.074	0.074	–0.189	0.069	–0.391	**AP**	
TN	–0.515	0.034	–0.034	–0.059	–0.37	–0.308	0.147	**TN**
CEC	–0.571	–0.183	0.183	–0.101	–0.468	0.02	–0.325	0.599

Due to anthropogenic activities, land use influences the metabolic efficiency of the MB, as well as the degree of recalcitrance of the substrates that act as energy sources. The action of the pool of microorganisms in terms of their effects of promoting and/or inhibiting the mineralization processes is attributed to multiple factors, ranging from the quality and quantity of the organic matter sources to variables such as environmental factors (humidity, temperature) and vegetation.

Stable aggregates (>0.5 mm) were found to predominate in all evaluated land uses, and their stability was shown to be related to SOC storage capacity. Land uses did not directly influence the structural stability of the soil aggregates, which allows us to infer that the soils developed from volcanic ash in La Cocha wetland are very stable and that the pedogenetic factors are driving the soil physicochemical behavior. Due to the physical and chemical particularities of páramo Andisols, it is necessary to implement strategies for ecosystem services conservation in soils, related to erosion, water fluxes, and high mountain wetlands ecosystems regulation, protection of soil biodiversity, and natural heritage (52% of paramo ecosystems in the world are in the Colombian Andes). To overcome the limitations of standard physical analyses, a micromorphological approach is recommended, which is a useful tool for explaining the processes involved in soil evolution under different management practices in La Cocha wetlands.

Acknowledgments

The authors gratefully acknowledge the wetland Laguna de La Cocha community for their contributions in recording soil samples. Facultad de Minas (2023–2024) financial support for style correction of research papers in English, Hermes code 59905. Thanks to Dexter from Enago for the language and grammar edition.

Conflict of interest

The authors state that they have no known financial interests or personal relationships that could have influenced the findings presented in this paper.

Author Contributions

Eliana Coral-Paredes Data curation, Funding acquisition, Investigation, Validation, Visualization, Writing- original draft, Writing. **Juan Carlos Loaiza-Usuga** Conceptualization, Investigation, Methodology, Supervision, Validation, Visualization, Writing- original draft, Writing- review & editing **Tatiana Rondon** Funding acquisition, Investigation, Supervision, Writing- original draft, Writing- review & editing. **Jenny Huertas**-Conceptualization, Supervision, Visualization, Writing- original draft. All authors read and approved the final manuscript.

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