Soils and land use in the study of soil organic carbon in Colombian highlands catena

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ABSTRACT

Andean highland ecosystems (known as paramos) have a great potential to store water and organic carbon, which fulfill the inherent functions associated to the regulation of carbon and water cycles, characteristics linked to their parent material (volcanic ash). However, paramos are at high risk of degradation associated with land use dynamics that affect organic carbon quality in the surface soil. Changes in vegetation cover, with transition from natural forest to tillage and then pasture, make the soil vulnerable to degradation by compaction, erosion, and carbon dioxide emissions associated with increased anthropogenic activity. Despite this cover change, information on soil carbon dynamics in paramos is scarce, impeding conservation management strategies in these ecosystems. This study evaluates the impact of different soil uses within a transect in the Guerrero paramo estimated from soil organic carbon (SOC) stock in the upper meter and carbon condition (expressed as stratification ratio, SR) in the surface soil. Carbon storage varied from 165.2 to 721.9 t ha^{-1} in the upper meter of soil with $SR_{1\ (0\text{–}10/10\text{–}20\text{cm})}$ between 0.92 and 2.01 and $SR_{2\ (0\text{–}10/20\text{–}30\text{cm})}$ between 0.99 and 2.05. Results of this study highlighted that in the fragile ecosystems than Andean paramos, the geomorphological position in relation to soil uses and management practices conditioned soil carbon availability, affecting pedogenetic processes. SR of SOC associated to anthropogenic intervention activities it does not indicate by itself C sequestration. In future researches it is necessary include additional parameters than net primary productivity and historic vegetation.

KEYWORDS

Andisol; Paramo ecosystem; catena; soil organic carbon; land use

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1. Introduction

Soil is an important emission source and reservoir of organic carbon (OC). At the global scale, it is the second largest reservoir of carbon (C) and the highest C pool in terrestrial ecosystems, storing between 1462–1548 Pg of C in the upper meter (Batjes 1996), about twice that of the atmosphere (750 Pg of C) and vegetation (650 Pg of C) (FAO 2002). Soil organic carbon (SOC) stock comprises 69.8% of the biosphere OC (FAO 2002) and >71% of the terrestrial C reserves (Parras-Alcántara et al. 2015). SOC is an important component of the biogeochemical cycle and its dynamics are controlled by the vertical and lateral C fluxes (Armas 2009). SOC plays a key role in relation to physical, chemical and biological properties of soil, conditioning the fertility, productivity and soil quality (Batjes 1996; Post and Kwon 2000). Soil fertility (biological, physical and chemical) in the tropics particularly benefits from SOC inputs because of the poor nutrient status and highly weathered soil conditions. According to Kim et al. (2004) and Brady and Weil (2007), reduction in SOC content will be accentuate by degradation processes (erosion, compaction, nutrient loss, leaching and acidification), what leads to loss of biodiversity and soil productivity and even severe environmental problems, such as floods, droughts, underground water shortage, soil depletion and other unpredicted events.

Tropical rainforests store most of their C in vegetation, whereas paramos mostly store C in soils (CODESAN 2009) because of lower decomposition rates and nutrient recycling related to low temperatures that promote C accumulation. Thus, C in paramos mineralizes slowly and converts to humus, storing up to 1700 t C ha^{-1}, whereas soils from tropical rainforests only store 50 t of C ha^{-1} (Hofstede et al. 2003). From a global change perspective, land management influences the ability of soils to serve as both a source and a sink of SOC and nutrients (Schrumpf et al. 2011). Land use/cover change (LUCC) affects the global C balance and is recognized as a major factor affecting soil carbon storage over decades to centuries (Scott et al. 2002). Soil degradation worldwide due to anthropic activities is estimated at approximately 1094 million ha: 43% of this land degradation is due to forest conversion or other vegetation cover change, 29% to pastures, 24% by poor management, and 4% to over-use of natural resources (Walling and Fang 2003).

Among Colombian paramo soils, Andisols (soils derived from volcanic ash weathering, with accumulation of short range order minerals and stable organo-mineral complexes) dominate. These soils have high OC, with the vertical OC distribution directly dependent on vegetation and geomorphology (Nanzyo 2002). The Andisols in Colombian mountains have good structure associated to high organic matter (OM) and presence of allophane parameters that have been extensively studied (Jenny 1950; Flórez and Parra 2001). In natural paramo hillslopes, little surface water erosion occurs on Andisols, but this behavior changes when the natural vegetation is converted to agriculture due to intense mechanized tillage or conversion to pastures where trampling occurs (Pla 1990; Dörner et al. 2016). Some contradictory findings on erosion resistance related to the degree of disturbance of Andisols have been reported (Pla 1990; Nanzyo et al. 1993; Dahlgren et al. 2004).

Numerous studies in Colombia have quantified total carbon stocks within different compartments of heterogeneous tropical and neotropical forests, including aboveground biomass, belowground biomass, necromass, and soils (Jenny 1950; Loaiza et al. 2010; 2013). However, information on carbon dynamics in different ecosystem components in paramos is scarce or non-existent, especially for the relation of SOC with land use and the consequences on soil quality. The aims of this study were to estimate the impact of several land uses on the quality of the soils along a transect in the Guerrero Paramo (Cundinamarca – Colombia) and propose the use of SOC stocks and stratification ratio (SR) as indicators of SOC dynamics in the paramo in relation to land use. In addition, we aim to understand the C variability of the topsoil layer, as this layer has the highest potential of mobilizing substantial amounts of C under climate or land use changes.

2. Materials and Methods

2.1 Study site

The study area is located in the Guerrero paramo at Tausa village on the Cundinamarca region (Colombia). The coordinates of the study site in Colombia are 5°12′48″N 74°00′16″W and 5°11′47″N 74°1′20″W (Figure 1). Soil parent material is composed of Upper Cretaceous and Lower Tertiary sedimentary rocks, mainly composed of compact sandstones with friable insertions of siliceous siltstones, mudstones, claystones and shales, local volcanic ash layers, and consolidated and semi consolidated Quaternary sediments (Ávila 2005). There are three different morphogenetic environments: (1) structural denudated mountains (60%) divided into glaci-structural mountains (24%) and structural-erosional mountains (36%), (2) fluvial accumulation processes (31%) and (3) glacial plains or depressions (9%) (Ávila 2005; CAR et al. 1997) (Table 1). A description of the complete soil survey can be found in IGAC (2000). The main climate in this zone is moist and cold, with some small zones classified as extremely cold and moist or semi-moist and very cold, according to Caldas-Lang classification. There is bimodal precipitation regime which varies from 865 mm (Salitre-El Neusa station) to 1107 mm (Los Pinos station) as multiannual

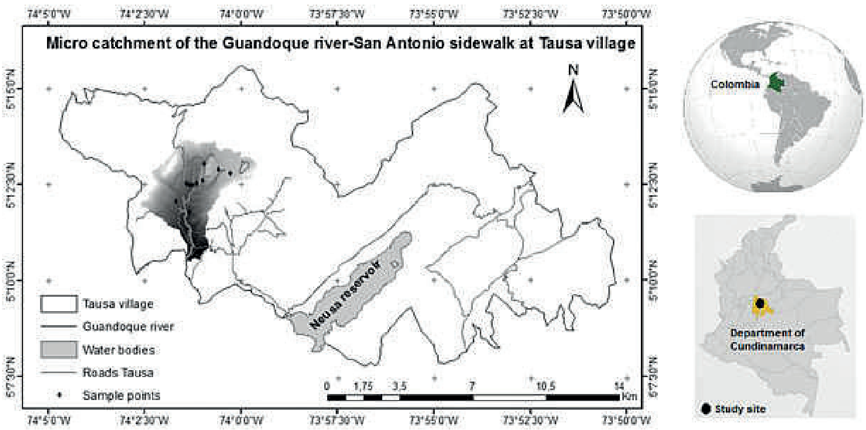

Fig. 1 Study site location.

Tab. 1 Description of characteristics in the field study sites and SR.

Profile	Soil classification (SSS, 2014)	Geomorphology	Vegetation	Land use	Environmental conditions	Slope (%)	Elevation (m.a.s.l.)	SR1 (0–10/10–20)	SR2 (0–10/20–30)
I	Typic Endoaquand	Fluviolacustrine Plain	scrublands and mosses, *C nitida*, *C multiflora*, *D granadensis*, *Espeletia* sp,	Natural high mountain	Extremely cold and moist	3–7	3629	0.92	1.15
II	Typic Endoaquand	Moraines				7–12	3610	1.08	1.28
III	Pachic Melanudand	Abrupt homoclinal crest	*Espeletia* and shrubs		Really cold and moist	25–50	3542	1.20	1.42
IV	Lithic Humudept	Slope					3569	1.35	1.39
V	Pachic Melanudand	Accumulation Glacis	Pasture	Pasture			3452	1.08	1.14
VI	Pachic Melanudand	Valley				12–25	3404	1.06	1.09
VII	Typic Endoaquand	Accumulation Glacis					3432	1.00	0.99
VIII	Pachic Melanudand	Hill	Forest *Weinmannia*	Natural high mountain			3462	0.98	1.01
IX	Pachic Melanudand	Hill	Bare Soil-Potatoes	Intensive agriculture			3437	1.02	1.00
X	Pachic Melanudand	Hill	Pasture-Potatoes			25–50	3369	2.01	2.05

averages. Soil use is classified into high mountain park (855 ha), grazing (345 ha), intensive agriculture (292 ha), wetlands (16.5 ha) and mining (0.5 ha).

2.2 Field and Laboratory study

Soil organic carbon (SOC) was studied using a geomorphic transect through the Guerrero paramo considering the relationship between soil and geormorphology in the context of soil forming components (Buol et al. 1989; Birkeland 1999; Birkeland et al. 2003). Soils profiles across different geomorphological positions in the Guerrero Paramo ecosystem, which determine the organic matter behavior and many of the morphological properties, vegetation and land use are shown in Figure 2. The transect length is 4.8 km with altitudes ranging from 3,369 to 3,630 m.a.s.l. The four representative land uses are potatoes, pasture, paramo vegetation, and natural forest. The main characteristics of transect are shown in Tables 1, 2 and Figure 2.

Ten representative soils profiles associated with different geomorphological positions, vegetation, and land use for study zone were selected, described according to Soil Survey Manual (SSS, 1993) and classified according to Soil Taxonomy (SSS, 2014). The soils that integrate this catena correspond to nine Andisols of the suborder Udands and one Inceptisol of the suborder Udepts (Table 1). The soils with andic properties (according to soil taxonomy parameters) are characterized by dark and deep morphogenetic horizons, with high organic matter content and low bulk densities (less than 0.9 g cm^{-3}). Soils are extremely acidic to moderately acidic, with low and very low Cation Exchange Capacity (CEC), high organic matter (OM), OC and nitrogen (N) contents, medium C/N ratio, phosphorous (P) very low to high, calcium (Ca) very low to medium, potassium (K) very low to high, magnesium very low to low, sodium (Na) low to medium, aluminum (Al) low to high; and textures that vary with depth, progressing from coarse to fine and finally very fine textures. A detailed result for soil profiles laboratory analysis are showed in Table 2. For each soil profile used in the SOC stock assessment, undisturbed soil samples were taken with split tube

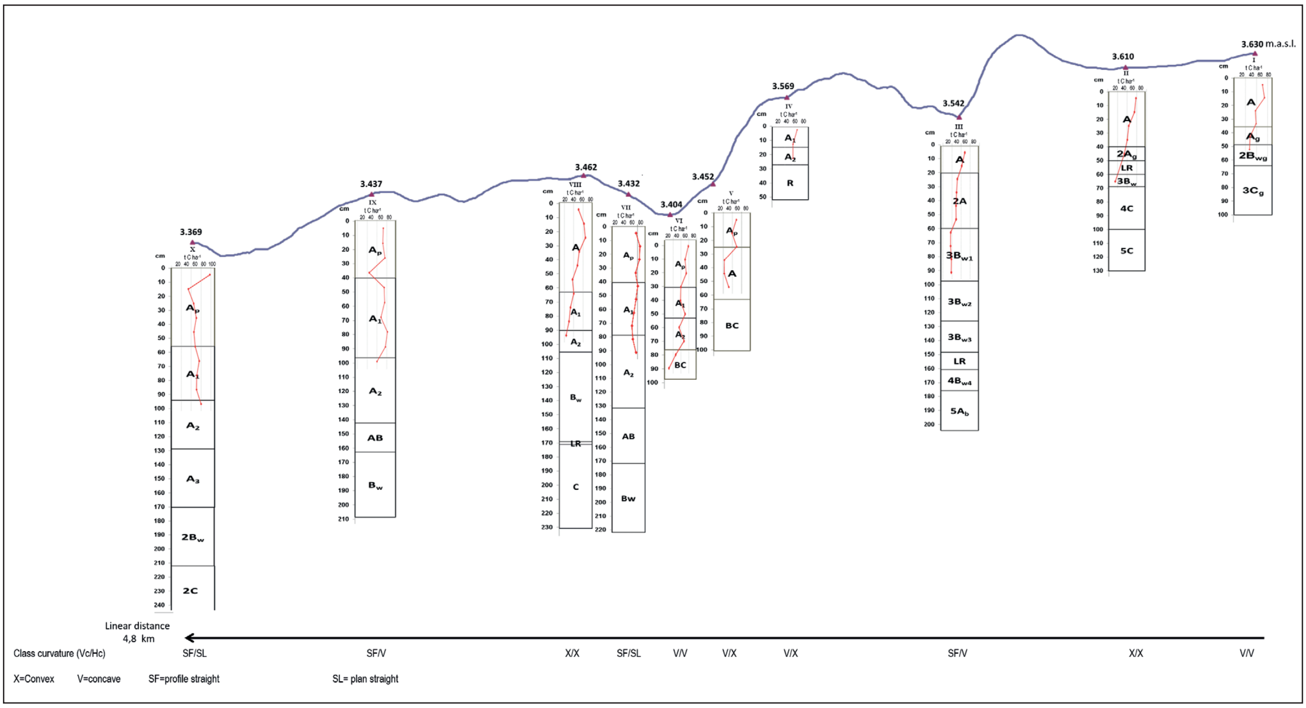

Fig. 2 Vertical distribution of SOC (t ha^{-1}) up to one meter depth, along the study transect. Soils are described according to Soil Survey Manual SSS (1993).

sampler (Eijkelkamp ®) to a maximum depth of one meter to determine bulk density; and disturbed samples were collected at the same depths to determine SOC. Samples were analyzed according to SSS (2004) methodologies. Subsequently Total Carbon (TC) was determined through dry combustion with an elemental analyzer (Leco CNS®).

2.3 Soil organic carbon and stratification ratio calculation

The model used to calculate SOC from Total Carbon (TC) is based on Goidts et al. (2009) equation:

$$\text{SOC Stock} = d \times C \times \rho\,[1 - RM] / 100$$

Where stock is the SOC stock (t C ha^{-1}), d is the sampling depth considered (m), C is the soil organic carbon concentration (g C kg^{-1}), ρ is the bulk density (kg m^{-3}), and RM is the mass proportion of rock fragment content (dimensionless).

Stratification Ratio (SR) was determined according Franzluebbers (2002) methodology as a soil quality indicator:

$$SR_1 = COT_{0\text{–}10\ \text{cm}} / COT_{10\text{–}20\ \text{cm}} \text{ and } SR_2 = COT_{0\text{–}10\ \text{cm}} / COT_{20\text{–}30\ \text{cm}}$$

Where COT is the concentration of SOC (g kg^{-1}) and sampling depths (subscripts) are 0–10 cm, 10–20 cm, and 20–30 cm.

3. Results and discussion

3.1 Soil organic carbon stock

The current study found that SOC stock fluctuates from 165.1 to 721.8 t ha^{-1}. In the Table 3 the behavior of SOC stocks for different combinations of soils and soil use in relation to geomorphological position are showed. The first set of transect consist of Profiles I–V. Profile III has higher SOC stocks (350.6 t ha^{-1}, Figures 2 and 3), where surface curvature (Terrain based classification) indicate that profile or vertical curvature (Vc) was classified as flat and favors the deposition of colluvium in the concave plan or horizontal curvature (Hc) direction; allow much colluvium to deposit resulting in deeper profiles and horizons (Yoo et al. 2006). Deep soil profiles were developed in flat topographic conditions that favors organic matter enrichment, soil profile stability and rejuvenation (Buol et al. 1989; Birkeland et al. 2003; Mora et al. 2014).

Profile II accumulated 339.3 t C ha^{-1}, this behavior is associated to concave and flat slopes that promote accumulation of organic matter transported from Profile I. In Profile I, there is material loss by surface runoff, which despite the flat and concave topography (Vc and Hc) and slightly rolling slopes (3–7%), decreased the SOC content by 33% compared to Profile II.

Profiles I and II have high potential of C storage due to the geomorphological position. A second set within the study transect, consists of Profiles VI to X. The lowest SOC values along the whole toposequence were

Tab. 2 Characteristics of soils in the study sites.

Profile	Horizon	Depth (cm)	Texture	BD	pH	%OC	%OM	%N	P	Ca	K	Mg	Na	Al	%BS	CEC
									ppm	meq 100 g^{-1}						cmol kg^{-1}
I	A	0–36	Silty clay	0.36	4.0	26.00	45.51	2.27	29.20	1.33	0.17	0.17	0.09	4.55	1.76	6.31
	Ag	36–49	Clay	0.53	4.6	8.95	15.43	1.00	3.96	0.52	0.13	0.11	0.08	5.37	0.84	6.21
	2Bwg	49–64	Clay	0.72	4.7	3.39	5.84	0.29	4.33	0.16	0.08	0.04	0.07	7.49	0.35	7.84
	3Cg	64x	Clay	–	4.4	0.74	1.28	2.00	4.09	0.20	0.21	0.05	0.07	9.86	0.53	10.39
II	A	0–40	Clay loam	0.41	4.0	19.00	32.07	1.60	7.74	0.27	0.20	0.18	0.11	7.64	0.76	8.40
	2Ag	40–60	Clay	0.49	5.0	9.89	17.05	0.85	2.73	0.18	0.07	0.07	0.1	1.78	0.42	2.20
	3Bw	60–69	Clay	0.76	5.1	3.26	5.62	0.28	3.98	0.18	0.11	0.03	0.25	1.85	0.57	2.42
	4C	69–90x	Clay	–	4.6	0.44	0.76	0.04	12.80	0.29	0.08	0.06	0.11	7.32	0.54	7.86
III	A	0–19	Clay loam	0.64	5.0	14.00	23.27	1.17	16.40	0.13	0.32	0.15	0.1	0.48	0.70	1.18
	2Ag	19–58	Sandy loam	0.65	5.3	9.29	16.02	0.80	12.10	0.17	0.11	0.08	0.05	1.05	0.41	1.46
	3Bw1	58–95	Sandy loam	0.58	5.5	4.32	7.45	0.37	5.88	0.17	0.04	0.04	0.08	0	0.33	0.33
	3Bw2	95–123	Sandy loam	0.60	5.5	3.84	6.62	0.33	3.97	0.14	0.02	0.02	0.07	0	0.25	0.25
	3Bw3	123–157	Sandy loam	–	5.5	3.32	5.72	0.29	2.50	0.11	0.01	0.01	0.06	0	0.19	0.19
	4Bw4	157–172	Sandy loam	–	5.2	4.69	8.09	0.40	4.84	0.16	0.05	0.04	0.1	0.53	0.35	0.88
	5Ab	172x	Loamy sand	–	5.3	9.86	17.00	0.85	21.00	0.21	0.02	0.06	0.08	1.06	0.37	1.43
IV	A1	0–14	Clay	0.74	4.0	16.00	26.89	1.34	9.15	1.34	0.21	0.15	0.08	6.10	1.78	7.88
	A2	14–26	Clay	0.78	4.7	12.30	21.21	1.06	2.12	0.15	0.09	0.08	0.08	4.26	0.40	4.66
	R	26x	–	–	–	–	–	–	–	–	–	–	–	–	–	–
V	Ap	0–25	Clay loam	0.62	5	14.00	24.83	1.24	105.00	5.56	0.17	0.71	0.15	1.66	6.59	8.25
	A	25–63	Sandy loam	0.73	5.3	9.29	16.02	0.80	24.50	4.84	0.11	0.75	0.1	0.85	5.80	6.65
	BC	63–100x	Sandy clay loam	0.75	5.6	2.92	5.03	0.25	>116	2.54	0.05	0.29	0.19	0	3.07	3.07
VI	Ap	0–34	silty clay	0.72	5.0	15.00	26.03	1.30	>116	1.39	0.89	0.28	0.12	4.09	2.68	6.77
	A1	34–56	Clay loam	0.68	4.5	14.40	24.83	1.25	>116	1.51	0.53	0.18	0.11	3.9	2.33	6.23
	A2	56–79	Loam	0.96	4.7	11.60	20.00	1.00	10.50	1.43	0.44	0.12	0.07	2.35	2.06	4.41
	BC	79–100x	Clay loam	0.85	5.1	1.86	3.21	0.16	27.10	0.52	0.22	0.05	0.06	0.24	0.85	1.09
VII	Ap	0–41	Clay loam	0.76	5.0	15.00	25.17	1.26	>116	2.87	0.48	0.33	0.06	2.90	3.74	6.64
	A1	41–79	Sandy loam	0.68	4.9	15.00	25.86	1.30	104.00	1.70	0.15	0.31	0.07	3.00	2.23	5.23
	A2	79–132	Silty clay loam	0.62	4.9	13.80	23.79	1.19	2.74	0.42	0.13	0.13	0.06	2.59	0.74	3.33
	AB	132–172	Silty clay loam	0.60	4.9	8.90	15.34	2.19	2.03	0.35	0.09	0.07	0.05	2.41	0.56	2.97
	Bw	172–222x	Sandy loam	–	5.0	6.20	10.69	3.19	1.86	0.25	0.15	0.24	0.05	1.34	0.69	2.03
VIII	A	0–63	Silty clay loam	0.50	5.0	17.00	29.83	1.49	25.70	0.42	0.36	0.25	0.08	2.98	1.11	4.09
	A1	63–90	Sandy loam	0.52	5.0	10.90	18.79	0.94	2.50	0.18	0.09	0.04	0.07	0.58	0.38	0.96
	A2	90–105	Sandy loam	0.63	5.0	6.08	10.48	0.59	1.78	0.22	0.09	0.03	0.07	0.31	0.41	0.72
	Bw	105–170	Sandy loam	–	5.1	5.10	8.79	0.44	2.26	0.21	0.12	0.05	0.07	0.19	0.45	0.64
IX	Ap	0–40	Silty clay loam	0.5	4.0	15.00	26.55	1.33	29.20	1.33	0.17	0.17	0.09	4.55	1.76	6.31
	A1	40–95	Silty clay loam	0.54	4.5	14.80	25.52	1.28	9.01	0.61	0.07	0.04	0.09	2.82	0.81	3.63
	A2	95–140	Sandy clay loam	0.56	4.6	6.86	11.83	0.59	3.04	0.25	0.06	0.02	0.05	0.34	0.38	0.72
	AB	140–160	Loam	–	4.5	5.70	9.83	0.49	2.04	0.25	0.08	0.03	0.06	0.48	0.42	0.9
	Bw	160–205x	Sandy loam	–	4.6	4.92	8.48	0.42	2.28	0.25	0.08	0.01	0.06	0.28	0.40	0.68
X	Ap	0–55	silty clay	0.82	5.0	11.00	18.10	0.91	>116	4.34	1.08	0.5	0.06	2.80	5.98	8.78
	A1	55–92	Clay	0.77	4.4	13.00	22.41	1.12	82.00	1.96	0.59	0.14	0.08	3.91	2.77	6.68
	A2	92–127	Clay	0.80	4.4	13.70	23.62	1.18	12.50	0.68	0.41	0.1	0.05	4.70	1.24	5.94
	A3	127–168	silty clay	–	4.8	10.00	17.24	0.86	7.10	0.31	0.29	0.04	0.05	2.35	0.69	3.04
	2Bw	168–209	silty clay	–	5.1	2.86	4.93	0.25	1.82	0.54	0.21	0.08	0.06	5.60	0.89	6.49

OC: organic carbon, OM: organic matter, N: nitrogen, P: phosphorous, Ca: calcium, K: potassium, Mg: magnesium, Na: sodium, SB: base saturation, CEC: cation exchange capacity, Al: Aluminum

Tab. 3 Carbon Stock on t ha^{-1} along the Catena (every 10 cm up to one meter m depth).

Depth (cm)	I	II	III	IV	V	VI	VII	VIII	IX	X
0–10	63.55	72.87	60.14	63.82	60.69	73.15	72.58	52.93	63.89	96.89
10–20	67.93	68.94	51.80	50.72	49.05	62.86	79.38	70.53	64.05	42.37
20–30	47.52	54.19	39.78	50.60	61.65	66.63	78.31	67.15	70.32	55.64
30–40	49.02	50.39	37.61	–	28.21	49.32	71.86	63.04	29.43	58.27
40–50	35.47	42.71	35.92	–	27.95	48.21	75.51	59.89	63.82	53.58
50–60	34.25	30.97	36.35	–	40.10	63.01	72.46	46.61	69.53	56.59
60–70	–	19.24	21.42	–	–	43.90	68.63	49.74	60.14	58.15
70–80	–	–	21.11	–	–	59.44	63.92	40.98	76.21	64.04
80–90	–	–	23.47	–	–	32.90	66.76	35.87	71.47	63.39
90–100	–	–	22.99	–	–	11.16	72.48	27.45	49.36	75.12
SOC Stock	297.74	339.31	350.59	165.14	267.65	510.58	721.89	514.19	618.22	624.04

found in profiles IV and V with C values of 165.14 t C ha^{-1} and 267.65 t C ha^{-1}, respectively. Presence of rugged topography (25–50% of slope) favored a decrease of SOC in all profiles referring to the second set of transect. Profile V has 62% more SOC than Profile IV, likely due to the concave planform, which favors higher accumulation of material from zones close to Profile IV. The thin soils and surface rocks (paralithic contact) provide evidence of the influence of climate and relief conditions on soil profile evolution.

Profile VII has the highest SOC values (721.9 t C ha^{-1}); this area is covered by pasture. Traditionally pasture zones correspond to recovering or fallow lands, some of which employ alternating tillage cycles about every 5 years. The highest OM incorporation in forest soils under volcanic ash soils is well documented by Loaiza et al. (2010), Mora et al. (2014), Peña-Ramírez et al. (2009). Land use change leads to the loss of carbon stock from natural forests (Kim et al. 2004); however, SOC is somewhat influenced by root inputs and more strongly affected by fauna bioturbation (Tonneijck and Jongmans 2008). According to Wang et al. (2012), the increase of SOC content could be attributed to fertilizer contribution during tillage periods.

The SOC stock in X profile is 624.1 t C ha^{-1}; an ancient tillage site that experienced occasional trampling by cattle and sheep despite the steep gradient. In profile IX, SOC values are relatively high (618.2 t C ha^{-1}); however, they show negative effects of tillage on surface horizons (20 to 40 cm depth), where SOC declines may reach 40% (Figure 2) with respect to the upper 10 cm of soil. Conversion from native forest to pasture can lead to soil degradation related to intensification of land use (Dörner et al. 2010, 2016). However, changes on SOC stocks associated with land use change mainly affects the upper 10 cm of sin the studied soil catena, where between 10 % and 40% of the total carbon (between 52.93 and 96.89 t C ha^{-1}), see Figure 2 and Table 3. Farming also conspicuously changes chemical and biological properties of Andisols, such as decreasing organic carbon content (Shoji et al. 1993). Profile X exhibited two trends related to material behavior: (1) colluvium material accumulation associated with concave slopes, and (2) transport of materials across convex slopes. Under forests (profile VIII), SOC stocks were 514.2 t C ha^{-1} with 60% of the C found in the A horizon (Figure 2). This behavior is more evident in forest ecosystems despite the presence of undulating slopes with concave and flat segments where the organic-rich A horizon, derived from volcanic ashes, reaches a depths greater than one meter. Volcanic soils have a large potential for organic carbon storage and forest growth, particularly in moist temperate climates (Mora et al. 2014; Peña-Ramírez et al. 2009). In Andisols under natural forests (montane moist forest life zone), decomposition and OM accumulation are very efficient, and this promotes aggregate stability and erosive resistance (Loaiza et al. 2010, Mora et al. 2014; Peña-Ramírez et al. 2009). In Profile VI, under tillage of potatoes and pasture with crop rotation, SOC values reach 510.6 t C ha^{-1} on undulating, planar, and concave slopes which favor accumulation, that coincide with findings of Jenny (1950), Nanzyo et al. (1993), Buytaert et al. (2002), Dahlgren et al. (2004).

Soil profiles III, VII and X on the lowest parts of the slope and in the zones with gradients between 25% and 50%, may be considered accumulation sections along the transect because on their concave, flat and foot slope profiles. Vertical distribution of SOC is negatively correlated with soil depth (Table 3 and Figure 2), similar to Zhang et al. (2015) Jobbágy and Jackson (2000) Mora et al. (2014) reports.

3.2 Stratification of Organic Carbon

Throughout our study site, $SR_{1\ (0\text{–}10cm/10\text{–}20cm)}$ fluctuated between 0.92–1.35 scrublands, 1–1.08 pasture, 098 natural forest and 0.98–2.01 potato rotation and for $SR_{2\ (0\text{–}10cm/20\text{–}30cm)}$ variations were 1.15–1.42 scrublands, 0.99–1.14 pasture, 1–2.05 and 1.01 natural forest potato rotation. When grouping all land use, SR_1 varies between 0.92–2.01 and SR_2 varies between 0.99 and 2.05 (Table 1). Results of Franzluebbers (2002) showed stratification ratios of soil organic C from 1.1 to 1.9 under conventional tillage (CT) and 2.0 to 3.4 under no tillage. Values found in our study are lower than other studies, possibly related to the exceptional physical conditions associated with paracrystalline amorphous clays and high organic matter content of soils derived from volcanic ash (Buol et al. 1989; Pla 1990; Dörner et al. 2010). Regarding OM percentage differences in surface layers (A horizons) under different land use (Table 2), OM contents were between 10.48% and 45.51%; the highest values were in high mountain natural park soils on the first section of transect and the lowest values in intensive agriculture soil of the second section of transect. High stratification ratios of soil C and N pools may be good indicators of dynamic soil quality, independent of soil type and climatic regime, because ratios >2 are uncommon under degraded conditions (Franzluebbers 2002). However, we observed on some soils (without regard to land use) that organic matter content in the underlying A horizon is higher than in the surface OM horizon, associated with the occurrence of buried soils, related to ancient volcanic activity.

Studies of SR as an indicator of soil quality under no-tillage, plow tillage and conversion of natural vegetation to cropland in Brazil showed an increase in SR of SOC also positively correlated with the rate and amount of SOC sequestered (Sá and Lal 2009). Nevertheless, in our study lower SR values do not explain land use dynamics, but, in our case, are related to deposition dynamics and transport on different sites, that can improve topsoil conditions.

All profiles, except the X Profile show a soil organic stratification ratio smaller than 2; such behavior is more associated with site conditions than anthropogenic effects, it is coincident with experimental result of Sá and Lal (2009) and Saiz et al. (2016).

The superficial part of the soil profile is strongly influenced by management practices (tillage, agricultural practices, and fertilization) and is more exposed to erosion, whereas the subsurface horizon is less affected by these practices. Thus, SR_2 is predominantly higher than SR_1 (Franzluebbers 2002, 2010). In most soil profiles where agricultural and livestock activity occurred, SR values are close to 1. Although SR_1 and SR_2 are not as low as in other studies (Franzluebbers 2002), this can be attributed to the high natural organic matter and carbon content of Paramo soils. Along the studied transect there is a direct relation between soil profile position and SR. Soils formed from volcanic ash parent material in cold and humid climates favor the accumulation of organic matter.

4. Conclusions

The current transformations of the wilderness paramo related to the change of use and coverage directly affect soil carbon stocks. The topographic variables helped to predict a significant part of the SOC storage variability in the paramo soils of the mountain landscapes in Guerrero. The conditions for high SOC storage in the study area were found on gentle slopes, which have more favorable conditions for plant productivity, C conversely accumulation along the altitudinal gradient did not change very much. Accumulation processes are associated to site position of the soil profile in relation to soil forming components more than soil use dynamics (which is conditioned by topographical conditions). The high percentages of carbon found in these soils coincide with the values reported by other authors for mountain Andisols. SOC storage exhibited a relatively smooth decrease with depth controlled by recurrent ash deposition and the presence of paleosols. Altitudinal changes in C content depend on aspect and slope gradient. When soils are cultivated, A horizons are partly degraded, and the organic litter layer disappears by erosion. These trends need to be considered when assessing impacts of land use on soil water behavior at the catchment scale. Site conditions related to topographic position (aspect and slope) are key factors for predicting C storage in paramo soils in Guerrero and must be considered when estimating C stocks in paramo ecosystems. In soils with lithic and paralithic contacts at highest altitudes, the variability of the OC content, explained by topographic variables, was partially related to plant communities and erosion process. While several studies report that SR of SOC is an efficient indicator of C sequestration and soil quality, however, under different soils uses in Guerrero Paramo SR of SOC associated to anthropogenic intervention activities does not indicate by itself C sequestration.

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