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Soil-Organic-Carbon Concentration and Storage under Different Land Uses in the Carrizal-Chone Valley in Ecuador

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Abstract: Soil organic carbon (SOC) is an important indicator of soil quality; an elevated percentage of SOC indicates very high-quality soil, physically as well as chemically. As such, the principal objective of the present study was to determine the concentration of SOC at different depths, as well as its accumulation through the entire soil profile. The Carrizal-Chone system (SCCH) area was stratified by agricultural use. Sixty-three soil samples were taken from different depths of up to a maximum of 150 cm. The physical and chemical properties of the soil were determined. SOC was determined by the Walkley and Black method. The following results are highlighted: (1) 21 different varieties of soil management were identified; (2) the largest area was livestock grazing land, which had the greatest concentration of SOC; (3) the type of soil with the greatest SOC sequestration capacity was silty clay loam; (4) the area cultivated with corn presented the highest accumulation of total carbon; and (5) the highest concentration of SOC was found in the top 40 cm, with a tendency to decrease with depth. It is concluded that soil management influences the concentration and accumulation of SOC in the topsoil layers and the entire soil profile.

Keywords: sequestration; organic matter; land use; Walkley–Black; agriculture

1. Introduction

Sustainable agroecosystems tend to balance land exploitation for human needs such as food, fiber, and wood with the long-term conservation of natural resources. Sustainable intensification (SI) is defined as a process or system where the agricultural yield is increased, or additional nonagricultural land is converted without adverse environmental impact [1]. Some benefits of this system, including productivity, decrease in erosion, conservation of soil moisture, greater soil biological activity, and reduction in production costs, have been previously described [2]. Global carbon balance is maintained when plant growth creates the ideal conditions for the decomposition of organic matter, while live roots contribute to respiration, according to Reference [3]. However, soil scientists are alarmed by the current status of global warming and positive carbon balance in Earth's atmosphere. This may be resolved by increasing soil-organic-carbon (SOC) sequestration and identifying areas and soils with the greatest potential to undergo this process by the spatial quantification of SOC, not only in the topsoil layer but also in deeper ones [4,5].

The province of Manabí has the largest concentration of agricultural land in Ecuador, 766.744 ha, including natural and cultivated pastures (INEC, 2017). The largest territory has slopes greater than

12% [6]. The main water reservoir in the province, which has a capacity of 450 Mm^3, is regulated by the La Esperanza dam. Its content is intended for human consumption and irrigation [7]. The current landscape in the study area, the Carrizal-Chone valley, is dominated by a conventional system of cultivated pastures, forestry, and crops such as banana, cacao, coffee, and citrus. The physical and chemical properties of the soil have been improved through the management of grazing [7]. However, the impact of these systems on soil-carbon sequestration have not been evaluated.

Proper soil-management practices benefit the sequestration of organic carbon, which has an essential role in soil properties [8]. However, the intensification of conventional agriculture means that soils are losing the capacity to sequester carbon, causing soil to become impoverished and lose its diversity over time [9]. Agroforestry systems aid the recuperation of degraded soils. Some soil factors, such as soil structure and aggregate stability, may improve porosity, decrease erosion, and increase soil productivity [10]. It is important to describe these and other factors that improve the capacity of soil to store carbon. Organic-carbon concentration and stock may vary by type of land use, as demonstrated by Reference [8], who found higher carbon accumulation in perennial and woody plantations compared to those of a short cycle and rotation. SOC storage and dynamics have long been known to depend on the region, soil-forming factors, climate, parent material, organisms, relief, time, and soil management [11,12]. Therefore, the aim of this study was to compare the influence of different land-management types on SOC.

2. Materials and Methods

2.1. Area Description

The work was carried out in the Carrizal-Chone System project (SCCH) area of interest, located in the central part of the Province of Manabí near the Chone and Tosagua counties. The study area is situated at 0°51′46″ S, 80°08′61″ W, and between 19 and 80 m.a.s.l. (Figure 1).

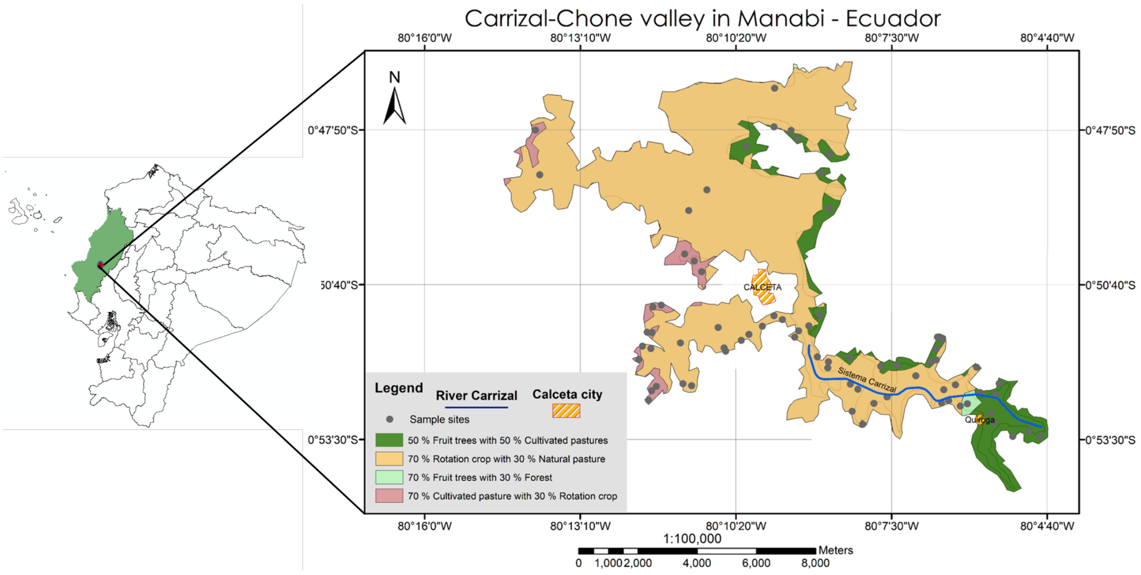

Figure 1. Area of study with the general land use in the Carrizal-Chone System (SCCH), Manabí, Ecuador.

The average annual temperature of the area is 25.6 °C, the average annual potential evapotranspiration is 1365.2 mm, and the average annual precipitation is 838.7 mm, with a dry period occurring from June to December, and a rainy period from January to May. The SCCH zone is composed of 50% natural pastures, 25% agricultural crops, 10% artificial pastures, 4% secondary forests, and 11% fallow, scrub, and others.

The slopes of the study area are less than 30%. The soil types are generally sandy silts of high plasticity, silty sands, and clay of high and low plasticity.

Agriculture is the dominant land use, occupying 75% of the territory [13].

2.2. Soil Profile Description and Sampling for Bulk Density and SOC

Sampling was carried out between March and August 2015, following the profile description method by Reference [14]. Sixty-four pits were created in different areas representing different soil-management types around the valley. Soil color was determined by the Munsell classification [15]. Soil samples were taken manually in each horizon, having previously been removed from the grass and mulch surface. The mean of horizon (Hz) thickness of the 218 sites was 40 cm. The top horizon's thickness varied between 15 and 60 cm depending on the soil type.

The samples were passed through a 2 mm sieve and homogenized, and stoniness was determined as % in mass. The samples were dried to a constant mass at 40 °C for 72 h. SOC concentration was determined in accordance with Reference [16], Equation (1). The stock of soil organic carbon for each soil-depth interval ($\mathrm{SOC_{stock}}$) and for the whole soil profile were calculated in accordance with Reference [17], Equation (2):

$$\mathrm{SOC} = M \times \frac{V_1 - V_2}{W} \times 0.30 \times CF \tag{1}$$

where M is the molarity of the $\mathrm{FeSO_4}$ solution (from a blank titration), V_1 is the volume (mL) of $\mathrm{FeSO_4}$ required in the blank titration, V_2 is the volume (mL) of $\mathrm{FeSO_4}$ required in actual titrations, W is the weight (g) of the oven-dried soil sample, and CF is the correction factor.

$$\mathrm{SOC_{stock}} = 10{,}000 SOC_i \times BD_i \times d \times (1 - \delta) \tag{2}$$

where $\mathrm{SOC_{stock}}\ i$ is the total soil organic carbon in a given layer (t/ha). SOC_i is the organic carbon concentration (g $\mathrm{g^{-1}}$), BD_i is bulk density (Mg $\mathrm{m^3}$), d is the thickness of the depth interval (m), δ is the fraction (0–1) of gravel larger than 2 mm in the soil, and n is the number of soil layers. So, Equation (3) gives the total soil organic carbon, $\mathrm{SOC_{stock}}$ (t/ha) of the whole soil profile:

$$\text{T-SOC}_{\mathrm{stock}} = \sum_{i=1}^{i=n} \mathrm{SOC_{stock}} \quad i. \tag{3}$$

Undisturbed soil samples were taken with a hand soil sampler for the determination of bulk density (BD). These samples were taken from every pit in each horizon, totalling 218 samples. The samples were dried to a constant mass at 105 °C for 48 h. Bulk density was calculated by dividing the dry mass by the volume of the cylinder, 98.2 $\mathrm{cm^3}$ [18].

2.3. Statistical Analysis

Statistical analysis was performed using InfoStat software, version 2018. The effect of each land use on SOC and stocks was analyzed using a Kruskal–Walis nonparametric test, and $\text{T-SOC}_{\mathrm{stock}}$ was analyzed with an ANOVA test. A test of data normality was done to verify the model assumptions. Data analysis was made by land-use groups as follows: abandoned (A), permanent cultivation (PC), rotation crop (RC), grazing (G), natural bush (N).

3. Results

Two different soil types were identified according to the United States Department of Agriculture–Natural Resources Conservation Service (USDA–NRCS) soil taxonomy: (a) Udic, Fluventic Hapludoit, and/or Tropofluvient, which are deep soils of variable texture (dominant loam), and (b) Ustic, Vertic Ustropept, and/or Ustret, which have hills with a slope of between 12% and 40%. Most soils are deeper than 50 m throughout the valley; only few sites are less than 15 cm in depth.

3.1. Bulk Density

No significant differences in bulk density (BD) (p-value = 0.858) were found between depths. When samples were grouped by land use, BD showed a nonsignificant tendency to be different between land uses. The values of each horizon (Hz) were averaged as follows: (Hz1) 1.25 ± 0.16 g/cm^3, (Hz2) 1.19 ± 0.12 g/cm^3, (Hz3) 1.21 ± 0.15 g/cm^3, (Hz4) 1.22 ± 0.11 g/cm^3, and (Hz5) 1.19 ± 0.10 g/cm^3.

3.2. Soil-Organic-Carbon Concentration in Soil Profile

In the SOC analysis, data were grouped by soil texture, soil management, and soil depth. The soil texture with the highest SOC concentration was loam-silt loam (1.57%), followed by clayey soil (1.07%). Soils with larger particles, such as sand, showed lower SOC values (Figure 2). There were higher SOC values in the first horizons where the greatest presence of roots is found.

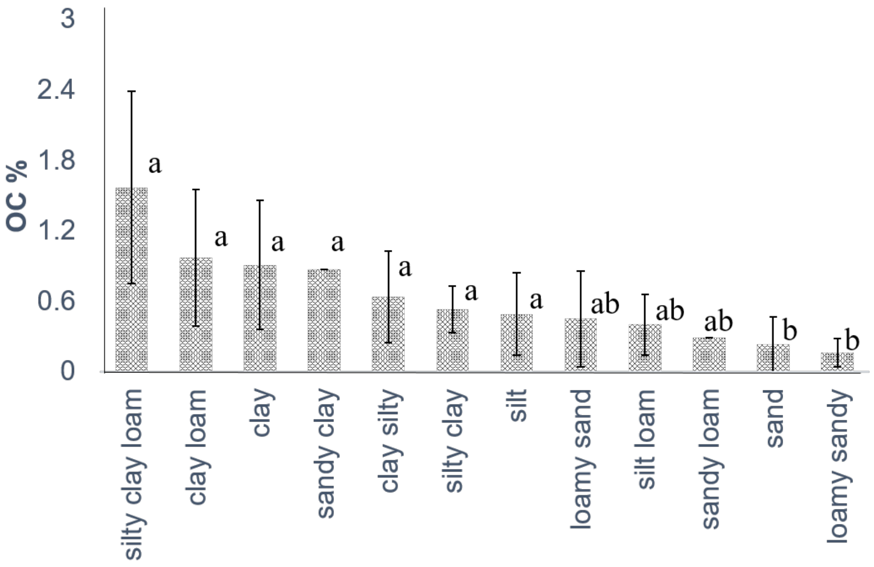

Figure 2. Distribution of soil-organic-carbon (SOC) concentration. Different letters indicate significant differences grouped by soil texture according to the Kruskal–Wallis test, ($p < 0.05$).

When management according to land use was grouped, there were no significant differences in SOC concentration (p-value = 0.347). The group with the highest concentration value was found in natural shrubs (N), with 0.62% organic carbon, compared to grazing (G), with 0.57%. The abandoned (A) group had the lowest concentration of organic carbon, with an average value of 0.26% SOC. This grouping shows that the study area has a high frequency of G for livestock (Table 1).

Table 1. SOC concentration in %, grouped by land use: abandoned (A), permanent cultivation (PC), rotation crop (RC), grazing (G), and natural bush (N) according to the Kruskal–Wallis test, ($p < 0.05$).

Group	Variable	*n*	Average	S.D.	E.E.	C.V.	F.G.	*p*-Value
A	OC	4	0.26	0.10	0.05	38.49	4	0.347
PC	OC	26	0.54	0.42	0.08	77.54		
RC	OC	50	0.57	0.39	0.05	67.66		
G	OC	135	0.57	0.44	0.05	79.97		
N	OC	3	0.62	0.12	0.07	19.52		

Data analysis by depth factor showed no differences in SOC concentration, (p-value = 0.0588). The thicknesses of all horizons were averaged and then analyzed with the Kruskal–Wallis test (Table 2). There was significant difference between horizons Hz (p-Value < 0.0001). Figure 3 shows that the surface horizon had the highest SOC concentration (Hz1) (0.87%), with a decrease in the second horizon (Hz2) (0.41%), and in the last horizon (Hz5) (0.36%).

Table 2. Average thickness in each horizon (Hz); standard deviation (SD).

Hz	*n*	Thickness (m)	SD
1	64	0.41	0.17
2	61	0.38	0.14
3	56	0.41	0.15
4	32	0.38	0.13
5	5	0.38	0.16

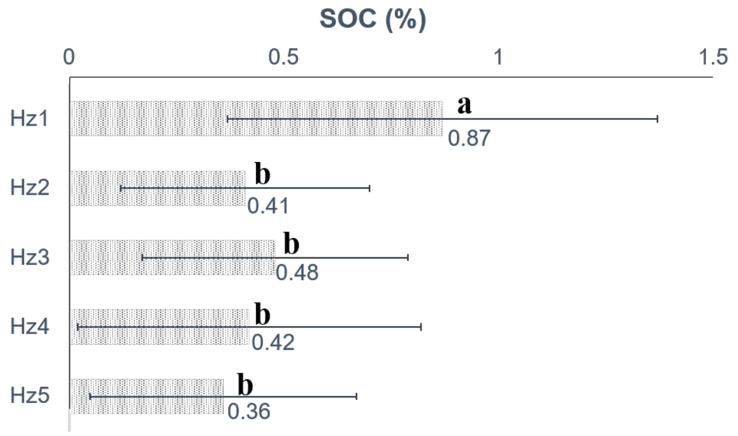

Figure 3. SOC in%. Different letters indicate significant differences according to the Kruskal–Wallis test ($p < 0.05$). Horizon (Hz).

3.3. SOC Concentration in Hz1

An average depth of 41 cm was found for the surface horizon (Hz1). Analysis was done with the type of texture factor, without taking land use as an influence or interaction. Silty clay loam soil (1.57%), clay loam (1.29%), and clay (1.14%) had the highest SOC-concentration percentages, with significant differences for (p-value = 0.001) silty clay, silt, and silt-loam textural soils (Figure 4).

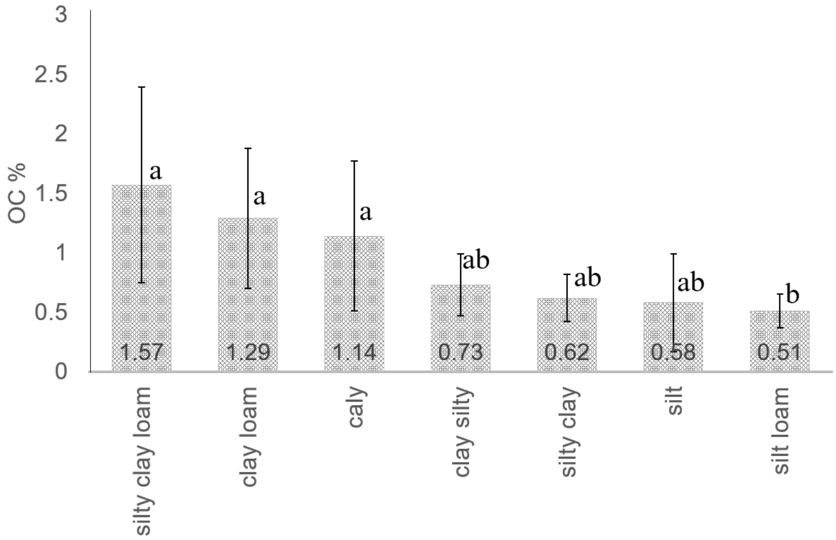

Figure 4. SOC concentration (%) for the surface horizon (Hz1). Different letters indicate significant differences based on soil texture according to the Kruskal–Wallis test, ($p < 0.05$).

3.4. SOC Concentration in Different Land Uses

We determined the significant differences between 21 different soil-management types (p value > 0.999) using the Kruskal–Wallis test (Figure 5). The highest percentages of organic carbon were found in areas cultivated with banana and cocoa—1.80% and 1.68%, respectively. The percentages of organic carbon for soil used for maize and cacao were 1.33% and 1.07%, respectively; these were the management types with the highest organic-carbon concentrations in the surface horizon. The lowest values were found in soils used for lemon cultivation and in the area of land plowed for the preparation of rotation crop use, with 0.35% organic carbon in both cases. These organic-carbon-concentration values were determined from the surface 41 cm of soil—the average depth of the surface horizon in each profile was studied.

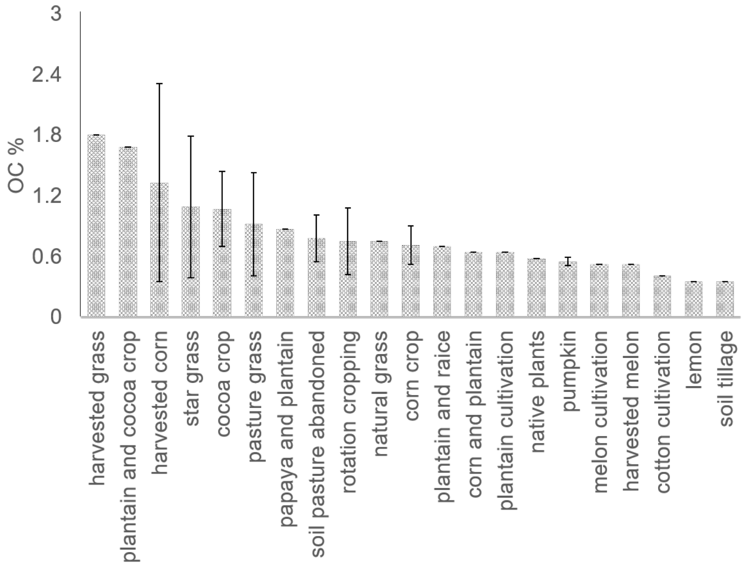

Figure 5. SOC concentration in % only in the surface horizon (Hz1). Different letters indicate significant differences based on soil land use according to the Kruskal–Wallis test, ($p < 0.05$).

3.5. SOC_{stock} Soil vs. Management

SOC_{stock} analysis showed that the surface horizon was different from the other horizons in all profiles; the accumulation was 41 ± 21 t/ha (Table 3).

SOC_{stock} was analyzed by land-use groups. No significant differences were found (p-value = 0.160) between natural (44.6 ± 10.5 t/ha), grazing (26.9 ± 22.2 t/ha), rotation-crop (26.8 ± 18.5 t/ha), permanent-crop (24 ± 18.8 t/ha), and abandoned (11.8 ± 4.3 t/ha) areas. Therefore, the greatest SOC_{stock} among the horizons was in the surface horizon.

Table 3. Distribution of soil-organic-carbon stock (SOC_{stock}, t/ha) by horizon (Hz). Different letters indicate significant differences according to the Kruskal–Wallis test ($p < 0.05$).

Hz	n	SOC_{stock} (t/ha)	S.D.	H	p-Value
1	64	41.32a	20.97	55.86	<0.0001
2	61	18.85b	16.84		
3	56	23.79b	19.71		
4	32	17.81b	13.2		
5	5	14.88b	12.71		

3.6. T-SOC_{stock}

Silt-loam texture had the greatest SOC_{stock} in the top soil horizon with 59 t/ha. The texture with the least SOC_{stock} was silt texture with 17 t/ha (Table 4).

Table 4. Distribution SOC_{stock} (t/ha) in Hz1 only. Different letters indicate significant differences according to the Kruskal–Wallis test ($p < 0.05$).

Soil Texture	*n*	SOC_{stock} (t/ha)	S.D.	H	*p*-Value
silt loam	5	58.6a	29.67	17.73	0.0069
clay	18	48.34a	18.04		
silty clay loam	2	43.65ab	25.53		
clay loam	20	40.28ab	17.94		
clay silty	12	37.51ab	22.87		
silty clay	5	20.88b	4.1		
silt	2	16.95b	14.07		

T-SOC_{stock} varied across different uses. However, abandoned soil had the highest T-SOC_{stock} with 177 t/ha, followed by native plants with 134 t/ha, and soil tillage had the lowest accumulation, with 47 t/ha. Although differences between land uses were notable, there were no statistically significant differences.

4. Discussion

4.1. Effects of Soil Texture and Land Use on SOC

In this study, silty clay loam soils (1.57%) had the highest SOC values, followed by clay loam (0.97%). Similarly, an SOC concentration of 1.85% was found in the Los Rios province in Ecuador under woody plantations with cacao CNN51 and national cacao [19].

According to Reference [20], the soils of the El Oro province could have higher or more frequent fertilization than the soils in Manabí since there is a strong demand for agronomic products there. On the other hand, concentrations vary with depth, with more concentrated SOC in the top soil layer (above 30 cm), but there are no significant differences across the whole profile. SOC concentration does not only depend on crop type, but also on soil type. In other regions of Ecuador, SOC concentration varies due to elevation, climate, or soil texture. Similar work on SOC in the Andean zone of Ecuador showed high SOC concentration due to the climate (constant humidity in soil) and the permanent vegetation in the Andean páramos that helps to sequester organic carbon over the long term [21].

4.2. Effects of Crops and Soil Management on SOC

SOC concentration is affected by changes in land use and various factors such as climatic conditions, soil texture, site preparation and management, vegetation type, and history of land use. [22]. In this study, the highest concentration of carbon in soil was found under cultivated pastures; the abundance of roots under this crop could explain the major concentration of SOC. Likewise, permanent plantain and cacao plantations have an abundance of roots, but the area is not totally covered by vegetation; thus, carbon concentration is lower than in grassy areas. However, the found values are not out of range for this type of soil use and management. Another factor that influences SOC is rainfall. Manabí has a dry tropical climate and rain is concentrated in winter; the significant amount of precipitation in February and March leads to a loss of fertile soil due to water erosion.

4.3. SOC_{stock} in Different Soil Uses

According to Reference [23], the accumulation of organic carbon at a depth of 20 cm varies between pastures and overgrazing with 37 and 49 t/ha, respectively, in land cultivated with cacao with 41 and 60 t/ha (depending on age of trees and management), and in the short-cycle corn group with 43 t/ha of stock. Compared to the present work in the same study area, the T-SOC_{stock} in the surface horizon (around 41 cm thickness) was shown to vary among cultivated grass (50.9 t/ha), cacao crop (43.8 t/ha), corn (47.7 t/ha), and the average of rotation crop (42.8 t/ha). The highest

SOC_{stock} was found in abandoned grass harvested corn (74.9 t/ha) and melon crop (61.7 t/ha). These results show a tendency for an increase in SOC_{stock} with adequate management of the plantations.

In Ecuadorian Amazon, the SOC_{stock} varies at a depth of 30 cm as follows: 49.44 t/ha in agroforestry systems and 36.75 t/ha in dali grass without three [24,25]. At a 10 cm depth in cacao-cultivation areas, the agroforestry system can reach 69 t/ha. This shows that the average accumulation of SOC in the surface horizon is low compared with the average of other regions. This can be related to rainfall—the Manabí area is drier compared to the Andean and Amazonian regions.

5. Conclusions

Soils that contain a high percentage of sand tend to have lower organic-carbon concentration than loamy and clayey soils.

The management of the first layer of soil is fundamental to the accumulation of SOC. The potential of organic-carbon sequestration increases throughout the profile with the management of soil and water resources.

Extending the cacao area could increase the potential concentration and accumulation of total organic carbon throughout the soil profile, benefiting soil, the environment, and system productivity.

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