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Research Article

Estimates of Soil Organic Carbon in the Ojos de Agua and El Quinillal Forests in the Central Huallaga of Peru

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The Peruvian Amazon has experienced large losses of forest cover due to changes in land use, contributing to increases in CO_2 in the atmosphere. This study estimated the organic carbon content of forest soil in two forests "Ojos de Agua" and "El Quinillal" in the Central Huallaga of Peru, establishing three types of cover: (i) primary, (ii) intervened, and (iii) deforested. For this purpose, 24 plots of 100 m^2 were established and samples were extracted at a depth of 0–20 cm. The effect of the type of forest cover on soil carbon (Organic Carbon-SOC, Inorganic Carbon-SIC, Saturated Carbon-SC, Critical Carbon-CC, Saturated Carbon Deficit-SCD, and Organic Carbon-OC) was analyzed by means of an Analysis of Variance, correlation. Likewise, the relationship between carbon (C) and soil properties was evaluated by principal component analysis and correlation network. The results indicated that the highest SOC averages were found in the primary forests of Ojos de Agua and El Quinillal with 3.54% and 2.51%. The lowest values were found in the deforested forests with 1.34% and 1.46%. The calculation of the saturated C levels of the soil showed an average of 28.63% ± 2.14% and the saturated carbon deficit of 26.63% ± 2.45%, whereas the critical threshold of C showed an average of 2.21% ± 0.18%. The highest SOC content found in the Ojos de Agua primary forest is due to the presence of dominant forest species such as *Manilkara bidentata* and *Brosimum alicastrum*. Likewise, the C deficit in the soils of the study area is very alarming because it is very close to saturation levels, especially in deforested forests.

Keywords: carbon saturation; critical carbon and inorganic carbon; intervened and deforested forests; organic carbon; primary

1. Introduction

The carbon (C) of primary tropical forest ecosystems is estimated at 141–159 Pg C (billion tonnes of C), representing about 49%–53% of all tropical forest C [1]. Soils with natural tropical forests have long provided essential ecosystem services such as nutrient storage and recycling [2], C storage and greenhouse gas (GHG) emissions [3, 4] and promote biodiversity through the diversity of trees and shrubs with regular litter input and deep permanent roots; while stimulating the activity of soil organisms [5]. Peruvian forests are considered among the main C reservoirs. It is estimated that Amazon forests in their aerial component alone harbor a total of 6928 million t CO_2e [6]. Primary forests lead to higher soil organic carbon storage (COS); while deforested forests to lower COS [4, 7].

Tropical deforestation in the Amazon and globally continues to be the largest contributor to the loss of natural forests [8]. It is estimated that between 2010 and 2015 tropical forests were deforested at a net rate of 5.5 million hectares annually [9]. The disturbance of this ecosystem reduces SOC, nutrient content, diversity of soil biota [10]. Deforestation in the Peruvian Amazon began in the 21st century, with a growth rate of 86.28% in the departments of Amazonas, Loreto, Ucayali, San Martin and Madre de Dios, with the figure increasing during the COVID-19 pandemic [11]. From 2001 to 2021, 2774.562 ha were deforested at an annual rate of 137,976 ha [12]. Deforestation in the Amazon is directly linked to economic activities [13], the main ones being shifting agriculture, oil palm plantations, timber extraction, road construction, coca cultivation, and illegal mining [14–16].

The Picota district in the San Martin region of the Peruvian Amazon, the seasonally dry forests of the central Huallaga is one of the most vulnerable ecosystems in Peru [17]. The socioeconomic process in the province of Picota started randomly in its 10 districts in the 1980s', where the main activities that motivated the use and occupation were timber extraction (deforestation), coca planting, opening of agricultural land for crop planting (e.g., rice and corn), as well as immigration [18, 19]. Activities normally supported by government policies [20] have seriously affected the dry forests of the Central Huallaga to date. The fragmentation of these forests could lead in the medium and long term to the extinction of many species of flora and fauna with restricted or endemic distribution in the area [21]. Reports conclude that the districts of Picota province presented a very high risk of forest cover loss by 2021 [22].

Despite these problems to date, little attention has been paid to the protection, benefits, and mitigation of this ecosystem. Therefore, it is important to make estimates of forest floor OC in forest forests of Central Huallaga of Perú, two large forests, in order to contribute to reducing the vulnerability of society to climate change [23]. The soil compartment contributed the largest C stock in agroforestry systems with coffee in Peruvian Amazonian ecosystems [24]. Likewise, SOC constitutes a vital component of the C inventory harbored in forest soils. Therefore, understanding the dynamics and distribution of SOC in forest soils of the Peruvian Amazon may be essential to better predict forest SOC inventories and may help provide a theoretical basis for future studies on soil C management technologies [25].

2. Materials and Methods

2.1. Study of the Site. The study was conducted in two forests: (i) "Ojos de Agua" of 2357.62 ha, located in the province of Picota, district of Pucacaca, on the left bank of the Huallaga River, at coordinates 6°50′50.99″S and 76°27′52.24″W, at 382 masl, and (ii) "El Quinillal" of 10,557.07 ha, located in the province of Picota, district of Winge, on the right bank of the Huallaga River, at coordinates 7°2′0.00″S and 76°19′52.42″W, at 309 masl. "Ojos de Agua" has a canopy of 15–30 m, undulating relief with moderate slopes of up to 50° inclination, mostly silty soil, and "El Quinillal" is characterized by a canopy of 10–20 m, relief with mostly moderate slopes, silty and clayey soil, no permanent water sources [21]. The climate has distinct seasons, with an average temperature of 26°C and an annual precipitation of 1164.4–1433.3 mm [17]. Likewise, in each forest type, three types of vegetation cover were selected: (1) Primary Forest, with a diversity of trees mostly dominated by Quinillal trees (*Manilkara bidentata* (A.DC.) A. Chev.) between 10 and 100 cm DBH, a species threatened by extensive agricultural practices such as corn plantations and climate change [26]. (2) Intervened forest by anthropogenic activities with trees in regeneration process from 1 to 50 cm DBH, and (3) deforested forest, with presence of shrubs; without the presence of trees.

2.2. Soil Sampling. For forest SOC estimates in the Ojos de Agua and El Quinillal Forests, 12 plots of 10×10 m were selected in each forest, following the methodology of Yu et al. [27]. Soil sampling was conducted from November 2023 to February 2024. The plots were randomly distributed in three vegetation cover types for each forest: primary forest, intervened forest and deforested forest. Four subplots were established in each plot. In each subplot, soil pits were excavated to study and collect soil samples at a depth of 0–20 cm for each plot; this depth was considered because in general, most of the SOC is retained in the surface soil layer (~20 cm) and decreases with soil depth [28].

2.3. Estimation of SOC. The study began with the physicochemical characterization of the soils that were collected, according to the Technical Sampling Guide, prepared by the Peruvian Ministry of Environment [23]. The samples were analyzed in the laboratory of the Universidad Nacional Agraria La Molina, Peru. The cylinder method of 5.2 cm diameter and 5 cm height proposed by Blake and Hartge [29] was used to calculate the bulk density (BD) of the soil in g cm^{-3}, considering three repetitions per subplot *y* determined by the following formula:

$$\mathrm{BD} = \frac{\mathrm{Wd}}{V}, \tag{1}$$

where BD is the bulk density (g cm^{-3}), Wd is the weight of the oven-dried soil sample (g) and V is the volume of the sampled soil (cm^3). Therefore, the SOC was determined using the method developed by Walkley and Black [30] in the laboratory, using the formula:

$$\mathrm{SOC}\left(\mathrm{tC\,ha^{-1}}\right) = \mathrm{OC} \times \mathrm{Ps} \times \mathrm{BD}, \tag{2}$$

where OC is the organic C content in the soil (%), Ps is the soil sampling depth (cm) and BD is the bulk density (g cm^{-3}). The soil texture was measured by the hydrometer texture method, the pH were measured with a potentiometer suspended in a 1:2.5 soil-water solution [31], carbonates ($CaCO_3$), soil inorganic C. were determined by the gas-volumetric method [32], SOC method [30] and soil organic matter (SOM) by the Porta et al. method [33].

The saturated C (SC) was determined by applying the Hassink equation [34]:

$$\text{Saturated C}\,(\%) = 4.09 + 0.37\,(\%\,\text{Clay} + \%\,\text{Fine Silt}). \tag{3}$$

The critical C. (CC) (%) was calculated considering the clay and silt fraction, applying the formula of Autfray et al. [35]:

$$\text{Critical C.}\,(\%) = \frac{0.32\,(\%\,\text{clay} + \%\,\text{Fine Silt}) + 0.87}{10}. \tag{4}$$

The stable C value was compared with the C measured in the soil and, from there, the saturated C deficit was measured [36]:

$$\text{Saturated C deficit (SCD)}\,(\%) = \text{C.sat} - \text{C.current}, \tag{5}$$

where Critical C. represents the minimum value of organic C in the soil that allows maintaining structural stability without risk of degradation [37].

2.4. Statistical Analysis. Statistical analysis was performed in the R Studio program [38]. The effect of forest cover type (PF, IF, and DF) on soil C was determined using an Analysis of Variance (ANOVA). The data met the assumptions of normality and homogeneity of variance (Shapiro Wilk and Bartlett tests, $p < 0.05$). The comparison of means was performed using the Tukey test ($p < 0.05$) from the “agricolae” package [39]. The relationship between SOC and SIC was evaluated using the Pearson test of function “cor.test” ($p < 0.05$). Additionally, a Principal Component Analysis (PCA) was performed to determine the relationship of the variables and coverage types, using the “Factoextra” package of R [40]; and a correlation network was carried out to evaluate the variables associated with OC and SOC through the “corrr” package [41].

3. Results and Discussion

3.1. SOC Distribution With Different Forest Covers. There are differences in the distribution of OC studied in soils at a depth between 0 and 20 cm in primary, intervened and deforested forests. The highest value of SOC was found in soils between 0 and 20 cm in the primary forest Ojos de Agua with an average of 131.38 ± 25.63 t ha^{-1} and El Quinillal with 108.52 ± 21.73 t ha^{-1}, presenting significant differences with deforested forests ($p < 0.05$), where the lowest values were obtained with 43.44 ± 25.63 and 43.2 ± 5.81 t ha^{-1}, respectively; while the intervened forests of El Quinillal and Ojos de Agua showed intermediate averages with 91.20 ± 9.14 and 85.51 ± 8.10 t ha^{-1} (Table 1). The SOC present in the two forests of Central Huallaga measured an average of 119.95 ± 23.68 t ha^{-1} and 43.32 ± 8.50 t ha^{-1} in the primary and deforested forests, respectively. This is due to the frequent change of use that the forests are undergoing for agricultural crops; basically, corn crops, generating a critical degradation in the forests of Picota. These conditions have influenced the renewal of soil organic matter and, therefore, the storage of SOC reserves [37]. The results obtained confirm what has been established by several authors, that plant formations have a profound effect on soil C stocks [35–38]. The impact of agricultural activity indicates that areas with intensive agrarian use exhibit lower SOC, with values ranging from 0 to 3 kg/m^2 [42]. These results are congruent to that reported by Berihu et al. [43] who found that the Afromontane dry forest had 83.7 and 63 t ha^{-1} of C sequestered by the surface layer, while deforested soils (croplands) had the lowest amount of C sequestration with a mean of 26.1 t ha^{-1}. Land-use change due to forest clearing causes a severe and long-term impact on ecosystem C [44]. After deforestation, ecosystem C losses occur rapidly, within a few years [45], so vegetation plays a crucial role in determining the spatial distribution of SOC according to tree species composition; influencing the amount and composition of organic matter inputs especially in the upper soil layers [46].

The SIC presented significant differences according to the type of cover ($p < 0.05$). In El Quinillal Forest, the highest values were recorded in the deforested and intervened forests, differing statistically from the primary forest (PF-EQ) (Table 1). The highest SIC content in a deforested forest is due to changes in land use from natural vegetation to cropland. These can rapidly induce the loss of SIC that has been stable for several years [47]. Therefore, due to changes in vegetation species and land management approaches, land cover as well as land use types have a substantial impact on SIC content [48].

3.2. Saturation Rate, OC, Deficit, and Critical Soil Carbon With Different Types of Forests. The calculation of soil SC levels showed an average of 28.84 ± 1.48. Based on Table 2 for the Ojos de Agua Forest, we show that the maximum SC of SOC was obtained in the deforested forest with 34.62 ± 0.37%, presenting significant differences with the values obtained in the other coverages (26.62 ± 1.35 and 29.07 ± 1.26% for primary and intervened forests, respectively). In the El Quinillal Forest, there were no significant differences among coverages obtained in the deforested, intervened and primary forests, with averages of 27.77 ± 0.43, 26.29 ± 4.74, and 25.67 ± 0.7, respectively.

The CC threshold varied between 1.96 ± 0.06% and 2.73 ± 0.03%, showing an average critical threshold of 2.23 ± 0.13%. Significant differences exist among coverages, the highest values were recorded in the deforested forest of the Ojos de Agua Forest with 2.73 ± 0.03 (Table 2). The Tessala Mountains in Algeria [37], recorded a critical threshold ranging from 0.7% to 1.7%, while Tunisia, under almost similar conditions [49], recorded a critical threshold ranging from 1.79% to 2.70%, very close to our study. There were significant differences for SCD, with the highest values recorded in the deforested Ojos de Agua Forest with 33.09 ± 1.73. Zhang et al. [50] found the highest SCD in

Table 1: Variation of soil organic C (SOC) stocks and inorganic carbon stock (SIC) under selected vegetation covers.

		PF-EQ	IF-EQ	DF-EQ	PF-OA	IF-OA	DF-OA	AGV
SOC (t ha^{-1})	Avg-SD	108.52 ± 21.73	91.2 ± 9.14	43.2 ± 5.81	131.38 ± 25.63	85.51 ± 8.10	43.44 ± 11.18	83.88 ± 13.60
	Group	ab	b	c	a	b	c	
SIC (t ha^{-1})	Avg-SD	12.75 ± 2.43	36.47 ± 8.97	46.57 ± 13,63	30.42 ± 10.75	29.44 ± 3.51	34.81 ± 2.63	31.74 ± 6.99
	Group	b	a	a	ab	ab	a	

Note: Groups according to a Tukey test.

Abbreviations: Avg, average; DF-OA, deforested forest Ojos de Agua; DF-EQ, deforested forest El Quinillal; IF-OA, intervened forest Ojos de Agua; IF-EQ, intervened forest El Quinillal; PF-OA, primary forest Ojos de Agua; PF-EQ, primary forest El Quinillal; SD, standard deviation.

Table 2: Variation of saturated carbon (CS), critical carbon (CC), saturated carbon deficit (SCD), and organic carbon (OC) under selected vegetation covers.

Carbon			PF-EQ	IF-EQ	DF-EQ	PF-OA	IF-OA	DF-OA	AGV
CS	%	Avg-SD	25.67 ± 0.7	26.29 ± 4.74	27.77 ± 0.43	29.62 ± 1.35	29.07 ± 1.26	34.62 ± 0.37	28.84 ± 1.48
		Group	b	b	b	b	b	a	
	T ha^{-1}	Avg-SD	677.7 ± 18.48	701.9 ± 126.56	749.8 ± 11.61	808.6 ± 36.86	854.7 ± 37.04	1028.2 ± 10.99	865.20 ± 44.4
		Group	b	b	b	b	b	a	
CC	%	Avg-SD	1.96 ± 0.06	2.01 ± 0.41	2.14 ± 0.04	2.3 ± 0.12	2.25 ± 0.11	2.73 ± 0.03	2.23 ± 0.13
		Group	b	b	b	b	b	a	
	T ha^{-1}	Avg-SD	51.74 ± 1.58	2.01 ± 0.41	57.78 ± 1.08	62.79 ± 3.28	66.15 ± 3.23	81.08 ± 0.89	66.90 ± 3.9
		Group	b	b	b	b	b	a	
SCD	%	Avg-SD	21.63 ± 1.54	23.52 ± 4.74	26.43 ± 0.47	25.79 ± 1.97	26.12 ± 1.43	33.09 ± 0.54	26.10 ± 1.73
		Group	b	b	b	b	b	a	
	T ha^{-1}	Avg-SD	571.03 ± 40.66	627.98 ± 126.56	713.61 ± 12.69	704.07 ± 53.71	767.93 ± 42.04	982.77 ± 16.04	783 ± 51.9
		Group	b	b	b	b	b	a	
OC	%	Avg-SD	4.05 ± 0.84	3.02 ± 0.37	1.34 ± 0.22	3.83 ± 0.87	2.94 ± 0.25	1.53 ± 0.39	2.78 ± 1.17
		Group	a	a	b	a	a	b	a

Note: Groups according to a Tukey test.

Abbreviations: Average, Avg; deforested forest Ojos de Agua, DF-OA; deforested forest El Quinillal, DF-EQ; intervened forest Ojos de Agua, IF-OA; intervened forest El Quinillal, IF-EQ; Standard deviation, SD; primary forest Ojos de Agua, PF-OA; primary forest El Quinillal, PF-EQ.

Maolan grass with 83.34% and the lowest in trees with 25.69%, similar to that found by Merabtene et al. [37]. The average saturation rate in Picota forest soils was 865.20 ± 44.40 t ha^{-1}. This means that it is possible to increase the average C content to 781.32 ± 30.8 t ha^{-1}. The current C content of Picota forest soils is very low (83.88 ± 13.60 t ha^{-1}) and closer to the critical threshold (66.90 ± 3.9 t ha^{-1}) than to its maximum storage capacity represented by C saturation (865.20 ± 44.4 t ha^{-1}), Table 1 and 2. The OC varied between 1.34 ± 0.22% and 4.05 ± 0.84%, with an average of 2.78 ± 1.17%. It was determined that there are significant differences between coverages, the lowest values were recorded in deforested forests (DF-EQ and DF-OA). The C deficit in the soils of the study area is very alarming because it is very close to saturation levels (783 ± 51.9 t ha^{-1}). It is known that SCD is an important indicator of SOC sequestration potential [50]; therefore, soils with *C* level distant from saturation will have high SCD (high *C* stabilization capacity) [51].

3.3. SOC and SIC Stocks on Soils With Different Forest Types.

A SIC of 12.75 t ha^{-1} (5.93%) with a SOC of 108.52 t ha^{-1} was recorded in the primary forest, so much so that the soil with 46.57 t ha^{-1} (18.22%) of the total carbonate content only recorded 43.20 t ha^{-1} of SOC in the deforested forest of El Quinillal. Whereas with a SIC of 30.42 t ha^{-1} (11.01%), a SOC of 131.38 t ha^{-1} was recorded in the primary forest, so much so that the soil with 34.81 t ha^{-1} (15.32%) of total carbonate content only recorded 43.44 t ha^{-1} of SOC in the deforested forest of Ojos de Agua (Figure 1). Likewise, the results obtained show that SIC has a negative correlation with SOC, with a correlation coefficient of −0.40 ($p < 0.05$). Soil with higher SIC values presented lower SOC accumulation and vice versa (Figure 2). Our study shows agreement with Wang et al. [52] who found that there was a significant negative relationship between SIC and SOC in rice fertilized soils. Previous studies reported negative SIC-SOC relationships, under other land uses (such as shrub, grassland, and forest) in the Loess Plateau of China [51, 52]. However, there were other studies that showed positive relationships between SIC and SOC in a 0–100 cm layer of northern China [53]. Similar results were presented by Merabtene et al. [37], who indicated that SIC had a negative correlation with SOC, finding that 3% SIC recorded a maximum value of SOC (121 t ha^{-1}), while soil with 22% of total carbonate content only recorded 38 t ha^{-1} of SOC. SOC and SIC stocks were probably significantly influenced by soil organic matter (Table 3), which is why primary forests showed higher SOC and lower SIC. Wang et al. [52] observed a significant increase in SOC with higher organic fertilization rate, whereas fertilization had no significant effect on SIC in the 0–20 cm layer.

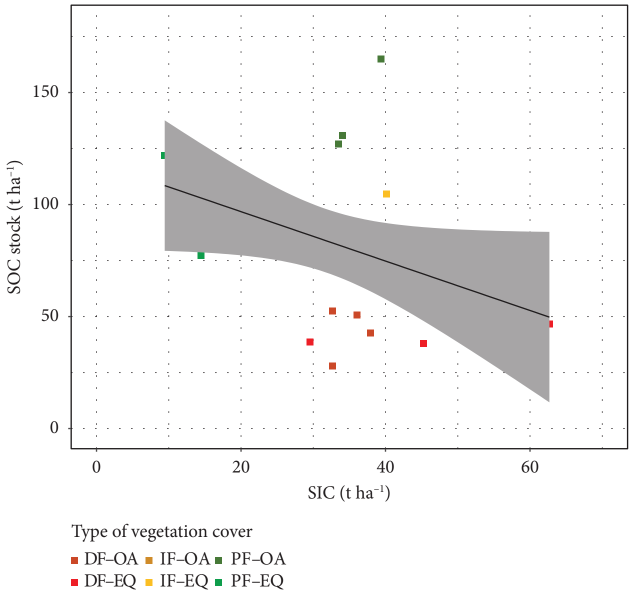


FIGURE 1: SOC and SIC stocks in soils with different forest types.

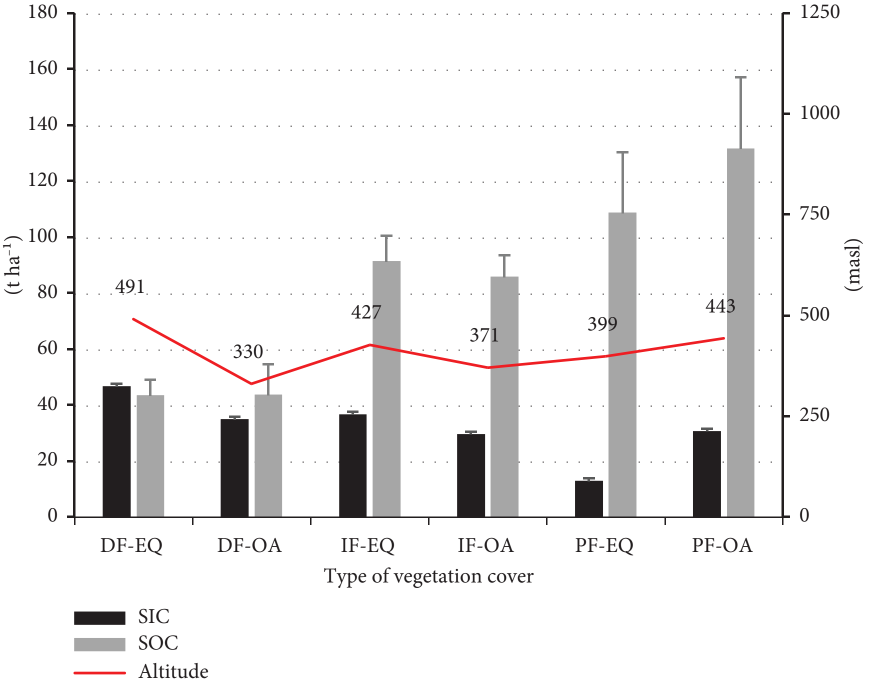


FIGURE 2: Relationship of SIC and SOC with altitude.

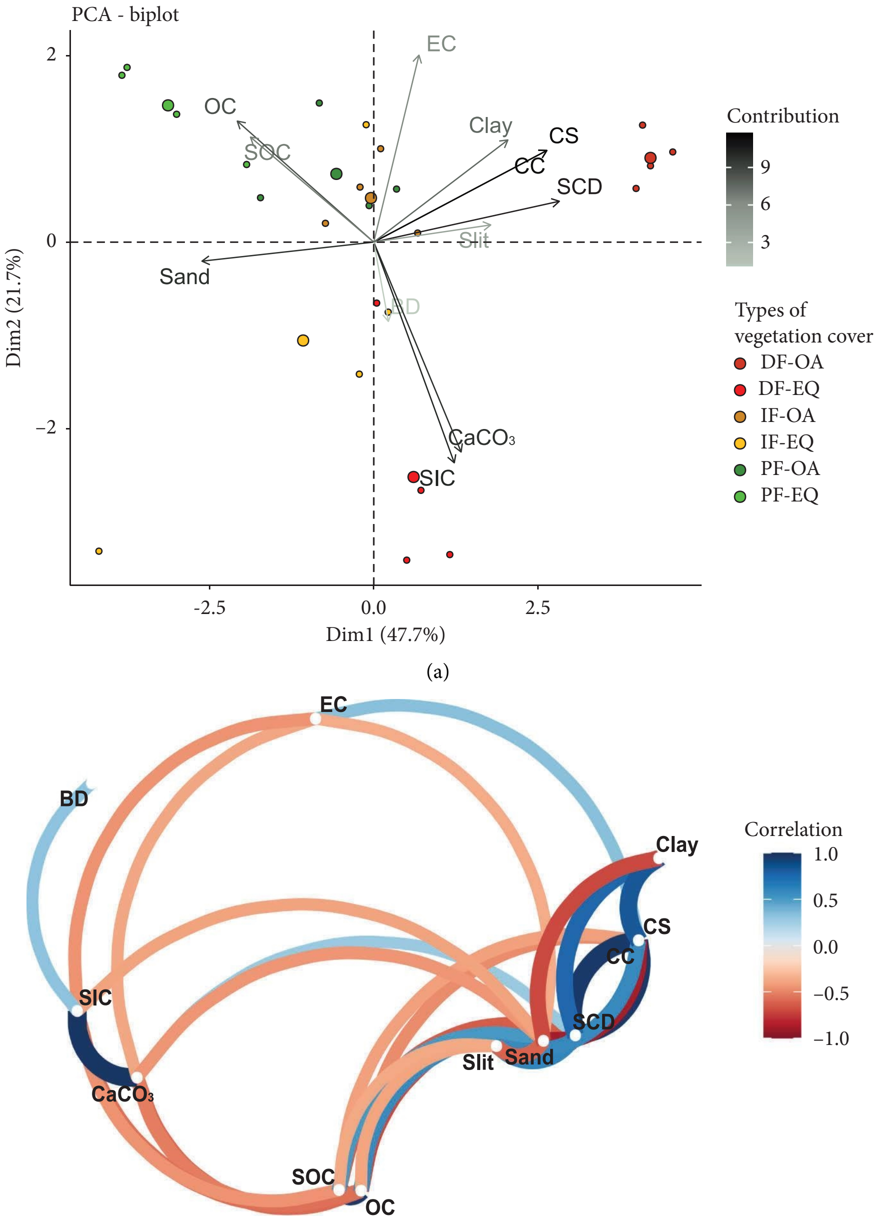
3.4. Correlation Between Soil and SOC Properties (PCA). The principal components selected are the Dim1 axis, which provides the most important statistical information with a representation rate of 45.5% and the Dim2 axis with 23.4%. These two axes explain 68.9% of the existing variability (Figure 3(a)). The variables that presented the greatest contribution in explaining the existing variability in the soils of the Central Huallaga forests were SCD, SC, CC, Sand, and SIC with 10.8%, 10.2%, 10.2%, 9.4% and 9.4%, respectively. It is evident that the primary forest in El Quinillal presented the highest values for OC and SOC. On the other hand, the highest values for SCD, CC and SC were recorded in the deforested forest of Ojos de Agua. The SCD is an indicator of the level of future C sequestration potential of SOC or the amount of space available for sequestration [37]. The higher the SCD, the greater the potential for future SOC sequestration [50]. At the same time the upper limit of SOC is not subject to decomposition due to mineral protection [54] especially clay. The SOC were influenced by vegetation cover, primary forests on average presented the highest values of OC and SOC, with the El Quinillal forest standing out, while deforested forest soils presented the opposite.

Table 3: Main physical and chemical characteristics of the soil in the forests studied.

Code	Representative species	pH	CaCO3 (%)	CEC (mS/cm)	OM (%)	BD (g/cm^3)	Sand (%)	Silt (%)	Clay (%)	Alt. (m)
PF-OA	*Manilkara bidentata* (A.DC.) A. Chev. Y *Brosimum alicastrum* swartz	7.9	11.01	17.60	6.6	0.9	35	27	38	399
IF-OA	*Attalea phalerata* mart. Ex spreng., *Trema micrantha* L y *Acacia polyphylla* DC.	7.9	12.69	13.60	4.2	1	33	29	38	427
DF-OA	*Zea Mays L.*	7.9	15.32	12.65	4.2	1.1	17.5	34	48.5	491
PF-EQ	*Manilkara bidentata* (A.DC.) A. Chev. Y *B. rosimum alicastrum* swartz	7.7	5.93	18.34	5.8	1.2	40.5	25	34.5	443
IF-EQ	*Trema micrantha* L y *Acacia polyphylla* DC.	8	15.17	21.50	5.4	1	33.5	39	27.5	371
DF-EQ	*Zea Mays L.*	8.4	18.22	21.72	2.5	1	35.5	30.5	34	330

Note: Sand: arena, Silt: limo, Clay: arcilla, Alt: altitude.

Abbreviations: BD, bulk density; $CaCO_3$, carbonate capacity; CEC, cation exchange; DF-EQ, deforested forest El Quinillal; DF-OA, deforested forest Ojos de Agua; IF-EQ, intervened forest El Quinillal; IF-OA, intervened forest Ojos de Agua; OM, organic matter; PF-OA, primary forest Ojos de Agua; PF-EQ, primary forest El Quinillal.



(a)

(b)

Figure 3: Correlation between soil and SOC properties. (a) Principal component analysis (b) correlation network.

Therefore, SOC reserves in the forests studied were affected by the type of vegetation (primary forest, intervened and deforested) and the physicochemical characteristics of the soil, as mentioned by Merabtene et al. [37] and Vallejos-Torres et al. [7]. This study shows that OC and SOC presented significant and positive correlations with sand with values of 0.594 and 0.528, respectively (Figure 3(b)). Likewise, sand presented significant and negative correlations with CS (−0.814), SCD (−0.856), CC (−0.814), Slit (−0.543) and Clay (−0.636). Therefore, higher SOC accumulation will be associated with macroparticles (fine to coarse sand) [55]. Climate change and changes in land use/land cover greatly influenced terrestrial C sequestration. Meanwhile, the *C* deficit in the soils of the study area is very alarming because it is very close to saturation levels. Likewise, this study allows us to demonstrate that the lowest SIC content was found in the primary forest, due to land use changes from natural vegetation to cropland.

4. Conclusions

The highest SOC averages were found in the primary forests of Ojos de Agua and El Quinillal, due to the fact that they still conserve adult forest species of great height and diameter, and the lowest were found in the deforested forests. This is due to the frequent change of use that the forests are undergoing for agricultural crops, basically corn crops, generating a critical degradation in the forests of Picota. These conditions have influenced the renewal of soil organic matter and, therefore, the storage of SOC reserves. The higher COS content found in the Ojos de Agua primary forest is due to the presence of dominant forest species such as *Manilkara bidentata* and *Brosimum alicastrum*. Likewise, the C deficit in the soils of the study area is very alarming because it is very close to saturation levels, and the lowest SIC content was found in a primary forest, due to changes in land use from natural vegetation to cropland. These can rapidly induce the loss of SIC that has been stable for several years.

Data Availability Statement

The data used to support the findings of this study are available upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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