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Forest land-use change affects soil organic carbon in tropical dry forests of the Peruvian Amazon

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Abstract

Aim of study: The loss of forest cover is a global problem that alters ecosystems, contributing to carbon emissions. This study measured the soil organic carbon (SOC) at different soil depth in tropical dry forests of the Huallaga Central in the Peruvian Amazon.

Area of study: San Martín Region, Peruvian Amazon.

Material and methods: A total of 24 plots of 100 m^2 were selected in primary (~200 years), intervened (~50 years since intervention), and deforested forests (10 years ago), with 120 soil samples collected across five depths. Soil texture (hydrometer), bulk density (cylinder method), SOC content, SOC density, and erodibility (K parameter) were calculated.

Main results: SOC content in the 0-20 cm soil horizon was 79.5±21.3 t ha^{-1} for the primary forest, 58.5±11.8 t ha^{-1} for the intervened forest, and 41.8±10 t ha^{-1} for the deforested forest. A soil erodibility K of 0.065 was observed for primary forests and 0.076 and 0.093 for intervened and deforested forests. In average, the SOC density obtained in this study was 7.6±5.1 t ha^{-1} in the primary forest, 6.2±3.6 t ha^{-1} in the intervened forest, and 4.7±2.7 in the deforested forest.

Research highlights: Primary forests had the highest SOC content and SOC density, followed by intervened and deforested forests, while the opposite pattern was found for soil erodibility. These patterns were especially marked in the first 40 cm of soil depth.

keywords: carbon stocks; land-use change; Peru; tropical dry forests; soil erodibility; soil depth; soil organic carbon density.

El cambio en el uso del suelo forestal afecta al carbono orgánico del suelo en los bosques secos tropicales de la Amazonía peruana

Resumen

Objetivo del estudio: La pérdida de cobertura forestal es un problema global que altera los ecosistemas, contribuyendo a las emisiones de carbono. Este estudio midió el carbono orgánico del suelo (COS) a diferentes profundidades en los bosques secos tropicales de la Huallaga Central en la Amazonía peruana.

Área de estudio: Región de San Martín, Amazonía peruana.

Material y métodos: Se seleccionaron un total de 24 parcelas de 100 m^2 en bosques primarios (~200 años), intervenidos

(~50 años desde la intervención), y deforestados (hace 10 años), con 120 muestras de suelo recolectadas a cinco profundidades. Se calcularon la textura del suelo (hidrómetro), la densidad aparente (método del cilindro), el contenido de COS, la densidad de COS, y la erodabilidad (parámetro K).

Resultados principales: El contenido de COS en el horizonte de suelo de 0-20 cm fue de 79.5±21.3 t ha^{-1} para el bosque primario, 58.5±11.8 t ha^{-1} para el bosque intervenido y 41.8±10 t ha^{-1} para el bosque deforestado. Se observó una erodabilidad K de 0.065 para los bosques primarios y de 0.076 y 0.093 para los bosques intervenidos y deforestados, respectivamente. En promedio, la densidad de COS obtenida en este estudio fue de 7.6±5.1 t ha^{-1} en el bosque primario, 6.2±3.6 t ha^{-1} en el bosque intervenido y 4.7±2.7 t ha^{-1} en el bosque deforestado.

Aspectos destacados de la investigación: Los bosques primarios presentaron el mayor contenido de COS y densidad de COS, seguidos por los bosques intervenidos y deforestados, mientras que el patrón opuesto se encontró para la erodabilidad del suelo. Estos patrones fueron especialmente marcados en los primeros 40 cm de profundidad del suelo.

Palabras clave: reservas de carbono; cambio en el uso del suelo; Perú; bosques secos tropicales; erodabilidad del suelo; profundidad del suelo; densidad de carbono orgánico del suelo

The translation of the title, abstract, and keywords from the original version in English to Spanish has been generated using OpenAI, ChatGPT GPT-4o mini (2024).

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Introduction

More than 40% of global terrestrial carbon is stored in primary tropical forests, although they only cover 6% of the world's terrestrial area (Ren et al., 2014). Most of the carbon of these primary forests stably accumulates in the soil (Zhou et al., 2006). Worldwide, tropical primary forests are especially susceptible to global climate and land-use changes. In a global-scale meta-analysis, Zhou et al. (2018) found reduced soil organic carbon (SOC) content when converting this type of forests to other land uses. About one third of the global soil carbon budget is stored in tropical soils (Jackson et al., 2017). Soil organic carbon would be relatively easily destabilized by the projected warming of tropical regions during the XXI century, which could accelerate global climate change by releasing more CO_2. Soil organic carbon consists of different chemical moieties of different stability, which, in addition to spatial inaccessibility (occlusion and organo-mineral associations) constitute an important stabilization mechanism (Yang et al., 2020).

Different factors affect how SOC is horizontally and vertically distributed, including environmental factors and human activities, which usually results in a high heterogeneity at different spatial scales. Climate, soil texture (Yuan et al., 2022), land use, plant cover, and root traits (Cusack et al., 2021) affect SOC content and spatial distribution through very specific inputs and outputs. Currently, the alarming tropical deforestation vastly decreases organic matter input into the soil, destabilizing soil organic matter, which ultimately alters soil carbon content of worldwide terrestrial ecosystems (Veldkamp et al., 2020). This is particularly the case in the Peruvian Amazon, where many areas have significant losses of plant cover and above- and underground biomass. Peru has approximately 740,000 km^2 of forests, most of them in the Amazon basin (MINAM, 2016). Annual deforestation in 2014 exceeded 1,770 km^2 and it is estimated that by 2030 it will exceed 3,500 km^2 (MINAM, 2016).

Very fast changes in forest cover have been occurring in the Peruvian Amazon due to the increase of the agricultural frontier and extractive activities. Peruvian forests are among the world's central carbon reserves of tropical forests, particularly in the Amazon. It is estimated that the Peruvian forests host a total of 6,928 PgC (only counting aerial carbon); from these, only 2.9 PgC are in protected areas (Csillik et al., 2019). According to reports from the National Forestry and Wildlife Inventory of Peru, carbon is mostly stored in the lowland forests, with carbon stocks of 138.8 t C ha^{-1} (SERFOR, 2021). However, these lowland forests generate 51.35% of all greenhouse gas emissions in Peru, with 97.393 GgCO_{2eq} that come mainly from the conversion of forest or protected lands to agricultural land use and other human activities in the Peruvian Amazon (MINAM, 2021). It is estimated that between 2010 and 2019, Peru annually emitted an average of 75,774,039.55

t CO_{2e} due to deforestation of Amazon forests (MINAM, 2021).

Soil organic carbon content plays a critical role in maintaining carbon balance and mitigating climate change, both nationally and globally. Soil organic carbon density is an important indicator of SOC content. Exploring the spatiotemporal dynamics of SOC density could allow policymakers to develop strategies to reduce carbon emissions (Chen et al., 2023). Soil erodibility is affected by soil aggregation, which in turn is affected by the land use system (Wassie, 2020). Therefore, erodibility has been considered in our study because soils in deforested sites have been evaluated for planting agricultural crops such as corn and rice, generating a strong change in land use. It is crucially important to carry out studies on carbon content of these dry forest soils. Thus, this study aimed to measure SOC content and SOC density, and soil erodibility, of the dry forest soils in the Peruvian Amazon with different plant covers, and at different soil depths.

Material and methods

Site of study

The study took place at two sites: i) “Ojos de Agua” forest, of 2,357.62 ha (6°50’50.99”S, 76°27’52.24”W; 382 m a.s.l.; mean annual temperature: 25.0°C; annual precipitation: 1167 mm; mean annual relative humidity: 73%; soil type: Eutric Cambisol), and ii) “El Quinillal” forest, of 10,557.07 ha (7°2’0.00”S, 76°19’52.42”W; 309 m a.s.l.; mean annual temperature: 25.5°C; annual precipitation: 1278 mm; mean annual relative humidity: 74%; soil type: Eutric Leptosol), which is located on the right bank of the Huallaga River (Fig. 1). Both forests are considered tropical dry forests and the tree species ‘Manchinga’ (*Brosimum alicastrum* (Swartz)) and Quinilla (*Manilkara bidentata* (A. DC.) Chev.) dominate. In recent years, they are affected by climate change and extensive corn crops (Vallejos-Torres et al., 2021). Both forests had the three plant covers subject of this study: primary forest (trees of approximately 200 years), intervened forest (intervention done approximately 50 years ago), and deforested forest (trees were cut down 10 years ago) (Fig. 1). Both sites were approximately 50 km from each other, and within each site, each plant cover type was 500-1000 m apart from each other.

Soil sampling

Soil sampling took place in April 2023. It was carried out with a shovel and a metal bar. Pits were made that were 1 m deep and 1 m wide. Before making the pits, the site was cleaned of weeds and leaf litter. Samples were taken from 0 to 100 cm because several previous studies (Xie et al., 2023; Ryzhova et al., 2023; Zhao et al., 2022), found significant C stock variation up to that depth. To study the vertical variation of SOC at the two sites, we selected a total of 24 plots (10 m × 10 m each), following the methodology of

Table 1. Characteristics of the forests (primary, intervened and deforested), sampled in the Huallaga Central, Peru.

Site	Cover type	Number of plots	Main plant species	Number of collected samples
Pucacaca	Primary forest	4	*Manilkara bidentata* (A. DC.) *A. Chev. y Brosimum alicastrum* (Swartz)	20
	Intervened forest	4	*Attalea phalerata* (Mart. ex Spreng.), *Trema micrantha* (L.), *Acacia polyphylla* (DC.)	20
	Deforested forest	4	*Zea mays* (L.)	20
Winge	Primary forest	4	*M. bidentata y B. alicastrum*	20
	Intervened forest	4	*T. micrantha, A. polyphylla*	20
	Deforested forest	4	*Z. mays*	

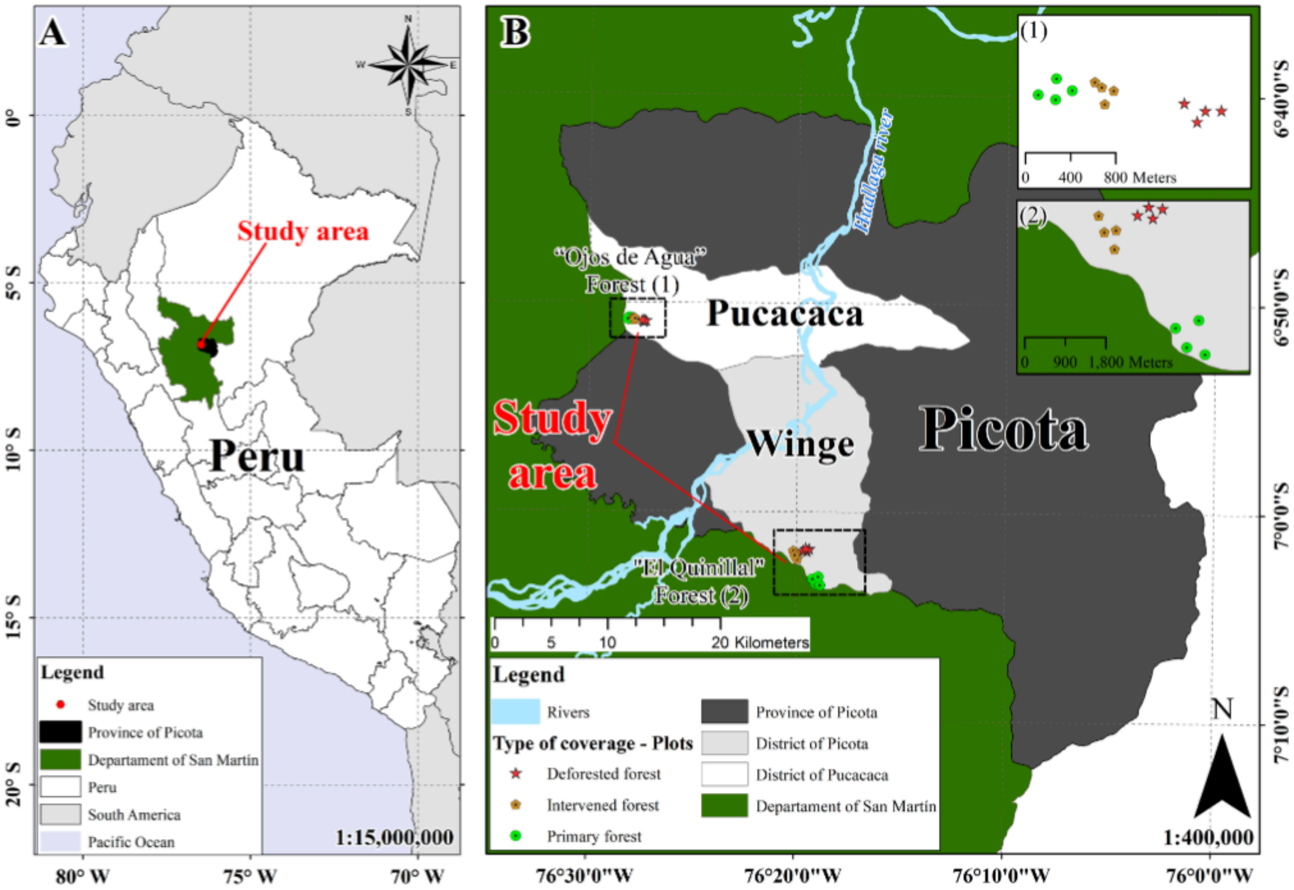

Figure 1. Map of the study area indicating the distribution of the sampled plots in the different types of forest in the Huallaga Central, San Martín, Peru.

Yu et al. (2019) and distributed in three vegetation covers, these being primary forest, intervened forest, and deforested forest (Table 1). The distance between coverages was 221 m, 1298 m and 2551 m minimum, average and maximum, respectively. In each cover, 4 randomly distributed plots were installed, the distance between them was minimum, average and maximum of 76 m, 350 m and 882 m (Fig. 1). Pits were made for study and sample collection at five soil depths for each plot along 0–20, 20–40, 40–60, 60–80, and 80–100 cm, with a total of 120 soil samples analyzed.

Soil organic carbon estimation

The cylinder (5.5 cm diameter, 5 cm height) method (Blake & Hartge, 1986) was used to estimate soil bulk density (BD) (in g cm^{-3}), as it follows:

BD: Wd/V…………….............................…..…… (1)

where: Wd: weight of the (oven-dried) soil sample (g), and V: sampled soil volume (cm^3). SOC concentration was estimated by wet oxidation following the Walkley & Black (1934) method; SOC stocks were calculated as it follows:

SOC (t ha^{-1}) = OC × De × BD……………………… (2)

where: OC: organic carbon content in the soil (%), De: sampling depth (cm), and BD: bulk density (g cm^{-3}).

Estimation of soil erodibility and SOC density

Soil erodibility (K) was estimated following Williams et al. (1984) model, as it follows:

$$K=\{0.2+0.3\exp[-0.0256SAN(1-SIL/100)]\}x\left[\frac{SIL}{CLA+SIL}\right]^{0.3}x\left[1.0-\frac{0.25SOC}{SOC+e^{3.72-2.95SOC}}\right]x\left[1.0-\frac{0.75SN_1}{SN_1+e^{-5.51+22.9SN_1}}\right]$$

where: SAN: sand content (%); SIL: silt content (%); CLA: clay content (%); SOC: soil organic carbon (%); and =1-SAN/100.

Soil organic carbon density (SOCD) at each soil depth (0–20, 20–40, 40–60, 60–80, and 80–100 cm) was calculated using the following formula:

$\mathrm{SOCD} = \mathrm{H_{ha}} \times \mathrm{BD_{ha}} \times \mathrm{SOC_{ha}} \times (1\text{-}\mathrm{C_{ha}})/100$

where: Hha: soil thickness (cm), BD$_{ha}$: soil bulk density (g cm^{-3}), SOC: soil organic carbon (t ha^{-1}), and C$_{ha}$: percentage of the soil volume with a fraction >2mm. All values in this formula were transformed to hectares.

Statistical analyses

All statistical tests were run in R Studio (R Core Team, 2024). The effects of vegetation cover in SOC at different depths were evaluated by analysis of variance (ANOVA)

Table 2. Pearson correlation between soil organic carbon (SOC) content and the variables studied at different soil depths.

Variable/soil depth	**0-20 cm**	**20-40 cm**	**40-60 cm**	**60-80 cm**	**80-100 cm**
Cover type	-0.742**	-0.559*	-0.284ns	-0.504*	-0.356ns
Sand (%)	0.322ns	0.181ns	0.084ns	0.324ns	-0.794**
Silt (%)	-0.346ns	0.106ns	-0.628**	-0.528*	0.531*
Clay (%)	-0.074ns	-0.287ns	0.699**	0.235ns	0.685**
Soil density (g/cm^3)	0.013ns	-0.137ns	-0.182ns	-0.615**	-0.488*
Soil water content (%)	0.203ns	-0.141ns	0.314ns	0.138ns	0.431ns
Soil erodibility	-0.386ns	-0.043ns	-0.600**	-0.485*	0.610**

*$p < 0.05$, **$p < 0.01$, ^{ns} non-significant.

at a significance level of 5%, while means comparison was performed with Tukey's test using the *agricolae* package in R Studio (Mendiburu, 2010). The categorical variable (cover type) was coded numerically following the methodology established by Yu et al. (2019): 0= Primary forest, 1= Intervened forest, and 2= Deforested forest. The correlation between SOC, vegetation cover type, and soil characteristics was evaluated by the Pearson's correlation test (α = 0.05), using the base R cor function. To evaluate the response variables that helped explain SOC content at different depths, a principal component analysis (PCA) together with a multiple linear regression (MLR) analysis (Kaiser, 1960) were run.

Results

Soil organic carbon content changes under different vegetation cover and soil depth

Soil organic carbon content decreased with increasing soil depth (Fig. 2). The mean SOC content in the primary

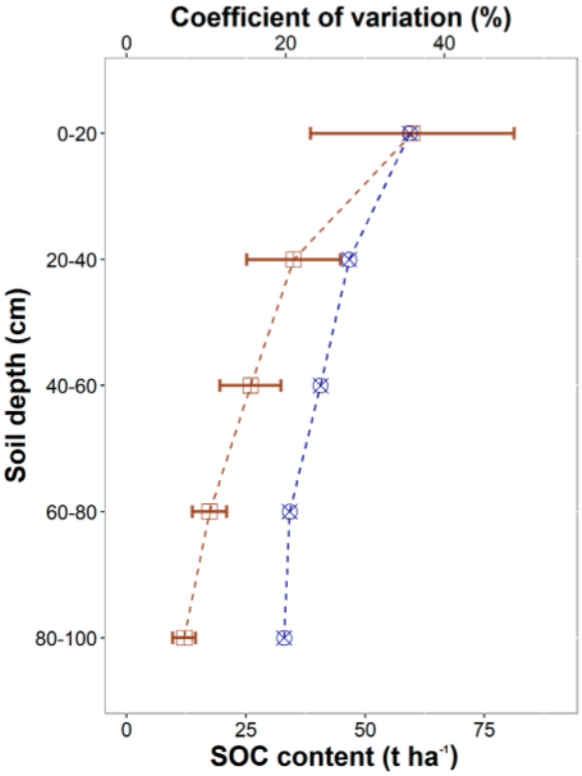

Figure 2. Vertical distributions of soil organic carbon (SOC) content (blue circles) and its coefficient of variation (CV) (brown squares), averaging across all land uses.

forest was 36.7±9.5 t ha^{-1}, for the intervened forest was 29.5±7.6 t ha^{-1}, and for the deforested forest, it was 22.8±7.6 t ha^{-1}, decreasing with increasing soil depth. In the superficial soil layer (0-20 cm), SOC content in the primary forest had a value of 79.5±21.3 t ha^{-1}, while in the deep layer (80-100 cm), it was 11.1±3.5 t ha^{-1}. The SOC content of the superficial soil layer (0-20 cm) in the intervened forest was 58.5±11.8 t ha^{-1} and in the deep layer (80-100 cm) was 12.8±2.4 t ha^{-1}. Meanwhile, the SOC of the superficial soil layer (0-20 cm) in the deforested forest had a value of 41.8±10 t ha^{-1}, while in the deep layer (80-100 cm), it was 7.4±5.3t ha^{-1} (Fig. 3). The mean SOC value at the superficial (0-20 cm) layer was 59.9±21.3 ha^{-1} and decreased at greater depth with values of 10.4±4.3 ha^{-1} (80-100 cm). With increasing soil depth, it was observed that the coefficient of variation (CV) decreased from 35.6% in the 0-20 cm soil layer to 19.8% in the 80-100 cm soil layer (Fig. 2). The SOC content in the three forest canopies showed significant differences for the first and second soil depths, with the primary forest having the highest SOC. In general, in the first 0-40 cm, the SOC content decreased rapidly with soil depth, showing significant differences between plant covers, but below 40 cm, it did not show significant differences (Fig. 3).

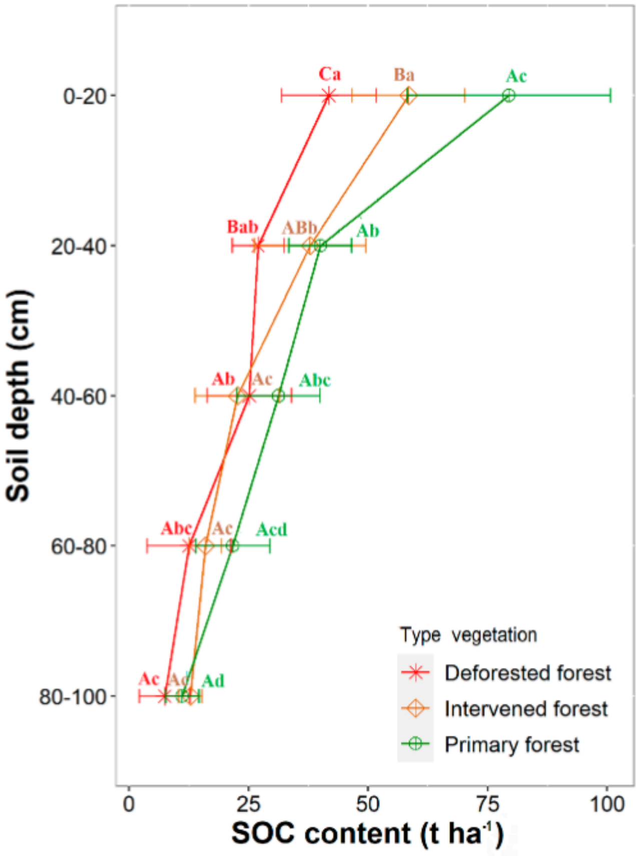

Figure 3. Distribution of mean soil organic carbon (SOC) content across different land uses and soil depths. Uppercase and lowercase letters represent significant differences between land use types and soil depth ($p < 0.05$), respectively.

Soil organic carbon correlation analyses

The cover type and SOC had a significant, negative correlation at soil depths from 0 to 40 cm and 60 to 80 cm soil depth (Table 2). Overall, most tested variables were not correlated with SOC for the first 40 cm soil depth, but after this depth, variables like clay, silt, and soil erodibility presented some significant correlations (Table 2).

Factors contributing to SOC variation

The main variables that contributed to explain the SOC in the superficial horizon (0-20 cm) were cover type, soil density, and soil erodibility with 13.8%, 13.4%, and 12.6%, respectively (Fig. 4). In the 20-40 cm horizon, the main variables were sand content, soil erodibility, and cover type with 14.9%, 13.5%, and 11.3%, respectively. In the 40 to 60 cm horizon, the main variables were soil erodibility, silt content, and clay content with 14.6%, 13.4%, and 13.1%, respectively. For the 60 to 80 cm horizon, the main variables were cover type and sand content with 13.2% and 12.9%, respectively. And for the 80 to 100 cm horizon, sand and silt content with 13.7% and 12.2%, respectively. It is generally evident that SOC was mostly explained by soil erodibility, followed by cover type and texture with an average of 12.8%, 11.53%, and 11.08%, respectively. Soil water content presented the lowest contribution, with an average of 7.3 % (Fig. 4).

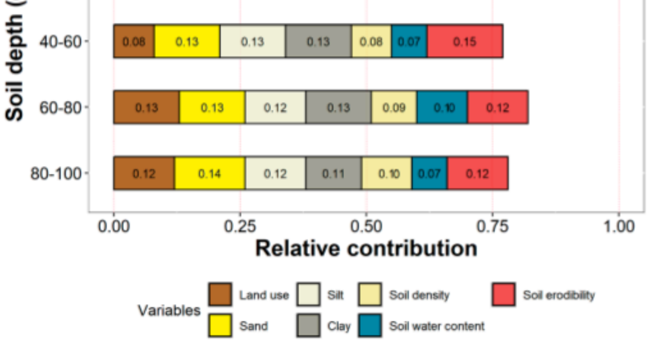

Figure 4. Relative contribution of different soil variables to soil organic carbon (SOC) content at different soil depths.

The profile distribution of SOC fractions

The SOC obtained in this study was 7.6±5.1 t ha^{-1} in the primary forest, 6.2±3.6 t ha^{-1} in the intervened forest, and 4.7±2.7 t ha^{-1} in the deforested forest when evaluated between 0 to 100 cm depth. SOC density presented significant differences in the layers from 0 to 40 cm, but not from 40 to 100 cm (Fig. 5 A). The highest SOCD content was recorded in the surface layer from 0 to 20 cm with an average of 11.69 t ha^{-1}, representing 40.4% of the total SOC stock in the entire profile (0–100 cm). In the 20 - 40 cm soil layers, the average SOCD was 7.2 t ha^{-1}, representing 23.5% of the total SOC stock. In the 40 to 60-cm soil layers, the average SOCD was 5.7 t ha^{-1}, representing 17.7% of the total SOC stock. In the 60 to 80-cm soil layers, the average SOCD was 3.8 t ha^{-1}, representing 11.3% of the total SOC stock. In the 80–100 cm soil layers, the mean SOCD was 2.4 t ha^{-1}, representing 7% of the total SOC stock in the entire 0–100 cm soil profile (Fig. 5 B).

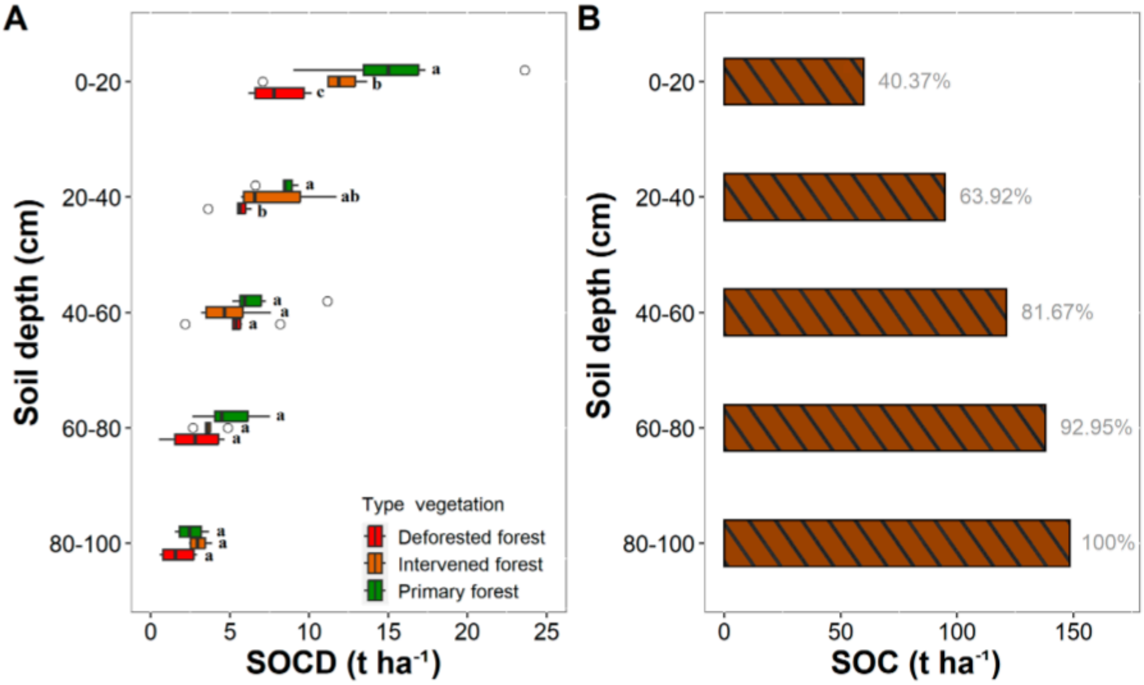

Figure 5. A. Mean soil organic carbon density (SOCD) in various soil layers and land uses. Lowercase letters represent significant differences between vegetation types ($p < 0.05$). B. Accumulated soil organic carbon (SOC) pool across soil depths.

Discussion

Soil organic carbon characteristics in the soil profile

The results found are close to those reported by Solis et al. (2020), who showed 87 t C ha^{-1} in a coffee system with *Inga* trees. Plant cover profoundly affects soil carbon stocks (Arasa-Gisbert et al., 2018) and soil carbon sequestration, more precisely at the 0-15 cm layer (between 33.2 t ha^{-1} and 52.7 t ha^{-1}) (Boulmane et al., 2010). A possible reason for this is the soil's microbial communities – which differ among plant covers, and their influence in the cycling and accumulation of SOC (Weverka et al., 2023).

Soil organic carbon variation with soil depth and plant cover

Species-rich plant communities are more productive and exhibit more significant long-term SOC content. Soil microorganisms are essential for converting plant organic matter into SOC; consequently, the greater the canopy cover and height, the greater the SOC content (Siswo et al., 2023). Overall, our findings were consistent with many previous studies showing that vegetation increases SOC (Saíz et al., 2012; Gruba et al., 2015). In our study, primary forests present Manchinga (*B. alicastrum*) and Quinilla (*M. bidentata*) trees as dominants with a larger diameter at breast height and greater height, while in intervened and deforested forests there are no trees of these species due to the massive extraction of wood, making *M. bidentata* a threatened species (Vallejos-Torres et al., 2021). The distribution of C components in the soil surface is largely influenced by the chemical nature of the forest litter from which SOC originates. The species-specific litter quality determines the compositional characteristics of organic matter input to the soil and influences the magnitude of decomposition processes by microorganisms. Leaf litter introduces organic materials into the soil in different quantities and qualities, influencing the formation and stability of the soil C reserve. Dissolved organic matter in forest ecosystems significantly affects soil carbon cycling due to litter decomposition (Morffi-Mestre et al., 2023); therefore, litter-derived dissolved organic carbon is considered an important source of stabilized C in soil (Preusser et al., 2021). Vegetation type and soil depth affect soil carbon distribution by changing soil physical and chemical properties and microbial activity, as shown in previous research (Song et al., 2016). Soil organic carbon content was generally low in deforested forests with weeds due to sparse vegetation, shallower root systems, and lower root biomass, especially evidenced by fewer roots in deeper soils (Jia et al., 2017).

Soil organic carbon correlation analyses

Our land-use results showed a significant correlation at soil depths from 0-40 cm and from 60-80 cm depth and of soil erodibility with SOC between 0-80 cm depth, similar to the results found by Yu et al. (2019). The lower soil erodibility in the primary forest can be attributed to the greater amount of soil organic matter (SOM) compared to intervened and deforested forests. Land use type can affect soil properties and plant community characteristics, likely affecting soil erodibility (Chen et al., 2023). In turn, soil erodibility is related to the granulometry, structure, and stability of soil aggregates, which indicates that soils with higher silt content are more erodible than clay soils. Meanwhile, SOM also plays a vital role in soil erodibility by maintaining the stability of soil aggregates (Deng et al., 2018). In our results, the clay fraction did not show a significant correlation with SOC. At the same time, there was a negative correlation of SOC with the sand fraction, results consistent with Zhong et al. (2018). The physicochemical properties of soil are interrelated and affected by land use and management activities (Thabit et al., 2023). Primary forests influence carbon contents due to the large amounts of organic matter associated with the thickest soil fraction.

Contributions of environmental factors to variations in SOC

Soil organic carbon is affected by many related factors and is regulated in complex ways, with spatial differences both higher and lower in the soil column. Land use and soil factors significantly influenced SOC content. In this study, the effects of soil water content on SOC content also decreased with soil depth, influenced by the vegetation cover (Wang et al., 2022). The physicochemical properties of top soils and deep soils were significantly different. Therefore, the regulatory factors and mechanism of SOC varied between soil layers. Generally, the accumulation of SOC on the surface results from interactions between abiotic processes regulated by environmental factors and biotic processes regulated by microbes. Because the surface soil contains a large amount of plant litter, sufficient water and air on the surface are also conducive to increase soil microbial activity (Zhang et al., 2021). The SOC changed significantly in the different forest types. This can be attributed to the increase in organic materials (litter and roots), as Xing et al. (2023) indicated that the highest SOC content found in the first soil horizons in primary forests is due to the presence of roots.

In this study we found a significant negative correlation between soil bulk density and SOC, indicating that bulk density does not influence the leaching of surface SOC to deep soil layers since low SOC in deep soils is related to the high density in tropical forests (Yang et al., 2016). In our study we found some contrasting results with Jia et al. (2017), who investigated carbon stocks in different vegetation covers in deep soils and indicated that land use significantly affects deep SOC. In addition to land use type, soil factors also significantly impact the vertical distribution of SOC (Jiang et al., 2017). Soil moisture content positively correlated with SOC; therefore, SOC decomposition and soil C content were associated with changes in soil environment and soil microbial biomass due to soil moisture variation.

Soil organic carbon fraction distribution

In our study, 37.80% of SOCD and 40.37% of SOC were concentrated between 0-20 cm soil depth, and this decreased with soil depth in such a way that 7.88% of SOCD and 7.05% of SOC occurred in the 80-100 cm depth profile in the forests studied. This fraction distribution is controlled by factors such as humidity and bulk density along soil depths (Zhuo et al., 2022). It is known that soils with high SOCD contain a high accumulation of organic matter (Arunrat et al., 2020) and, therefore, high carbon content, as found in our study. The vegetation cover type also influenced SOCD; primary forests with dense vegetation cover have the highest SOCD, followed by intervened forests, and forests deforested with cultivars (Zhu et al., 2021). Studies have shown that an increase in vegetation cover, such as in a primary forest, could facilitate carbon accumulation in the soil and, therefore, increase SOCD (Gong et al., 2017). This can be attributed to (i) an increase in plant root productivity, (ii) a reduction in SOC loss by effectively blocking wind erosion, and (iii) the accumulation of litter on the soil surface. Generally, the increase in vegetation is followed by an increase in litter (Tian et al., 2022). Yu et al. (2019) found that the SOC content of each vegetation type ranged in the following order: forest land, cropland, and grassland. This is corroborated by Zhao et al. (2019), who found that humidity is one of the most critical factors that control the variations of SOCD studied between 0 cm to 100 cm soil depth.

In summary, this study of vertical variation of carbon at depths of 0-100 cm showed that vegetation cover significantly affects soil carbon stocks, more significantly at the 0-20 cm layer. Primary forests present Manchinga (*B. alicastrum*) and Quinilla (*M. bidentata*) trees as dominants with a larger diameter at chest height and greater height, while in the intervened and deforested forests, there are no trees of these species. The lower soil erodibility found in the primary forest can be attributed to a greater soil organic matter (SOM) content compared to intervened and deforested forests. Land use affects soil properties and plant community characteristics, which are likely to affect soil erodibility. In this study, the effects of soil water content on SOC content also decreased with soil depth, influenced by the vegetation cover index and soil bulk density. The types of vegetation cover also influenced SOC density. Above all, primary forests with dense vegetation cover have the highest SOC density, followed by intervened forests and forests deforested with cultivars.

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