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RESEARCH ARTICLE

Soil organic carbon balance across contrasting plant cover ecosystems in the Peruvian Amazon

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ABSTRACT

The Peruvian Amazon has been significantly affected by land use and climate change, decreasing decomposition processes, which cause a significant depletion of soil C stocks. In this study, we estimated soil organic C (SOC) mediated by different plant covers in coffee (*Coffea arabica* L.) plantations and secondary forests in several districts of the San Martín Region, Peru. We calculated the critical threshold, saturation point, and the organic C deficit of these Amazonian soils. The association between geography, soil physical-chemical characteristics, and SOC was estimated through principal component analysis. Across all sites of the study, SOC stock had an average value of 69.19 t ha^{-1}, with 48.95 t ha^{-1} constituting inorganic C. The highest SOC stock (225.28 t ha^{-1}) was observed under secondary forest in the Jepelacio district. The SOC stocks were positively correlated with altitude and $CaCO_3$ content only in secondary forests. The current measured amount of organic C within 15 cm soil depth was 28.5 g C kg^{-1}, which is very low and close to the critical threshold (20.6 g C kg^{-1}) -estimated based on its clay and silt contents. Our SOC stocks measurements indicated a worrisome situation, as they are close to the critical threshold, which exposes this area to a greater and stronger degradation.

Key words: *Coffea arabica*, critical threshold, forestry soil, Peru, plant cover, saturation point, SOC deficit.

INTRODUCTION

Over the last decades, C sequestration in soils has been considered one of the fundamental solutions to mitigate the considerable global increases in CO_2 levels -and its warming effects- in the atmosphere. Therefore, soils fulfill a fundamental global ecosystem function service, C storage (Baveye et al., 2020). For the period 2010-2019, the global CO_2 budget in soils and permafrost was 1700 and 1200 PgC yr^{-1}, respectively. The CO_2 budget in soil is higher than the budget in the surface + dissolved organic C of the ocean (1600 PgC yr^{-1}), and 3.8 and 2.9 times higher than the budgets from vegetation and the atmosphere, respectively (Canadell et al., 2021). Increasing soil organic C (SOC) stocks could become an important alternative towards the development of more sustainable agricultural systems, while addressing climate change, sustainable and safe food production, and poverty (Begum et al., 2022).

It is crucial to implement efficient management strategies for soils with permanent vegetation and plantations with shade trees. Thus, because plant functional traits mediate interspecific differences in productivity, they in turn influence the magnitude of belowground C stocks (Waring et al., 2022). Furthermore, on a global scale, elevated CO_2 tends to increase plant biomass but decrease soil C (Terrer et al., 2021), implying that higher plant production may actually lead to underground C losses. Vegetation type plays a crucial role in determining SOC stocks and soil physical, chemical, and biological properties, especially in the upper layers (Zhang et al., 2021).

In the Peruvian region of San Martín, agroforestry systems can play an important role in mitigating the effects of climate change, given their ability to increase tree diversity and store more C than conventional trees used in agriculture. The largest C stocks in different agroforestry systems with coffee trees (*Coffea arabica* L.) in the Amazon rainforest of Peru have been found in the soil (67%-96% of the total C stocks) (Solis et al., 2020), demonstrating that is fundamental to include trees in agricultural systems to improve soil properties and increase C stocks (Alegre et al., 2017; Dollinger and Jose, 2018). Therefore, secondary forests growing on previously cleared land could be a low-cost climate change mitigation strategy due to their high potential to sequester CO_2 (Veldman et al., 2019; Elias et al., 2022).

There are few detailed studies that provide precise SOC stock estimations in the San Martín region and in the Peruvian Amazon overall (Solis et al., 2020). Furthermore, few studies have investigated SOC balance (organic C, saturated C, C saturation deficit, current C, critical C, among others) in Amazonian ecosystems, accounting for geographical, plant, and soil physical-chemical characteristics. Previous studies in the Peruvian Amazon have investigated soil texture and total SOC contents, so, the next logical step is to understand the spatial distribution and balance of SOC, based on soil physical and chemical characteristics in coffee plantations and secondary forests. Based on this, we aimed to: 1) Quantify the SOC stocks in coffee plantations and secondary forests in the Peruvian Amazon; 2) analyze the effects of different agroforestry covers and soil physical-chemical properties on the SOC stocks; and 3) break down the general balance of SOC based on its critical threshold.

MATERIALS AND METHODS

Study area

Coffee (*Coffea arabica* L.) plantations and secondary forests were located in the Provinces of Moyobamba and Lamas in the districts of Soritor (977-1065 m a.s.l.), Jepelacio (1209-1332 m a.s.l.), and Tabalosos (704-783 m a.s.l.), San Martín Region, Peru (Table 1, Figure 1). The San Martín Region presents a heterogeneous physiography, with two physiographic provinces, the Andean Mountain range and the Amazon plain, characterized by mountainous and flat relief, respectively. The average annual precipitation and temperature in these provinces is 1800 mm and 25 °C, respectively (Solis et al., 2020).

Experimental design

We investigated three Districts in the San Martín Region, Perú: Tabalosos (T), Soritor (S), and Jepelacio (J). Each District had a total of four sites: Three coffee plantation systems, namely coffee monoculture (CM), coffee with guaba (*Inga* spp.) (CG), and coffee with polycultures (CP), and a secondary forest (BS, by its initials in Spanish) (Table 1); overall we investigated 12 sites. On each site, three plots (5 m × 20 m) were established (36 plots), and a composed sample was taken by plot (36 soil samples analyzed). For soil sampling, the technical guide for soil sampling of the Ministry of the Environment (MINAM, 2014) was followed. Soil samples were collected between September and November 2022 at a depth of 0-15 cm. During the sampling period average monthly temperature and average monthly relative humidity were 26.4, 26.01, 25.83 ºC and 86.65%, 87.04%, 87.42% for T District; 22.91, 23.21, 23.64 ºC and 82.16%, 81.43%, and 80.88% for S District; and 22.18, 23.13, 22.74 ºC and 82.83%, 83.77%, and 82.68% for J District, respectively. Data were taken from the Peruvian SENAMHI (2022) database on each respective climatic station.

Table 1. Characteristics of the selected coffee plantations and secondary forests in the districts of Tabalosos, Soritor and Jepelacio in the San Martín region, Peru. Abbreviations for first two letters: Coffee monoculture (CM), coffee with guaba (CG), coffee with polycultures (CP), and secondary forest (BS). Abbreviation for third letter: Tabalosos (T), Soritor (S), and Jepelacio (J) districts, San Martín Region, Peru.

Sites abbreviation	Altitude (m a.s.l.)	Soil type	Soil texture	Dominant vegetation
CMT	772	Inceptisol	Clay loam	*Coffea arabica* L.
CMS	977	Humic tropical Mollisol	Clay loam	
CMJ	1221	Alluvial Entisol	Clay loam	
CGT	783	Inceptisol	Clay	*C. arabica*, *Inga* spp.
CGS	1061	Humic tropical Mollisol	Sandy clay loam	
CGJ	1217	Alluvial Entisol	Clay	
CPT	704	Inceptisol	Clay	*C. arabica*, *Cedrela odorata* L., *Citrus ×sinensis* (L.) Osbeck, *Persea americana* Mill., *Theobroma cacao* L.
CPS	1065	Humic tropical Mollisol	Clay loam	*C. arabica*, *Inga* spp., *Schizolobium amazonicum* Huber ex Ducke, *Musa ×paradisiaca* L., *T. cacao*
CPJ	1209	Alluvial Entisol	Clay	*C. arabica*, *Inga* spp., *C. odorata*, *S. amazonicum*
BST	769	Inceptisol	Clay loam	*Inga* spp., *Trema micrantha* (L.) Blume, *Colubrina glandulosa* Perkins, *Cecropia sciadophylla* Mart., *Manilkara zapota* (L.) P. Royen
BSS	1038	Humic tropical Mollisol	Clay	*C. sciadophylla*, *Calophyllum brasiliense* Cambess., *Cordia alliodora* (Ruiz & Pav.) Oken, *Ocotea* spp.
BSJ	1332	Alluvial Entisol	Sandy clay loam	*C. brasiliense*, *C. alliodora*, *Nectandra* spp.

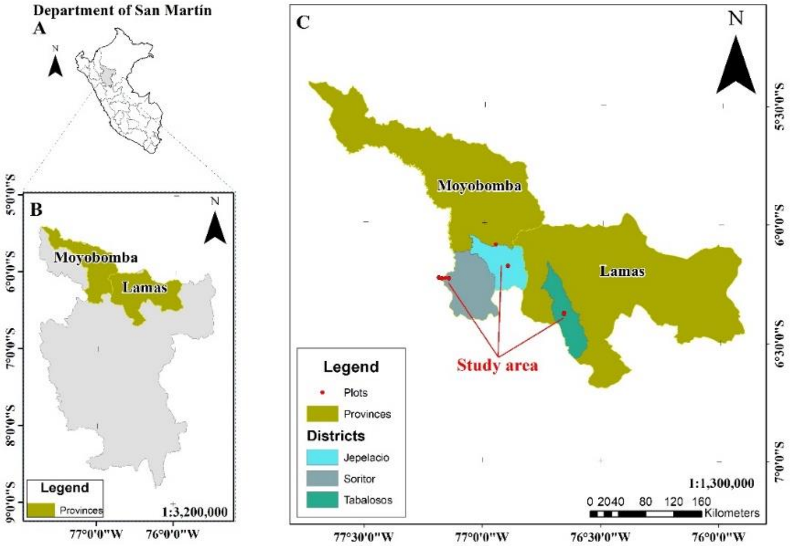


Figure 1. Map of the study area indicating the distribution of the sampled plots.

Soil analyses

For the physical-chemical characterization of the soils, samples were taken to the laboratory of the Institute of Tropical Crops, San Martín, Peru. The cylinder method of 5.2 cm in diameter and 5 cm in height proposed by Blake and Hartge (1986) was used to calculate soil bulk density (BD), determined by the following formula:

$$BD = Wd/V \qquad (1)$$

where BD is bulk density (g cm^{-3}), Wd is weight of the oven-dried soil sample (g), and V is the volume of sampled soil (cm^3). Therefore, SOC was determined using the method developed by Walkley and Black (1934) in the laboratory, using the formula:

$$SOC\ (t\ C\ ha^{-1}) = OC \times Sd \times BD \qquad (2)$$

where OC is organic C content in soil (%), Sd is depth of soil sampling (cm), and BD is bulk density (g cm^{-3}). Soil texture was measured by the hydrometer texture method, pH and electrical conductivity were measured using a suspension potentiometer in a 1:2.5 soil-water solution, carbonates ($CaCO_3$) -inorganic C- of soil was determined by the gas-volumetric method, soil organic matter (SOM) by the Walkley and Black method, cation exchange capacity (CEC) by potential acidity + sum of bases, and calcium carbonate by the volumetric gas method. Saturated C (SC) was determined by applying the Hassink (1997) equation:

$$C_{saturation}\ (\%) = 4.09 + 0.37\ (\%\ Clay + \%\ Fine\ silt) \qquad (3)$$

Stable C value was compared with the soil C measured, and from there, the saturated C deficit was measured (Angers et al., 2011):

$$C_{saturation\ deficit} = C_{saturation} - C_{current} \qquad (4)$$

Critical C (%) was calculated considering the clay and silt fraction, applying the formula of Autfray et al. (2009):

$$C_{critical}\ (\%) = [0.32\ (\%\ Clay + \%\ Fine\ silt) + 0.87]/10 \qquad (5)$$

where $C_{critical}$ represents the minimum value of organic C in the soil that allows maintaining structural stability without risks of degradation (Merabtene et al., 2021).

Statistical analyses

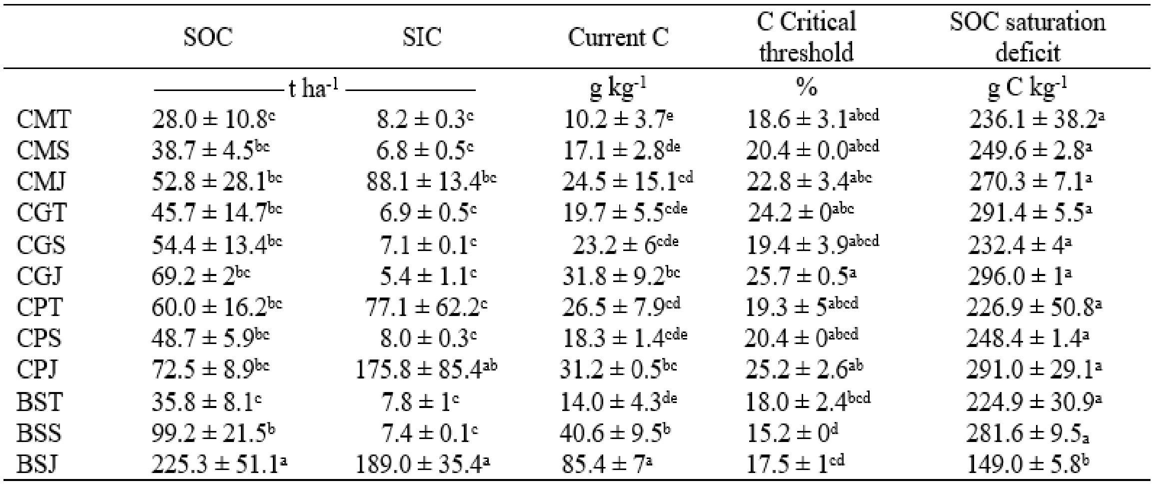
The collected data were processed in R Studio (R Core Team, 2020). First, the existence of significant differences between canopy types was verified for the variables SOC, inorganic C, current C, critical threshold, and SOC deficit (Tukey, $p < 0.05$). Subsequently, two bivariate correlation tests were performed (Spearman, $p < 0.05$). The quantitative variables evaluated were CO (%), altitude, $CaCO_3$, and SOC. Correlation was performed with the R base *cor* function and a linear regression model was also fitted with the R base *lm* function. A principal component analysis (PCA) was performed to determine if there is a correlation between the variables and their influence on the sites and cover types; a correlogram was also performed to check these correlations. The *fviz_pca_biplot* function of the Factoextra package of R (Kassambara and Mundt, 2020) was used to perform the PCA.

RESULTS AND DISCUSSION

Variation of SOC stock under different vegetation covers

The highest OC values were obtained under secondary forest vegetation covers located in the districts of Jepelacio and Soritor (which had higher altitude), with rates of 8.54% and 4.06%, respectively (Table 1). Among coffee plantation plots, the one with Inga shade trees in Jepelacio presented the highest OC with 3.18%. The lowest percentages were registered under covers of secondary forest and coffee without shade located in the district of Tabalosos, with 1.40% and 1.02%, respectively. At the same time, among coffee plantations, coffee cultivars with polyculture in the Jepelacio district presented the highest C content with 72.51 t ha^{-1}. The maximum value of SOC stocks was found in the secondary forest of Jepelacio district with a value of 225.28 t ha^{-1} ($p < 0.05$). The soils with coffee establishment as a monoculture and secondary forest of the district of Tabalosos presented the lowest C contents with 28.02 and 35.80 t ha^{-1} ($p < 0.05$), respectively (Table 2).

Table 2. Variation of soil organic C (SOC) stocks, soil inorganic C (SIC), current C content, C critical threshold and SOC saturation deficit of soils under the selected vegetation covers in coffee plantations and secondary forest of Moyobamba and Lamas, San Martín region. Coffee monoculture (CM), coffee with guaba (CG), coffee with polycultures (CP), and secondary forest (BS). Abbreviation for third letter: Tabalosos (T), Soritor (S), and Jepelacio (J) districts, San Martín Region, Peru. Avg-SD: Average-standard deviation. Groups according to a Tukey test.



	SOC	SIC	Current C	C Critical threshold	SOC saturation deficit
	t ha^{-1}		g kg^{-1}	%	g C kg^{-1}
CMT	28.0 ± 10.8^{c}	8.2 ± 0.3^{c}	10.2 ± 3.7^{e}	18.6 ± 3.1^{abcd}	236.1 ± 38.2^{a}
CMS	38.7 ± 4.5^{bc}	6.8 ± 0.5^{c}	17.1 ± 2.8^{de}	20.4 ± 0.0^{abcd}	249.6 ± 2.8^{a}
CMJ	52.8 ± 28.1^{bc}	88.1 ± 13.4^{bc}	24.5 ± 15.1^{cd}	22.8 ± 3.4^{abc}	270.3 ± 7.1^{a}
CGT	45.7 ± 14.7^{bc}	6.9 ± 0.5^{c}	19.7 ± 5.5^{cde}	24.2 ± 0^{abc}	291.4 ± 5.5^{a}
CGS	54.4 ± 13.4^{bc}	7.1 ± 0.1^{c}	23.2 ± 6^{cde}	19.4 ± 3.9^{abcd}	232.4 ± 4^{a}
CGJ	69.2 ± 2^{bc}	5.4 ± 1.1^{c}	31.8 ± 9.2^{bc}	25.7 ± 0.5^{a}	296.0 ± 1^{a}
CPT	60.0 ± 16.2^{bc}	77.1 ± 62.2^{c}	26.5 ± 7.9^{cd}	19.3 ± 5^{abcd}	226.9 ± 50.8^{a}
CPS	48.7 ± 5.9^{bc}	8.0 ± 0.3^{c}	18.3 ± 1.4^{cde}	20.4 ± 0^{abcd}	248.4 ± 1.4^{a}
CPJ	72.5 ± 8.9^{bc}	175.8 ± 85.4^{ab}	31.2 ± 0.5^{bc}	25.2 ± 2.6^{ab}	291.0 ± 29.1^{a}
BST	35.8 ± 8.1^{c}	7.8 ± 1^{c}	14.0 ± 4.3^{de}	18.0 ± 2.4^{bcd}	224.9 ± 30.9^{a}
BSS	99.2 ± 21.5^{b}	7.4 ± 0.1^{c}	40.6 ± 9.5^{b}	15.2 ± 0^{d}	$281.6 \pm 9.5_{a}$
BSJ	225.3 ± 51.1^{a}	189.0 ± 35.4^{a}	85.4 ± 7^{a}	17.5 ± 1^{cd}	149.0 ± 5.8^{b}

The OC measured at 15 cm soil depth in the Moyobamba and Lamas districts registered an average of 30.21 g kg^{-1}, with the highest and lowest recorded in the secondary forest in Jepelacio and in the soils with coffee plantations without shade trees located in the district of Tabalosos with 85.40 and 10.2 g kg^{-1} ($p < 0.05$), respectively (Table 2). These results are close to those obtained by Merabtene et al. (2021), where they estimated organic C stocks of the forest floor of Mount Tessala in northwest Algeria with reliefs from 500 to 1000 m a.s.l. Bounouara et al. (2017) recorded 100 and 168 t ha^{-1} of SOC stocks in the Skikda region, Algeria, at altitudes ranging from 13 m to 140 m a.s.l. Similarly, Solis et al. (2020) found that SOC stocks in coffee plantations represented 67%, 82%, and 96% of the total C reserve.

Regarding coffee growing with shade trees, Solis et al. (2020) found SOC stocks in the shaded coffee polyculture system of 189 t C ha^{-1}, while coffee with shade (Inga) and without shade was 146 and 113 t C ha^{-1}, respectively. In our study, coffee with shade trees had 72.51 t ha^{-1}. Balaba and Byakagaba (2016) found that there was a higher SOC stock under coffee with agroforestry systems than under coffee monocultures; likewise, they found a higher C content between 0 and 15 cm soil depth, than on deeper soils. Higher C content can clearly be noted in a Jepelacio secondary forest at higher elevations, followed by the secondary forest of the Soritor. These results are similar to those shown by França et al. (2022), where SOC concentrations decreased under coffee at a soil depth of 0 to 5 cm, but increased below 10 cm soil depth at 1260 m a.s.l., compared to a native forest control. Wallwork et al. (2022) reported a strong association between the functional composition of the forest mass and the C reserves of the soil between 0 and 10 cm of depth, therefore, the C reserves increased due to the effect of tree species that demand light.

Relationship between SOC and altitude

In the secondary forest, altitude and SOC showed a significant positive correlation ($R^2 = 0.979$, $p < 0.001$) (Figure 2). The Jepelacio soils under secondary forest showed an average SOC stock of 225.28 t ha^{-1} at an altitude of 1332 m a.s.l., while the soils with the lowest C content were located in the Tabalosos district under coffee monoculture without shade trees, with an average of 28.02 t ha^{-1} at an altitude of 772 m a.s.l. (Figure 3). Many authors have presented similar patterns, such as Okello et al. (2022), who revealed that along the altitudinal gradient, soil organic C increased six times from 2.6% at 1.250-1.300 m a.s.l. to 16.0% at 2700-3000 m a.s.l. Likewise, Dieleman et al. (2013) found that SOC in tropical forests varied in a predictable manner with altitude, ranging from 4.8 to 19.4 kg C m^{-2} and increasing by 5.1 kg C m^{-2} for every 1000 m increase in altitude. Also, it has been shown that SOC and the stability of recalcitrant and labile soil aggregates increased with altitude (Abalori et al., 2022). Tashi et al. (2016) indicated that C content was similarly correlated with altitude, with temperature apparently being the driver of soil C content along the altitudinal gradient. The accumulation of SOC along the altitudinal gradient occurs due to slower decomposition activities under cooler conditions at higher elevations compared to lower elevations (Luo et al., 2006), resulting in an accumulation of organic matter (Spehn et al., 2012). Elevation changes are known to create gradients in factors that in turn affect soil erosion and C cycling (Guangyu et al., 2022).

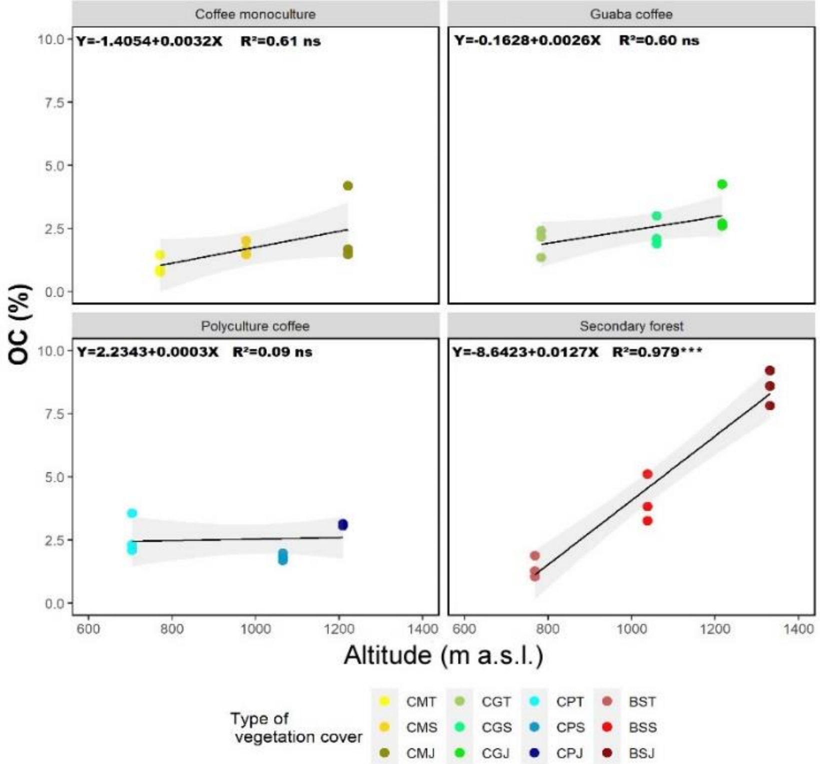


Figure 2. Correlation between altitude and soil organic C (OC) on different plant covers. Coffee monoculture (CM), coffee with guaba (CG), coffee with polycultures (CP), and secondary forest (BS). Abbreviation for third letter: Tabalosos (T), Soritor (S), and Jepelacio (J) districts, San Martín Region, Peru.

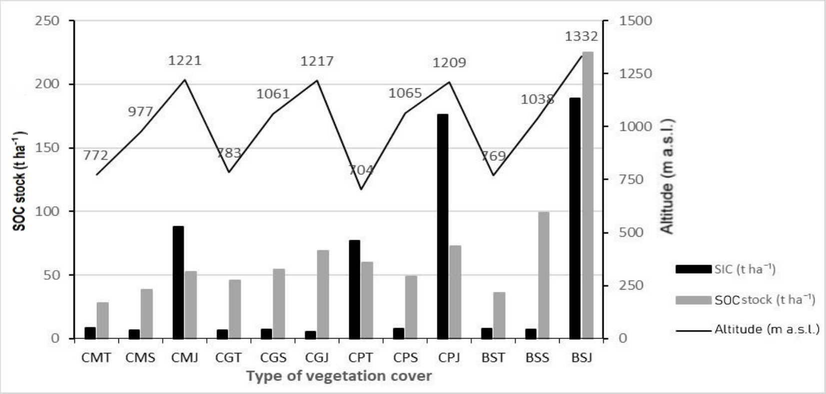


Figure 3. Soil organic C (SOC) stock variation according to soil inorganic C (SIC) ($CaCO_3$) and altitude. in the different types of vegetation cover. CM: Coffee monoculture; CG: coffee with guaba; CP: coffee with polycultures; BS: secondary forest. Abbreviation for third letter: Tabalosos (T), Soritor (S), and Jepelacio (J) districts, San Martín Region, Peru.

Soil inorganic C stocks

The highest average soil inorganic C (SIC) was obtained in the secondary forest in the Jepelacio district, with 189 t ha^{-1} (BSJ), evaluated at a depth of 0-15 cm, followed by the coffee system associated with various agricultural crops (polyculture) in the same district with 175.77 t ha^{-1}, while the lowest values were found in the monoculture coffee system in the district of Soritor, followed by the coffee with guaba in the Jepelacio district with values of 6.8 and 5.44 t ha^{-1}, respectively (Table 2). Our results indicated that $CaCO_3$ has a significant positive correlation with SOC contents ($p < 0.05$) under secondary forests (Figure 4), with the highest values recorded in the secondary forest of the Jepelacio district. Additionally, soil with higher SIC values exhibited lower SOC accumulation and vice versa, for example, at a SIC of 0.3%, a maximum value of SOC stock of 28.02 t ha^{-1} was obtained, while the soil with 7.22% of the total carbonate content registered 225.28 t ha^{-1} of SOC stocks. These results are in accordance with those by Rowley et al. (2020), who found that SOC was approximately double on the site with $CaCO_3$ (5.2%) compared to $CaCO_3$-free soils (2.5%). Likewise, Shi et al. (2017) and Guo et al. (2016) stated that total inorganic C is positively correlated with total organic C content in arid and semi-arid zones and in irrigated crops. This is probably because the SIC has a positive effect on the stabilization of soil organic matter and soil structure (Shi et al., 2017; Quijano et al., 2020). However, the exact mechanisms behind this relationship and the actual consequences on SOC stocks remain unclear, as many factors, such as soil texture, pH, organic inputs, and distribution, can interfere with these mechanisms (Merabtene et al., 2021).

Relationships between geography, soil properties, and SOC

Altitude had a positive correlation with EC, $CaCO_3$, OC, pH, and saturated C deficit (Figure 5A); being the plots located in the Jepelacio sector that were located at the highest altitude those that presented the highest SOC stocks. Such SOC stocks were influenced by plant cover, being more marked the effects of the secondary forest (BSJ). Soil pH was significantly correlated with $CaCO_3$. Likewise, soil texture presented significant correlations with saturated and critical C, being positive for clay and silt and negative for sand (Figure 5B). It has been observed that, in addition to the soil physical and chemical properties of the studied sites, geographical/environmental factors also affect SOC stocks, such as topography, warming, and the various types of forest cover evaluated (Zhang et al., 2018). Climatic conditions had a strong influence on OC, such that the climates of the districts of Soritor and Jepelacio (the coldest one) are strongly distanced from those of the Tabalosos district (the warmest one). Therefore, SOC stocks in the provinces of Moyobamba and Lamas were affected by the type of vegetation, the topographic characteristics, and the physicochemical characteristics of the soil as mentioned by Merabtene et al. (2021).

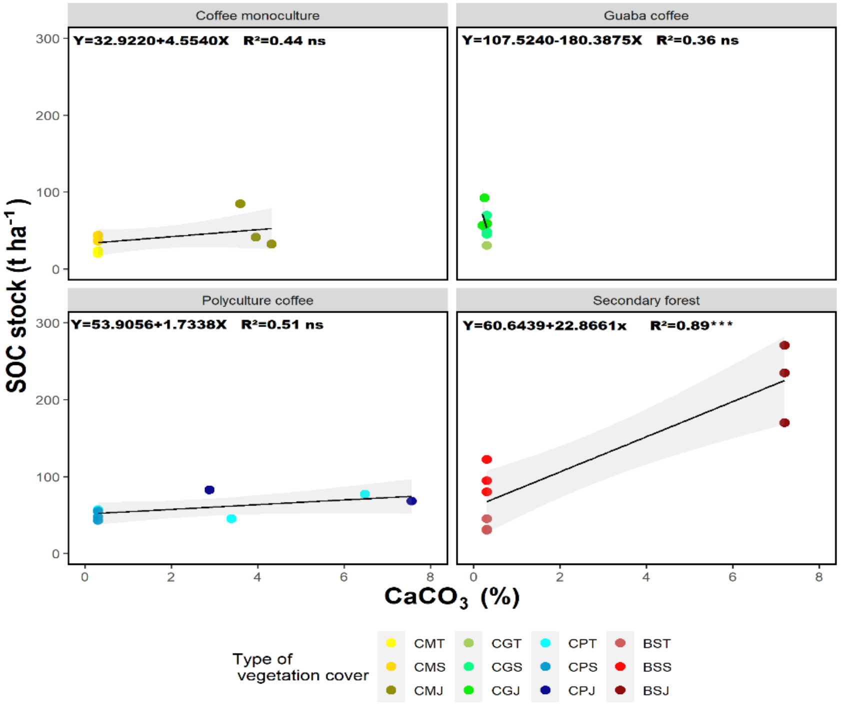


Figure 4. Correlation between soil carbonates ($CaCO_3$) and soil inorganic C (SOC) stocks in the different types of vegetation cover. CM: Coffee monoculture; CG: coffee with guaba; CP: coffee with polycultures; BS: secondary forest. Abbreviation for third letter: Tabalosos (T), Soritor (S), and Jepelacio (J) districts, San Martín Region, Peru.

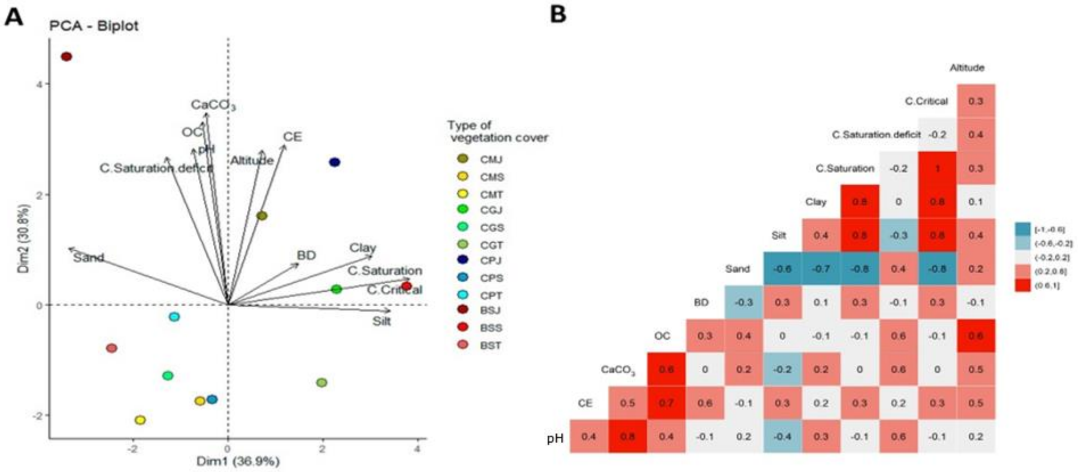


Figure 5. Multivariate distribution of variables. A) Multivariate analysis of edaphic variables measured for the sample localities and the different vegetation covers (PCA). B) Correlogram of edaphic variables: Clay, silt, sand, bulk density (BD), OC: organic C stock, soil inorganic C (SIC) ($CaCO_3$), electrical conductivity (EC). CM: Coffee monoculture; CG: coffee with guaba; CP: coffee with polycultures; BS: secondary forest. Abbreviation for third letter: Tabalosos (T), Soritor (S), and Jepelacio (J) districts, San Martín Region, Peru.

In our study, soils had particularly large amounts of SOM associated with the coarser soil fraction (Martí-Roura et al., 2019). The SOC saturation suggests that the amount of stable SOC is limited and determined by the content of fine particles (clay and fine silt) (Hassink, 1997; Angers et al., 2011; Ben Hassine et al., 2012). In our study there is an increase in the flux of SOC with greater vegetation cover; in turn due to the increase in precipitation and temperature conditions that accelerate C mineralization (Novara et al., 2018). Other factors, such as clay content, have the same impact on SOC regardless of climate (Takoutsing et al., 2016).

Soil carbon saturation rate and critical thresholds

Calculation of soil saturated C levels has made it possible to estimate the SOC stocks in the soil. Based on Table 2 (values are presented in g kg^{-1}), we show that the maximum SOC stock is observed under coffee with guaba in Jepelacio with 32.78%, followed by the secondary forest in Soritor and coffee with polyculture in Jepelacio with a similar value of 32.22% SOC stock. The lowest saturated C was obtained in soils with secondary forest, coffee without shade trees, and coffee with polycultures in the district of Tabalosos, with values of 23.9%, 24.64%, and 25.38%, respectively. The critical C threshold varied between 1.52% and 2.57%. The average SOC concentration rate in the study area was 28.5 g C kg^{-1}, and the average critical threshold was 20.6 g kg^{-1} (Table 2). The average saturation rate was 249.8 g C kg^{-1}. In the Tessala mountains of Algeria in altitudes between 500 to 1000 m a.s.l. and semi-arid climatic characteristics (i.e., a distinct dry and wet season; Merabtene et al., 2021), a critical threshold was recorded varying from 0.7% to 1.7% (7.6 to 17.3 g C kg^{-1}). While Tunisia, under conditions almost similar to those of Algeria (Ben Hassine et al., 2012), registered a critical threshold that varied between 1.79% to 2.70% (17.9 to 27.0 g C kg^{-1}), very close to our study. The lowest registered deficit of 148 g C kg^{-1} was for the soils under secondary forest present in the Jepelacio district, located at a higher altitude (1332 m a.s.l.) As described in this study, smaller C deficits occur at higher altitudes, probably due to the combined effect of cooler temperature and the presence of slopes. Table 2 shows that the current C content (28.5 g kg^{-1}) of the soils of the Jepelacio, Soritor, and Tabalosos districts in the San Martín region of Peru is very low and closer to the critical threshold (20.6 g kg^{-1}), which is the maximum storage capacity represented by the critical C threshold. The C deficit (249.8 g kg^{-1}) in the soils of the study area is very alarming because it is very close to saturation levels (278.3 g kg^{-1}), as similarly found by Merabtene et al. (2021).

CONCLUSIONS

Our study showed that coffee plantations would sequester more C if intercropped with fruit trees and much more if secondary forests are preserved next to them. Vegetation cover with tree species had a positive impact on soil organic C (SOC) stocks in the soil. Altitude and SOC showed a significant positive correlation in secondary forests; thus, temperature apparently is a driving factor for SOC content along the altitudinal gradient, due to slower decomposition activities. Furthermore, only in secondary forests there were significant differences in SOC among the different districts (Tabalosos, Soritor, and Jepelacio). In contrast, in the coffee plantations under different systems (monoculture, with guaba shade, with polyculture shade) there were -mostly- nonsignificant differences across districts, neither effect of altitude. In this study, the highest SOC stock was found in secondary forests, followed by coffee plantations with guaba and polyculture. In general, we found that coffee growing with shade trees contributed the greatest SOC stocks and, that soils from the Jepelacio district had the greatest SOC stock retention capacity due to the physical protection of SOM induced by fine-particle aggregation, like clay and silt. Finally, our SOC stocks measurements indicated a critical C threshold, which exposes this area to greater and more degradation.

Author contributions

Conceptualization: G.V-T., N.G-J. Methodology: G.V-T., C.M.L. Software: G.V-T. Validation: A.L. K.R. Formal analysis: C.I.P. Investigation: C.M.L. Resources: A.A-A. Data curation: G.V-T., W.M-C. Writing-original draft: K.R. Writing-review & amp; editing: J.S-R. Visualization: L.A. Supervision: N.G-J. Project administration: G.V-T. Funding acquisition: J.R.B-V. All co-authors reviewed the final version and approved the manuscript before submission.

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References

Abalori, T.A., Cao, W., Weobong, C.A.-A., Wang, S., Anning, D.K., Sam, F.E., et al. 2022. Spatial variability of soil organic carbon fractions and aggregate stability along an elevation gradient in the alpine meadow grasslands of the Qilian Mountains, China. Chilean Journal of Agricultural Research 82:52-64. doi:10.4067/S0718-58392022000100052.

Alegre, J., Lao, C., Silva, C., Schrevens, E. 2017. Recovering degraded lands in the Peruvian Amazon by cover crops and sustainable agroforestry systems. Peruvian Journal of Agronomy 1:1-7. doi:10.21704/pja.v1i1.1005.

Angers, D.A., Arrouays, D., Saby, N.P.A., Walter, C. 2011. Estimating and mapping the carbon saturation deficit of French agricultural topsoils. Soil Use Management 27(4):448-452. doi:10.1111/j.1475-2743.2011.00366.x.

Autfray, P., Guillaume, P., Forest, F., Chabanne, A., Husson, O. 2009. Outils de gestion des matières organiques en agriculture de conservation en Tunisie. Conference Journée Nationale La gestion du stock organique dans les sols de Tunisie, El Kef, Tunisia. 4 June 2009. Available at https://agritrop.cirad.fr/551981/1/document_551981.pdf.

Balaba, S., Byakagaba, P. 2016. Soil organic carbon stocks under coffee agroforestry systems and coffee monoculture in Uganda. Agriculture, Ecosystems & Environment 216:188-193. doi:10.1016/j.agee.2015.09.037.

Baveye, P.C., Schnee, L.S., Boivin, P., Laba, M., Radulovich, R. 2020. Soil organic matter research and climate change: Merely re-storing carbon versus restoring soil functions. Frontiers in Environmental Science 8:579904. doi:10.3389/fenvs.2020.579904.

Begum, K., Zornoza, R., Farina, R., Lemola, R., Álvaro-Fuentes, J., Cerasuolo, M. 2022. Modeling soil carbon under diverse cropping systems and farming management in contrasting climatic regions in Europe. Frontiers in Environmental Science 10:819162. doi:10.3389/fenvs.2022.819162.

Ben Hassine, B., Karbout, N., Kridane, K., Sanaa, M., Jedidi, N. 2012. Caractérisation des fractions colloïdales minérales et organiques des horizons superficiels des sols d’une toposéquence en zone semi-aride de la Tunisie. Etudes et Gestion des Sols 19(2):105-118. doi:10.13140/RG.2.1.4581.5121.

Blake, G.R., Hartge, K. 1986. Bulk density. p. 363-375. In Klute, A. (ed.) Methods of soil analysis: Part 1 Physical and mineralogical methods. American Society of Agronomy, Madison, Wisconsin, USA. doi:10.2136/sssabookser5.1.2ed.c13.

Bounouara, Z., Chevallier, T., Balesdent, J., Toucet, J., Sbih, M., Bernoux, M., et al. 2017. Variation in soil carbon stocks with depth along a toposequence in a sub-humid climate in North Africa (Skikda, Algeria). Journal of Arid Environments 141:25-33. doi:10.1016/j.jaridenv.2017.02.001.

Canadell, J.G., Monteiro, P.M.S., Costa, M.H., Cotrim da Cunha, L., Cox, P.M., Eliseev, A.V., et al. 2021. Global carbon and other biogeochemical cycles and feedbacks. p. 673-816. In Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., et al. (eds.) Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, USA. doi:10.1017/9781009157896.007.

Dieleman, W.I., Venter, M., Ramachandra, A., Krockenberger, A.K., Bird, M.I. 2013. Soil carbon stocks vary predictably with altitude in tropical forests: Implications for soil carbon storage. Geoderma 204:59-67. doi:10.1016/j.geoderma.2013.04.005.

Dollinger, J., Jose, S. 2018. Agroforestry for soil health. Agroforest Systems 92:213-219. doi:10.1007/s10457-018-0223-9.

Elias, F., Ferreira, J., Resende, A.F., Berenguer, E., França, F., Smith, C.C., et al. 2022. Comparing contemporary and lifetime rates of carbon accumulation from secondary forests in the eastern Amazon. Forest Ecology and Management 508:120053.doi:10.1016/j.foreco.2022.120053.

França, E.M., Silva, C.A., Zinn, Y.L. 2022. Coffee plantations can strongly sequester soil organic carbon at high altitudes in Brazil. Soil Research 61(2):198-207. doi:10.1071/SR22103.

Guangyu, Z., Lihua, Z., Xianjin, H., Pei, W., Dunmei, L., Shenhua, Q., et al. 2022. Effects of elevation gradient on soil carbon and nitrogen in a typical Karst Region of Chongqing, Southwest China. doi:10.1029/2021JG006742.

Guo, Y., Wang, X.J., Li, X.L., Wang, J.P., Xu, M.G., Li, D.W. 2016. Dynamics of soil organic and inorganic carbon in the cropland of upper Yellow River Delta, China. Scientific Reports 6:36105. doi:10.1038/srep36105.

Hassink, J. 1997. The capacity of soils to preserve organic C and N by their association with clay and silt particles. Plant and Soil 191(1):77-87. doi:10.1023/A:1004213929699.

Kassambara, A., Mundt, F. 2020 Factoextra: Extract and visualize the results of multivariate data analyses. R Package Version 1.0.7. Available at http://www.sthda.com/english/rpkgs/factoextra.

Luo, Y., Field, C.B., Jackson, R.B. 2006. Does nitrogen constrain carbon cycling, or does carbon input stimulate nitrogen cycling? Ecology 87(1):3-4. doi:10.1890/05-0923.

Martí-Roura, M., Hagedorn, F., Rovira, P., Romanya, J. 2019. Effect of land use and carbonates on organic matter stabilization and microbial communities in Mediterranean soils. Geoderma 351:103-115. doi:10.1016/j.geoderma.2019.05.021.

Merabtene, M.D., Faraoun, F., Mlih, R., Djellouli, R., Latreche, A., Bol, R. 2021. Forest soil organic carbon stocks of Tessala Mount in North-West Algeria-Preliminary estimates. Frontiers in Environmental Science 8:520284. doi:10.3389/fenvs.2020.520284.

MINAM. 2014. Guía para el muestreo de suelos. Available at https://www.minam.gob.pe/calidadambiental/wpcontent/uploads/sites/22/2013/10/GUIA-PARA-EL-MUESTREO-DE-SUELOSfinal.pdf. Ministerio del Ambiente (MINAM), Lima, Perú.

Novara, A., Sarno, M., Pereira, P., Cerdà, A., Brevik, E.C., Gristina, L. 2018. Straw uses trade-off only after soil organic carbon steady-state. Italian Journal of Agronomy 13(3):216-220. doi:10.4081/ija.2018.1101.

Okello, J., Bauters, M., Verbeeck, H., Kasenene, J. Boeckx, P. 2022. Response of Afromontane soil organic carbon, nitrogen, and phosphorus to *in situ* experimental warming along an elevational gradient. Frontiers in Soil Science 2:905010. doi:10.3389/fsoil.2022.905010.

Quijano, L., Kuhn, N.J., Navas, A. 2020. Effects of interrill erosion on the distribution of soil organic and inorganic carbon in different sized particles of Mediterranean Calcisols. Soil and Tillage Research 196:104461. doi:10.1016/j.still.2019.104461.

R Core Team. 2020. A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available at https://www.R-project.org/.

Rowley, M.C., Grand, S., Adatte, T., Verrecchia, E.P. 2020. A cascading influence of calcium carbonate on the biogeochemistry and pedogenic trajectories of subalpine soils, Switzerland. Geoderma 361:114065. doi:10.1016/j.geoderma.2019.114065.

SENAMHI. 2022. Pronóstico del tiempo a nivel nacional. Servicio Nacional de Meteorología e Hidrología del Perú (SENAMHI), Lima, Perú. Available at https://www.senamhi.gob.pe/?p=pronostico-meteorologico.

Shi, H.J., Wang, X.J., Zhao, Y.J., Xu, M.G., Li, D.W., Guo, Y. 2017. Relationship between soil inorganic carbon and organic carbon in the wheat-maize cropland of the North China Plain. Plant and Soil 418:423-436. doi:10.1007/s11104-017-3310-1.

Solis, R., Vallejos-Torres, G., Arévalo, L., Marín-Díaz, J., Ñique-Alvarez, M., Engedal, T., et al. 2020. Carbon stocks and the use of shade trees in different coffee growing systems in the Peruvian Amazon. The Journal of Agricultural Science 158(6):450-460. doi:10.1017/S002185962000074X.

Spehn, E.M., Rudmann-Maurer, K., Korner, C., Maselli, D. 2012. Mountain biodiversity and global change. Global Mountain Biodiversity Assessment (GMBA)-DIVERSITAS, Basel, Switzerland.

Takoutsing, B., Weber, J., Aynekulu, E., Martín, J.A.R., Shepherd, K., Sila, A., et al. 2016. Assessment of soil health indicators for sustainable production of maize in smallholder farming systems in the highlands of Cameroon. Geoderma 276:64-73. doi:10.1016/j.geoderma.2016.04.027.

Tashi, S., Singh, B., Keitel, C., Adams, M. 2016. Soil carbon and nitrogen stocks in forests along an altitudinal gradient in the eastern Himalayas and a meta-analysis of global data. Global Change Biology 22(6):2255-2268. doi:10.1111/gcb.13234.

Terrer, C., Phillips, R.P., Hungate, B.A., Rosende, J., Pett-Ridge, J., Craig, M.E., et al. 2021. A trade-off between plant and soil carbon storage under elevated CO_2. Nature 591:599-603. doi:10.1038/s41586-021-03306-8.

Veldman, J.W., Aleman, J.C., Alvarado, S.T., Anderson, T.M., Archibald, S., Bond, W.J., et al. 2019. Comment on “The global tree restoration potential”. Science 366:6463. doi:10.1126/science.aay7976.

Walkley, A., Black, I.A. 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Science 37:29-38. doi:10.1097/00010694-193401000-00003.

Wallwork, A., Banin, L.F., Dent, D.H., Skiba, U., Sayer, E. 2022. Soil carbon storage is related to tree functional composition in naturally regenerating tropical forests. Functional Ecology 36:3175-3187. doi:10.1111/1365-2435.14221.

Waring, B.G., Smith, K.R., Belluau, M., Khlifa, R., Messier, C., Munson, A., et al. 2022. Soil carbon pools are affected by species identity and productivity in a tree common garden experiment. Frontiers in Forests Global Change 5:1032321. doi:10.3389/ffgc.2022.1032321.

Zhang, Y., Ai, J., Sun, Q., Li, Z., Hou, L., Song, L., et al. 2021. Soil organic carbon and total nitrogen stocks as affected by vegetation types and altitude across the mountainous regions in the Yunnan Province, south-western China. Catena 196:104872. doi:10.1016/j.catena.2020.104872.

Zhang, T., Niinemets, Ü., Sheffield, J., Lichstein, J.W. 2018. Shifts in tree functional composition amplify the response of forest biomass to climate. Nature 556:99-102. doi:10.1038/nature26152.