Wiley
International Journal of Agronomy
Volume 2026, Article ID 5533519, 11 pages
https://doi.org/10.1155/ioa/5533519

WILEY

Research Article

Soil Organic Carbon Variability in Tropical Cropping Systems: Interactions With Texture, pH, Macronutrients, and Organic Matter

Richard Solórzano,[1,2] Juancarlos Cruz,[1] Rodolfo Chuchon-Remon,[3] Nery Gaona-Jimenez,[4] and Geomar Vallejos-Torres[3,4]

[1]*Directorate of Supervision and Monitoring of Agricultural Experimental Stations, National Institute of Agrarian Innovation (INIA), Lima, Peru*
[2]*Faculty of Environmental Sciences, Universidad Científica del Sur (UCSUR), Lima, Peru*
[3]*El Porvenir Agricultural Experimental Station, Directorate of Supervision and Monitoring of Agricultural Experimental Stations, National Institute of Agrarian Innovation (INIA), San Martín, Peru*
[4]*Faculty of Agricultural Sciences, Universidad Nacional de San Martín, San Martín, Peru*

Correspondence should be addressed to Geomar Vallejos-Torres; gvallejos@unsm.edu.pe

Received 9 May 2025; Revised 4 December 2025; Accepted 20 December 2025

Academic Editor: Othmane Merah

Soil organic carbon (SOC) plays a crucial role in mitigating climate change and enhancing soil fertility. Its storage and dynamics are particularly significant in agricultural ecosystems of the Peruvian Amazon, where the expansion of agriculture and livestock farming may disrupt the regional carbon balance. This study aimed to analyze SOC variability and its relationship with edaphic and nutritional properties in agricultural systems in Eastern Peru (San Martín and Loreto regions). Four representative cropping systems were evaluated: coffee grown in agroforestry and polyculture systems; maize as a monoculture; and camu-camu and cocoa cultivated in monoculture and agroforestry systems, respectively. The highest SOC content (80.70 $t{\cdot}ha^{-1}$), phosphorus (12.03 $mg{\cdot}kg^{-1}$), and moisture (52.36%) were observed in coffee-growing soils, likely due to the presence of shade trees that enhance organic matter inputs in soils at 0–20 cm depth. In contrast, soils under maize cultivation exhibited the highest levels of nitrogen (0.19%), potassium (364.02 $mg{\cdot}kg^{-1}$), and pH (7.61), likely due to the frequent fertilization applied to this crop. The lowest carbon saturation deficits were found in soils under camu-camu (31.67%), cocoa (26.88%), maize (24.80%), and coffee (20.59%), with the most pronounced deficits occurring in camu-camu and cocoa soils in Yurimaguas (Loreto), indicating a heightened vulnerability to carbon loss. These findings underscore the significant influence of crop type and management practices on carbon and nutrient dynamics in tropical soils. Long-term studies are recommended to assess carbon sequestration over extended periods, informing sustainable soil management policies in the Peruvian Amazon.

Keywords: camu-camu; carbon deficit; cocoa; coffee; maize; saturation

1. Introduction

Land cover has been undergoing rapid transformation due to intensive human activities for agricultural production. Consequently, quantifying land-use change dynamics is crucial for addressing global societal challenges, including food security, climate change, and biodiversity loss [1]. Numerous studies have demonstrated a significant relationship between climate change and alterations in vegetation cover in agricultural systems. Such changes directly influence soil structure; in fact, monoculture systems lacking shade trees tend to exert a greater impact on soil conditions than agroforestry systems that incorporate shade vegetation, thereby contributing more strongly to climate change [2]. Between 1959 and 2019, approximately 19% of total net CO_2 emissions resulted from land-use change, whereas terrestrial ecosystems absorbed nearly 32% of global emissions during the same period [3]. Agriculture plays a key role in ensuring food security, one of the Sustainable Development Goals outlined in the United Nations 2030 Agenda. However, if poorly managed, it can significantly harm the environment by reducing its environmental efficiency [4]. Indeed, agricultural expansion has replaced natural ecosystems worldwide, emerging as a major driver of carbon emissions, biodiversity loss, and freshwater depletion [5].

The distribution of soil organic carbon (SOC) across different soil types provides valuable insights into carbon (C) dynamics within terrestrial ecosystems. It also plays a critical role in understanding climate feedback mechanisms and developing appropriate SOC management decisions at the farm level [6]. In the Peruvian Amazon, significant forest cover loss, driven primarily by land-use changes, particularly for the cultivation of oil palm, maize, and rice, has increased atmospheric CO_2 emissions, thereby exacerbating climate change [7]. Additionally, this region has undergone significant changes in land use, with forests being cleared for silvopasture and agricultural crops, such as coffee and cocoa, which have contributed to increased atmospheric CO_2 levels.

Peru contains a substantial portion of the South American tropical rainforest. With an average deforestation rate of 145,000 ha per year, it has become the country with the largest source of greenhouse gas (GHG) emissions [8]. SOC sequestration has been promoted as a strategy to mitigate climate change while enhancing soil fertility under various land uses in the Peruvian Amazon. However, its direct quantitative contribution to crop productivity remains uncertain [9], particularly in key crops such as camu-camu, coffee, cocoa, and maize. Moreover, poor extensive agricultural practices have led to nutritional deficiencies, erosion, and loss of soil moisture (SM) and carbon. These soil limitations significantly impact agricultural productivity and food security by affecting soil health and crop yields [10].

The concept of SOC saturation suggests that the amount of stable SOC is limited and determined mainly by the content of fine particles (clay and fine silt) in the soil [11]. Critical carbon (CC) refers to the minimum level of organic carbon (OC) below which soil structure deteriorates and the risk of degradation increases due to reduced structural stability [12]. In contrast, the carbon saturation (CS) deficit represents the remaining potential for stable SOC sequestration [13]. Several authors have reported important findings regarding these carbon fractions. For example, Merabtene et al. [14] estimated that the OC reserves of forest soils on Mount Tessala, under current natural conditions, are critically low, approaching the threshold at which degradation becomes increasingly severe. Similarly, Mendoza-Lopez et al. [15] reported that the SOC deficit in the study area is highly concerning, approaching saturation levels, particularly in deforested areas.

These agricultural crops are essential to the livelihoods of local communities and serve as key pillars of the regional economy in the Peruvian Amazon. Within this context, the present exploratory study aimed to quantify the distribution of SOC, saturated carbon (SC), CC, and saturated carbon deficit (SCD) and to analyze their interactions with soil properties and nutritional elements in agricultural soils under camu-camu, cacao, coffee, and maize cultivation, representing the main subsistence and production systems in the region.

2. Materials and Methods

2.1. Study Area. The study was conducted between August and December 2024 in two provinces of the San Martín region and one province of the Loreto region, located in Eastern Peru (Figure 1). The San Martín region spans an area of 51,253.31 km^2. It is characterized by a predominantly subtropical and tropical climate with two distinct seasons: a dry season from June to September and a rainy season from October to May. Temperatures range from 23°C to 27°C, and average annual precipitation is approximately 1,500 mm. In contrast, the Loreto region, spanning 368,852 km^2, boasts a tropical climate with average and minimum temperatures of 25.0°C and 23.0°C, respectively, and an annual rainfall range of 2,000 to 3,000 mm. The study area extended geographically from 5°42′30.98″S to 7°2′38.47″S latitude and from 76°37′2.11″W to 76°4′54.19″W longitude, encompassing elevations ranging from 145 to 1,400 m above sea level. In the San Martín region, the studied agricultural systems included coffee grown under agroforestry systems and maize cultivated as a monoculture. In the Loreto region, the focus was on camu-camu cultivated as a monoculture and cacao cultivated within agroforestry systems.

2.2. Sampling Design. Four agricultural cropping systems were identified across four study sites—two in the San Martín region and two in the Loreto region. These included (1) coffee cultivated within an agroforestry and polyculture system in the district of San José de Sisa, province of El Dorado; (2) maize grown as a monoculture in the district of Leoncio Prado, province of Picota—both located in the San Martín region; (3) camu-camu cultivated as a monoculture; and (4) cacao grown in an agroforestry system—both located in the district of Yurimaguas, province of Alto Amazonas, within the Loreto region (Table 1). Soil samples were collected from each of the four sites at 0–20 cm depth by excavating soil pits within each management system. Ten subplots were established per system, yielding a total of 40 soil samples. The 0–20 cm depth was selected because the majority of SOC is typically concentrated in the soil surface layer and tends to decrease with soil depth [16].

2.3. Calculation of Soil Edaphic and Nutritional Parameters. The collected soil samples were analyzed at the accredited laboratory of the National Institute of Agrarian Innovation (INIA), Peru. Soil texture was determined using the hydrometer texture method, and pH was measured with a potentiometer in a 1:2.5 soil-to-water suspension [17]. Soil organic matter (SOM)

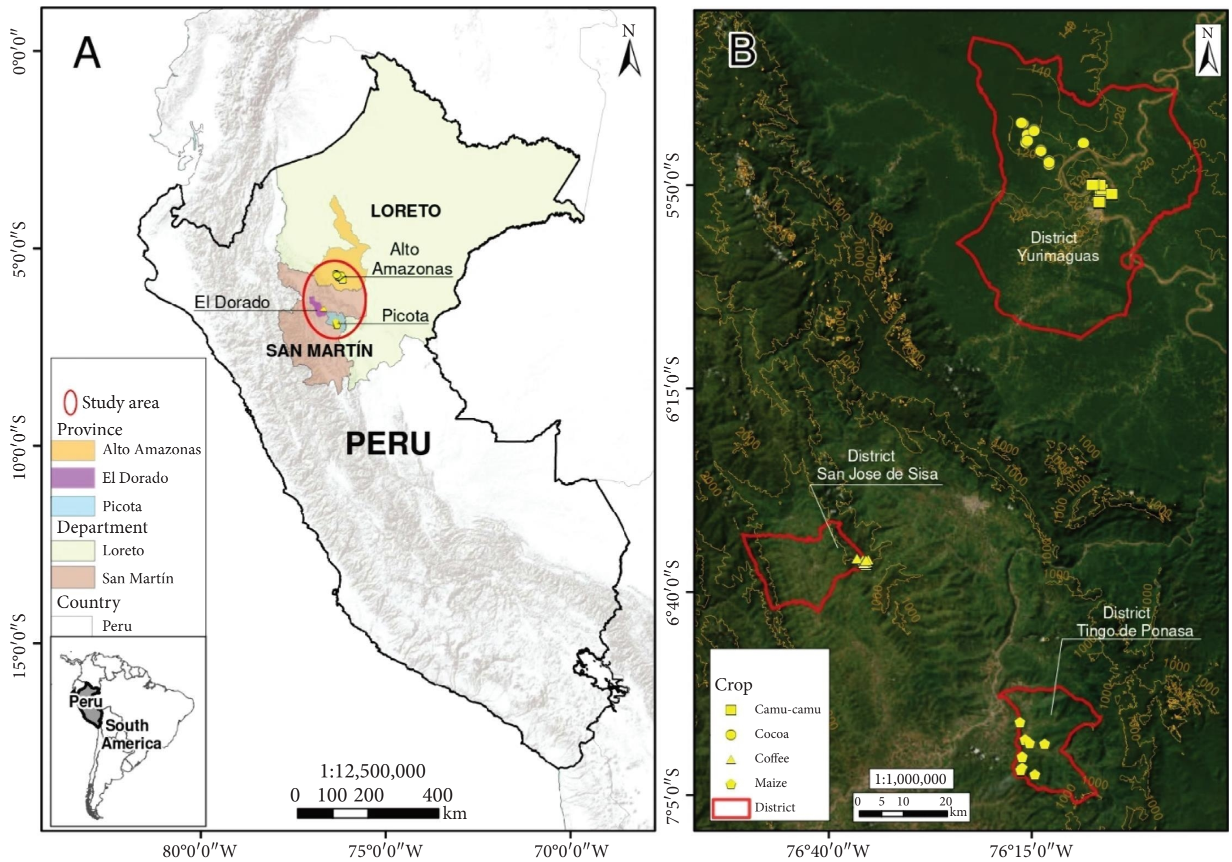

Figure 1: Location of study sites. (A) San Martin and Loreto regions in Eastern Peru. (B) Study plots with coffee, maize, camu-camu, and cocoa crops.

was quantified following the method described by Porta et al. [18]. Total nitrogen was determined using the Kjeldahl method [19]. Available phosphorus and potassium were measured according to standard procedures outlined in [20, 21], respectively.

Soils under camu-camu cultivation were classified as predominantly clayey (43%). In contrast, soils supporting coffee cultivation were sandy, whereas soils under cocoa and coffee cultivation exhibited uniform proportions of sand, silt, and clay.

2.4. Calculation of OC, SC, CC, and SCD. SOC was determined in the laboratory using the method developed by Walkley and Black [22], applying the following formula:

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

where OC is the SOC content (%), Sd is the soil sampling depth (cm), BD is the bulk density ($\mathrm{g{\cdot}cm^{-3}}$), and $\mathrm{tC{\cdot}ha^{-1}}$ represents tons of carbon per hectare.

SC was determined by applying the equation developed by Hassink [23]:

$$\text{Saturated C}\,(\%) = 4.09 + 0.37\,(\%\,\text{Clay} + \%\,\text{Fine Silt}). \tag{2}$$

CC was calculated based on the clay and silt fractions, using the formula proposed by Autfray et al. [24]:

$$\text{Critical C}\,(\%) = \frac{(0.32\ (\%\,\text{Clay} + \%\,\text{Fine Silt}) + 0.87)}{10}. \tag{3}$$

The SC value was compared with the measured C in the soil, from which the SCD was then determined [14].

$$\text{Saturated}\ C\ \text{deficit (SCD)}\,(\%) = C_{\cdot\mathrm{sat}} - C_{\cdot\mathrm{current}}, \tag{4}$$

where Critical C represents the minimum value of OC in the soil required to maintain structural stability without the risk of degradation [14].

2.5. Statistical Analyses. Statistical analyses were performed using R Studio [25]. To assess the effect of the crop factor on the response variables, including carbon content and soil properties (physical and chemical), the nonparametric Mann–Whitney test was applied to compare medians between crops at a 5% probability of error. Additionally, the

TABLE 1: Characteristics of the agricultural crops studied.

Crop species	System type	Yield (kg/ha)	Crop age and prior land use	Fertilization	Under the shade of tree species
Camu-camu	Monoculture	6000	Age between 6 and 12 years. Before crop establishment, the areas were covered with shrub vegetation and secondary forest.	Organic application once a year using compost.	No shade
Coffee	Agroforestry	1000	Coffee stands are divided into ages of 8–11 years. Before crop establishment, the areas were covered with shrub vegetation	Application of compost twice a year.	*Inga* spp., *Persea americana*, *Cedrela odorata*, and *Calycophyllum spruceanum*.
Cacao	Agroforestry	600	Age greater than 7–11 years. Before crop establishment, the area was fallow (purma) and forested.	With applications of island guano and compost.	*Cedrela odorata*, *Inga* spp., *Guazuma crinita*
Maize	Monoculture	3500	Annual crop. Before crop establishment, the areas were covered with shrub vegetation	Without any fertilizer application	*Setaria* sp., *Cyperus rotundus*, *Bidens* sp.

relationships among SOC, soil texture, pH, and organic matter (OM) were examined using linear regressions. Finally, a correlogram was constructed using the Pearson correlation coefficient ($p < 0.05$), utilizing the *ggpairs* function from the GGally package in R [26].

3. Results and Discussion

3.1. Distribution of SOC, SC, CC, and SCD in Soils. The distribution of SOC content among the different studied crops revealed significant differences. The highest SOC content was observed in soils under coffee cultivation, averaging 80.70 t ha^{-1}, followed by maize at 76.87 t·ha^{-1}. These values were considerably higher than those recorded for camu-camu and cocoa crops, which had average SOC contents of 35.30 and 31.59 t·ha^{-1}, respectively (Figure 2). The maximum CS was observed in soils under camu-camu cultivation, with an average of 32.69%, significantly higher than the values found in soils under cocoa (27.75%), maize (26.70%), and coffee (22.66%) cultivation (Figure 2). A similar trend was observed for CC, with camu-camu crops recording the highest average value (2.56%), followed by cocoa (2.13%), maize (2.04%), and coffee (1.69%), as shown in Figure 2. The nearest SCD was 31.67%, 26.88%, 24.80%, and 20.59% for soils under camu-camu, cocoa, maize, and coffee cultivation, respectively. The highest SCD values were observed in soils from camu-camu and cocoa crops in the Yurimaguas province of the Loreto region. In contrast, the lowest SCD values were recorded in soils from maize and coffee crops in the El Dorado and Picota provinces of the San Martín region.

The higher SOC content observed in coffee-growing soils can be attributed to the association of this crop with various shade trees, forming an agroforestry system. Numerous studies have reported elevated SOC contents in coffee-growing soils. For example, Niguse et al. [27] reported an average SOC stock of 91.5 t·C·ha^{-1} at 0–30 cm depth, while another study documented an SOC content of 91.0 t·ha^{-1} in shaded coffee agroforestry systems [28]. These high SOC stocks found in coffee ecosystems may result from the diversity of shade trees, which contribute substantial amounts of organic debris to the soil, thereby enhancing surface OM [29]. Furthermore, coffee plants in agroforestry systems sequester significant amounts of carbon, which, in turn, is influenced by the compatibility of the trees present in the management system [30]. Similarly, the elevated SOC content found in maize cultivation areas may be due to the historical use of these lands, which were often previously forested. The study area likely had a high forest density in the past, and given that soils can retain carbon for up to 500 years, this legacy may explain the current high SOC levels [31]. This is particularly evident in the province of Picota, where seasonally dry forests have been replaced by maize [15].

The CS results obtained in this study are consistent with those reported by Mendoza-Lopez et al. [15], who observed an average CS of 28.84% in forest soils. Similarly, Zhang et al. [32] recorded the highest CS value in the Maolan grassland system (83.34%). Comparable findings were reported by Siddique et al. [33] for rice soils, which exhibited an average CS of 76%. Notably, both rice and camu-camu crops require substantial water availability for their development and productivity.

Regarding CC, the values obtained in this study are also in line with those reported by Mendoza-Lopez et al. [15], who recorded values of 1.96% and 2.73%, with an average critical threshold of 2.23%. Comparable results were observed in Tunisia under nearly identical conditions by Hassine et al. [34], who reported a critical threshold of 1.79%–2.70%, which is very close to our findings. The SCD values in this study closely resemble those reported by Mendoza-Lopez et al. [15] for soils under different vegetation coverage in the province of Picota. Dinakaran et al. [35] also found that mean SCD values in soil ranged from 25% to 36%. It is well established that SCD is a key indicator of the SOC sequestration potential [32]. Soils with carbon levels far below saturation tend to exhibit a high SCD, indicating a greater capacity for carbon stabilization [36].

3.2. Nutritional Characteristics, pH, and Moisture of Soils in Different Agricultural Crops. The distribution of phosphorus (P) content among the different studied crops showed significant differences. The highest P content was found in coffee soils, averaging 12.03 mg·kg^{-1}, followed by camu-camu, maize, and cocoa crops, averaging 7.62, 6.33, and 3.45 mg·kg^{-1}, respectively (Figure 3). Similarly, potassium (K) content differed significantly among crop soils, with the highest value recorded in maize (364.02 mg·kg^{-1}), followed by coffee (110.41 mg·kg^{-1}), cocoa (100.21 mg·kg^{-1}), and camu-camu (73.65 mg·kg^{-1}) (Figure 3). Total nitrogen (N) content also varied significantly among the crops. Soils under maize and coffee cultivation in the San Martín region exhibited the highest nitrogen levels, averaging 0.19% and 0.18%, respectively. In contrast, soils under camu-camu and cocoa cultivation in the Loreto region had lower averages of 0.10% and 0.08%, respectively. The distribution of pH between the different studied crops showed significant differences. The highest pH was observed in maize soils, with an average of 7.61, followed by camu-camu (5.49), cocoa (5.23), and coffee (4.29) (Figure 3). OM content also showed significant differences. The highest OM levels were recorded in coffee and maize soils in the San Martín region, with averages of 3.56% and 3.27%, respectively. In contrast, lower OM contents were found in the soils of camu-camu (1.76%) and cocoa (1.50%) from the Loreto region. The highest SM was observed in coffee soils, averaging 52.36%, while the lowest values were observed in maize (37.44%), cocoa (29.57%), and camu-camu (28.45%) soils.

The phosphorus (P) values found in this study were higher than those reported by Vallejos-Torres et al. [30], who recorded P concentrations ranging from 1.32 to 3.22 mg·kg^{-1} in coffee agroforestry systems. Similarly, Vallejos-Torres et al. [37] reported P contents of 6.77–8.65 mg·kg^{-1} in cocoa plantation soils with tree cover and higher levels of 13.40–19.18 mg·kg^{-1} in cocoa plantations without tree cover. Regarding potassium (K), the same researchers found concentrations ranging from 43 to

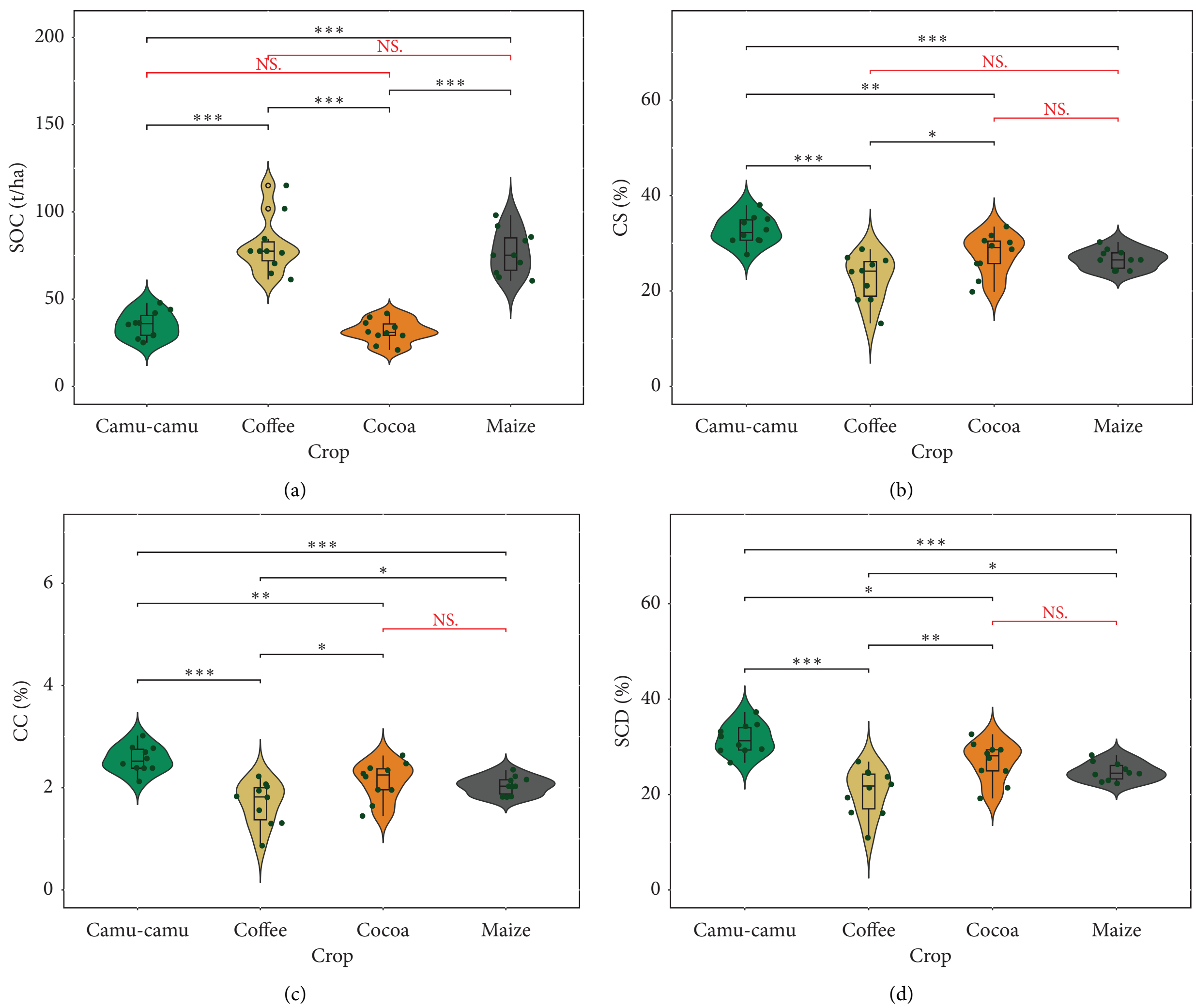

Figure 2: Soil carbon contents in different agricultural crops. SOC: soil organic carbon; CS: saturated carbon; CC: critical carbon; SCD: saturated carbon deficit. Mann–Whitney test: * for $p < 0.05$, ** for $p < 0.01$, *** for $p < 0.001$, and NS (not significant) for $p > 0.05$.

327 mg·kg^{-1} in cocoa-growing soils in the San Martín region of Peru, which fall within the range observed in this study across different crops. The highest average K content was observed in maize soils, likely due to site background and the chemical and organic fertilizers applied by the producers of this cereal. Potassium is a key nutrient for plant physiological processes and is essential for optimal maize (*Zea mays* L.) production [38]. A similar trend was observed for nitrogen (N), with higher contents recorded in maize soils. Wang et al. [39] suggested that an optimal nitrogen application rate for maximum maize yield is approximately 289 kg·ha^{-1}, regardless of inherent soil fertility. Likewise, Zou et al. [40] recommended appropriate N fertilization rates of 170–235 kg·ha^{-1} for maize. The elevated nitrogen content in coffee soils can be attributed to coffee agroforestry systems, which are effective strategies for enhancing soil nitrogen sequestration following forest conversion [41]. Soil pH values in this study ranged from 5.55 to 6.71. In comparison, rice cultivation soils exhibited pH values ranging from 6.16 to 7.57 [42], which are similar to those observed in maize soils. The pH levels observed in the soils of camu-camu, cocoa, and coffee fall within the normal range. However, when the pH exceeds 6.5, the absorption of phosphorus, iron, zinc, and copper is blocked, resulting in a lower availability of these nutrients, particularly in coffee crops [43]. Regarding OM content, Vallejos-Torres et al. [30] reported an average of 3.90% in coffee ecosystems. Regional analyses and global data syntheses have demonstrated that higher soil OM content generally enhances crop yields, although this benefit tends to plateau at approximately 4% [44, 45]. Thus, the OM levels observed in coffee and maize soils in this study are considered adequate to support crop growth and development. SM exhibited similar variability across crop types. Zhao et al. [46], for example, found SM levels ranging from approximately 10% to 50% in a forest ecosystem undergoing restoration. In this study, the higher moisture content in coffee soils is likely due to shade cover in agroforestry systems, which helps reduce evaporation and transpiration, thereby enhancing SM retention [47]. Understanding SM dynamics during different stages of agricultural production is essential for effective water resource management [48].

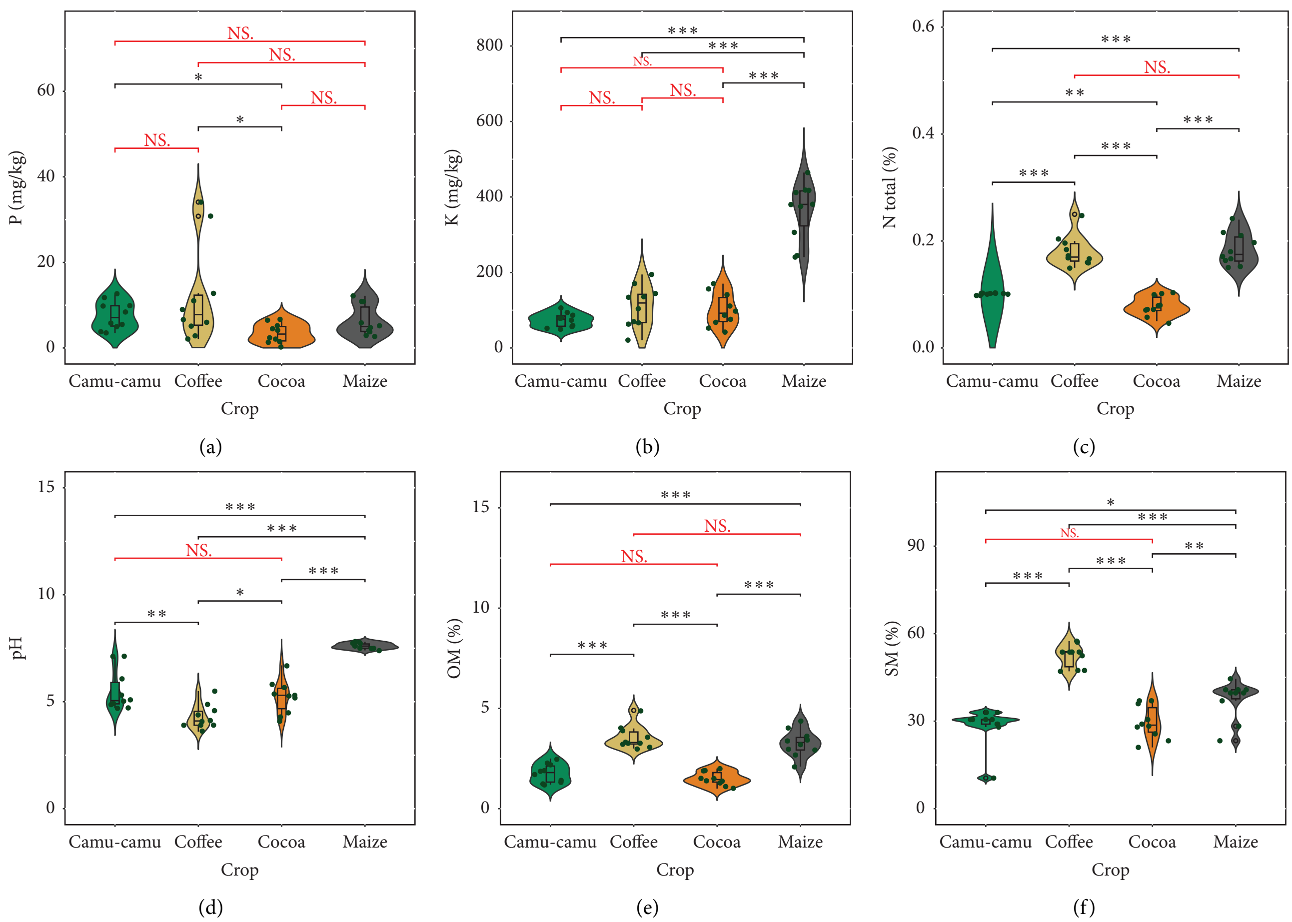

FIGURE 3: Nutritional characteristics, pH, and moisture in different agricultural crops. P: total phosphorus; K: total potassium; N: total nitrogen; OM: organic matter; SM: soil moisture. Mann–Whitney test: * with $p < 0.05$, ** with $p < 0.01$, *** with $p < 0.001$, and NS (not significant) with $p > 0.05$.

The availability of plant-accessible phosphorus, as well as total soil phosphorus content, is enhanced by the presence of nitrogen-fixing shade tree species [49], such as guava, a species commonly associated with coffee farms in the Peruvian Amazon. In soils under maize cultivation, high fertilizer application rates are typically used, which often result in elevated K concentrations [50].

3.3. Relationship Between SOC and Edaphic Factors in Soils Under Different Agricultural Crops. Significant regressions and correlations were observed between SOC and various edaphic factors ($p < 0.05$). In the cocoa crop, significant negative regression and correlation were found for soil sand content, with coefficients of determination and correlation of 0.649 and −0.805, respectively (Figure 4). Similarly, significant positive regression and correlation were recorded between SOC and silt content in cocoa soils, with coefficients of determination and correlation of 0.510 and 0.715, respectively. However, no significant association was detected for clay content at the crop level (Figure 4). A strong negative regression ($p < 0.001$) was identified between SOC and pH in camu-camu soils, with an R^2 of 0.520 (Figure 4). In contrast, a significant positive regression was observed between SOC and soil OM for camu-camu, cocoa, and coffee crops, with coefficients of determination of 0.98, 0.94, and 0.76, respectively.

In contrast, Gabarrón-Galeote et al. [51] reported that SOC tends to be concentrated primarily in the silt and clay size fractions. Vegetation characteristics can locally modify clay content, even under similar climatic conditions. Thus, the observed correlations between SOC concentration and sand content in coffee, maize, and camu-camu soils may reflect localized, climate-dependent dynamics, modulated by substantial differences in SM. Moisture plays a critical role in driving the significant positive correlation observed between SOC and the sand fraction [52]. Comparable results have been documented in other studies. Ghimire et al. [6] reported a significant correlation ($p < 0.001$) between SOC and clay content, while Merabtene et al. [14] noted a correlation with silt content in cocoa soils. A negative correlation between SOC and soil pH was also reported by Wang et al. [53]. This inverse relationship can be attributed to the effect of pH on SOC decomposition and dynamics, which are governed by physical, chemical, and biological processes. For instance, acidic soils with low pH often suppress microbial activity, thereby reducing SOC levels [6]. Additionally, low pH reduces the solubility of SOC, thereby

Figure 4: Correlogram showing the relationships between variables and their differences in soils from different agricultural crops studied. Pearson test: * for $p < 0.05$, ** for $p < 0.01$, *** for $p < 0.001$, and NS (not significant) for $p > 0.05$.

limiting its adsorption onto soil particles [54]. Conversely, Sajjad et al. [55] found a positive correlation between soil pH and SOC, suggesting that higher pH levels may enhance nutrient availability, such as phosphorus and nitrogen, which is consistent with observations in coffee soils. Furthermore, significant positive correlations between SOC and OM were observed in the soils of camu-camu, cocoa, and coffee. This relationship reflects the net balance between OM inputs and SOC mineralization rates [56], with OM input largely determined by vegetation cover and root biomass [57]. Therefore, changes in vegetation type can substantially influence the dynamics of soil carbon inputs and outputs, ultimately altering SOC content [58]. In contrast, a significant positive correlation was observed between total N and SOC for coffee, cocoa, and maize crops, whereas a nonsignificant negative correlation was found between soil pH and SOC.

4. Conclusions

Coffee cultivation, when integrated into agroforestry systems with shade trees, exhibited the highest levels of SOC, phosphorus (P), OM, and moisture. This suggests a greater input and accumulation of organic residues. However, a concerning deficit in SC was observed, particularly in soils under camu-camu and cacao cultivation in the Loreto region, potentially indicating a progressive decline in the soil's capacity to retain carbon in these systems.

Agricultural soils under maize cultivation exhibited the highest concentrations of potassium (K) and total nitrogen (N), likely reflecting the crop's high nutritional demand and the frequent application of fertilizers. Meanwhile, the low pH observed in coffee soils indicates slightly acidic conditions, which may be attributed to continuous cultivation without adequate soil management practices. A significant positive correlation between SOC and OM was identified in the soils of camu-camu, cacao, and coffee, underscoring the pivotal role of OM in regulating soil carbon content.

Taken together, these findings highlight the need for crop-specific soil management strategies and caution against simplistic interpretations that favor one crop over others. However, since the data reflect a single time-point measurement, future studies should aim to establish continuous monitoring over multiple years, incorporating estimates of carbon dioxide (CO_2) emissions and land-use change assessments to provide a more robust understanding of carbon dynamics in these tropical agricultural systems.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Richard Solórzano: conceptualization, investigation, and writing–review and editing. Juancarlos Cruz: supervision, writing–original draft, and writing–review and editing. Rodolfo Chuchon-Remon: writing–review and editing. Nery Gaona-Jimenez: formal analysis and investigation: Juancarlos Cruz: funding acquisition. Geomar Vallejos-Torres: investigation, writing–review and editing, and data curation.

Funding

This research was funded by the Instituto Nacional de Innovación Agraria, within the framework of the project: Mejoramiento de los servicios de investigación y transferencia tecnológica en el manejo y recuperación de suelos agrícolas degradados y aguas para riego en la pequeña y mediana agricultura en los departamentos de Lima, Áncash, San Martín, Cajamarca, Lambayeque, Junín, Ayacucho, Arequipa, Puno y Ucayali (CUI 2487112).

References

[1] K. Winkler, R. Fuchs, M. Rounsevell, and M. Herold, "Global Land Use Changes Are Four Times Greater Than Previously Estimated," *Nature Communications* 12, no. 1 (2021): 2501, https://doi.org/10.1038/s41467-021-22702-2.

[2] Y. A. Bununu, A. Bello, and A. Ahmed, "Cobertura y Uso del Suelo, Cambio Climático y Seguridad Alimentaria," *Sustainable Earth Reviews* 6, no. 1 (2023): 16, https://doi.org/10.1186/s42055-023-00065-4.

[3] P. Friedlingstein, M. O'Sullivan, M. W. Jones, et al., "Global Carbon Budget 2020," *Earth System Science* 12 (2020): 3269–3340, https://doi.org/10.5194/essd-12-3269-2020.

[4] G. Fusco, F. Campobasso, L. Laureti, M. Frittelli, D. Valente, and I. Petrosillo, "The Environmental Impact of Agriculture: An Instrument to Support Public Policy," *Ecological Indicators* 147 (2023): 109961, https://doi.org/10.1016/j.ecolind.2023.109961.

[5] R. M. Beyer, F. Hua, P. A. Martin, A. Manica, and T. Rademacher, "Relocating Croplands Could Drastically Reduce the Environmental Impacts of Global Food Production," *Communications Earth and Environment* 3, no. 1 (2022): 49, https://doi.org/10.1038/s43247-022-00360-6.

[6] S. Ghimire, R. B. Ojha, C. Shrivastav, S. Bhatta, and D. Panday, "Profile Distribution and Edaphic Controls of Soil Organic Carbon in Dominant Soil Orders of Chitwan, Nepal," *Carbon Research* 3, no. 1 (2024): 57, https://doi.org/10.1007/s44246-024-00139-8.

[7] G. Vallejos-Torres, O. Ríos-Ramírez, H. Saavedra, N. Gaona-Jimenez, F. Mesén-Sequeira, and C. Marín, "Vegetative Propagation of *Manilkara bidentata* (A.DC.) A.Chev. Using Mini-Tunnels in the Peruvian Amazon Region," *Forest Systems* 30, no. 2 (2021): eRC01, https://doi.org/10.5424/fs/2021302-17971.

[8] D. D. L. T. Ugarte, M. Collado, F. Requejo, X. Gomez, and C. Heros, "A Deep Decarbonization Pathway for Peru's Rainforest," *Energy Strategy Reviews* 36 (2021): 100675, https://doi.org/10.1016/j.esr.2021.100675.

[9] Y. Ma, D. Woolf, M. Fan, L. Qiao, R. Li, and J. Lehmann, "Global Crop Production Increase by Soil Organic Carbon," *Nature Geoscience* 16, no. 12 (2023): 1159–1165, https://doi.org/10.1038/s41561-023-01302-3.

[10] T. Li, L. Cui, V. Filipović, et al., "From Soil Health to Agricultural Productivity: The Critical Role of Soil Constraint Management," *Catena* 250 (2025): 108776, https://doi.org/10.1016/j.catena.2025.108776.

[11] J. Hassink, "The Capacity of Soils to Preserve Organic C and N by Their Association With Clay and Silt Particles," *Plant and Soil* 191, no. 1 (1997): 77–87, https://doi.org/10.1023/A:1004213929699.

[12] P. Loveland and J. Webb, "Is There a Critical Level of Organic Matter in the Agricultural Soils of Temperate Regions: A Review," *Soil and Tillage Research* 70, no. 1 (2003): 1–18, https://doi.org/10.1016/S0167-1987(02)00139-3.

[13] D. A. Angers, D. Arrouays, N. P. A. Saby, and C. Walter, "Estimating and Mapping the Carbon Saturation Deficit of French Agricultural Topsoils," *Soil Use and Management* 27, no. 4 (2011): 448–452, https://doi.org/10.1111/j.1475-2743.2011.00366.x.

[14] M. D. Merabtene, F. Faraoun, R. Mlih, R. Djellouli, A. Latreche, and R. Bol, "Forest Soil Organic Carbon Stocks of Tessala Mount in North-West Algeria-Preliminary Estimates," *Frontiers in Environmental Science* 8 (2021): 520284, https://doi.org/10.3389/fenvs.2020.520284.

[15] K. Mendoza-Lopez, L. Ordoñez-Sánchez, M. J. Valdez-Andía, et al., "Estimates of Soil Organic Carbon in the Ojos de Agua and el Quinillal Forests in the Central Huallaga of Peru," *International Journal of Financial Research* 2024, no. 1 (2024): 5692145, https://doi.org/10.1155/2024/5692145.

[16] X. Hao, X. Han, L. Li, W. Zou, X. Lu, and Y. D. Qiao, "Profile Distribution and Storage of Soil Organic Carbon in a Black Soil as Affected by Land Use Types," *Yingyong Shengtai Xuebao* 26, no. 4 (2015): 965–972, https://pubmed.ncbi.nlm.nih.gov/26259435/.

[17] E. O. Mclean and A. L. Page, "Soil pH and Lime Requirement," *Agronomy Monographs* (Hoboken: Wiley, 1982), 199–224, https://doi.org/10.2134/agronmonogr9.2.2ed.c12.

[18] J. Porta, M. López-Acevedo Reguerín, and R. M. Poch, *Soil Science: Soil Use and Protection, Revised and Expanded* (Mundi-Prensa, 2014).

[19] J. M. Bremmer, "Nitrogen-Total. En: Methods of Soil Analysis," *Part 3 Chemical Methods*, ed. D. L. Sparks (Madison: SSSA, 1996), 1103–1108, https://doi.org/10.2136/sssabookser5.3.c37.

[20] S. R. Olsen and L. E. Sommers, "Phosphorus," in *Methods of Soil Analysis Part 2 Chemical and Microbiological Properties*, ed. A. L. Page (Madison: American Society of Agronomy, 1982), 403–430, https://doi.org/10.2134/agronmonogr9.2.2ed.c24.

[21] Natural Resources and Environment Secretary, "Mexican Official Standard. Specifications of Fertility, Salinity, and Soil Classification," *Study, Sampling and Analysis* (2002).

[22] A. Walkley and I. A. Black, "Un Examen del Método de Degtjareff Para Determinar la Materia Orgánica del Suelo y una Modificación Propuesta del Método de Titulación de Ácido Crómico," *Soil Science* 37, no. 1 (1934): 29–38, https://doi.org/10.1097/00010694-193401000-00003.

[23] J. Hassink, "The Capacity of Soils to Preserve Organic C and N by Their Association With Clay and Silt Particles," *Plant and Soil* 191, no. 1 (1997): 77–87, https://doi.org/10.1023/A:1004213929699.

[24] P. Autfray, P. Guillaume, F. Forest, A. Chabanne, and O. Husson, "Outils de Gestion des Matières Organiques en Agriculture de Conservation En Tunisie," in *Proceedings of the Conference Journée Nationale La gestion du stock organique dans les sols de Tunisie* (El Kef, Tunisia, June, 2009).

[25] R Core Team, *R: A Language and Environment for Statistical Computing* (R Foundation for Statistical Computing, 2024), https://www.R-project.org/.

[26] B. Schloerke, J. Allen, B. Tremblay, F. Van Dunné, and S. Vandewoude, "R Studio Plumber: An API Generator for r" (2022).

[27] G. Niguse, B. Iticha, G. Kebede, and A. Chimdi, "Contribution of Coffee Plants to Carbon Sequestration in Agroforestry Systems of Southwestern Ethiopia," *The Journal of Agricultural Science* 160, no. 6 (2022): 440–447, https://doi.org/10.1017/S0021859622000624.

[28] Z. Xiao, X. Bai, M. Zhao, et al., "Soil Organic Carbon Storage by Shaded and Unshaded Coffee Systems and Its Implications for Climate Change Mitigation in China," *The Journal of Agricultural Science* 158, no. 8-9 (2020): 687–694, https://doi.org/10.1017/S002185962100006X.

[29] K. Hairiah, M. Van Noordwijk, R. R. Sari, et al., "Soil Carbon Stocks in Indonesian (Agro) Forest Transitions: Compaction Conceals Lower Carbon Concentrations in Standard Accounting," *Agriculture, Ecosystems and Environment* 294 (2020): 106879, https://doi.org/10.1016/j.agee.2020.106879.

[30] G. Vallejos-Torres, N. Gaona-Jimenez, R. Pichis-García, et al., "Carbon Reserves in Coffee Agroforestry in the Peruvian Amazon," *Frontiers in Plant Science* 15 (2024): 1410418, https://doi.org/10.3389/fpls.2024.1410418.

[31] B. Belay, E. Pötzelsberger, and H. Hasenauer, "The Carbon Sequestration Potential of Degraded Agricultural Land in the Amhara Region of Ethiopia," *Forests* 9, no. 8 (2018): 470, https://doi.org/10.3390/f9080470.

[32] L. Zhang, Y. Wang, J. Chen, L. Feng, F. Li, and L. Yu, "Características y Factores que Impulsan el Déficit de Saturación de Carbono Orgánico del Suelo en los Bosques Kársticos de China," *Diversity* 14, no. 2 (2022): 62, https://doi.org/10.3390/d14020062.

[33] M. N. E. A. Siddique, L. A. L. de Bruyn, Y. Osanai, and C. N. Guppy, "Based on Soil Carbon Saturation Capacity What is the Potential for Soil Carbon Improvement in Rice-Based Cropping Systems of Northwest Region of Bangladesh?" *Geoderma Regional* 42 (2025): e00975, https://doi.org/10.1016/j.geodrs.2025.e00975.

[34] H. Hassine, N. Karbout, K. Kridane, M. Sanâa, and N. Jedidi, "Caractérisation des Fractions Colloïdales, Minérales et Organiques des Horizons Superficiels des Sols d'Une Topséquence en Zone Semi–Aride de la Tunisie," *Étude et Gestion des Sols* 19 (2012): 106–118.

[35] J. Dinakaran, A. Chandra, K. P. Chamoli, and K. S. Rao, "Evaluation of Organic Manure Amendments on Soil Carbon Saturation Deficit in a Rainfed Agriculture System of Himalaya, India," *Communications in Soil Science and Plant Analysis* 55, no. 21 (2024): 3204–3220, https://doi.org/10.1080/00103624.2024.2385597.

[36] L. A. T. Rodrigues, S. J. Giacomini, J. Dieckow, M. R. Cherubin, A. S. Ottonelli, and C. Bayer, "Carbon Saturation Deficit and Litter Quality Drive the Stabilization of Litter-Derived C in Mineral-Associated Organic Matter in Long-Term No-Till Soil," *Catena* 219 (2022): 106590, https://doi.org/10.1016/j.catena.2022.106590.

[37] G. Vallejos-Torres, N. Gaona-Jimenez, A. Alva Arevalo, et al., "Cadmium Uptake and Mycorrhization by Cacao Clones in Agroforestry and Monoculture Systems of Peruvian Amazon," *Bioagro* 35, no. 3 (2023): 237–246, https://doi.org/10.51372/bioagro353.7.

[38] G. L. Drescher, N. A. Slaton, T. L. Roberts, and A. D. Smartt, "Corn Yield Response to Phosphorus and Potassium Fertilization in Arkansas," *Crop, Forage and Turfgrass Management* 7, no. 2 (2021): e20120, https://doi.org/10.1002/cft2.20120.

[39] G. Wang, Y. Ye, X. Chen, and Z. Cui, "Determining the Optimal Nitrogen Rate for Summer Maize in China by Integrating Agronomic, Economic, and Environmental Aspects," *Biogeosciences* 11 (2014): 3031–3041, https://doi.org/10.5194/bg-11-3031-2014.

[40] X. Zou, W. Wang, X. Sun, D. Jiang, and J. Wang, "Analysis of Soil Fertility and Optimal Nitrogen Application of Brown Earth (Luvisols) in China," *Soil Use and Management* 38, no. 3 (2022): 1416–1429, https://doi.org/10.1111/sum.12791.

[41] P. Soilueang, K. Jaikrasen, Y. Chromkaew, et al., "Dynamics of Soil Nitrogen Availability Following Conversion of Natural Forests to Various Coffee Cropping Systems in Northern Thailand," *Heliyon* 9, no. 12 (2023): e22988, https://doi.org/10.1016/j.heliyon.2023.e22988.

[42] G. Vallejos-Torres, N. Gaona-Jimenez, L. Ordoñez-Sánchez, et al., "Effects of Arbuscular Mycorrhizal Fungi, Poultry Manure Compost, and Cadmium on Plant Growth and Nutrient Absorption of *Oryza sativa*," *Chilean Journal of Agricultural Research* 83, no. 6 (2023): 656–665, https://doi.org/10.4067/S0718-58392023000600656.

[43] E. D. León, J. F. Casanova, J. C. Corrales, and C. Figueroa, "Sustainability-Driven Fertilizer Recommender System for Coffee Crops Using Case-Based Reasoning Approach," *Frontiers in Sustainable Food Systems* 8 (2025): 1445795, https://doi.org/10.3389/fsufs.2024.1445795.

[44] E. E. Oldfield, M. A. Bradford, and S. A. Wood, "Global Meta-Analysis of the Relationship Between Soil Organic Matter and Crop Yields," *Soils* 5, no. 1 (2019): 15–32, https://doi.org/10.5194/soil-5-15-2019.

[45] E. E. Oldfield, M. A. Bradford, A. J. Augarten, et al., "Positive Associations of Soil Organic Matter and Crop Yields Across a Regional Network of Working Farms," *Soil Science Society of America Journal* 86, no. 2 (2022): 384–397, https://doi.org/10.1002/saj2.20349.

[46] X. Zhao, W. Zhang, Y. Feng, et al., "Soil Organic Carbon Primarily Control the Soil Moisture Characteristic During Forest Restoration in Subtropical China," *Frontiers in Ecology and Evolution* 10 (2022): 1003532, https://doi.org/10.3389/fevo.2022.1003532.

[47] B. B. Lin, "The Role of Agroforestry in Reducing Water Loss Through Soil Evaporation and Crop Transpiration in Coffee Agroecosystems," *Agricultural and Forest Meteorology* 150, no. 4 (2010): 510–518, https://doi.org/10.1016/j.agrformet.2009.11.010.

[48] N. Ghasemloo, A. A. Matkan, A. Alimohammadi, H. Aghighi, and B. Mirbagheri, "Estimating the Agricultural Farm Soil Moisture Using Spectral Indices of Landsat 8, and Sentinel-1, and Artificial Neural Networks," *Journal of Geovisualization and Spatial Analysis* 6, no. 2 (2022): 19, https://doi.org/10.1007/s41651-022-00110-4.

[49] M. Getachew, K. Verheyen, K. Tolassa, et al., "Effects of Shade Tree Species on Soil Biogeochemistry and Coffee Bean Quality in Plantation Coffee," *Agriculture, Ecosystems and Environment* 347 (2023): 108354, https://doi.org/10.1016/j.agee.2023.108354.

[50] D. J. Heuschele, J. Gamble, J. A. Vetsch, et al., "Influence of Potassium Fertilization on Alfalfa Leaf and Stem Yield, Forage

Quality, Nutrient Removal, and Plant Health," *Agrosystems, Geosciences and Environment* 6, no. 1 (2023): e20346, https://doi.org/10.1002/agg2.20346.

[51] M. A. Gabarrón-Galeote, S. Trigalet, and B. Van Wesemael, "Effect of Land Abandonment on Soil Organic Carbon Fractions Along a Mediterranean Precipitation Gradient," *Geoderma* 249 (2015): 69–78, https://doi.org/10.1016/j.geoderma.2015.03.007.

[52] Z. Zhong, Z. Chen, Y. Xu, et al., "Relationship Between Soil Organic Carbon Stocks and Clay Content Under Different Climatic Conditions in Central China Forests," *Forests* 9, no. 10 (2018): 598, https://doi.org/10.3390/f9100598.

[53] T. Wang, F. Kang, X. Cheng, H. Han, and W. Ji, "Soil Organic Carbon and Total Nitrogen Stocks Under Different Land Uses in a Hilly Ecological Restoration Area of North China," *Soil and Tillage Research* 163 (2016): 176–184, https://doi.org/10.1016/j.still.2016.05.015.

[54] F. J. Garbuio, D. L. Jones, L. R. Alleoni, D. V. Murphy, and E. F. Caires, "Carbon and Nitrogen Dynamics in an Oxisol as Affected by Liming and Crop Residues Under No-Till," *Soil Science Society of America* 75, no. 5 (2011): 1723–1730, https://doi.org/10.2136/sssaj2010.0291.

[55] H. Sajjad, P. Kumar, P. K. Srivastava, et al., "Assessing Soil Organic Carbon and Its Relation With Biophysical and Ecological Parameters in Tropical Forest Ecosystem India," *Geocarto International* 40, no. 1 (2024): 2441388, https://doi.org/10.1080/10106049.2024.2441388.

[56] H. Sheng, P. Zhou, Y. Zhang, et al., "Loss of Labile Organic Carbon from Subsoil Due to Land-Use Changes in Sub-Tropical China," *Soil Biology and Biochemistry* 88 (2015): 148–157, https://doi.org/10.1016/j.soilbio.2015.05.015.

[57] Y. Zhang, J. Ai, Q. Sun, et al., "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 (2021): 104872, https://doi.org/10.1016/j.catena.2020.104872.

[58] Y. Luo, Y. Li, S. Liu, and P. Yu, "Effects of Vegetation Succession on Soil Organic Carbon Fractions and Stability in a Karst Valley Area, Southwest," *Environmental Monitoring and Assessment* 194, no. 8 (2022): 1–11, https://doi.org/10.1007/s10661-022-10254-x.