

Article

Soil Organic Carbon Storage in Different Land Uses in Tropical Andean Ecosystems and the Socio-Ecological Environment

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Abstract

This study investigates the relationship between land use and soil organic carbon (SOC) storage in tropical Andean ecosystems, introducing a socio-ecological perspective to assess how community conservation perceptions influence SOC storage and contribute to climate change mitigation strategies. Background and Objectives: Land-use change reduces carbon stocks in tropical ecosystems. Focusing on the Las Piedras River basin (Popayan, Colombia), we evaluated SOC storage under four plant cover types—riparian forests (RFs), ecological restoration (ER), natural regeneration (NR), and livestock pastures (LSs)—and examined its association with local conservation perceptions. Materials and Methods: SOC storage at 30 cm depth, carbon inputs and outputs, and soil physicochemical properties were measured across land-use types. Conservation perceptions were assessed through 65 community surveys. Data analyses included ANOVA, principal component analysis, and multinomial logistic regression. Results: SOC storage was highest in RFs (148.68 Mg ha^{−1}), followed by ER and LSs, and lowest in NR (97.30 Mg ha^{−1}). A positive relationship was observed between high conservation perception and greater SOC content. Conclusions: SOC storage is strongly influenced by land use and community conservation values. Active restoration efforts, coupled with environmental education, are essential for enhancing the socio-ecological resilience of these ecosystems.

Keywords: carbon sequestration; ecosystem services; socio-ecological systems; soil properties



Academic Editor: Charles Jones

Received: 21 July 2025

Revised: 20 August 2025

Accepted: 22 August 2025

Published: 8 September 2025

Citation: Mondragón Valencia, V.A.; Figueroa Casas, A.; Macías Pinto, D.J.; Rosas-Luis, R. Soil Organic Carbon Storage in Different Land Uses in Tropical Andean Ecosystems and the Socio-Ecological Environment. *Earth* **2025**, *6*, 106. <https://doi.org/10.3390/earth6030106>

Correction Statement: This article has been republished with a minor change. The change does not affect the scientific content of the article and further details are available within the backmatter of the website version of this article.

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1. Introduction

The transformation of natural areas into anthropized zones, driven by rapid economic growth, decreases biodiversity and ecosystem services (ESs) and increases the concentration of greenhouse gases (GHGs), often exceeding the regulatory capacity of different ecosystems [1]. Agricultural land for food production currently occupies approximately 38–55% of the planet's habitable land, and the global food system is responsible for around 37% of anthropogenic GHG emissions and could add almost 1 °C to warming by 2100 [2]. To maintain food production and environmental conditions at local, regional, and global scales, soil is a vitally important resource, and its role as a sink or source of carbon (C) is determined by its vegetation covers, which modify its structure and increase the mineralization rates of organic matter, releasing CO₂ into the atmosphere [3].

The quantification of C storage in biomass and soil and GHG emissions such as CO₂ are the most studied ESs because soil plays a fundamental role in stabilizing C levels, which will help meet the climate objectives of the 2015 Paris environmental summit to limit global warming to less than 2 °C by 2100 and reduce CO₂ levels through the ecosystem service of soil organic carbon (SOC) sequestration [4]. Some areas can be strategic to achieve this objective, such as the ecosystems of the tropical Andean slope of Colombia, with soils that are mostly derived from volcanic ash and important carbon stocks and stabilizers; due to their high content of organic matter, these ecosystems present high biological, cultural, and agricultural diversity [5]. However, due to their conditions, they support a constant growth of human populations that demand a large amount of natural resources, which leads to the loss of natural vegetation cover [6].

The analysis of the deterioration of Andean ecosystems must be approached within the complexity of socio-ecological systems (SESs), requiring the understanding of the components for the sustainability of this region [7]. Agricultural activities are the primary drivers of land-use dynamics, characterized by intensive crop cultivation and extensive grazing, which hinder forest regeneration [8]. This problem affects the physical, chemical, and biological properties of the soil, which can reduce SOC by more than 50% at a depth of 20 cm and between 25 and 30% at 100 cm during agricultural periods of 30 to 50 years [9]. Increases in SOC stocks have been shown to improve crop yields in high-input commercial agriculture but especially on low-input degraded lands, making SOC a crucial nutrient source for agricultural production [10]; given its importance in soil health, a decrease in SOC content is a threat to food security and the agrarian socio-economics of the country [11].

With population growth and the expansion of the agricultural frontier, there is a growing demand for water and fertile soils [12]. An example of this is the Las Piedras River basin, which supplies water to the Popayan municipality (Colombia) and constitutes a buffer zone for the Purace National Natural Park, home to a variety of conserved natural ecosystems. However, agricultural expansion has led to landscape changes with the loss of native vegetation [13]. These anthropogenic processes, such as extensive livestock pastures (LSs), increase GHG emissions, reduce biodiversity, and reduce the provision of ESs such as water regulation and SOC storage due to reduced inputs of organic matter and physical soil protection [14]. Given this situation, initiatives have been generated for the protection and care of this watershed with different conservation uses such as conserved riparian forests (RFs), ecological restoration (ER), and natural regeneration (NR) as sustainable management measures and practices appropriate for land-use change. This research evaluates how soil organic carbon (SOC) stocks vary across different land uses (LSs, RFs, ER, NR) in a tropical Andean ecosystem of Colombia and explores how these patterns relate to local socio-ecological perceptions. By combining soil measurements, structured community surveys, spatial analysis, and multinomial regression modeling, this study offers an integrated perspective that links biophysical and social dimensions of carbon storage. This approach is novel in Andean contexts, where the interaction between ecological knowledge, land use, and soil carbon dynamics remains poorly explored. Previous studies in Andean ecosystems have focused primarily on biophysical factors and the importance of SOC in these areas, without considering social elements. For example, ref. [15] emphasized the relevance of SOC in high-mountain systems, ref. [16] implemented geospatial methods to map SOC distribution based on environmental predictors, and ref. [17] applied spatial interpolation techniques to model variability in SOC stocks. In contrast, our research integrates detailed measurements of SOC across diverse land-use types with socio-ecological data—specifically, conservation perceptions—that can help elucidate how local values and land management practices influence SOC storage, an aspect that, to our knowledge, has not been extensively examined in Andean ecosystems.

2. Materials and Methods

2.1. Site and Land-Use Description

The Piedras River basin is in the intertropical equatorial Andes at coordinates $2^{\circ}1'35''$ N and $76^{\circ}33'10''$ and has an area of 58 km² (Figure 1). The average monthly temperature varies between 10.4 °C and 18.4 °C, with an altitudinal range between 1980 and 3820 masl that corresponds to the sub-Andean forest and Andean forest formations, made up of a mountainous relief, with steep, long, and straight slopes that are between 35 and 98% in the high zone, 16 and 35% in the middle zone, and 3 and 15% in the low zone. The soils are mainly formed from volcanic ash, with a medium texture of poorly structured and well-drained clayey loam; they have strong acidity [18].

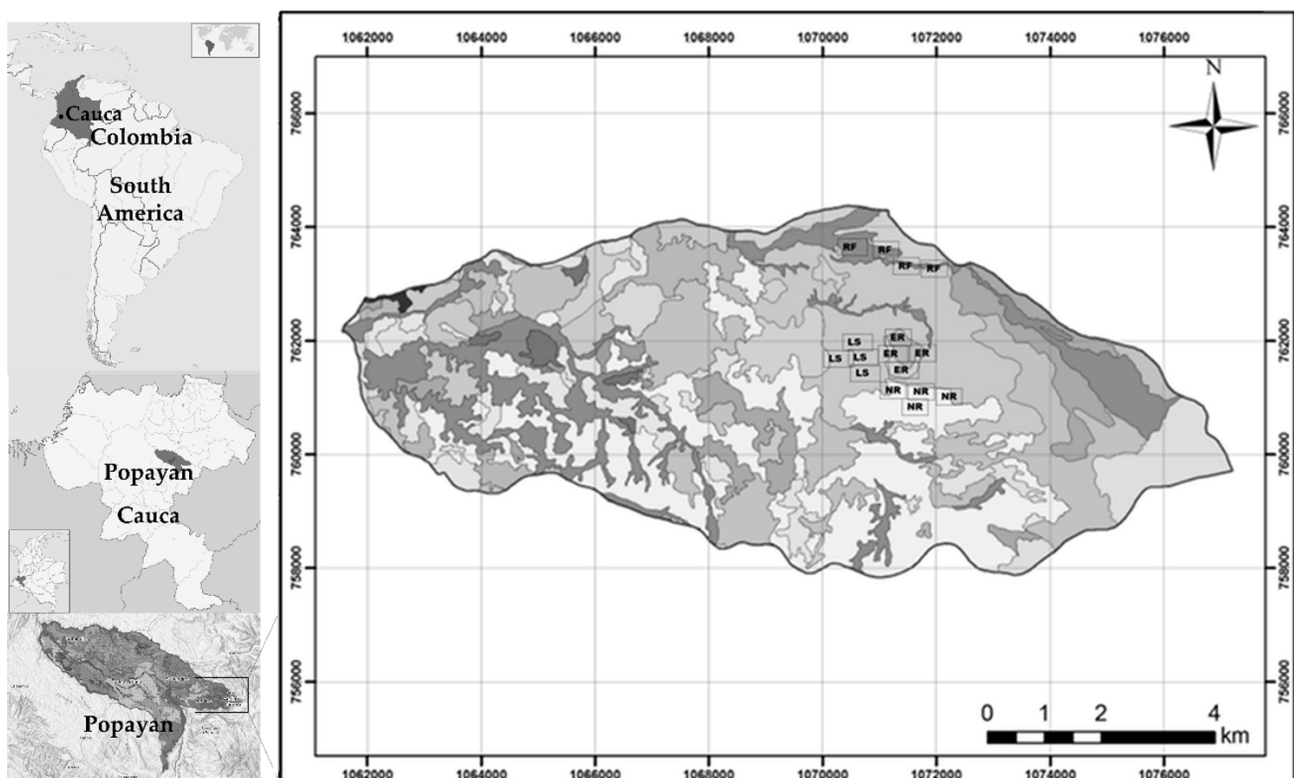


Figure 1. Location of the study area and distribution of sampling plots across different plant cover: riparian forest (RF), ecological restoration (ER), and natural regeneration (NR).

In each conservation land-use type, RFs, ER, and NR, three rectangular transects of 300 m² (10 m × 30 m) were established following established protocols for tropical Andean forest structure assessment [19]. Transects were positioned randomly within each site to ensure the representative coverage of vegetation. Within each transect, all woody individuals (trees and shrubs) with a diameter at breast height (DBH) ≥ 0.1 m, measured at 1.3 m above ground using a diameter tape, were recorded. For each individual, DBH was used to calculate the basal area (m² ha⁻¹) using the equation $BA = \pi \times (DBH/2)^2$, and values were summed per transect. Tree density (trees ha⁻¹) was obtained by scaling the count of individuals in 300 m² to a per-hectare basis using the factor 10,000/300. Species were identified in the field using regional floras and reference collections. In pasture sites (LSs), the presence of dominant herbaceous species was recorded visually. The highest basal area and tree density were observed in RFs (15.75 ± 1.03 m² ha⁻¹; 1138 ± 1.49 trees ha⁻¹), followed by ER and NR, which showed the lowest values (6.08 ± 1.45 m² ha⁻¹ and 873 ± 1.87 trees ha⁻¹, respectively). In NR, 20 native tree species were identified, while in LSs, three dominant

grass species of the Poaceae family were present: *Holcus lanatus*, *Pennisetum purpureum*, and *Lolium multiflorum* (Table 1).

Table 1. Forestal structure to the plant covers.

Variables	Plant Cover		
	RF	ER	NR
Basal area/ha (m ²)	15.75 ± 1.03	16.33 ± 1.29	6.08 ± 1.45
No. trees/ha (DBH > 0.1 m)	1138 ± 6.49	1085 ± 5.57	873 ± 3.87

Values are mean ± standard deviation (SD), n = 3 transects per land use. Tree density values (trees ha^{−1}) were obtained by scaling counts from 300 m² transects to a per-hectare basis. RF: riparian forest; ER: ecological restoration; NR: natural regeneration.

2.2. Data Collection

2.2.1. Determination of Soil Carbon Inputs and Outputs

Sampling was conducted between October 2023 and September 2024. In the tropical Andean region, the climate is relatively stable. Popayan, Colombia, receives approximately 2100 to 2600 mm of rainfall annually and maintains an average temperature of 17–19 °C throughout the year, with no distinct temperature seasons but with bimodal rainfall peaks (April–June and October–December) [20]. This climatic stability, combined with the absence of El Niño and La Niña events during the study period, ensured that the observations reflected typical ecosystem dynamics.

To determine C inputs in the studied vegetation covers, litter production was estimated in the forested plots. Twelve litter collection baskets, each 1 m² in area, were established. The litter was collected every 30 days for a year and weighed fresh and dry (oven-dried at 65 °C for 24–48 h) [21]. For this study, grass litter was considered to be all senescent material not attached to the plant (loose on the soil or tangled in stems) [22]. The weights obtained every three months were averaged to obtain four reference values for estimating carbon inputs from leaf litter (C-LL). Additionally, carbon in the mulch layer (C-MULCH) was quantified to account for surface organic material not included in leaf litterfall. Mulch samples were collected from each plot using a 25 × 25 cm frame, oven-dried at 65 °C for 48 h, and analyzed for carbon content using dry combustion. This variable represents another significant input to the soil carbon pool, especially in land covers with dense herbaceous or woody vegetation [21]. Carbon dioxide emissions into the atmosphere were estimated to be from basal soil respiration (SBR). CO₂ was measured by the respirometry method (C–CO₂) in the field. The sodium hydroxide (NaOH) sample was placed on a tripod in a closed system for 24 h then precipitated with barium chloride, followed by the addition of two drops of phenolphthalein. Finally, the sample was titrated with 0.1 N hydrochloric acid to quantify the amount of hydroxide that does not react with CO₂, and a control or blank was used. The metabolic quotient (qCO₂) allowed the evaluation of emissions from the organic component of the soil; for this purpose, the values obtained every three months were averaged to obtain four reference values to estimate carbon outputs in the soil.

2.2.2. Soil Sampling

Four 20 m² sampling plots were established for each land use, with soil and terrain conditions as similar as possible to allow valid comparisons between them. Five 60 g subsamples were taken from each plot to form the corresponding 300 g composite sample. The samples were taken at a depth of 30 cm in the A horizon.

2.3. Laboratory Analysis

2.3.1. Soil Chemical Properties

Organic carbon and nitrogen: Two grams of macerated soil samples was used to determine the carbon and nitrogen contents using an NC 1500 elemental analyzer (Carlo Erba Instruments, Milan, Italy). Elemental analysis was employed to quantitatively determine the elemental composition (C and N) of the soil samples from the different vegetation covers under study [23].

Soil organic carbon: With the data obtained from the carbon content and apparent density at each sampling depth, the carbon content of SOC was estimated (Equation (1)):

$$SOC = (A) \times (C_{org}) \times (BD) \times (D) \quad (1)$$

where SOC is the organic carbon stored in the soil (Mg ha^{-1}), A is the area ($1 \text{ ha} = 10,000 \text{ m}^2$), C_{org} is the grams of organic carbon in soil ($\text{Mg C}/100 \text{ Mg}$), BD is the bulk density of the soil (g/cm^3), and D is the depth of the soil layer. Since the content was estimated for the first 30 cm of soil depth, $D = 0.3 \text{ m}$.

The pH was determined using a potentiometer in a 1:1 soil–water suspension. The suspension was stirred intermittently for one hour, and the reading was taken. The effective cation exchange capacity (ECEC) was determined as the sum of exchangeable bases (Ca, Mg, and K) extracted with 1 N ammonium acetate and neutral, plus the exchangeable Al content, extracted with 1 N KCl [24].

2.3.2. Soil Physical Properties

Bulk density (BD) g/cm^3 was determined by the soil core method [25], with a cylinder of 64.45 cm^3 and five subsamples per plot. Soil texture was determined by the hydrometer method [25]. Hygroscopic moisture content (HSM)% equilibrates a previously oven-dried soil sample in a controlled relative humidity environment (usually 98–100%). This is performed by placing the sample in a desiccator with a saturated salt or water solution at the bottom, allowing it to reach an equilibrium state. Moisture content was calculated by measuring the mass change between dry soil and equilibrated soil [26]. Field soil moisture (SM)% was determined gravimetrically by relating the mass of water and the mass of soil solids, which is necessary to express results on a dry basis and compare results as a function of time [27].

2.4. Socio-Ecological Information ReCompilation

To complement the biophysical data and better understand local perceptions and practices related to natural resource management, a socio-ecological information survey was carried out across the study area. A total of 65 structured surveys were administered using the ArcGIS Survey123 platform (Esri, Redlands, CA, USA) [28]. The survey aimed to assess the perceived importance of natural resource conservation by local stakeholders, with responses categorized into three levels: high, medium, and low.

The questionnaire included items on land-use practices, conservation awareness, perceived ecosystem services, and community involvement in sustainable resource management. Survey responses were georeferenced and spatially correlated with environmental variables such as input and output flows, soil organic carbon (SOC) storage, and soil bulk density (BD), to explore relationships between socio-ecological perceptions and soil condition indicators.

2.5. Data Analysis

Data were analyzed using a block design. The results were subjected to analysis of variance to detect significant differences among land uses for inputs, outputs, and

SOC storage. A principal component analysis (PCA) was performed to identify patterns in the data and reduce dimensionality while preserving as much variability as possible. This analysis allowed for the exploration of relationships between the studied variables (SOC, SBR, and C-LL) and different land uses (RFs, ER, NR, LSs); multinomial logistic regression (a generalized linear model with a multinomial logit link) was used to assess the relationship between SOC storage and land uses (RFs, ER, NR, LSs) and the importance the community places on natural resource conservation (high, medium, and low). The model provides coefficients for the probability of being in medium and low relative to the base category, high. Residual Deviance was used, which is a metric analogous to the sum of squared errors (SSE) in linear regression adapted for maximum likelihood models such as logistic regression. The Akaike Information Criterion (AIC) is a metric used to evaluate and compare statistical models where one of the levels of the dependent variable (in this case, conservation importance) is used as the reference or base category [29]. This means that the model calculates the probabilities of the other levels (in this case, low and medium) relative to this reference category. The data obtained was processed in the statistical package R 4.3.1 (R Core Team, Vienna, Austria).

3. Results

3.1. C Inputs and Outputs and SOC Storage in Different Land Uses

The average values of C-LL ($\text{Mg ha}^{-1} \text{ month}^{-1}$) were significantly higher in RFs = $4.65 \text{ Mg ha}^{-1} \text{ month}^{-1}$, and the lowest contents were found in LSs (Figure 2a). The values obtained from soil basal respiration on the rate of release of carbon dioxide (CO_2) from the soil were significantly higher in ER $179.28 (\mu\text{g C-CO}_2 \text{ g}^{-1} \text{ d}^{-1})$, followed by NR and LSs and significantly lower in RFs (Figure 2b). The amount of C-Mulch $8.11 (\text{Mg/ha}^{-1})$ had a similar behavior to that obtained in the average values of C contents in leaf litter and were significantly higher in RFs. In contrast, the lowest contents were found in LSs (Figure 2c). SOC contents were significantly higher in RFs ($148.68 \text{ Mg/ha}^{-1}$), followed by ER, LSs, and NR (Figure 2d).

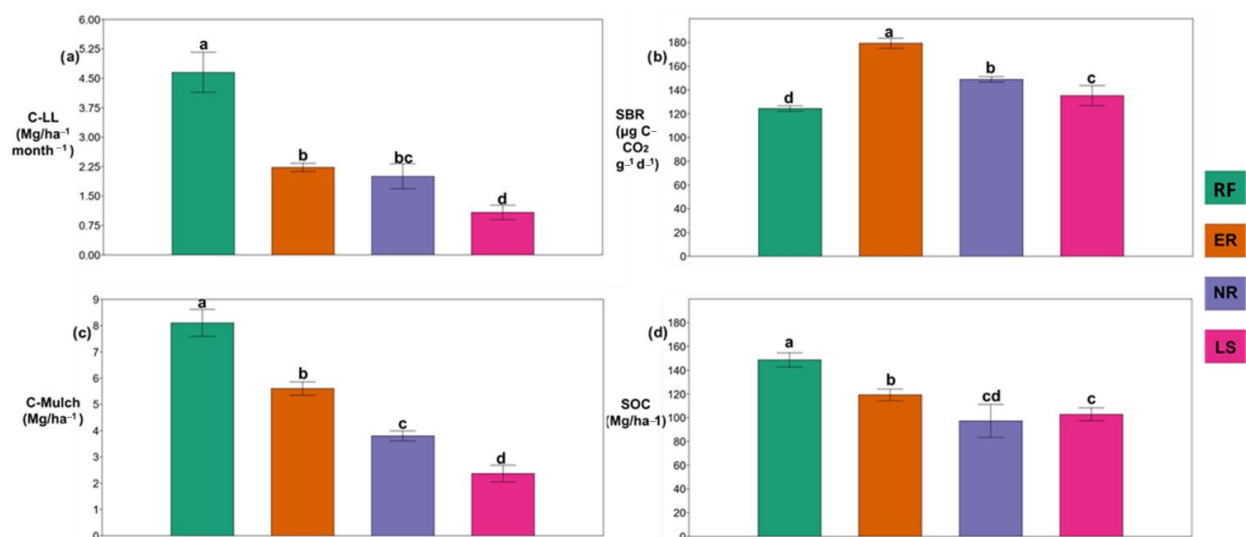


Figure 2. Comparison of the means for the variables studied in the different land uses: RF: riparian forest, ER: ecological restoration, NR: natural regeneration, LS: livestock. (a) Leaf litter carbon input (C-LL, $\text{Mg ha}^{-1} \text{ month}^{-1}$). (b) Soil basal respiration (SBR, $\mu\text{g C-CO}_2 \text{ g}^{-1} \text{ d}^{-1}$). (c) Mulch carbon (C-MULCH, Mg ha^{-1}). (d) Soil organic carbon (SOC, Mg ha^{-1}). Bars represent standard deviations. Different letters indicate significant differences between land uses ($p < 0.05$).

3.2. Physicochemical Properties

The average values of the physicochemical properties of the studied soils (standard deviation) are presented in Table 2: BD (g/cm^3) was significantly higher in RFs and ER at 1.01 and $1.06 \text{ g}/\text{cm}^3$, respectively, followed by NR. Significantly lower values were found in LSs ($p < 0.05$). SM (%) showed significantly higher values in RFs and ER at 13.49 and 11.32%, respectively, followed by LSs. Significantly lower values were found in NR ($p < 0.05$). MS (%) values were significantly higher in ER at 65.97%, followed by RF. No differences were found between LS and NR, with significantly lower values. Regarding the values obtained in the particle size of the soil texture, it was observed that all these soils have a high content of sand (%) and are significantly lower in ER at 72%. The rest did not differ from each other, and the content of silt (%) was significantly higher in ER at 23.39%, followed by NR. Significantly lower values were presented in LSs and RFs; the clay content (%) did not present significant differences between RFs, ER, and LSs. Significantly lower values were presented in NR (4.05%) $p < 0.05$. The contents of SOC (Mg ha^{-1}) were significantly higher in RFs at $148.68 \text{ Mg ha}^{-1}$, followed by ER and LSs, and in NR were significantly lower. The values obtained from soil basal respiration ($\mu\text{g C-CO}_2 \text{ g}^{-1} \text{ d}^{-1}$) for the carbon dioxide (CO_2) release rate from the soil were significantly higher in ER at $179.28 \mu\text{g C-CO}_2 \text{ g}^{-1} \text{ d}^{-1}$, followed by NR and LSs, and significantly lower in RFs. pH values denoted acidic soils and did not differ between land uses. ECEC values ($\text{meq}100 \text{ g}^{-1} \text{ s}$) were significantly higher in LSs at $5.70 \text{ meq}100 \text{ g}^{-1} \text{ s}$, followed by NR and ER. The significantly lowest values were found in RF. The complete set of soil physical and chemical properties by sampling plot is presented in Appendix A (Table A1).

Table 2. Physicochemical properties determined in different land uses.

Soil Characteristics		Land Use			
		RF	ER	NR	LS
Physical	BD (g/cm^3)	$1.01^a \pm 0.01$	$1.06^a \pm 0.01$	$0.95^{ab} \pm 0.08$	$0.90^b \pm 0.02$
	HSM (%)	$13.49^a \pm 0.40$	$11.32^a \pm 0.56$	$10.52^c \pm 0.55$	$10.08^b \pm 0.49$
	SM (%)	$64.96^b \pm 0.80$	$65.97^a \pm 0.61$	$62.83^c \pm 0.25$	$62.75^c \pm 0.72$
	Sand (%)	$73.41^a \pm 2.52$	$72.00^b \pm 3.01$	$73.50^a \pm 2.52$	$73.46^a \pm 2.52$
	Silt (%)	$21.01^c \pm 1.51$	$23.39^a \pm 3.03$	$22.40^b \pm 2.52$	$21.04^c \pm 2.00$
	Clay (%)	$5.58^a \pm 1.15$	$4.61^{ba} \pm 0.50$	$4.10^b \pm 0.50$	$5.50^a \pm 1.01$
Chemical	SOC (Mg ha^{-1})	$148.68^a \pm 6.07$	$119.24^b \pm 5.04$	$97.30^{cd} \pm 14.13$	$102.85^c \pm 5.55$
	SBR ($\mu\text{g C-CO}_2 \text{ g}^{-1} \text{ d}^{-1}$)	$124.31^d \pm 2.41$	$179.28^a \pm 4.34$	$148.91^b \pm 2.31$	$135.25^c \pm 8.58$
	pH	$4.93^a \pm 0.05$	$5.14^a \pm 0.05$	$4.98^a \pm 0.21$	$5.13^a \pm 0.16$
	ECEC ($\text{meq}100 \text{ g}^{-1} \text{ s}$)	$3.73^c \pm 0.21$	$4.21^b \pm 0.21$	$4.38^b \pm 0.39$	$5.70^a \pm 0.50$

BD: bulk density, HSM: hygroscopic soil moisture, SM: soil moisture, SOC: soil organic carbon, SBR: basal respiration soil, ECEC: effective cation exchange capacity. RF: riparian forest, ER: ecological restoration, NR: natural regeneration, LS: livestock. Different letters between rows represent significant differences ($p < 0.05$) with the Tukey test for each variable.

The PCA results showed that PC1 (43.3%): Mainly separates soils with higher SOC and BD content and lower proportion of sand (RFs and LSs) and PC2 (27.1%): Distinguishes more humid soils (SM, NR) from those with higher biological activity (SBR, ER); the particular associations with each type of land use are highlighted, highlighting the closer relationship of SOC with forest conservation uses such as RF. The ellipses suggest a clear differentiation between land uses, indicating that the systems have specific characteristics that group them according to their physical properties: particle sizes (sand, silt and clay) and apparent density, chemical properties: ECEC ($\text{meq}100 \text{ g}^{-1} \text{ s}$), pH and ecological properties: HSM: hygroscopic soil moisture, SM: soil moisture, SOC: soil organic carbon, SBR: (Figure 3).

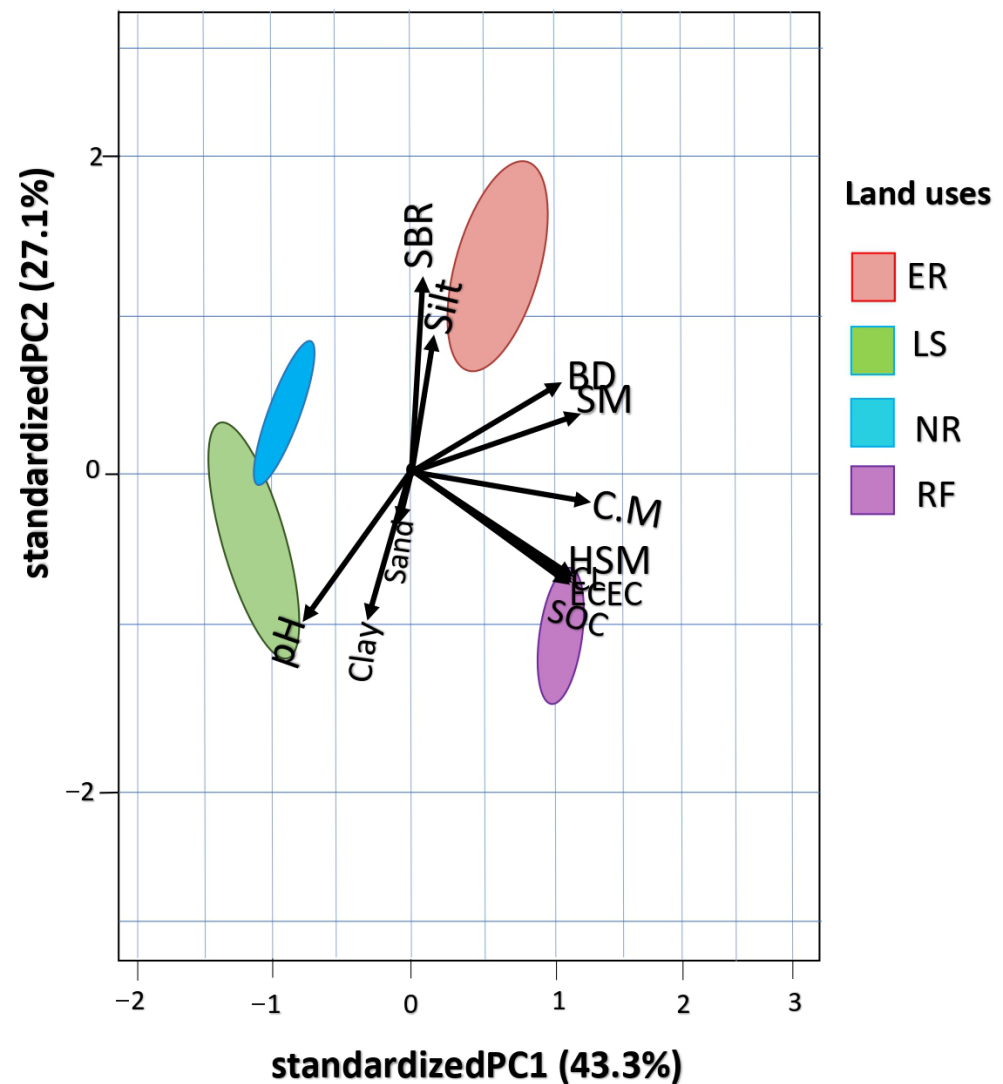


Figure 3. PCA: BD: bulk density, HSM: hygroscopic soil moisture, SM: soil moisture, SOC: soil organic carbon, SBR: basal respiration soil, ECEC: effective cation exchange capacity. RF: riparian forest, ER: ecological restoration, NR: natural regeneration, LS: livestock. Different letters between rows represent significant differences ($p < 0.05$) with the Tukey test for each variable.

3.3. Socio-Ecological Perception of Conservation and Environmental Priorities

3.3.1. Survey Information Collection Points and Environmental Preferences

A total of 65 structured surveys were conducted to explore local perceptions regarding natural resource conservation in the Las Piedras River basin. The spatial distribution of responses, classified by residence time in the basin, is shown in Figure 4. The data reveal that most respondents have lived in the area for more than 20 years, demonstrating long-standing relationships with the territory and its resources.

When asked about the most important measure to improve the environment, the majority of respondents prioritized ecological restoration or natural regeneration (35.4%), followed by support for ecological agriculture (27.7%) and soil recovery (16.9%). Less frequent responses included responsible livestock management, greater reuse of agricultural waste, and riverbed and livestock route restoration (Figure 5).



Figure 4. Spatial distribution of survey responses classified by residence time in the Las Piedras river basin.

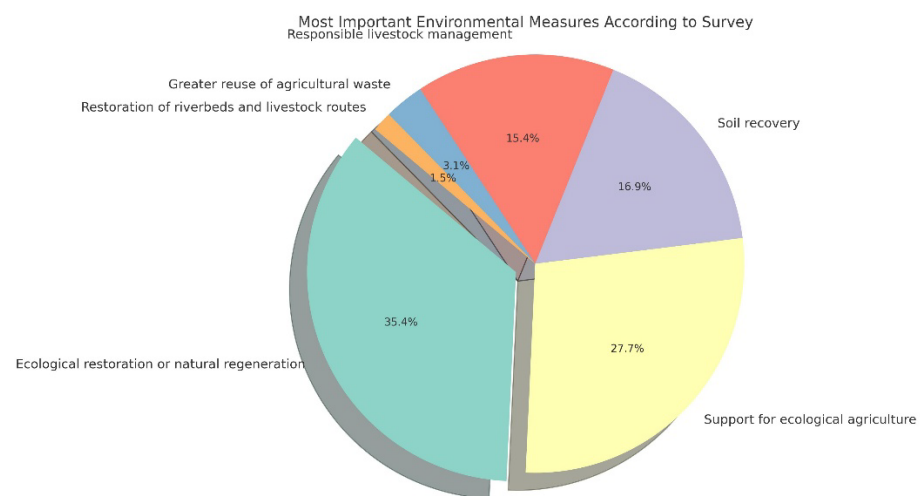


Figure 5. Most important environmental measures according to survey respondents (n = 65).

3.3.2. Multinomial Logistic Regression

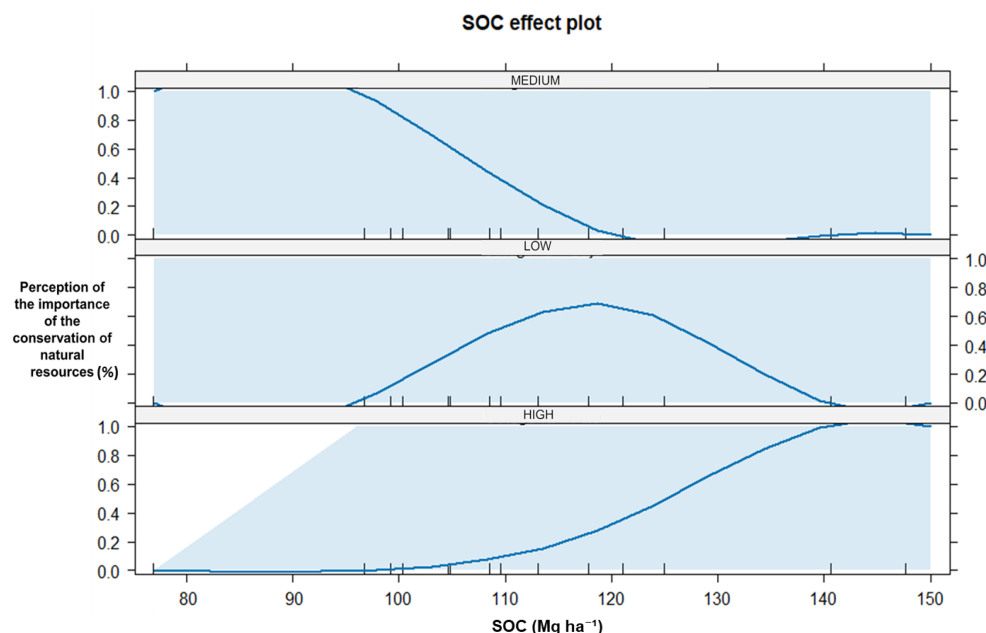
The generalized linear model with a multinomial logit link indicated that the soil types measured based on the variables evaluated are associated with the categories of importance for the conservation of the watershed's natural resources. The variables SOC, SBR, CL, and C_MU have a complex relationship with the conservation categories. SOC and C_MU have a negative relationship with the probability of being in the low and medium categories, while BD and SBR have clearer and more positive effects for low and medium. When Andean communities attach importance to natural resource conservation and reflect this in their land use, SOC storage increases. The low Residual Deviance (4.83×10^{-6}) and AIC (24) indicate a robust model fit. The estimated coefficients for each explanatory variable and conservation importance category are presented, along with their standard errors and significance levels (Table 3). Positive coefficients indicate a higher probability of belonging to the respective category compared to the high category, while negative coefficients indicate the opposite relationship.

Table 3. Multinomial logistic regression between the importance of community conservation (high, medium, and low) and soil properties that regulate SOC storage.

Coefficients:	Intercept	BD	SOC	SBR	CL	C_MU
Low	32.16	18.38	−0.49	0.81	24.14	−34.16
Medium	−32.05	−18.61	−1.23	0.93	−19.93	20.52
Std. Errors:	Intercept	BD	SOC	SBR	CL	C_MU
Low	331.36	311.13	6292.85	7496.41	1131.01	548.08
Medium	299.04	245.43	6265.70	7576.90	1017.60	1731.31
Residual Deviance: 4.84×10^{-6}						
AIC: 24						

The results of multinomial logistic regression between community conservation importance (high = reference category; medium; and low) and soil properties regulating SOC storage are shown above. Coefficients represent changes in the log-odds of belonging to the medium or low conservation importance category relative to high, with a per-unit increase in the explanatory variable. Positive coefficients indicate a higher probability of belonging to that category, while negative values indicate the opposite. Standard errors (SEs) indicate the precision of estimates. Residual Deviance and AIC are reported as overall measures of model fit.

The relationship between SOC stocks and the perception of the importance of natural resource conservation was classified into three categories: low, medium, and high. This varies depending on the soil organic carbon (SOC) content. It is observed that the probability of belonging to the low category is higher at intermediate SOC values, reaching a peak between 110 and 120 g/kg. The medium category has a higher probability of lower SOC values, decreasing as SOC increases. In contrast, the probability of belonging to the high category increases considerably with higher SOC values, demonstrating its greater relevance in soils with higher levels of carbon storage (Figure 6).

**Figure 6.** Perception of the importance of the conservation of natural resources vs. SOC stocks.

4. Discussion

4.1. Carbon Stocks

Understanding the balance between carbon inputs and outputs in tropical Andean ecosystems and their storage in the soil is essential to mitigate the effects of global warming, food security, and other ecosystem services. Research such as that by [15] highlights that SOC reserves are potentially endangered by global warming and that land uses play a fundamental role in SOC content; however, there are limited data and studies available to be conclusive, and some contradictory results are reported. For example, higher SOC stocks have been reported in restored forest sites compared to grasslands [30,31], while [32] no significant differences have been observed between these land uses in certain Andean paramo regions. Such discrepancies may be linked to differences in soil type, altitude, management history, and sampling depth. Our results align more closely with those of [30,31], as SOC stocks were consistently higher in conservation-oriented land uses (RFs, ER, and NR) compared to livestock pastures (LSs), likely due to greater organic matter inputs from woody vegetation and reduced soil disturbance. This pattern is also reflected in the measurements found, which show that the SOC stored in the soils of the study area is highest in RFs at $148.68 \text{ Mg/ha}^{-1}$, followed by ER, while other uses such as NR and LSs have lower values (Figure 2d), which may be related to the contributions of C inputs from litterfall, where the highest values are found in RFs at $4.65 \text{ Mg ha}^{-1} \text{ month}^{-1}$, followed by ER, NR, and LSs (Figure 2a). This pattern reinforces the idea that the most intervened ecosystems, such as LSs, have a lower accumulation of aboveground biomass compared to conserved or restored ecosystems. The C stored in the mulch had a similar behavior, which significantly decreases from RFs to livestock use (LSs) (Figure 2c), reflecting a reduction in the accumulation of organic material.

The functions of SOC are highlighted in several studies, which indicate that its concentration changes significantly between different land uses [33]. Specifically for tropical ecosystems, they also show that riparian forests have a greater storage of SOC due to their constant inputs of organic matter and lower disturbances [34]. This balance in SOC stocks reflects a greater equilibrium of this type of use, which presented significantly lower SBR values. While significantly higher values were presented in ER, followed by NR and LSs (Figure 3), this may be related to greater microbial activity in these soils and a greater amount of easily degradable C, results that contradict those reported by [35] showing how ER can decrease SBR; however, these results can be partially explained by the high inputs of C from leaf litter and C from mulch in an ecosystem that is not yet in equilibrium and has greater inputs of light and humidity, which favors the decomposition of organic matter [36]. Considering that the system is not yet in equilibrium, these results show that conservation practices such as forest protection and active ER with community support are more effective in storing SOC, which may be related to a more developed forest structure in these land uses [37].

4.2. Soil Properties and SOC in Different Land Uses

The PCA highlights the importance of soil organic carbon (SOC) and soil basal respiration (SBR) as key indicators to differentiate land uses in tropical Andean ecosystems (Figure 3). The PCA shows a clear differentiation in soil properties based on different land uses: RFs, ER, NR, and LSs. The variance explained by the first two components was 70.4% of the total variability of the data, reflecting a consistent multivariate structure of the relationship between soil properties and their different uses. It is also evident that the variables BD and SOC are directly related, and they tend to increase SOC contents when BD increases, which is consistent with what was reported by [38,39], who emphasized that making a good measurement of the apparent density and having knowledge of this variable helps to better

understand the dynamics of SOC storage in different contexts. These results and those previously reported demonstrate how SOC storage regulates the physical properties of the soil, specifically BD. In addition, the separation of the groups in a two-dimensional space indicates that the evaluated land uses generate differentiated impacts on soil properties, which reinforces the importance of generating specific management strategies for each type of land use.

Regarding the physical properties studied, BD, HSM, and SM, and the percentage of particle size (sand, silt, and clay) (Table 2), land uses with significantly higher SOC content presented significantly higher HSM and SM percentages, which is related to better structural development of the soil because of stored organic matter. SOM, due to its amorphous characteristics, has, by itself, a high water storage capacity [40]. Just 1 g of SOC can retain up to 3.5 g of water at field capacity [41]. The percentages of sand, silt, and clay are relatively consistent among land uses, although ER showed a higher silt content (23.39%), which could be related to the incorporation of fine sediments through agricultural practices [42]. Soils dedicated to RF conservation, despite having a high SOC, had a lower SBR (124.31 mg CO₂/h), likely due to soil acidity, which can limit microbial enzymatic activity [43]. These soils had a slightly acidic pH across all uses, ranging from 4.93 to 5.14. RFs showed the most acidic pH (4.93), which is common in forest soils due to the accumulation of organic matter and natural leaching processes [44]. LSs presented the highest ECEC (5.70 meq/100 g), suggesting a greater capacity of the soil to retain nutrients, favoring plant growth during the restoration process [45]. Based on these results, RFs stand out as an important strategy for soil stability in Andean ecosystems in terms of food and water security and overall soil health. ER shows good potential to recover degraded soil properties, especially in terms of microbial activity (SBR), although it is crucial to monitor that it does not translate into excessive losses of organic carbon in the long term. NR represents an intermediate alternative with benefits for carbon sequestration but is less efficient than active restoration strategies, and it is suggested that it is good to accompany the uses of LSs with the greater conservation of existing forest remnants in the territory for the health of its soils.

4.3. Socio-Ecological Relationships Between Soil Variables and Conservation Perception

The survey results revealed that local communities consider ecological restoration and natural regeneration to be the most important environmental measures for improving watershed conditions, followed by support for organic agriculture and soil restoration (Figure 5). This prioritization reflects not only a direct concern about environmental degradation but also a strong understanding among residents of the need to maintain healthy and functioning ecosystems. Notably, these priorities align with so-called nature-based solutions, such as forest restoration, agroecological practices, and soil conservation, which seek to rehabilitate degraded landscapes while supporting local livelihoods and cultural continuity [46]. In the Andean context, these actions are not merely technical interventions; they are often deeply rooted in long-standing relationships with the land, shaped by traditional ecological knowledge and collective memory. Similar patterns have been documented in other rural communities where local actors are actively involved in defining conservation agendas. Recognizing and integrating these socio-ecological values into land management strategies can be essential for strengthening long-term ecological resilience [46]. Furthermore, the concordance between these perceptions and the soil conditions measured in this study reinforces the idea that communities are not only aware of environmental change but also propose practical and contextualized responses to address it. This relationship is particularly relevant considering that land covers with the highest perceived conservation value also exhibited the highest levels of soil organic carbon (SOC), suggesting a

direct relationship between community practices, soil health, and carbon storage potential. These findings underscore the role of local awareness and land management as crucial components in land-based climate change mitigation strategies.

The regression model results suggest that the community perception of conservation is closely related to soil biophysical variables. Higher BD appears to be associated with a lower perception of the importance of conservation. This could be related to these factors, often indicating less productive or compacted soil conditions [47], which could negatively influence soil-dependent agricultural or economic activities. Conversely, an increase in soil basal respiration (SBR) is related to a higher average perception, possibly reflecting greater biological activity and healthier soil, which is valued by local communities, as active ER has benefits on soil microbiology [48,49]. This relates to the results of this study, which highlight ER as a positive strategy to improve soil microbiology and SOC storage, thereby contributing to the water security of the territory.

Conservation perceptions reveal how local communities interact with their environment and prioritize ecological sustainability. The inverse relationship between SOC content and low perceptions of the importance of resource conservation may reflect a connection between the ecological value of this land property and its appreciation by inhabitants, highlighting that conserving natural areas is important for various ecological functions, including improving SOC stocks. From the socio-ecological environment, spatially explicit relationships are identified between the supply and demand of regulating ecosystem services and carbon storage and sequestration [50]. Other research focuses on measuring the interactions between human interactions with their ecosystems, such as the establishment of home gardens, forest conservation, and the establishment of farms and their effect on SOC sequestration [51]. However, the number of publications addressing SOC sequestration from a socio-ecological perspective is low [52]. The perception of the importance of conserving natural areas by communities and its relationship with SOC storage suggests a connection between the ecological value of this ecosystem service and its recognition by communities in the territories. However, research addressing SOC sequestration from a socio-ecological perspective is still scarce, which highlights the importance of continuing to address these issues from a complex perspective.

The results of the multinomial regression highlight the SBR and C_MU variables in the mean perception and underscore the need to implement practices that promote the well-being of soil biology and the maintenance of organic cover as central components of conservation policies in tropical Andean ecosystems. Therefore, awareness-raising and environmental education strategies need to be strengthened to emphasize the benefits of SOC in climate change mitigation and soil productivity. The results of this research highlight that the perception of natural resource conservation is associated with better soil mulch conservation practices, which influences soil properties; it regulates temperature, preserves its structure, reduces salinity problems, increases water content, and reduces erosion [53,54], which in turn improves soil microbiology that is fundamental in nutrient cycling, greenhouse gas modulation, and overall ecosystem health, offering new perspectives for the design of ecosystem restoration strategies that drive sustainable agriculture [55].

5. Conclusions

This study highlights a significant connection between land use, soil properties, and how communities view natural resource conservation in a tropical Andean basin. The findings reveal that conservation-focused land uses—especially riparian forests (RFs) and ecological restoration (ER)—boast higher levels of soil organic carbon (SOC) storage and soil biological activity (SBR) compared to areas that are degraded or dominated by live-stock (LSs). Regression analysis showed that higher bulk density (BD) was linked to a

lower perceived importance of conservation, while increased biological activity (SBR) was positively associated with a greater conservation value.

The socio-ecological survey data shed more light on these connections. Most respondents, particularly those who have lived in the basin for a long time, emphasized ecological restoration, sustainable agriculture, and soil recovery as the top environmental priorities. This alignment between community values and soil health indicators suggests that local ecological knowledge can significantly influence effective land management strategies.

The relationship between community perceptions of conservation and SOC storage underscores the need to incorporate socio-ecological approaches into ecosystem restoration and sustainable land-use planning. Enhancing environmental education and using participatory strategies could boost stewardship and help ensure these ecosystems remain resilient in the long term. Promoting agroecological practices, restoring degraded lands, and aligning policy frameworks with local insights will be crucial for improving soil health, food security, and climate resilience in the tropical Andes.

To better capture temporal variability in tropical Andean ecosystems, future research should investigate the long-term monitoring of SOC dynamics under various land-use transitions. Integrating geospatial modeling with remote sensing could strengthen the mapping of SOC storage at larger scales. Likewise, combining biophysical measurements with socio-ecological indicators in different communities would provide a more complete understanding of how land management decisions impact carbon storage and ecosystem services.

Author Contributions: Conceptualization, V.A.M.V. and R.R.-L.; methodology, V.A.M.V., A.F.C. and R.R.-L.; software, V.A.M.V. and R.R.-L.; validation, V.A.M.V., A.F.C. and R.R.-L.; formal analysis, V.A.M.V.; investigation, V.A.M.V.; resources, A.F.C. and D.J.M.P.; data curation, D.J.M.P.; writing—original draft preparation, V.A.M.V.; writing—review and editing, V.A.M.V., R.R.-L. and A.F.C.; visualization, D.J.M.P.; supervision, R.R.-L.; project administration, V.A.M.V.; funding acquisition, V.A.M.V. and D.J.M.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Doctorado en Ciencias Ambientales, Universidad del Cauca. The APC was funded by the Doctorado en Ciencias Ambientales, Universidad del Cauca.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: Thanks are given to the Trophic Ecology Laboratory of the Chetumal Technological Institute for their invaluable support during the doctoral internship carried out at their facilities. We thank the academic and technical team of the Doctorate in Environmental Sciences of the institution for granting us access to their spaces and for their willingness to share knowledge and experiences that contributed considerably to the development of this research. Their collaboration was fundamental for the analysis of the data obtained and the strengthening of research capacities.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Soil physical and chemical properties by sampling plot.

Plot	Land Use	BD (g/cm ³)	HSM (%)	SM (%)	Sand (%)	Silt (%)	Clay (%)	pH	ECEC (meq/100 g)	SOC (Mg ha ⁻¹)	SBR (μg C-CO ₂ g ⁻¹ d ⁻¹)
RF1	RF	1.01	13.4	65.1	73.2	21.2	5.6	4.92	3.65	150.2	124.8
RF2	RF	1.0	13.55	64.8	74.0	20.6	5.4	4.95	3.78	147.5	123.7
RF3	RF	1.02	13.5	65.0	72.8	21.3	5.9	4.94	3.75	149.1	124.2

Table A1. Cont.

Plot	Land Use	BD (g/cm ³)	HSM (%)	SM (%)	Sand (%)	Silt (%)	Clay (%)	pH	ECEC (meq/100 g)	SOC (Mg ha ⁻¹)	SBR (μg C-CO ₂ g ⁻¹ d ⁻¹)
RF4	RF	1.01	13.6	64.9	73.0	21.0	6.0	4.91	3.73	148.9	124.5
ER1	ER	1.06	11.3	65.8	72.0	23.5	4.5	5.14	4.19	120.0	180.2
ER2	ER	1.05	11.35	66.1	71.5	23.8	4.7	5.16	4.25	118.5	179.0
ER3	ER	1.07	11.25	66.0	72.5	23.0	4.5	5.13	4.2	119.3	178.5
ER4	ER	1.06	11.38	65.9	72.3	23.2	4.5	5.12	4.21	119.1	179.4
NR1	NR	0.95	10.45	62.9	73.6	22.0	4.4	4.97	4.3	96.5	147.2
NR2	NR	0.96	10.6	62.7	74.2	21.8	4.0	4.99	4.35	97.9	149.1
NR3	NR	0.94	10.55	62.8	73.4	22.3	4.3	4.98	4.37	96.8	148.3
NR4	NR	0.95	10.52	62.75	73.9	22.1	4.0	4.96	4.36	97.1	148.9
LS1	LS	0.9	10.1	62.6	73.5	21.0	5.5	5.15	5.68	103.1	135.5
LS2	LS	0.91	10.0	62.7	73.7	21.2	5.1	5.14	5.7	102.4	134.2
LS3	LS	0.89	10.05	62.85	73.6	21.3	5.1	5.12	5.73	102.8	136.1
LS4	LS	0.9	10.08	62.75	73.6	21.4	5.0	5.11	5.68	103.0	135.2

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