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Silvopastoral Systems Enhance Soil Health in the Amazon Region

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Abstract: Silvopastoral systems (SPS), an integrated farming system in which tropical grasses are combined with trees and shrubs, have been implemented in the last years in the Amazon region in order to mitigate the impacts generated by the traditional cattle ranching system. However, despite the multiple SPS's benefits to soil and ecosystem, there is a paucity of comprehensive studies revealing the potential soil health (SH) restoration through SPS. Here, by developing an overall SH index using local native vegetation (Amazon rainforest) as a reference, we aimed to assess SH changes induced by the land transition from the traditional livestock production system to the SPS in the Colombian Amazon region. A chronosequence conformed by three areas: (i) native vegetation, (ii) traditional pasture and (iii) silvopastoral system was established in two study sites located in the Colombian Amazon, specifically in Caquetá State, the second hotspot of deforestation in the Amazon Basin. The results indicated high soil compaction and loss of macrofauna diversity and richness due to pasture management, causing a loss of 9% of soil capacity to function. In contrast, by integrating 31 soil indicators, our SH assessment revealed that SPS was an effective strategy for the recovery of SH, impacting positively multiple soil functions related to nutrient dynamics, water retention and supply, and biological activity.

Keywords: pastures; cattle ranching; soil quality; soil degradation; integrated production systems

Citation: Silva-Olaya, A.M.; Olaya-Montes, A.; Polanía-Hincapié, K.L.; Cherubin, M.R.; Duran-Bautista, E.H.; Ortiz-Morea, F.A. Silvopastoral Systems Enhance Soil Health in the Amazon Region. *Sustainability* **2022**, *14*, 320. https://doi.org/10.3390/su14010320

Academic Editor: Emanuele Radicetti

Received: 12 October 2021
Accepted: 17 December 2021
Published: 29 December 2021

1. Introduction

The establishment of pastures for cattle ranching has been closely associated with deforestation in the Amazon basin, the largest rainforest in the world [1–3]. After the region, called "arc of deforestation" in Brazil, a significant area of tree cover (138,000 ha) is lost every year in Colombia, a country responding for the third-largest Amazon territory [4–6], which occupies about 43% of the national territory.

The slash-and-burn practice, widely used during that land-use change, favors soil chemical fertility [7], which favors pasture growth at an early stage [1,8]. Nevertheless, in the following years, after deforestation, poor or absence of management and overgrazing pastures cause soil compaction, acidification, nutrient depletion, and soil erosion, leading to a scenario of land degradation [9–14]. Thus, the land and soil degradation caused by these improper management practices become important drivers to further land-use change to explore new areas for cattle ranching [15–17].

To mitigate the impacts generated by the traditional cattle ranching system, alternative production systems such as the silvopastoral systems, in which trees and shrubs are intercropped into tropical grasses, have been implemented in the last years [18–20].

Although the costs associated with the establishment and maintenance of a silvopastoral system are considered high compared with traditional extensive cattle ranching, globally, the adoption of integrated production systems has been associated with multiple benefits to soil and ecosystem, such as enhanced soil health indicators (chemical, physical and biological), biodiversity conservation, and the provision of soil-related ecosystem services, such as C sequestration and erosion control [21–24]. The mix of woody and herbaceous plants in those systems contributes to nutrient cycling from the soil's deeper layers to the surface [13,25], improving soil structure and water retention [14,26–28]. Furthermore, these systems favor soil biota (macroorganisms, mesoorganisms, and microorganisms), which fulfills vital roles to sustain soil health and ecosystem functions (e.g., biological N fixation, decomposition, nutrient cycling, soil aggregation, plant growth promotion, among others) [13,28,29].

However, despite all those benefits, there is a paucity of comprehensive studies that encompass the impact of this land-use change on physical, chemical, and biological indicators, as well as their interactions. Although the land-use change processes directly affect the capacity of soils to function [30], its impact is not uniform across the regions; therefore, a quantitative assessment from integrated soil indicators is necessary to reveal the status of soil health in traditional pasturelands and the potential soil health restoration through silvopastoral systems in the Colombian Amazon.

A growing interest in assessing and monitoring soil health for land evaluation has resulted in dozens of protocols and approaches to develop comprehensive soil quality/health indices for different ecosystems around the world [31–40]. Although some indexing strategies had been proposed for Colombian [39] and other tropical regions of Latin America [37], none were applied to integrated systems in Amazonian soil conditions. Therefore, it is still necessary to develop adapted soil health index protocols to help farmers, scientists, and local authorities to monitor soil health in this strategic region.

In this context, this study aimed to assess the soil health changes induced by the land transition from the traditional livestock production system to the silvopastoral system in the Colombian Amazon region. Moreover, we developed an overall soil health index using local native vegetation (Amazon rainforest) as a reference. We hypothesized that the mix of trees and grasses in silvopastoral systems along with the cultural operations performed under that management would improve soil physical and chemical functioning contributing to the restoration of soil health. Furthermore, we also believe that the indexing strategy used would be sensitive to detect those soil health changes.

2. Material and Methods

2.1. Study Sites and Land Use

The study was performed in Caquetá state, specifically in La Montañita (Site 1) and El Doncello counties (Site 2), which are located in the northwestern Colombian Amazon (Figure 1). These sites are located in a zone that has been strongly affected by deforestation for pastures establishment involving traditional cattle ranching. Nevertheless, there are oldest silvopastoral systems implemented in the region as a sustainable strategy for ecological restoration and yield improvement.

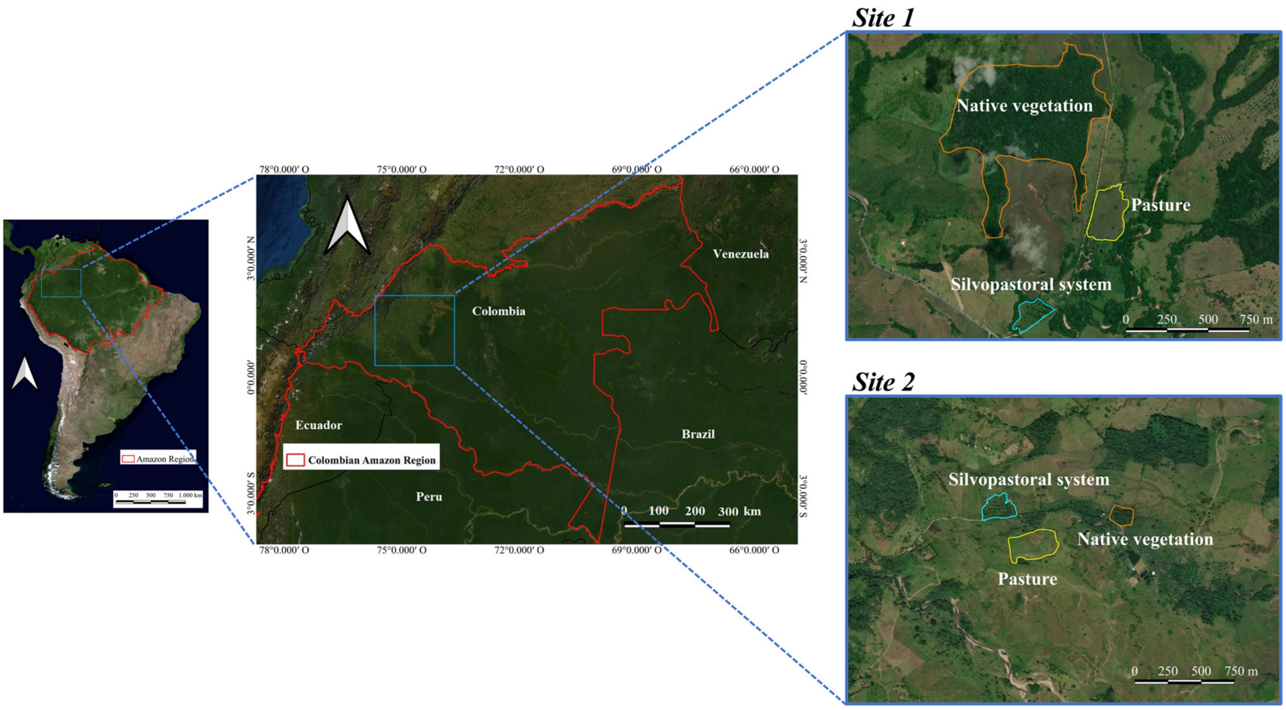

Figure 1. Location of study sites and land-use systems in La Montañita (Site 1) and El Doncello (Site 2) in the Amazon region.

Climatic classification in this region corresponds to tropical rainforest according to Koppen-Geiger classification, showing annual precipitation of 3235 mm and an average temperature of 25.1 °C [6].

Soils in both study sites are typically very acidic, with high Al saturation and low cation exchange capacity, total bases (Ca, Mg, K and Na), and base saturation [41,42]. In Site 1, the soils are classified as Dystrudepts and in Site 2 as Hapludox, according to USDA soil taxonomic classification [41].

In each study site, three land-use systems, (i) native vegetation (ii)–pasture and (iii) silvopastoral, with similar soil classification, climatic and topographic conditions were evaluated using the chronosequence approach. Those land uses are described in Olaya-Montes et al. [13] and Polanía-Hincapié et al. [14]. Briefly, the main characteristics of land-use evaluated were: (i) Native vegetation (NV) corresponding to a predominantly dense tropical forest of the Amazon forest biome, with their vegetative structure consisting of several vertical layers, including the overstory with a height greater than 15 m, canopy, understory, and shrub layer (Figure 2A); (ii) Pasture (PAST) with approximately 20 years of establishment after slash and burn of native forests, composed by *Brachiaria* sp. (*Urochloa*) which is managed under rotational grazing systems with an occupation of approximately 7 cattle head by hectare, and an occupation and recovery period of 15 and 40 days respectively (Figure 2B), and (iii) Silvopastoral system (SPS) established in 2005 over traditional 20 years old pastures (Figure 2C). During the establishment of that system, the soil was tilled and limed (274 kg Ca ha^{-1} and 131 kg Mg ha^{-1}), and phosphorus was applied at a rate of 24 kg ha^{-1} by phosphoric rock before planting a mix of *Brachiaria humidicola* and *Arachis pintoi*. A combination of trees such as *Gmelina arborea*, *Erythrina poeppigiana*, *Tectona grandis*, and *Cariniana pyriformis* were also planted in a density of 100 trees ha^{-1} (regular distance: 5 × 20 m). In this system, approximately 15 cattle head are grazing in paddocks of 2000 m^2 over 36 h with a resting period of 40 days by paddock. A schematic representation of the study areas is provided in Figure 2.

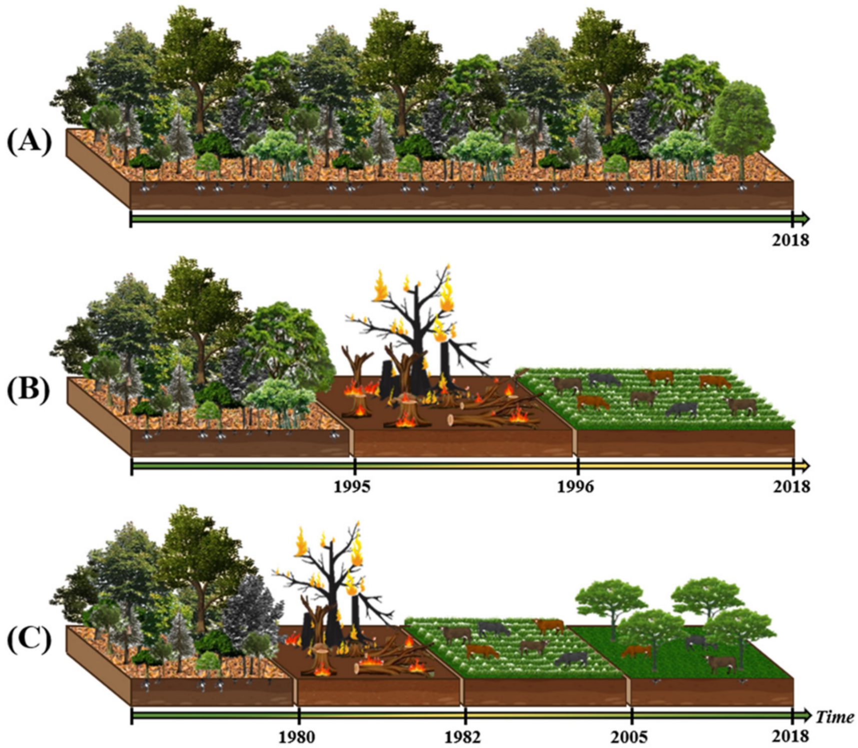

Figure 2. Land-use history of study areas in Colombian Amazon, where (**A**) Native vegetation; (**B**) Pasture; (**C**) Silvopastoral system.

2.2. Soil Sampling and Analysis

Soil samples were collected using a randomized design. A sampling grid comprised of six plots of 4 m^2 spaced 70 m apart was established in each study area. At each sampling plot, a small trench (30 × 30 × 30 cm) was opened in order to collect both disturbed and undisturbed soil samples from the 0–10, 10–20, and 20–30 cm depths, totaling 108 samples for chemical, 108 for bulk density, and 108 for soil structure analyses (soil blocks). In addition, 36 soil samples for macrofauna analysis were collected by using a monolith with dimensions of 30 × 30 × 30 cm (2700 cm^3), which was taken down to a depth of 30 cm according to the TSBF method [43] and ISO 23611-5: 2011 standard [44]. Subsequently, the soil was stratified in the same depths described previously for the macrofauna extraction and taxonomic classification.

Soil chemical indicators, such as macronutrients (available phosphorus (P) potassium (K), calcium (Ca), magnesium (Mg)) were measured according to Bray and Kurtz [45] and Sparks [46] respectively; soil micronutrients (copper (Cu), manganese (Mn), iron (Fe), and zinc (Zn)) were extracted by double acid solution (Mehlich I) and determined by atomic absorption spectrophotometer [41]. Active acidity was determined in $CaCl_2$, potential acidity (H + Al) and exchangeable aluminum (Al) were extracted by KCl solution 1 M and determined by titration with NaOH 0.01 M using phenolphthalein as indicator, and by back titration with NaF after acidification with HCl 0.01 M, respectively [41]. Soil base saturation and cation exchange capacity (CEC) was calculated according to Raij et al. [47].

Soil physical indicators were evaluated through both in situ and laboratory methodologies. In the field, soil penetration resistance was assessed by using a hand penetrometer (Eijkelkamp) (angle and surface area of a cone of 60 and 2 cm^2, respectively) as described by Polanía-Hincapié et al. [14], and soil structural quality using the Visual Evaluation of Soil Structure (VESS) method, proposed by Guimarães et al. [48] and applied previously in this Amazon region by Cherubin et al. [20].

In the laboratory, soil bulk density, macro and microporosity, and wet aggregate stability were assessed according to analytical methods described by Polanía-Hincapié et al. [14]. Briefly, undisturbed soil samples collected in a cylinder (98 cm^3) were saturated by capillarity rise and then weighed and transferred to a tension table at −6 kPa water potentials until reaching the hydraulic equilibrium, time after which the soil water content and soil bulk density were determined. For wet aggregate stability evaluation, the Yoder wet sieving procedure [49] was used, and then the mean weight diameter was calculated according to [50]. The structural stability index (SSI) was estimated according to [51] as SSI = ((SOC × 1.724)/(silt + clay)) × 100, where SOC is soil organic carbon content (g kg^{-1}), 1.724 is a factor to convert SOC to soil organic matter; silt and clay are particle size fractions (g kg^{-1}).

Soil organic C concentration was determined by a modified wet oxidation method, without external heating procedure, followed by the colorimetric method using a UV–visible spectrophotometer [52]. Microbial C was measured according to [53] with the extraction of OC from fumigated and non-fumigated soils by K_2SO_4 and C determination through a TOC analyzer (Shimadzu TNM-1, Japan). Macroinvertebrates were classified into the following taxonomic orders: Coleoptera, Haplotaxide (earthworms), Hymenoptera, and Isoptera. Macrofauna abundance (MAbun) was determined as the number of individuals per square meter (indiv m^{-2}), whereas macrofauna richness and diversity were calculated by Margalef's and Shannon's ecological indexes, respectively, as reported by Magurran [54].

2.3. Soil Health Assessment

A comprehensive soil health index was developed following the three-step procedure: (i) selection, (ii) interpretation, and (iii) integration of soil health indicators, as suggested by Cherubin et al. [37]. (i) Selection of soil health indicators: the total dataset was composed of 31 indicators, including 14 chemical, 8 physical, and 9 biological soil indicators (Table 1). This detailed evaluation included the indicators more frequently used in soil health assessments [40], related to multiple functions and soil-related ecosystem services (i.e., support to plant growth, supply and cycling of nutrients, water flux regulation, C storage, biodiversity) [37,40,55]. In order to perform an overall evaluation for 0–30 cm soil layer, soil data from the 0–10, 10–20, and 20–30 cm layers were grouped to an average value for each physical, chemical, and biological indicator evaluated. (ii) Interpretation of soil health indicator: This step is fundamental to transform/normalize measured values into unitless scores ranging from 0 to 1. For that, we adapted and combined statistical procedures proposed by Velásquez et al. [39] and Cherubin et al. [37], as follows:

Initially, measured values were normalized into an ordinal score from 0 to 1 by using non-linear scoring curves. The scoring curve shape: "more is better" (upper asymptote sigmoid curve), "less is better" (lower asymptote sigmoid), and "optimal midpoint" (Gaussian curve) were defined for each indicator based on the relationship between the indicator and a given soil function, supported by literature review and expert opinion (Table 1).

Non-linear Equations (1) and (2) were used for "more is better" and "less is better" criteria, respectively. For "optimum mid-point" curves, was used the Equations (3) and (4) for the left and right side of the Gaussian curve, respectively:

$$\text{Score} = \frac{a}{\left[1 + \left(\frac{LB-UT}{x-UT}\right)^{s}\right]} \tag{1}$$

$$\text{Score} = \frac{a}{\left[1 + \left(\frac{LB-LT}{x-LT}\right)^{s}\right]} \tag{2}$$

$$\text{Score} = \frac{a}{\left[1 + \left(\frac{LB-O}{x-O}\right)^{s}\right]} \tag{3}$$

$$\text{Score} = \frac{a}{\left[1 + \left(\frac{UB-O}{x-O}\right)^{s}\right]} \tag{4}$$

The score is the unitless value of the soil indicator, which ranges from 0 to 1, a is the maximum score, which was equal to 1 in this study, *B* is the baseline value (left side of the curve) of the soil indicator where the score equals 0.5, *LB* is the lower threshold, *UB* is the baseline value (right side of the curve) of the soil indicator where the score equals to 0.5; *LT* is the lower threshold, *UT* is the upper threshold, *O* is optimum mind-point value, *x* is the measured soil indicator value, and *S* is the slope of the equation set to −2.5. Threshold and baseline values for each soil indicator were based on literature references (Table 1).

Table 1. Indicator thresholds and scoring curves.

Indicator ǂ	Unit	Lower Threshold	Lower Baseline	Upper Threshold	Upper Baseline	Optimum Mid-Point	Scoring Curve Shape	Reference
				Chemical indicators				
pH ($CaCl_2$)	unitless	2.0	3.0	8.0	7.5	5.5	Optimum	[37]
Base saturation	%	35	50	85			More is better	[42]
Al	mmol kg^{-1}	0.0	10.0	20.0			Less is better	[56]
H + Al	mmol kg^{-1}	0.0	45.0	90.0			Less is better	[56]
ECEC	mmol kg^{-1}	0.0	75.0	150.0			More is better	[56]
P	mg kg^{-1}	0.0	6.0	12.0			More is better	[56]
K	mmol kg^{-1}	0.4	0.8	1.6			More is better	[37]
Na	mmol kg^{-1}	4.0	8.0	16.0			Less is better	[42]
Ca	mmol kg^{-1}	0.0	20.0	40.0			More is better	[56]
Mg	mmol kg^{-1}	1.0	4.0	7.0			More is better	[37]
Cu	mg kg^{-1}	0.0	0.75	2.7			More is better	[56]
Fe	mg kg^{-1}	0.0	17.0	63.0			More is better	[56]
Mn	mg kg^{-1}	0.0	5.0	18.0			More is better	[56]
Zn	mg kg^{-1}	0.0	1.0	3.5			More is better	[56]
				Physical indicators				
Bulk density	g cm^{-3}	0.75	1.25	1.75			Less is better	[56]
SPR	MPas	2.0	3.0	5.0			Less is better	[37]
MWD	mm	0.0	2.8	5.8			More is better	[56]
VESS	score	1.5	3.5	5.0			Less is better	[37]
Total porosity	cm^3 cm^{-3}	0.2	0.35	0.5			More is better	[37]
Microporosity	cm^3 cm^{-3}	0.0	0.3	0.6			More is better	[56]
Macroporosity	cm^3 cm^{-3}	0.0	0.13	0.06			More is better	[56]
SSI	%	5.0	7.0	9.0			More is better	[37]
				Biological indicators				
SOC	g kg^{-1}	10.0	17.5	25.0			More is better	[37]
MBC	mg kg^{-1}	0.0	450	800			More is better	[56]
MDiver	unitless	0.4	0.8	1.6			More is better	[37]
MRich	ord m^{-2}	6.0	9.0	13.0			More is better	[57]
MAbun	indiv m^{-2}	480	850	2500			More is better	[57]
Coleoptera	indiv m^{-2}	16	1200	219			More is better	EO
Haplotaxida	indiv m^{-2}	32	608	250			More is better	EO
Hymenoptera	indiv m^{-2}	256	5500	1604			More is better	EO
Isoptera	indiv m^{-2}	84	4544	1001			More is better	EO

ǂ pH: potential of hydrogen in a solution of $CaCl_2$ (1:2.5); Al: exchangeable aluminum; H + Al: potential acidity; ECEC: effective cation exchange capacity; P: available phosphorus; K: potassium; Na: Sodium; Ca: calcium; Mg: magnesium; Cu: copper; Fe: iron; Mn: manganese; Zn: zinc; SPR: soil penetration resistance; MWD: mean weight diameter; VESS: visual evaluation of soil structure; SSI: structural stability index; SOC: soil organic carbon; MBC: microbial biomass carbon; MDiver: macrofauna diversity; MRich: macrofauna richness, MAbun: macrofauna abundance; EO: Expert opinion.

(iii) Integration into a Soil Health Index (SHI): A principal component analysis (PCA) was performed using transformed data for each study site. In these PCAs, following the Kaiser criteria, only principal components with eigenvalues greater than 1.0 were retained to subsequent steps. Subsequently, a weighted SHI was generated for each land-use system by using Equation (5):

$$SHI = \sum_{k=1}^{n} a\ x\ (Is \times Iw) \quad (5)$$

where *SHI* is the soil health index, *a* is the total variance explained by the principal component (eigenvalues), *Is* is the indicator score (normalized value), and *Iw* is the indicator weight based on its eigenvector within each principal component.

Once the *SHI*s were calculated and weighted, the mean values were transformed linearly into scores ranging from 0 to 1, whereby the land-use system with the highest value received score 1 and the other land uses received proportional values.

2.4. Data Analysis

To test the effects of land use on soil indicators and SHI scores, the data from the different soil indicators assessed (0–30 cm depth) were tested for normality using Shapiro-Wilk's tests ($p > 0.05$) and then an analysis of variance (ANOVA) was performed. If the ANOVA F statistic was significant ($p < 0.05$), the means were compared using Tukey's test ($p < 0.05$).

The PCAs were performed using the Statistical Analysis System–SAS v.9.3 software (SAS Inc., Cary, NC, USA) to determine the loadings for each indicator in the SHI calculation. The SHI was calculated using Excel spreadsheet®, and the SHI scores of each land use were compared according to Tukey's test ($p < 0.05$) in SAS software.

3. Results

3.1. Responses of Soil Health Indicators to Livestock's Systems Management

Traditional pasture establishment caused alterations in soil chemical, physical and biological properties compared to native vegetation (Table 2). A reduction in soil acidity attributes was detected along with the NV-PAST transition, which favored the improvement of bases saturation in site 1. Higher values of soil P and K contents in NV than PAST were also detected in site 2. The PAST management resulted in an increase of soil micronutrients Cu, Zn, Mn, and Fe. Land-use change from NV to PAST also caused an increase in the soil compaction as well as a decrease in soil structural quality, with higher values of soil bulk density, soil penetration resistance, and VESS scores in PAST areas (Table 2). Soil carbon content was greater in PAST of site 2, but a reduction in macrofauna abundance, richness, and diversity was observed due to PAST management in both study sites (Table 2). A high abundance of Coleoptera in the PAST area and a reduction in Isoptera individuals were also detected, evident at site 1.

In contrast, the implementation of SPS enhanced most of the soil health indicators compared to traditional PAST. Active and exchangeable acidity and Al^{+3} content decreased along with the transition PAST-SPS in both study sites, favoring the percentage of charged sites occupied by bases. The content of soil macronutrients such as Ca^{+2} and Mg^{+2} was also higher ($p < 0.05$) in SPS than PAST (Table 2). The same pattern was observed with soil micronutrients availability Cu, Mn, and Zn whose concentration increased in response to SPS establishment while decreasing Fe content in the soil.

The degradation of the soil's physical properties due to PAST management was later mitigated by the establishment of SPS. Lower soil bulk density, soil resistance to penetration, and higher soil structural quality were observed in SPS areas, denoting an important contribution of those integrated systems in improving soil physical functioning (Table 2).

Table 2. Mean values of soil health indicators (0–30 cm) in native vegetation (NV), pasture (PAST) and silvopastoral systems (SPS) in the Amazon region.

Indicator [ł]		**Site 1_La Montañita**			**Site 2_El Doncello**		
		NV	**PAST**	**SPS**	**NV**	**PAST**	**SPS**
				Chemical indicators			
pH ($CaCl_2$)	unitless	3.55 (±0.02) c *	3.74 (±0.01) b	4.08 (±0.05) a	3.97 (±0.02) b	3.93 (±0.01) b	4.42 (±0.03) a
Base saturation	%	8.16 (±0.14) c	23.26 (±0.99) b	54.8 (±2.51) a	11.14 (±0.33) b	12.47 (±0.8) b	55.64 (±1.69) a
Al	mmol kg^{-1}	29.38 (±0.93) a	16.53 (±0.25) b	5.19 (±0.11) c	10.45 (±0.33) a	6.68 (±0.53) b	2.04 (±0.15) c
H+Al	mmol kg^{-1}	52.96 (±0.8) a	31.8 (±1.73) b	23.1 (±1.95) c	79.61 (±2.11) a	74.84 (±6.02) a	18.79 (±1.4) b
ECEC	mmol kg^{-1}	34.11 (±0.88) a	26.02 (±0.21) b	33.06 (±0.28) a	21.05 (±0.31) b	16.85 (±0.57) c	28.23 (±0.77) a
P	mg kg^{-1}	4.41 (±0.13)	4.24 (±0.13)	4.26 (±0.3) ns	1.67 (±0.11) a	1.21 (±0.06) b	1.38 (±0.07) ab
K	mmol kg^{-1}	0.89 (±0.06)	1.04 (±0.06)	1.07 (±0.04) ns	1.73 (±0.06) a	1.31 (±0.03) b	1.17 (±0.03) b
Na	mmol kg^{-1}	0.18 (±0.0) c	0.21 (±0.0) b	0.29 (±0.01) a	0.49 (±0.02) b	0.73 (±0.05) a	0.67 (±0.03) a
Ca	mmol kg^{-1}	2.4 (±0.04) c	6.73 (±0.14) b	19.58 (±0.22) a	6.15 (±0.18) b	5.89 (±0.11) b	19.34 (±0.56) a
Mg	mmol kg^{-1}	1.24 (±0.01) b	1.48 (±0.07) b	6.91 (±0.22) a	2.21 (±0.09) b	2.22 (±0.19) b	4.98 (±0.26) a
Cu	mg kg^{-1}	0.37 (±0.01) c	1.03 (±0.01) b	2.04 (±0.02) a	1.14 (±0.01) b	1.07 (±0.03) b	1.3 (±0.03) a
Fe	mg kg^{-1}	54.84 (±1.7) b	83.98 (±4.41) a	51.07 (±1.22) b	18.79 (±0.37) b	64.98 (±3.64) a	17.5 (±0.33) b
Mn	mg kg^{-1}	3.49 (±0.13) c	6.82 (±0.37) b	21.5 (±0.83) a	57.02 (±0.89) b	14.32 (±0.98) c	137.8 (±1.76) a
Zn	mg kg^{-1}	0.5 (±0.01) c	1.2 (±0.06) b	2.86 (±0.04) a	0.8 (±0.02) c	0.99 (±0.03) b	2.61 (±0.08) a
				Physical indicators			
Bulk density	g cm^{-3}	1.128 (±0.04) b	1.31 (±0.03) a	1.07 (±0.04) b	0.99 (±0.01) c	1.2 (±0.03) a	1.09 (±0.02) b
SPR	MPas	2.85 (±0.2) b	4.34 (±0.3) a	2.93 (±0.19) b	3.7 (±0.25) b	4.99 (±0.15) a	4.62 (±0.21) a
MWD	mm	2.03 (±0.12) b	2.58 (±0.17) ab	3.03 (±0.24) a	4.42 (±0.17)	4.57 (±0.16)	4.69 (±0.1) ns
VESS	score	1.73 (±0.11) b	2.85 (±0.21) a	1.88 (±0.14) b	1.98 (±0.13) b	2.95 (±0.19) a	1.61 (±0.06) b
Total porosity	cm^3 cm^{-3}	0.57 (±0.02)	0.59 (±0.02)	0.59 (±0.01) ns	0.55 (±0.01) a	0.49 (±0.01) b	0.54 (±0.01) a
Microporosity	cm^3 cm^{-3}	0.35 (±0.01) b	0.4 (±0.02) a	0.37 (±0.01) ab	0.46 (±0.01)	0.43 (±0.01)	0.45 (±0.01) ns
Macroporosity	cm^3 cm^{-3}	0.22 (±0.02)	0.18 (±0.01)	0.22 (±0.01) ns	0.1 (±0.01) a	0.06 (±0.01) b	0.09 (±0.01) ab
SSI	%	4.87 (±0.3) b	6.24 (±0.35) a	5.37 (±0.17) ab	5.29 (±0.17) b	5.77 (±0.29) b	7.43 (±0.19) a
				Biological indicators			
SOC	g kg^{-1}	12.7 (±0.04) b	14.0 (±0.02) b	16.4 (±0.07) a	12.6 (±0.01) c	15.4 (±0.04) b	17.4 (±0.02) a
MBC	mg kg^{-1}	790.7 (±64.0)	839.4 (±61.2)	700.7 (±40.5) ns	679.2 (±19.2)	711.6 (±29.8)	780.4 (±49.5) ns
MDiver	unitless	1.16 (±0.12)	0.78 (±0.04)	1.02 (±0.18) ns	1.54 (±0.11) a	0.67 (±0.15) b	1.08 (±0.04) b
MRich	ord m^{-2}	6.25 (±0.95) a	3.41 (±0.4) b	5.25 (±0.92) a	11 (±0.58) a	4.17 (±0.4) b	5.5 (±0.34) b
MAbun	indiv m^{-2}	825 (±633)	905 (±423)	1806 (±1475) ns	2976 (±317) a	1404 (±288) b	2472 (±382) ab
Coleoptera	indiv m^{-2}	40 (±9) b	512 (±151) a	72 (±13) b	72 (±16) a	16 (±4) b	-
Haplotaxida	indiv m^{-2}	92 (±16) b	68 (±43) b	464 (±50) a	444 (±92)	424 (±113)	716 (±30) ns
Hymenoptera	indiv m^{-2}	340 (±18) b	2016 (±384) ab	4092 (±1550) a	828 (±233)	452 (±168)	480 (±116) ns
Isoptera	indiv m^{-2}	1776 (±603) a	84 (±53) b	360 (±90) b	492 (±255)	1108 (±242)	1000 (±359) ns

* Means followed by the same letter did not differ among themselves according to Tukey test ($p < 0.05$); ns: non-significant; ł pH: potential of hydrogen in a solution of $CaCl_2$ (1:2.5); Al: exchangeable aluminum; H + Al: potential acidity; ECEC: effective cation exchange capacity; P: available phosphorus; K: potassium; Na: Sodium; Ca: calcium; Mg: magnesium; Cu: copper; Fe: iron; Mn: manganese; Zn: zinc; SPR: soil penetration resistance; MWD: mean weight diameter; VESS: visual evaluation of soil structure; SSI: structural stability index; SOC: soil organic carbon; MBC: microbial biomass carbon; MDiver: macrofauna diversity; MRich: macrofauna richness, MAbun: macrofauna abundance.

The adoption of SPS also increases soil C compared to traditional pasture in both study sites (Table 2), as well as SPS supports greater macrofauna richness in those systems and an increased number of individuals from the Haplotaxida and Hymenoptera orders observed in site 1.

The overall land-use change effects on soil health indicators of both sites were verified by normalizing the data in scores through the non-linear transformation method (Figure 3). Our results revealed that soil's capacity to perform its chemical functioning was improved in SPS, livestock management that exhibited scores close to one value in most of the chemical indicators. A restoration in physical and biological functions was also observed since scores value close to those shown by native vegetation were exhibited.

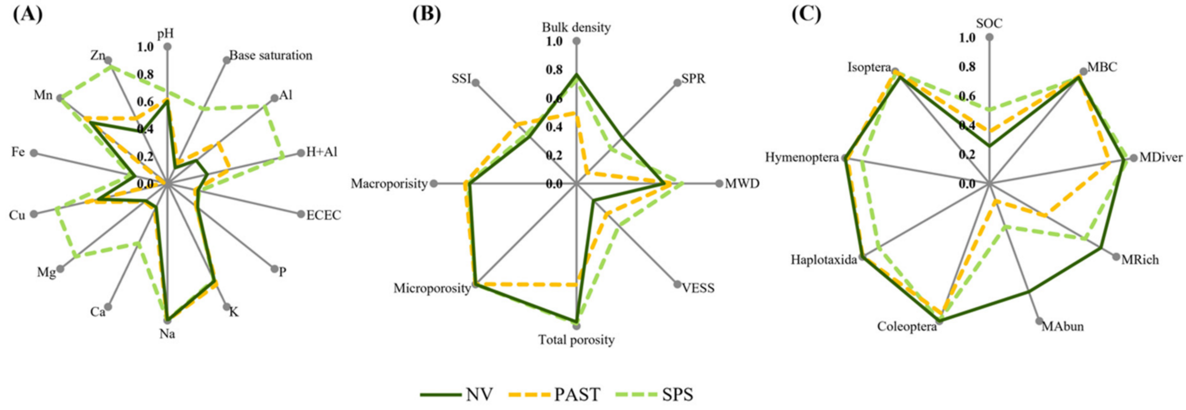

Figure 3. Overall scores of soil chemical (**A**), physical (**B**), and biological (**C**) indicators (0–30 cm) under native vegetation (NV), pasture (PAST), and silvopastoral system (SPS) in the Amazon region. pH: potential of hydrogen in a solution of $CaCl_2$ (1:2.5); Al: exchangeable aluminum; H + Al: potential acidity; ECEC: effective cation exchange capacity; P: available phosphorus; K: potassium; Na: Sodium; Ca: calcium; Mg: magnesium; Cu: copper; Fe: iron; Mn: manganese; Zn: zinc; SPR: soil penetration resistance; MWD: mean weight diameter; VESS: visual evaluation of soil structure; SSI: structural stability index; SOC: soil organic carbon; MBC: microbial biomass carbon; MDiver: macrofauna diversity; MRich: macrofauna richness, MAbun: macrofauna abundance.

3.2. Soil Health Index

Thirty-one indicators were measured at each study site as potential indicators to assess soil health responses to land-use change. Principal component analysis revealed that the first six components explained 88% of the accumulated data variance in site 1 (Table 3), with PC1 as the component with the highest loading (41% of the variance) and the chemical indicators: soil base saturation, Ca, Cu and Zn content, presented the highest absolute eigenvectors within this component. The PC2 explained 23.7% of the variance of the data. The ECEC, Mrich, and SPR were the indicators with the highest weight in the PC2. The remaining 23.3% of the variance was distributed among PC3–PC6.

In site 2, the first six principal components explained 91% of the data variance, with PC1 explaining the greatest variance percentage (41%) with soil Ca, base saturation, pH, and Mg as the most relevant indicators (Table 4) in that component. The PC2 explained 29% of the accumulated data variance, and the indicators with the highest loadings in this component were Mdiver, Mrich, and microporosity. The remaining 21% of the variance was explained between PC3 and PC6.

The SHI calculated in both study areas showed a similar pattern (Figure 4), indicating a relevant contribution of SPS to soil health restoration. The SHI average was 24% higher under SPS than in PAST areas.

Table 3. Principal components analysis results for site 1 in the Colombian Amazon.

	Principal Components						
	PC1	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	
Eigenvalues	12.74	7.36	2.76	1.85	1.49	1.21	
Variance (%)	41.08	23.74	8.9	5.95	4.81	3.92	
Cumulative (%)	41.08	64.83	73.72	79.67	84.48	88.4	
Soil indicators[ǂ]			**Eigenvectors**				**Communalities**
pH ($CaCl_2$)	**0.942**	0.010	0.252	0.046	−0.042	0.166	0.982
Base saturation	**0.979**	−0.050	0.123	0.037	−0.066	0.066	0.986
Al	**−0.960**	−0.184	−0.091	−0.115	0.084	0.041	0.985
H + Al	**−0.895**	−0.332	−0.132	−0.046	−0.022	0.005	0.932
ECEC	0.029	**−0.932**	0.066	−0.240	−0.053	0.102	0.946
P	−0.068	−0.065	0.060	−0.062	0.100	**0.924**	0.880
K	0.567	0.381	−0.180	0.030	−0.068	0.283	0.584
Na	**0.959**	−0.041	0.057	−0.091	−0.090	−0.056	0.945
Ca	**0.977**	−0.124	0.115	0.028	−0.090	−0.013	0.991
Mg	**0.915**	−0.324	0.131	0.011	−0.137	0.015	0.978
Cu	**0.984**	0.031	0.115	0.009	−0.079	−0.021	0.989
Fe	−0.245	0.826	0.042	−0.067	0.084	−0.131	0.772
Mn	**0.953**	−0.186	0.110	0.035	−0.091	−0.037	0.967
Zn	**0.982**	−0.080	0.084	0.039	−0.077	−0.043	0.986
Bulk density	−0.253	0.811	0.059	−0.077	−0.141	0.232	0.805
SPR	−0.080	**0.842**	0.166	−0.346	0.024	0.250	0.926
MWD	0.194	0.651	0.064	−0.490	0.179	−0.141	0.758
VESS	0.171	0.121	−0.215	**0.900**	0.102	−0.213	0.956
Total porosity	0.163	0.479	−0.558	0.269	0.295	−0.358	0.856
Microporosity	0.020	−0.384	0.358	0.746	−0.204	0.144	0.894
Macroporosity	0.821	−0.046	0.045	−0.022	0.171	−0.233	0.762
SSI	−0.005	0.805	−0.117	0.172	0.142	−0.120	0.727
SOC	−0.237	0.252	0.078	−0.071	**0.876**	0.128	0.914
MBC	0.450	−0.148	**0.851**	0.054	0.188	0.042	0.989
MDiver	0.102	−0.614	−0.619	0.117	−0.270	0.219	0.905
MRich	−0.168	**−0.871**	0.037	0.204	0.202	0.211	0.915
MAbun	0.450	−0.148	**0.851**	0.054	0.188	0.042	0.989
Coleoptera	−0.051	0.787	−0.123	0.016	0.297	0.133	0.744
Haplotaxida	0.813	−0.408	−0.114	0.085	−0.119	0.005	0.862
Hymenoptera	0.539	0.100	**0.795**	0.006	−0.060	0.064	0.940
Isoptera	−0.467	−0.593	0.154	0.054	0.474	−0.113	0.834

[ǂ] pH: potential of hydrogen in a solution of $CaCl_2$ (1:2.5); Al: exchangeable aluminum; H + Al: potential acidity; ECEC: effective cation exchange capacity; P: available phosphorus; K: potassium; Na: Sodium; Ca: calcium; Mg: magnesium; Cu: copper; Fe: iron; Mn: manganese; Zn: zinc; SPR: soil penetration resistance; MWD: mean weight diameter; VESS: visual evaluation of soil structure; SSI: structural stability index; SOC: soil organic carbon; MBC: microbial biomass carbon; MDiver: macrofauna diversity; MRich: macrofauna richness, MAbun: macrofauna abundance. Values highlighted in bold mean eigenvectors with the highest loads within each component. Communalities correspond to the portion of the variance in each soil indicator explained by the principal components and was calculated by taking the sum of the squared loadings for that indicator.

Degradation in soil health due to traditional PAST management was detected in site 2, with PAST soils functioning at 77% of their potential capacity, which was 9% lower than observed in NV (SHI = 0.86). Despite the negative responses of some soil indicators to the replacement of NV by PAST area in site 1, non−significant differences in the overall SHI scores between both NV and PAST were observed, with soils functioning in 73% of their potential capacity.

Table 4. Principal components analysis results for site 2.

	Principal Components						
	PC1	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	
Eigenvalues	12.74	9.06	2.26	1.83	1.22	1.01	
Variance (%)	41.11	29.23	7.28	5.89	3.93	3.24	
Cumulative (%)	41.11	70.34	77.62	83.52	87.44	90.69	
Soil indicators[ǂ]			**Eigenvectors**				**Communalities**
pH ($CaCl_2$)	**0.971**	−0.008	0.112	0.002	0.030	0.082	0.963
Base saturation	**0.986**	−0.088	0.046	0.024	0.021	0.116	0.996
Al	−0.847	0.467	0.113	0.071	0.089	−0.088	0.969
H + Al	**−0.955**	0.128	0.087	−0.061	0.140	−0.152	0.983
ECEC	**0.919**	0.271	0.127	0.131	0.146	−0.062	0.977
P	−0.105	0.649	0.000	0.411	0.044	0.507	0.860
K	−0.585	0.697	0.105	0.124	−0.206	−0.198	0.935
Na	0.215	−0.692	−0.434	−0.027	−0.005	−0.107	0.726
Ca	**0.992**	−0.051	0.041	0.060	0.046	0.036	0.995
Mg	**0.963**	−0.068	−0.006	−0.018	0.114	−0.114	0.958
Cu	0.880	0.122	0.039	0.151	−0.219	0.226	0.912
Fe	−0.558	−0.744	−0.165	−0.205	0.049	0.021	0.937
Mn	**0.950**	0.254	0.118	0.082	−0.002	0.057	0.990
Zn	**0.976**	−0.127	−0.030	0.005	0.079	0.101	0.985
Bulk density	−0.079	**−0.828**	0.005	−0.514	0.074	−0.040	0.962
SPR	0.162	−0.772	−0.357	0.144	0.080	−0.239	0.833
MWD	0.856	−0.160	−0.161	−0.243	0.246	−0.027	0.904
VESS	0.290	0.766	−0.015	0.491	0.003	0.013	0.912
Total porosity	0.136	0.259	0.287	**0.768**	0.288	0.064	0.845
Microporosity	0.258	**0.823**	−0.313	−0.101	−0.292	−0.046	0.940
Macroporosity	0.743	−0.523	−0.124	−0.304	0.204	0.052	0.977
SSI	−0.660	−0.576	−0.106	−0.111	−0.070	0.147	0.817
SOC	0.378	−0.149	0.123	0.015	−0.076	**0.841**	0.894
MBC	0.158	0.422	0.692	0.335	−0.415	0.044	0.968
MDiver	0.009	**0.871**	0.293	−0.047	0.174	−0.238	0.934
MRich	−0.254	**0.849**	0.209	0.195	−0.271	−0.051	0.943
MAbun	0.158	0.422	0.692	0.335	−0.415	0.044	0.968
Coleoptera	−0.494	0.741	−0.126	0.003	−0.038	−0.144	0.831
Haplotaxida	0.607	0.086	−0.227	−0.105	**−0.598**	0.104	0.807
Hymenoptera	−0.157	0.050	0.283	0.568	−0.447	−0.007	0.630
Isoptera	0.119	0.152	**0.905**	0.197	−0.054	0.067	0.903

[ǂ] pH: potential of hydrogen in solution of $CaCl_2$ (1:2.5); Al: exchangeable aluminum; H + Al: potential acidity; ECEC: effective cation exchange capacity; P: available phosphorus; K: potassium; Na: Sodium; Ca: calcium; Mg: magnesium; Cu: copper; Fe: iron; Mn: manganese; Zn: zinc; SPR: soil penetration resistance; MWD: mean weight diameter; VESS: visual evaluation of soil structure; SSI: structural stability index; SOC: soil organic carbon; MBC: microbial biomass carbon; MDiver: macrofauna diversity; MRich: macrofauna richness, MAbun: macrofauna abundance. Values highlighted in bold mean eigenvectors with the highest loads within each component.

To visualize the effects of land use on soil chemical, physical and biological functioning separately, a PCA per soil function was performed by incorporating the average value of both sites for all indicators related to it (Figure 5, Tables S1–S3). The results indicated that the first two components explained 81.5%, 69.6%, and 49.1% of the variance in chemical (Figure 5A, Table S1), physical (Figure 5B, Table S2), and biological functioning PCA (Figure 5C, Table S3), respectively. In chemical (Figure 5A) and biological functioning PCA (Figure 5C) the data were grouped in three clusters in consonance with land use. An improvement in soil chemical fertility is suggested as a response to SPS implementation, with higher values of macro and micronutrients accompanied by less soil acidity under that management than NV and PAST. A recovery in macrofauna diversity and richness was also observed in SPS (Figure 5C).

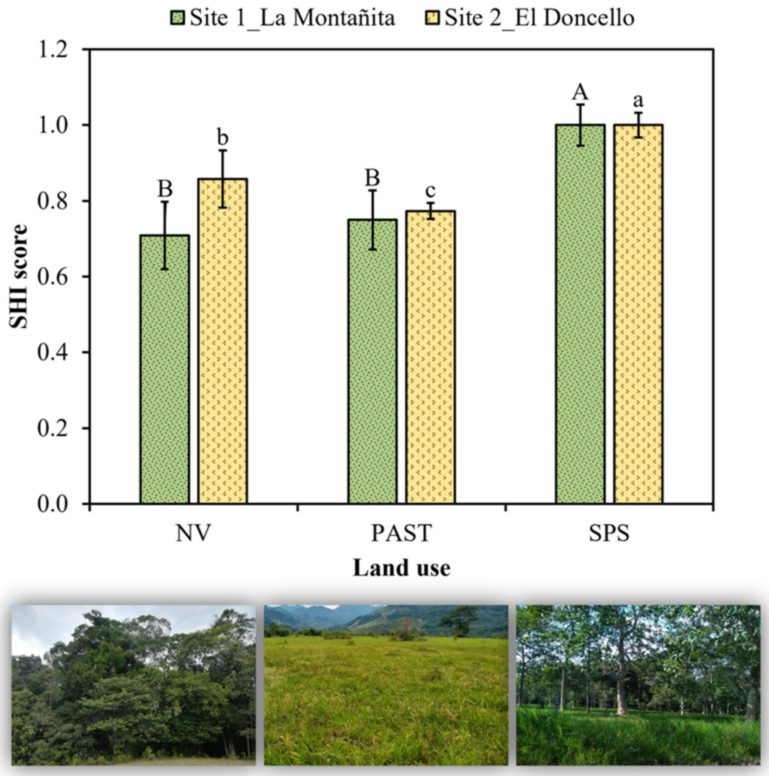

Figure 4. Soil health index (SHI) scores under native vegetation (NV), pasture (PAST), and silvopastoral system (SPS) in two sites in the Colombian Amazon region. Mean values within each study site followed by the same letter do not differ from each other according to Tukey's test ($p < 0.01$). Upper and lowercase letters compare land uses in site 1 and site 2, respectively. Error bars denote standard error.

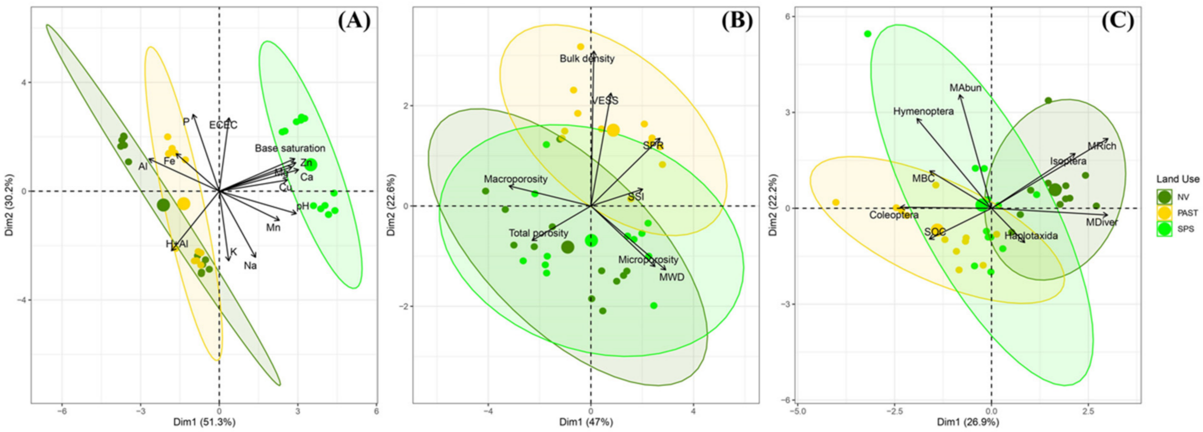

Figure 5. Principal component analysis (PCA) according to soil (**A**) chemical, (**B**) physical, and (**C**) biological functioning in native vegetation (NV), pasture (PAST), and silvopastoral system (SPS) areas in the Amazon region. Average indicators values from both study sites were used for this analysis.

Regarding the physical and functioning, the PCA separated soil data into two groups: (i) PAST and (ii) SPS and NV, suggesting that land-use transition from NV to PAST led to a degradation in the assessed soil physical properties (Figure 5B). Higher values of soil bulk density, SPR, and VESS and lower values of soil porosity were observed in PAST areas.

4. Discussion

4.1. Impacts of Traditional Pasture Land Use on Soil Health in Colombian Amazon Region

In general, soil chemical indicator data reflected typical characteristics of tropical soil from the Amazon region, where the intense weathering process has resulted in high acidity and poor fertility in NV areas. However, with the introduction of PAST over those NV areas, a slight reduction in soil acidity was observed. Some studies have associated that decrease in soil acidity with the burning process performed before pastures establishment, through which ashes containing basic cations [7], mainly K^+ and Ca^{2+} are added to soil, increasing base saturation, as well as Al^{+3} and H + Al neutralization [7,28,58,59].

The use of mineral supplements in livestock diet could have resulted in significant incorporation of soil micronutrients through the cattle manure over time, increasing its availability into PAST areas [60,61]. Furthermore, the long periods of grazing and cattle trampling seem to have direct effects on soil structure by increasing soil compaction [10,62,63], degrading the soil physical quality over time and leading to the development of hydromorphic and/or anoxic conditions along some periods [64]. This condition promotes Fe solubilization from the mineral fraction [60], resulting in higher Fe contents in those areas.

Soil penetration resistance values above the critical limit in PAST areas [65] and higher VESS scores ratified the soil structure degradation under PAST management. Compacted soils hinder plant root growth [48,66], decrease forage productivity [14,67], increase soil susceptibility to erosion processes, and, therefore, nutrients and SOC losses. Similar results were also reported by [20] and [68] in the Colombian and Brazilian Amazon regions, respectively.

Changes in soil chemical and physical properties induced by land use and management can affect the community of termites in the soil [69,70]. It can explain the reduction of the abundance of termites detected in the NV−PAST transition. Alterations in Coleoptera's abundance in site 1 were also promoted by the intensive land use in pastures, favoring the dominance of rove beetle (*Staphylinidae*). Although a higher prevalence of generalist staphylinid species over specialist species has been previously reported [71], a finer taxonomic resolution for this family Staphylinidae will be necessary to understand these results better.

By integrating the individual effects of all 31 indicators into an overall SHI, as proposed by Velazquez et al. [40] and Cherubin et al. [37], our results indicated that PAST establishment and the poor management implemented in those traditional livestock systems, which is characterized by the absence of fertilization, overgrazing, and poor rotation resulted in a loss of 9% of soil capacity to function in site 2. Cherubin et al. [37] found under Brazilian conditions that the conversion from native vegetation (Cerrado and Atlantic Forest) to extensive pasture reduced the soil functioning potential by 17%.

Despite all indicators that influenced the index performance, in our study, chemical indicators related to acidity criteria, exchangeable bases, and micronutrients; as well as physical indicators such as soil bulk density, VESS and penetration resistance, and the biological indicators MDiver, Mrich, and abundance of Haplotaxide showed the highest loadings in the components determined by PCA (Tables 3 and 4), and were, therefore, critical indicators to detected changes on soil health induced by the land transition from NV to PAST in the Amazon region.

In consonance with the "more is better" interpretation for most of the key chemical and biological indicators and the "less is better" criteria for physical indicators, in site 1 the improvements in soil chemical fertility with the transition NV−PAST overlapped the negative response of physical soil indicators, and, therefore, the overall impact of PAST land use on the soil health index was not detected. Despite that, by analyzing the chemical, physical and biological soil functioning, our findings indicated a physical and biological soil health degradation predominantly expressed by high soil compaction and loss of macrofauna diversity and richness associated with PAST establishment in the Colombian Amazon region. Therefore, we strongly encourage the use of scores of soil components (chemical, physical, and biological) as complementary data for detecting critical points that should be managed to promote soil health [37].

4.2. Adopting Silvopastoral Systems to Restore Soil Health in the Colombian Amazon Region

The liming incorporation performed during the establishment of SPS contributed to the reduction of soil acidity attributes. In addition, the association of trees and pastures in SPS favored increases in SOC (Table 2) [24,28,72], which could result in higher availability of exchangeable bases, allowing Al^{+3} displacement and the increase of cations in the soil colloidal fraction, especially Ca and Mg cations [73–76]. Those alterations in SPS favored the availability of soil micronutrients such as Cu, Mn, and Zn by reducing the soil redox potential [56,77,78].

Our study also revealed that PAST−SPS conversion allowed to mitigate the soil compaction process caused by traditional PAST management, enhancing soil porosity. The litter deposition, root activity to deeper layers, as well as an intense root turnover under those integrated systems, led to a recovery in soil structure [79–83].

The integration of different vegetation types (pasture and trees) in SPS influence the soil organic Cincorporation, promoting the production of organic compounds with diverse chemical nature and consequently the diversification of soil microbiota and the content of SOC, as was observed in both study sites [84]. This increase in SOC accumulation affected the abundance of soil macrofauna [82,85]. As reported in previous studies, the inclusion of legumes in open pasture systems enhances biomass production and the diversification of substrate and/or habitat of soil macrofauna, impacting the taxonomic richness and total abundance positively [82,86–88].

The reduction in grazing times, the addition of organic residues generated by the trees, and higher and more uniform distribution of animal dung and urine in SPSs could have also favored the high abundance of earthworms in those areas [89], which play a crucial role in soil aggregation and SOC stabilization within aggregates [90].

Overall, the soil health assessment revealed that long-term (15 years) adoption of SPS over extensive PAST areas was an effective strategy for the recovery of soil health. Higher SHI in SPS than in NV found in both study sites are a response to the indicator thresholds and scoring curves used as a reference for normalizing the data, which has been defined based on agricultural production. Besides, by resembling the functional and structural features exhibited by forest ecosystems and implementing intensive land management, involving liming, tillage, and fertilization, the SPSs had a positive effect on multiple soil functions related to nutrient dynamics, water retention and supply, biological activity, and plant growth, making this management a promising alternative to reconcile soil health promotion and land productivity [91–93].

By minimizing the negative historical impacts of traditional livestock practices and perhaps slightly improving the degraded grazing land resource, the SPS adoption could contribute to ensuring the long−term sustainability of rangelands livestock in Colombia and other tropical countries, while can also be a tool for decreasing further deforestation processes associated with the expansion of the agricultural frontier.

5. Conclusions

The long-term land transition from native vegetation to extensive and poor−managed pastures declines overall soil health, leading to significant physical and biological degradation, expressed by high soil compaction and loss of macrofauna diversity and richness.

Our soil health assessment approach detected the benefits (chemical, physical, and biological) promoted by the long-term (15 years) implementation of silvopastoral management over extensive pastures in the Amazon region, becoming an important strategy for restoring degraded land pastures and recovering soil health. The agricultural operations performed during SPS establishment and the land management in those livestock systems enhance soil chemical fertility by reducing soil acidity and increasing macro and micronutrients contents. Improvements in soil organic C in SPS favored biological activity, also mitigating the soil physical degradation processes caused by livestock activity.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su14010320/s1, Table S1. Principal components analysis results for chemical indicators, Table S2. Principal components analysis results for physical indicators, Table S3. Principal components analysis results for biological indicators.

Author Contributions: A.M.S.-O.: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing—original draft, and Writing—review and editing. A.O.-M.: Data curation, Formal analysis, Methodology, and Writing—original draft. K.L.P.-H.: Formal analysis, Methodology, Writing—review and editing, and Visualization. M.R.C.: Conceptualization, Data curation, and Writing—review and editing; E.H.D.-B.: Data curation, and Writing—review and editing. F.A.O.-M.: Conceptualization and Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Sistema General de Regalias—Minciencias (grant number 2013000100164).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available from the authors upon request.

Acknowledgments: Authors thank NGO Mision Verde Amazonia because of the support to develop this study and farmers for allowing us to work in their lands.

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

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