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RESEARCH ARTICLE

Changes in soil quality indicators in response to land use based on a minimum data set

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Abstract

The Ecuadorian Amazon region is permanently subject to deforestation processes and in parallel to the implementation of agricultural, and livestock management systems that can affect soil quality. This study assessed the effect of different land use types on soil quality using the Integrated Soil Quality Index (SQI) and minimum indicators. To do this, it considers representative soil samples, 4 types of land use, and a productive landscape in the province of Pastaza. The land use types evaluated were sugarcane (SC), agrosilvopastoral System (ASPS) silvopastoral timber system (SSTT), and secondary forest (SF). Land use type had significant effects on some soil properties and, therefore, on soil quality. The soil quality index was developed using BD, Ca+Mg/K, and SOM which had the highest weighting values, suggesting a higher contribution to the final SQI. The Soil Quality Index (SQI) showed significant differences ($p < 0.05$) between the different land uses, establishing the following order: SSPM (0.41) > SC (0.40) > B (0.34) > SASP (0.33). Therefore, the values obtained are considered low to moderate quality with SSPM and SC as the highest quality land uses. It is concluded that soil quality can be assessed and compared more accurately in the studies of land use using the current indexing framework due to its simplicity and quantitative flexibility. However, to evaluate soil quality more comprehensively and precisely, biological properties of soils should also be considered for SQI in future studies.

Keywords: Soil properties; fertility; forest; silvopastoral systems; deforestation; Amazon.

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1. Introduction

Ecuadorian Amazon (EA) is a territory that has been characterized as biodiverse with immense natural resources and a high vocation for forest uses (Nieto & Caicedo, 2012; Torres et al., 2019). However, since its colonization, large areas have been subjected to an intense deforestation process with a shift towards agricultural and livestock systems that have generated a great deterioration of its resources (soil, water, vegetation, biodiversity), affecting its productive potential and its capacity to provide ecosystem services (Bravo et al., 2015; Bravo-Medina et al., 2021; Torres et al., 2023). Consequently, one way of knowing the influence of human activities on the soil is through soil quality assessment. In this scenario, the vegetation, and soil are key elements impacted by the expansion of the agricultural frontier. Therefore, it is essential to prioritize the examination of soil quality as a fundamental resource (Bravo-Medina et al., 2021). The physical, chemical, and biological properties of the soil can be strongly altered by the change in land use from natural systems to agricultural systems. Consequently, the deterioration of soil quality results in a decrease in its functions in both natural and managed ecosystems (Drobnik et al., 2018). Soil quality is defined as the capacity of the soil to function as a living system, which implies adequate biological productivity and environmental quality (Doran & Safley, 1997). Therefore, soil constitutes an essential natural resource for ecosystem functions, the maintenance of ecological biodiversity, and the support of plants. and animal health (Karlen et al., 2006). Hence, it is crucial to uphold and enhance soil quality to guarantee the sustainability of ecosystems (Leul et al., 2023).

The quantification of soil quality is a complex process and there is not yet a fully established consensus in scientific society. In this context, the interrelationships between physical, chemical, and biological indicators are complex and the soil quality index is very variable among different regions, therefore, quality assessment has had several proposals that include soil indicators and parameters (Abera & Assen, 2019; Bravo-Medina et al., 2021; Leul et al., 2023). However, several methods seem to agree that to calculate the quality index, three steps must be followed: 1) select indicators from a data matrix, 2) score the indicators, and 3) rank the indicators according to their relative level of importance based on the soil type and the objectives defined for the land use (Andrews et al., 2003; Zhang et al., 2019; Bravo-Medina et al., 2021; Leul et al., 2023).

Studies in various parts of the world have shown that soil quality has suffered significantly due to human-induced disturbances due to land use changes (Viana et al., 2014; Molaeinasab et al., 2018; Safaei et al., 2019; Zhang et al., 2019; Leul et al., 2023) and natural processes (Pla, 2010; Peng et al., 2013; Zhang et al., 2019). Nevertheless, only a small number of studies have been conducted in the Ecuadorian Amazon to assess how the shift from forestry to agriculture and livestock systems impacts soil quality. This information could be highly valuable in determining the most suitable utilization of the region (González et al., 2019; Bravo-Medina et al., 2021). Proper land use planning and the implementation of appropriate sustainable land management practices quality required understanding the variability of the soil quality indicators to understand how land use changes impact soil quality (Bravo-Medina et al., 2023).

In this regard, the purpose of this study was to evaluate the impact of land use change on soil quality in the province of Pastaza, Ecuadorian Amazon.

2. Methodology

2.1. Study area

The present study was carried out northeast of the city of Puyo, in the Fátima parish, Pastaza province (Figure 1). The area is characterized by a topographic elevation that ranges from 960 to 1064 m.a.s.l with irregular slopes between 12% and 25%. The climate is categorized as tropical mega term humid, with an average annual temperature between 18 to 24 °C and relative humidity greater than 85%. Rainfall ranges from 3000 to 5000 mm per year, with April to July being the months of highest rainfall (MAE, 2012).

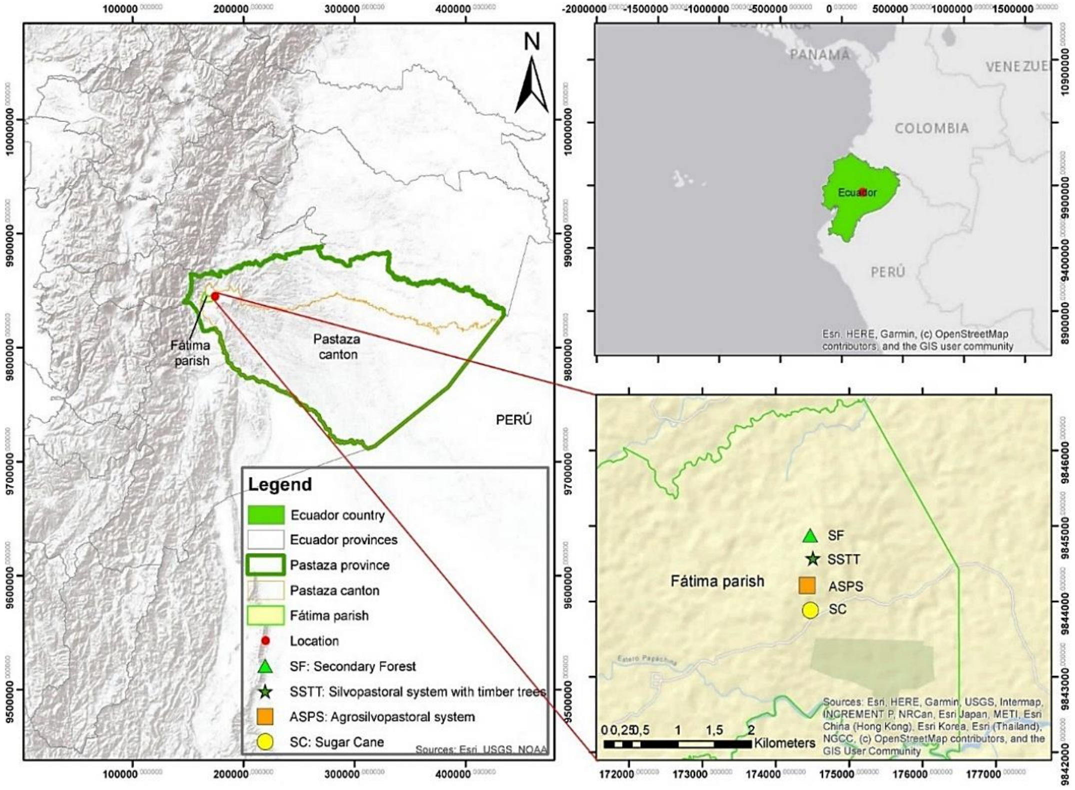

Figure 1. Geographical location of the study area in in the Fátima parish, Pastaza.

The soils have been taxonomically classified in the order Andisol (Soil Survey Staff 2006), with a clay loam texture and a structure ranging from granular to blocky. They are generally acidic and of low natural fertility (low P, K^+, Ca^{2+} and Mg^{2+} contents) and present saturation percentages with bases < 35%, and high Fe and Al^{3+} contents (Nieto & Caicedo, 2012; Espinosa et al., 2018). The region's forests are part of the Amazonian-Andean evergreen forest, with high biodiversity and medium stratification (MAE, 2012), and predominance of species of the Fabaceae families Pambil (*Iriartea deltoidea),* Uva de monte (*Pouroma minor),* Piton *(Grias neuberthi),* Huarumo (*Cecropia fycifolia),* Sapote de monte (*Matisia),* Guadua (*Guadua angustifolia*) (García Quintana et al., 2021).

2.2. Soil sampling and laboratory analysis

The selected uses corresponded to those local land use patterns prevailing in the province of Pastaza, Amazon region of Ecuador (Table 1).

Transects were established for each land use, and systematic sampling was carried out by placing five equidistant sampling points along the transect that covered the entire selected area. For each sampling point, we selected a 10 x 10 m subplot. In each subplot, we collected five soil subsamples at three different depths (0 - 10 cm, 10 - 20 cm, and 20 - 30 cm). Afterward, we combined the subsamples to create a composite sample for each point. In total, we collected 15 samples for each type of land use. In total, 180 soil samples were collected from all three soil layers across various land use types. 90 samples underwent chemical analysis while the remaining 90 were evaluated for their physical attributes. The soil samples were air-dried, ground, and then passed through a 2 mm sieve and used for physical and chemical evaluations. In parallel, in the central part of the subplot, undisturbed samples were collected with an Uhland-type sampling to evaluate physical parameters.

2.3. Soil physical analysis

The percentage composition of clay, silt, and sand was determined using the hydrometer method (Cole-Parmer, ASTM152H-Type hydrometer, USA) (Gee, 1979).

The physical attributes of the soil were determined by taking undisturbed samples with cylinders that were 5 cm high and 5 cm in diameter. The following variables were measured: a) bulk density (BD) using the cylinder method (Klute & Page, 1986); b) saturated hydraulic conductivity (K_{sat}) using the variable load method (Meter Group, ASTM D2434-compliant K_{SAT}, USA) (Reynolds et al., 2002). The saturation tension table method with -10 KPa matric potential (Soil Moisture, 1 Bar Pressure Plate Cell, USA), (Blake & Hartge, 1986) was used to determine the soil pore size distribution that included total porosity (TP); aeration porosity (AP: pores >15 μm radius), and retention porosity (RP).

2.4. Soil chemistry analysis and leaf litter

The chemical attributes evaluated included the determination of pH, which was measured by potentiometry (soil-water ratio 1:2.5) (Orion Start, A211, United States) (McLean 1965). Soil organic carbon (TOC) was measured using the Walkley and Black wet digestion method (Nelson & Sommers, 1982). Available P and extractable cations (K^+, Ca^{2+}, and Mg^{2+}) were removed using Olsen's extraction solution. P was measured colorimetrically using the molybdenum blue method (Thermo Scientific™, Spectrophotometer UV-Vis, Genesys 10, United States), while K^+, Ca^{2+}, and Mg^{2+} were determined using an atomic absorption spectrometer (Perkin Elmer, AAnalyst 800, United States) (Okalebo et al., 2002).

Finally, litterfall (LL) was calculated within the 10 x 10 m subplots using a 0.25 m^2 quadrat. For this purpose, all the material corresponding to dead plant material (such as leaves, stems, stalks, needles, and twigs) that had fallen to the ground and remains located inside it were collected. The collected material was weighed and placed in bags to dry at 105 °C for 24 hours until a constant weight was obtained. Dry matter was calculated in megagrams per hectare.

Table 1
Selected land uses in the area under study (Pastaza Province, Ecuadorian Amazon Region)

Land use	Crop	Coordinates WGS 84 – UTM, Zona 18 South	
		Latitude	Longitude
SC: Sugar Cane	Sugar Cane (*Saccharum officinarum*) sown in rows with high applications of organic fertilizer	174475.39	9843878.27
ASPS: Agrosilvopastoral system	Fodder grass (*Cenchrus purpureus*) with orange trees and some forest species	174433.20	9844212.14
SSTT: Silvopastoral system with timber trees	Timber trees such as: Chuncho (*Cedrelinga cateniformis*), Piwi (*Piptocona discolor*), Canelo (*Nectandra* sp.)	174509.05	9844570.00
SF: Secondary Forest	Great biodiversity and predominance of species such as: Pambil (*Iriartea deltoidea),* Uva de monte (*Pouroma minor*), Piton (*Grias neuberthi*), Huarumo (*Cecropia fycifolia*), Sapote de monte (*Matisia*), Guadua (*Guadua angustifolia*)	174470.80	9844873.52

2.5. Soil quality index (SQI) assessment

To obtain the SQI, three consecutive steps were followed (Zhang et al., 2019; Bravo-Medina et al., 2021): 1) selection of a minimum set of soil quality indicators, 2) scoring of the indicators, and 3) calculation of quality indices. The present study considered 26 soil quality attributes as a total data set and to choose the most representative indicators from the data matrix, a principal component analysis (PCA) was performed, and a Pearson correlation coefficient was determined. Thus, in each principal component, only factors with absolute loading values within 10% of the highest factor loading were selected. When more than one indicator is selected in a principal component, a Pearson correlation analysis is used to verify whether other indicators should be eliminated. If the indicators were adequately correlated, i.e. a Pearson's coefficient greater than 0.6 with each other, only the indicator with the highest weight in the principal components is selected. After selecting the indicators from the data matrix, a sigmoid nonlinear scoring function is used to transform the soil indicators into scores from 0 to 1, as follows.

$$S = \frac{a}{\left[1+\frac{x}{x_0}\right]^b} \quad (1)$$

Where *S* is the soil indicator score, a is the maximum score (a = 1), *x* is the indicator value, x_0 is the average value of each soil indicator, and b is the slope value of the equation. The slope values range from -2.5 to 2.5. Finally, with the indicator scores and their weighting values, the soil index is chosen using the following equation:

$$SQI \sum_{i=1}^{n} S_i W_i \quad (2)$$

Where W_i are the weighting values of the soil indicators selected by the PCA., S_i is the indicator score calculated with the above equation, and n is the number of indicators selected in the data matrix.

2.6. Statistical analysis

All statistical analyses were performed by Origin Pro 2020b (serial number: GF3S5-6089-7616982). A one-way analysis of variance (ANOVA) followed by a Tukey's mean comparison test ($p \leq 0.05$) was used to examine and compare differences in soil indicators and SQIs between different land use types at a level of $p < 0.05$. Principal component analysis (PCA) and correlation matrices between soil indicators were evaluated by Pearson correlation analysis. An additional ANOVA was performed on the general soil quality indicators with SQI and MDS scores to reveal the effect of different land use types on soil quality.

3. Results and discussion

3.1. Soil physical indicators under different land use types

The analysis of soil texture from 0 to 30 cm depth is shown in Table 2. Significant differences ($p \leq 0.05$) were only recorded for sand and silt content with predominantly loam textural classes, ranging from 34.33% to 51.44% for sand content, from 36.83% to 50.08% for silt content, and from 10.33% to 15.58% for clay content for all types of land uses.

The results indicate that the highest percentage of sand occurs in the use of Forest and SSTT, while the lowest percentage is in the SASP. The highest percentage of silt occurs in the ASPS, and the lowest percentage is in the sugarcane crop.

Table 2
Soil texture (sand, silt, clay) analysis for different land use types

Land use	Sand (%)	Silt (%)	clay (%)	Textural class
Depth 0-30 cm				
SC	49.83 ± 5.40 a	36.83 ± 1.84 b	13.33 ± 3.65 a	Loam
ASPS	34.33 ± 5.36 b	50.08 ± 3.27 a	15.58 ± 3.08 a	Silt Loam
SSTT	43.17 ± 4.05 a	46.17 ± 2.27 a	10.67 ± 2.00 a	Loam
SF	51.44 ± 6.26 a	38.22 ± 2.20 b	10.33 ± 4.11 a	Loam

Different lower-case letters indicate significant differences among different land use types (one-way ANOVA, Tukey, $p < 0.05$). SC: Sugar Cane; ASPS: Agrosilvopastoral system; SSTT: Silvopastoral system with timber trees and SF: Secondary Forest.

Table 3
Average values of physical properties of soil quality under different land uses in the Fatima Community, Pastaza Province

Soil properties	SC	ASPS	SSTT	SF
BD (Mg m^{-3})	0.53 ± 0.04 a	0.52 ± 0.07 a	0.48 ± 0.02 a	0.51 ± 0.21 a
Ksat (cm h^{-1})	40.81 ± 33.22 b	14.11 ± 6.85 c	60.04 ± 55.00 b	100.65 ± 65.56 a
TP (%)	92.03 ± 1.98 a	91.19 ± 2.49 a	91.00 ± 4.02 a	88.10 ± 7.75 a
AP (%)	11.64 ± 1.30 a	12.14 ± 2.04 a	10.95 ± 1.43 a	13.51 ± 2.44 a
RT (%)	80.39 ± 2.69 a	79.04 ± 2.25 a	80.04 ± 5.20 a	74.60 ± 5.39 a

Different lower-case letters indicate significant differences among different land use types (one-way ANOVA, Tukey, $p < 0.05$). SC: Sugar Cane; ASPS: Agrosilvopastoral system; SSTT: Silvopastoral system with timber trees and SF: Secondary Forest. BD: Bulk density; Ksat: Saturated hydraulic conductivity; TP: Total porosity; AP: Aeration porosity; RP: Retention porosity.

In general, the clay content did not exceed 15% in all the land uses evaluated. Soil structural quality was analyzed according to different physical properties under different land uses, whose average values are shown in Table 3. Only saturated hydraulic conductivity showed significant differences ($p \leq 0.05$). Bulk density varied in a range from 0.48 to 0.53 Mg m^{-3} in all uses, reflecting adequate values compared to the reference value (1.2 Mg m^{-3}) for this type of loam texture (Pla, 2017).

The highest saturated hydraulic conductivity (Ksat) value was found in the forest use (100.65 cm h^{-1}) and the lowest in the SASP with a conductivity of 14.11 cm h^{-1} respectively. The results for this variable showed the following order: BS > SSPM > SC > SASP, which is related to the values of pore size distribution, especially aeration porosity (AP). Likewise, the behavior of this variable is also related to the textural and structural condition that favors the penetration and movement of water in the soil profile (Bravo-Medina et al., 2021).

In all the land uses evaluated the values obtained are considered adequate, above the critical limit of 0.5 cm h^{-1} (Pla, 2010). Soil total porosity (TP presented high levels regardless of the type of land use with ranges from 88.10% to 92.03%, above the threshold considered critical (60%). The total porosity values obtained were closely related to bulk density (BD), suggesting that higher bulk density meant lower total porosity (TP) and vice versa. Regardless of soil cover, in the total pore fraction (TP), micropores or retention pores (RP) predominate over macropores (AP >15 μm) (Table 3), which confers a high moisture retention capacity. However, when analyzing the fraction of macropores, ranges between 10.95 and 13.51 were recorded, showing an inverse pattern to the bulk density and above the threshold value of 10% (Pla, 2010).A value of 10% in the AP allows a good transmission of water, air, and heat and facilitates root growth, improving the quality and productive potential of the soil (Pla, 2010; Blanco-Canqui & Ruis, 2018; Bravo-Medina et al., 2021). Therefore, the level of available SOM could be used as a critical indicator of soil quality in tropical soils, as verified in this study. Based on this, the results of this study related to physical indicators are strongly influenced by high organic matter content in the soil and therefore influence the physical variables associated with its structural quality, such as bulk density (BD), saturated hydraulic conductivity (Ksat) and porosity distribution (Blanco-Canqui & Ruis, 2018; Rabot et al., 2018; Bravo-Medina et al., 2023). In our study, the values of Bulk density (BD) under the different land uses ranged from 0.48 to 0.53 Mg m^{-3} (Table 3), which were below the threshold value of apparent density that is considered harmful to the seed germination, root development, and plant growth (Pla, 2010; Blanco-Canqui & Ruis, 2018). In this context, the interpretation of BD concerning soil functions depends on soil type, especially soil texture and soil organic matter (SOM) content (Bravo-Medina et al., 2021). Therefore, low bulk density (BD) values are supported by the permanent root systems of tree-based land uses and the high biological activity this can generate (Leul et al., 2023). Threshold values between soil textural classes may vary due to differences in soil particle size and shape; Threshold values can be >1.40 Mg m^{-3} for clay soils, >1.60 Mg m^{-3} for medium-textured soils, and > 1.80 Mg m^{-3} for coarse-textured soils (Blanco-Canqui & Ruis, 2018). It has been pointed out that soil BD is one of the most sensitive variables to changes in land use and has great influence on other attributes, such as porosity distribution, especially macroporosity (AP) and on Ksat, which affects the aeration capacity, the speed of water penetration and, therefore, the biogeochemical behavior of the soil (Pla, 2010; Blanco-Canqui & Ruis, 2018; Bravo-Medina et al., 2021). Regardless of land use, the physical indicators evaluated related to soil structure (BD, TP, AP, Ksat) show soil with adequate physical quality, without problems of compaction, aeration, and water movement through the profile. of soil, which is associated with the high contents of organic matter in all land uses characteristic of soils of the Ecuadorian Amazon region (Bravo-Medina et al., 2023; Espinosa, et al., 2018). Some researchers indicate that the physical quality of the soil plays a fundamental role in soil quality research, and therefore poor physical quality is manifested by low infiltration, high surface runoff, hardening, poor aeration, and poor rooting capacity (Farahani et al., 2019).

3.2. Soil chemical indicators under different land use types

Figure 2 shows two chemical properties related to soil quality for the four land uses evaluated. Acidity exhibited significant differences ($p \leq 0.05$) with acid pH levels, ranging from 5.15 to 5.36 for the uses with SF, ASPS, and SC respectively, while the highest value was obtained in the use of SSTT (5.73) (Figure 2a). Soil organic matter (SOM) content was significantly higher ($p < 0.05$) in the SSTT and sugarcane (SC) land uses (Figure 2b), with values between 12% and 13%. In the case of the use with forest (SF) and the agrosilvopastoral system, the values were around 8%, however, it is important to note that, despite these differences in all land uses, the values obtained are considered high SOM concentrations (>5%) (Espinosa, et al., 2018). On the one hand, the silvopastoral systems and the forest, it is related to the historical use of forest cover in the Ecuadorian Amazon Region, which leads to higher carbon storage (Nieto & Caicedo, 2012; Bravo-Medina et al., 2023; Torres et al., 2024).

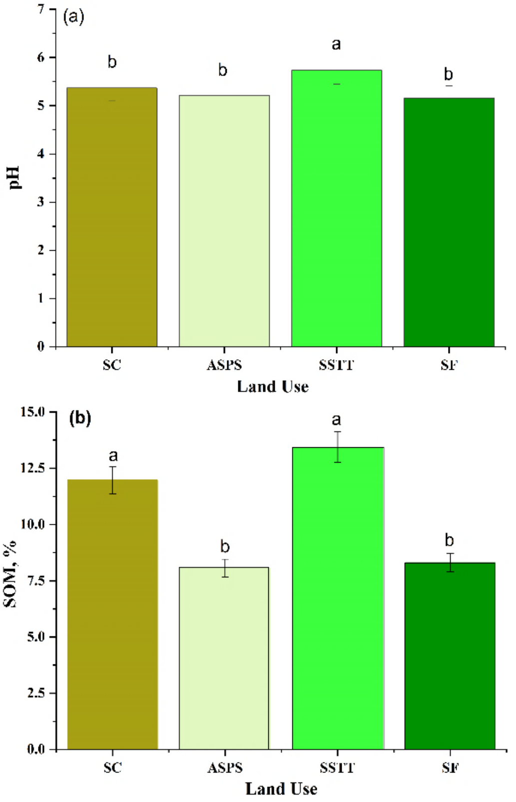

Figure 2. Chemical indicators associated with soil quality under different land uses. Different lower-case letters indicate significant differences among different land use types (one-way ANOVA, Tukey, p < .05). Error bars correspond to standard deviation. SC: Sugar Cane; ASPS: Agrosilvopastoral system; SSTT: Silvopastoral system with timber trees and SF: Secondary Forest. (a) pH; (b) Soil organic matter.

In the case of the sugarcane system, sugarcane is managed organically, and the fertility management plan includes high annual applications of organic matter in the form of compost. Nutrient availability showed significant differences for some parameters associated with nutrient quality ($NH4^+$, and Ca: Mg/K ratio). The NH_4^+ content varied from 120 to 150 mg kg^{-1} (Figure 3a), with the SSTT use having the highest content and the forest use the lowest. For this area, it has been pointed out that the diversity of plant species with litter and root production contributes to the development of biogeochemical cycles, thus fixing several nutrients such as N (Bravo et al., 2017). P content ranged from 4.56 to 6.75 mg kg^{-1} (Figure 3b), and the use of sugarcane (SC) was the one with the highest content, and the use of ASPS with the lowest concentration.

The results obtained related to available P in all the evaluated uses are categorized as very low values for being below the critical level of 10 mg kg^{-1} (Bai et al., 2013), and correspond with other research conducted in the area under study (Martín & Pérez, 2009; Bravo et al., 2017). In this regard, Martín & Pérez (2009) indicates that the soils of the Pastaza province are infertile due to their high acidity and toxicity because of excess Al and deficiency of P. In soils with pH below 5.5, phosphorus availability is reduced, because it reacts with Fe and Al dissolving in these reactions. Cation ratios (Ca+Mg/K) (Figure 3c) showed significant differences with values ranging from 27.85 meq 100 g s^{-1} (ASPS) to 66.87 m_{eq} 100 g s^{-1} (SF). Although in the secondary forest (SF) this ratio is significantly higher than the rest of the systems, it has been pointed out that the ratio (< 40) is adequate to favor potassium availability, while the ratio (> 40) indicates a potassium deficiency. Thus, the SF and SSTT use presented values higher than 40, indicating a potassium deficiency, which is characteristic of Amazonian soils. Zn content showed a similar behavior to P, with no significant differences among the different uses and with ranges from 4.58 mg kg^{-1} (SSTT) to 6.10 mg kg^{-1} (SC). Concentrations of available Zn < 3 mg kg^{-1} have been reported as critical, therefore, the values obtained were categorized as mean levels between 3 - 7 mg kg^{-1} (SSTT) and 6.10 mg kg^{-1} (SC). In this study, chemical properties showed slightly significant differences between the different land uses evaluated, which is associated with the nature of the soils of the Ecuadorian Amazon (Espinosa, et al., 2018; Bravo-Medina et al., 2023). Under these conditions, it is important to highlight that the quality of the attributes is deeply marked by the soil-forming factors of the Amazon region (Espinosa et al., 2018). In this regard, it has been described that the pedogenesis of Amazonian soils shows a very particular character, influenced by different factors, including a climate characterized by high and intense rainfall with annual averages of around 4000 mm, high temperatures that can range between 24 and 30 °C, and habitats ranging from tropical rainforest to very humid tropical rainforest (Nieto & Caicedo, 2012; Torres et al., 2019; Bravo-Medina et al., 2023).

3.3. Evaluation of the Soil Quality Index

The eigenvalues of the principal components were greater ≥ 1 and explained 86.04% of the total variance (Table 4). In the first component (PC1), the quality indicators with the greatest weight were bulk density (BD) and the Calcium, Magnesium, and

Potassium (Ca+Mg/K) ratio. Bulk density showed a high negative relationship with total porosity and microporosity (r > 0.70), therefore, it was considered a suitable variable as an indicator of soil physical quality.

Table 4
Principal component analysis of soil quality indicators

Variables	PC1	PC2	PC3	PC4
% Sand	0.06	0.05	-0.98	0.06
% Silt	0.09	0.04	0.91	-0.31
% Clay	-0.38	0.01	0.76	0.31
BD Mg m^{-3}	-0.80	-0.08	0.35	0.20
Ksat cm h^{-1}	0.08	0.13	-0.69	-0.39
TP %	0.73	0.40	0.00	0.30
AP %	0.51	-0.31	-0.41	-0.21
RP %	0.52	0.54	0.17	0.39
pH	-0.03	0.83	0.12	-0.42
NH_4^+	0.33	-0.11	0.02	0.26
P mg kg^{-1}	0.00	0.36	-0.17	0.76
K meq 100 g s^{-1}	0.75	0.34	-0.17	0.32
Ca meq 100 g s^{-1}	0.11	0.94	0.00	0.14
Mg meq 100 g s^{-1}	0.12	0.76	-0.15	0.32
S mg kg^{-1}	0.11	0.22	0.05	0.59
Ca:Mg	0.09	0.36	0.20	-0.08
Mg: K	-0.90	-0.13	-0.02	-0.15
(Ca+Mg)/K	-0.93	0.01	0.04	-0.18
Sum of Bases	0.16	0.94	-0.03	0.18
B mg kg^{-1}	0.13	0.19	-0.16	0.00
Zn mg kg^{-1}	0.44	0.14	0.13	0.73
Cu mg kg^{-1}	0.80	0.11	0.29	-0.17
Fe mg kg-1	0.24	0.06	0.85	-0.06
Mn mg kg^{-1}	-0.10	0.46	0.08	0.05
SOM %	0.16	0.94	-0.03	0.18
Litter Mg ha^{-1}	0.49	-0.12	0.02	0.06
Eigenvalues	2.77	7.08	1.18	2.89
Variance (%)	38.54	28.33	12.16	7.01
Accumulative variance (%)	38.54	66.87	79.03	86.04

Note: Bold factor is considered highly weighted; underline and bold factors are retained in the minimum data set (MDS). **PC-1**, **PC-2**, **PC-3**, and **PC-4** indicate first principal component, second principal component, third principal component, and forth principal component, respectively. **BD**: bulk density (Mg m^{-3}); **K_{sat}**: Saturated hydraulic conductivity (cm hr^{-1}); **TP**: Total porosity (%); **AP**: Aeration porosity (%); **RP**: Retention porosity; **SOM**: Soil organic matter (%); **P**: Available phosphorus (mg kg^{-1}); **K^+**: Exchangeable potassium (meq100 g s^{-1}); **Ca^{2+}**: Exchangeable calcium (meq 100 g s^{-1}); **Mg^{2+}**: Exchangeable magnesium (meq100 g s^{-1}); **Cu**: Available copper (mg kg^{-1}); **Zn**: Available zinc (mg kg^{-1}); **S**: Available sulfur (mg kg^{-1}), **Ca:Mg**: Calcium magnesium ratio; **Mg:K**: Potassium magnesium ratio; **Ca+Mg/K**: Calcium magnesium potassium ratio; **B**: Available boron (mg kg^{-1}), **Zn**: Available Zinc (mg kg^{-1}), **Cu**: Available copper (mg kg^{-1}), **Mn**: Available manganese (mg kg^{-1}), SOM: Soil organic matter (%); **LL**: Leaf litter.

A strong correlation (r > 0.70) was also observed between BD and the ratio (Ca + Mg/K) (Figure 4), therefore, both variables were selected as indicators in PC1. In the second principal component (PC2), the indicators with the highest loading were pH, Calcium availability (Ca^{2+}), the sum of bases (SB), and soil organic matter (SOM). SOM, BS, and Ca^{2+} showed strong correlations (r > 0.85) (Figure 4), therefore, SOM was selected as an indicator in PC2. In the third component (PC3) the indicators that showed a higher loading and high degree of significant association were % Sand and Fe^{2+} iron availability, showing a strong correlation (r > -0.80) (Figure 4), therefore % Sand was selected as the highest loading indicator in PC3.

Finally, in the fourth component (PC4), the availability of phosphorus and zinc was selected as indicators of PC4, as it exhibited the highest loads and a moderate correlation between both parameters (r > 0.45) and with other parameters related to fertility (r > 0.75). With this, the minimum set of data selected for calculating the soil quality index (SQI) was BD, Ca+Mg/K, SOM, % sand, and Zn. From the weights or loads based on the principal components analysis (Table 5).

SQI was calculated using the following equation:

$$SQI = 0.4153 \times S (BD) + 0.4153 \times S (Ca+Mg/K) + 0.3462 \times S (SOM) + 0.1326 \times S (sand) + 0.1151 \times S (P) + 0.1151 \times S (Zn)$$

In general, the soil quality index (SQI) showed significant differences ($p < 0.05$; Figure 5) between the different land uses, establishing the following order: SSTT (0.41) > SC (0.40) > SF (0.34) > ASPS (0.32). SQI values between 0.40 to 0.60 are categorized as moderate quality, while averages between 0.20 to 0.39 are indicated as low-quality values (Cantú et al., 2007). Therefore, the values obtained are considered of low to moderate quality, resulting in the silvopastoral system with timber trees and the use of land with sugar cane of higher quality compared to the use of forest and the agrosilvopastoral system. In this research, the greatest accumulation of soil organic matter was obtained in the silvopastoral system with timber trees (SSTT) and the use system with sugar cane (SC) compared to the secondary forest (Figure 2). Such results are associated in the case of the silvopastoral system with the incorporation of biomass through pasture, timber forest cover, and livestock manure while grazing.

Table 5
Normalization equation of scoring curves

Parameter	BD	Ca+Mg/K	SOM	Sand %	P	Zn
Average	0.51	10.17	6.24	44.69	5.34	5.38
Curve Type	Less is better	Less is better	More is better	Less is better	More is better	More is better
Slope (b)	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5
Normalization equation	$S = a/[1+(x/0.51)]^b$	$S = a/[1+(x/10.17)]^b$	$S = a/[1+(x/6.24)]^b$	$S = a/[1+(x/44.69)]^b$	$S = a/[1+(x/5.34)]^b$	$S = a/[1+(x/5.34)]^b$
Weighting value	0.41	0.35	0.13	0.13	0.10	0.10

Abbreviations: BD: bulk density; Ca+Mg/K: Calcium magnesium potassium ratio; SOM: Soil organic matter; P: Available phosphorous; Zn: available zinc.

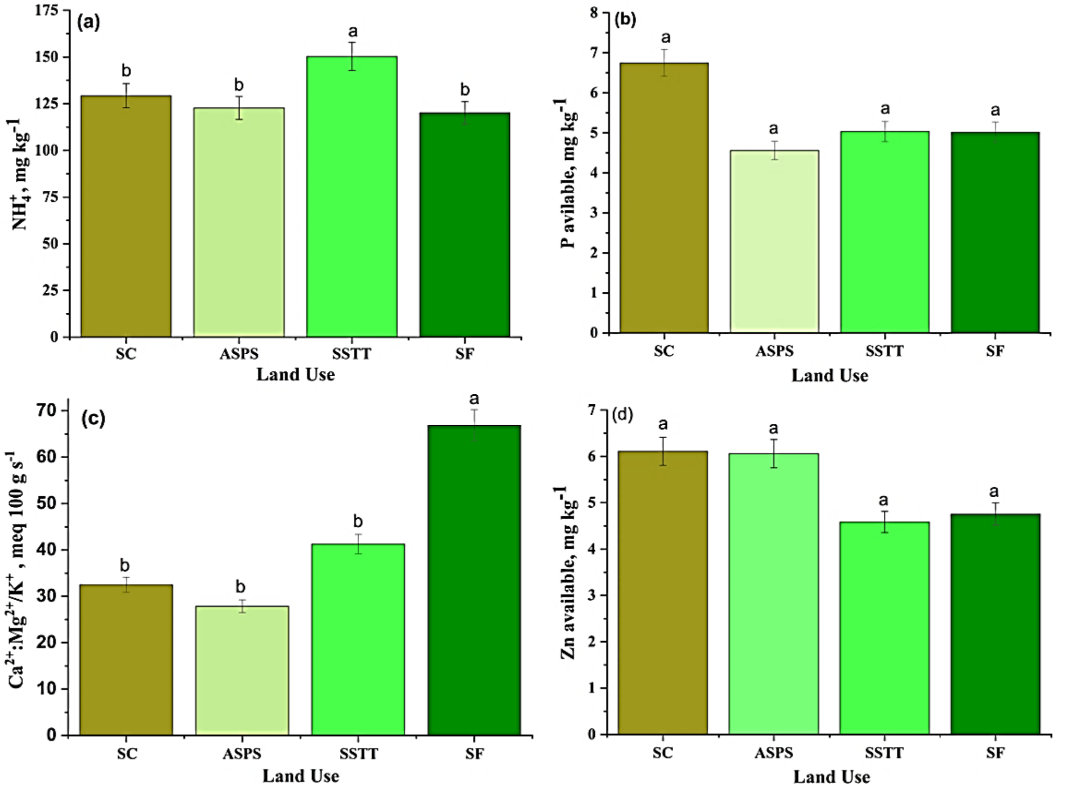

Figure 3. Chemical indicators associated with soil quality under different land uses. Different lower-case letters indicate significant differences among different land use types (one-way ANOVA, Tukey, $p < 0.05$). Error bars correspond to standard deviation. SC: Sugar Cane; ASPS: Agrosilvopastoral system; SSTT: Silvopastoral system with timber trees and SF: Secondary Forest. (a) Nitrogen, (b) Available phosphorous; (c) Ca:Mg/K, and (d) Available zinc.

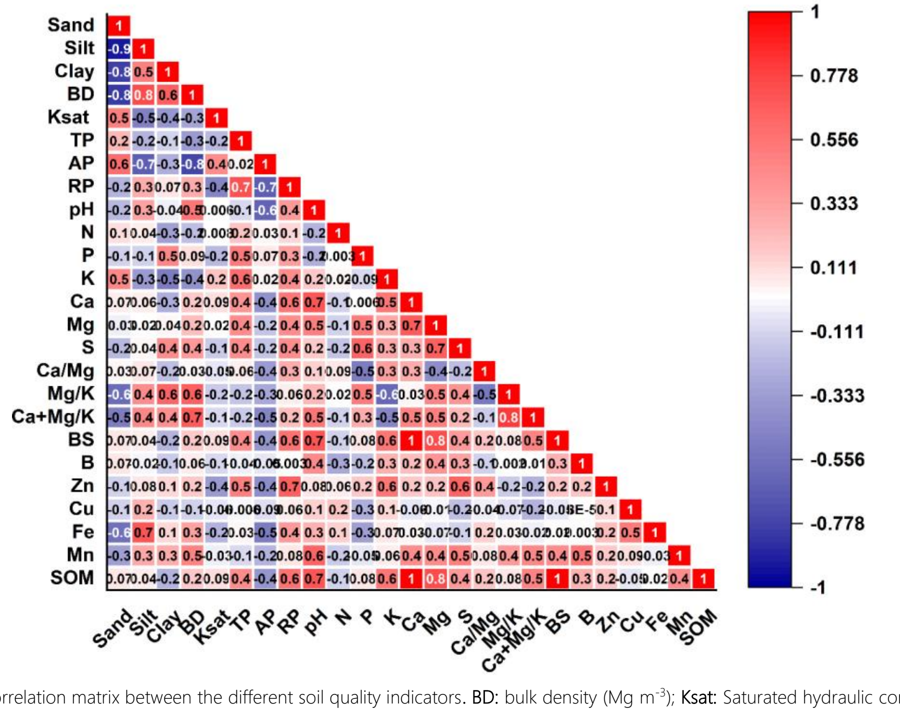

Figure 4. Correlation matrix between the different soil quality indicators. BD: bulk density (Mg m^{-3}); Ksat: Saturated hydraulic conductivity (cm hr^{-1}); TP: Total porosity (%); AP: Aeration porosity (%); SOM: Soil organic matter (%); P: Available phosphorus (mg kg^{-1}); K^+: Exchangeable potassium (meq100 g s^{-1}); Ca^{2+}: Exchangeable calcium (meq 100 g s^{-1}); Mg^{2+}: Exchangeable magnesium (meq100 g s^{-1}); Cu: Available copper (mg kg^{-1}); Zn: Available zinc (mg kg^{-1}); S Available sulfur (mg kg^{-1}), Ca:Mg :Calcium magnesium ratio; Mg:K: Potassium magnesium ratio; Ca+Mg/K: Calcium magnesium potassium ratio; B: Available boron (mg kg^{-1}), Zn: Available Zinc (mg kg^{-1}), Cu: Available copper (mg kg^{-1}), Mn: Available manganese (mg kg^{-1}), SOM: Soil organic matter (%);LL: Leaf litter.

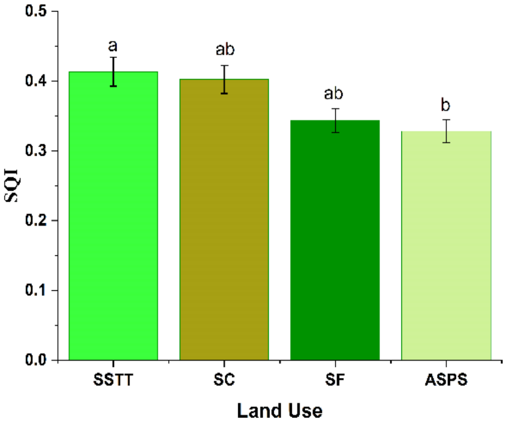

Figure 5. Soil quality index under different land uses. Error bars correspond to the standard deviation. Different lower-case letters indicate significant differences among different land use types at the same depth (one-way ANOVA, Tukey, $p < 0.05$). SSTT: Silvopastoral system with timber trees. SC: Sugar Cane; SF: Secondary Fores; ASPS: Agrosilvopastoral system.

Also, in silvopastoral and forest systems it is related to the historical use of forest cover in the Ecuadorian Amazon Region, which leads to greater carbon storage (Nieto & Caicedo, 2012; Bravo-Medina et al., 2023; Torres et al., 2023). In the sugarcane system, the accumulation of SOM is related to the high annual applications that are made in said crop as part of the fertilization management plan and its low mineralization because it is a low tillage intensity system. On the contrary, in other parts of the world, it has been reported that annual crops managed with high tillage intensity show that the rate of SOM loss was high in recently developed commercial agricultural soils due to the rapid mineralization of organic matter caused by the heat and tillage (Leul et al., 2023). Soil organic matter is considered one of the most important factors among soil quality indices and has a positive effect on soil properties and is also the central indicator of soil quality and health, which is strongly affected by agricultural management (Kiakojouri & Gorgi, 2014).

Two of the most relevant indicators for soil quality are the pH and the organic matter content of the soil due to its influence on other physical, chemical, and biological parameters of the soil. In our study, the pH presented values from slightly acidic to acidic (Figure 2), consequently, when the pH value is below 5.5, it generates a greater deterioration of the quality of the soil in the long term by making it difficult to obtain basic cations, and reduce nutrient availability, nutrient cycling, microbial biological activity, and the ability to decompose biomass (McGrath et al., 2014; Leul et al., 2023). Minerals of variable charge occur mainly in the terminal hydroxide groups located at the edges of 1:1 minerals (such as kaolinite) and oxides or hydroxides of Fe, Al, and Mn (such as goethite and gibbsite), typical of Amazonian soils (Espinosa, et al., 2018) and since they can acquire positive charges depending on the pH of the solution, they can absorb anionic nutrients, such as PO_4^{3-} and SO_4^{2-}. Thus, as the pH increases, the negative charge on the surface of the mineral increases and can improve cation retention.

4. Conclusions

The land uses with the Silvopastoral system with timber three (SSTT) and Sugarcane (SC) presented the highest quality indices, 0.41 and 0.40, respectively, indicating moderate quality and an improvement concerning the secondary forest. Our study revealed that the conversion of natural forest land to cropland resulted in statistically significant differences in some of the soil quality attributes evaluated between agrosilvopastoral, silvopastoral, and sugarcane systems. Consequently, bulk density, soil organic matter, pH, available phosphorus, and zinc, could be more effective and consistent indicators of changes in soil quality induced by the conversion of natural forest lands to forest use systems. silvopastoral and agricultural lands. These indicators in an Amazonian environment verified the deterioration or improvement of soil quality, particularly on agricultural lands and in silvopastoral systems managed by small farmers. Therefore, the estimated soil quality index could determine a threshold value for management actions necessary to prevent further degradation of soil quality indicators in cultivated ecosystems. The study shows that soil quality index analysis could be a viable tool for assessing soil health. Furthermore, this study will be useful for researchers, policymakers, and land use planners to understand the current state of the soil ecosystem and serve as a basis for future strategies and proper management of agricultural lands. Furthermore, sustainable ecological and land management strategies should emphasize sustainable, restorative, and long-term land use practices to improve the environmental and biological functions of soil in diverse land use systems at local and local levels. regional, especially in humid tropical ecosystems.

Statements and declarations conflict of interest

None of the authors has any conflict of interest in this research.

Author statement

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References

Abera, W., & Assen, M. (2019). Dynamics of Selected Soil Quality Indicators in Response to Land Use/Cover and Elevation Variations in Wanka Watershed, Northwestern Ethiopian Highlands. *Ekológia (Bratislava)*, *38*(2), 126–139. https://doi.org/10.2478/eko-2019-0010

Andrews, S. S., Flora, C. B., Mitchell, J. P., & Karlen, D. L. (2003). Growers' perceptions and acceptance of soil quality indices. *Geoderma*, *114*(3–4), 187–213. https://doi.org/10.1016/S0016-7061(03)00041-7

Bai, Z., Li, H., Yang, X., Zhou, B., Shi, X., Wang, B., Li, D., Shen, J., Chen, Q., Oenema, O., & Zhang, F. (2013). The critical soil P levels for crop yield, soil fertility and environmental safety in different soil types. *Plant Soil, 372*, 27–37. https://doi.org/10.1007/s11104-013-1696-y

Blake, G., & Hartge, K. (1986). *Bulk density 1. Methods of soil analysis: Part 1 Physical and Mineralogical Methods* (pp. 363–375).

Blanco-Canqui, H., & Ruis, S. J. (2018). No-tillage and soil physical environment. *Geoderma*, *326*, 164–200. https://doi.org/10.1016/j.geoderma.2018.03.011

Bravo-Medina, C., Goyes-Vera, F., Arteaga-Crespo, Y., García-Quintana, Y., & Changoluisa, D. (2021). A soil quality index for seven productive landscapes in the Andean-Amazonian foothills of Ecuador. *Land Degradation and Development*, *32*(6), 2226–2241. https://doi.org/10.1002/ldr.3897

Bravo-Medina, C., Torres-Navarrete, B., Arteaga-Crespo, Y., Garcia-Quintana, Y., Reyes-Morán, H., Changoluisa-Vargas, D., & Paguay-Sayay, D. (2023). Soil properties variation in a small-scale altitudinal gradient of an evergreen foothills forest, Ecuadorian Amazon region. In *European Journal of Forest Research*, *142*(6), 1325–1339. https://doi.org/10.1007/s10342-023-01593-6

Bravo, C., Benítez, D., Cesar, J., Burgos, V., Alemán, R., Torres, B., & Marín, H. (2015). Caracterización socio-ambiental de unidades de producción agropecuaria en la Región Amazónica Ecuatoriana: Caso Pastaza y Napo Socio-Environmental Characterization of Agricultural Production Units in the Ecuadorian Amazon Region, Subjects: Pastaza and Nap. *Revista Amazónica Ciencia y Tecnología*, *4*, 3–31.

Bravo, C., Ramírez, A., Marín, H., Torres, B., Alemán, R., Torres, R., Navarrete, H., & Changoluisa, D. (2017). Factores asociados a la fertilidad del suelo en diferentes usos de la tierra de la Región Amazónica Ecuatoriana. *Revista Electronica de Veterinaria*, *18*(11), 1–16.

Cantú, M. P., Becker, A., Bedano, J. C., & Schiavo, H. F. (2007). Evaluación de la calidad de suelos mediante el uso de inidicadores e índices. *Ciencia Del Suelo*, *25*(2), 173–178.

Doran, J. W., & Safley, M. (1997). Defining and assessing soil health and sustainable productivity. In C. Pankhurst, B. M. Doube, & V. V. S. R. Gupta (Eds.), *Biological indicators of soil health* (pp. 1–28). CAB International.

Drobnik, T., Greiner, L., Keller, A., & Grêt-Regamey, A. (2018). Soil quality indicators – From soil functions to ecosystem services. *Ecological Indicators*, *94*, 151–169. https://doi.org/10.1016/j.ecolind.2018.06.052

Espinosa, J., Moreno, J., Bernal, G., & Prat, C. (2018). *The soils of Ecuador* ((eds.) In J. Espinosa, J. Moreno & B. Gustavo (ed.); Issue October). World soils book series, (Vol. 7). Berlin: Springer International Publishing.

Farahani, E., Mosaddeghi, M. R., Mahboubi, A. A., & Dexter, A. R. (2019). Prediction of soil hard-setting and physical quality using water retention data. *Geoderma*, *338*, 343–354. https://doi.org/10.1016/j.geoderma.2018.12.012

García Quintana, Y., Arteaga-Crespo, Y., Torres-Navarrete, B., Bravo-Medina, C., & Robles-Murillo, M. (2021). Biomasa aérea de familias botánicas en un bosque siempreverde piemontano sometido a grados de intervención. *Colombia Forestal*, *24*(1), 45–59. https://doi.org/10.14483/2256201x.15939

Gee, B. J. (1979). Particle Size Analysis by Hydrometer: A Simplified Method for Routine Textural Analysis and a Sensitivity Test of Measurement Parameters. *Soil Science Society of America Journal*, *43*, 1004–1007. https://doi.org/10.2136/sssaj1979.03615995004300050038x

González, V., Bravo, C., Romero, M., Andrade-Yucailla, S., Andino, M., Valle, A., Hidalgo-Guerrero, I., & Andrade-Yucailla, V. (2019). Evaluación de la calidad de los suelos en cultivares de caña de azúcar (*Saccharum officinarum* L.) en la parroquia Fátima provincia de Pastaza. *Ciencia y Tecnología*, *12*(2), 15–22. https://doi.org/10.18779/cyt.v12i2.322

Karlen, D. L., Hurley, E. G., Andrews, S. S., Cambardella, C. A., Meek, D. W., Duffy, M. D., & Mallarino, A. P. (2006). Crop rotation effects on soil quality at three northern corn/soybean belt locations. *Agronomy Journal*, *98*(3), 484–495. https://doi.org/10.2134/agronj2005.0098

Kiakojouri, A., & Gorgi, M. M. T. (2014). Effects of land use change on the soil physical and chemical properties and fertility of soil in Sajadrood catchment. *Agricultural Engineering International: CIGR Journal*, *16*(3), 10–16.

Klute, A., & Page, A. L. (1986). Methods of soil analysis. Part 1. Physical and mineralogical methods; part 2. Chemical and microbiological properties. *Madison: American Society of Agronomy*.

Leul, Y., Assen, M., Damene, S., & Legass, A. (2023). Effects of land use types on soil quality dynamics in a tropical sub-humid ecosystem, western Ethiopia. *Ecological Indicators*, *147*, 110024. https://doi.org/10.1016/j.ecolind.2023.110024

MAE. (2012a). *Sistema de clasificación de los ecosistemas del Ecuador continental. Subsecretaría de Patrimonio Natural*.

MAE. (2012b). Sistema de clasificación de los ecosistemas del Ecuador continental. *Ministerio de Ambiente Del Ecuador*, *Subsecretaría de Oatrimonio Natural*.

Martín, N. J., & Pérez, G. (2009). Evaluación Agroproductiva de cuatro sectores de la provincia de Pastaza en la Amazonía Ecuatoriana. *Cultivos Tropicales*, *30*(1), 5–10.

McGrath, J. M., Spargo, J., & Penn, C. J. (2014). Soil Fertility and Plant Nutrition. In *Encyclopedia of Agriculture and Food Systems* (pp. 166–184). https://doi.org/10.1016/B978-0-444-52512-3.00249-7

Molaeinasab, A., Bashari, H., Tarkesh Esfahani, M., & Mosaddeghi, M. R. (2018). Soil surface quality assessment in rangeland ecosystems with different protection levels, central Iran. *Catena*, *171* (June 2017), 72–82. https://doi.org/10.1016/j.catena.2018.07.004

Nelson, D. W., & Sommers, L. E. (1982). *Total Carbon*, *Organic Carbon*, *and Organic Matter* (pp. 539–579). https://doi.org/10.2134/agronmonogr9.2.2ed.c29

Nieto, C., & Caicedo, C. (2012a). Análisis reflexivo sobre el desarrollo agropecuario sostenible en la Amazonía Ecuatoriana, INIAP – EECA. *Iniap*, *24–50*, 102. http://repositorio.iniap.gob.ec/handle/41000/3791

Okalebo, J. R., Gathua, K. W., & Woomer, P. L. (2002). Laboratory Methods of soil and plant analysis. *Working Manual*, 29-32, 67-68, 78, 86-87.

Peng, S., Chen, A., Fang, H., Wu, J., & Liu, G. (2013). Effects of vegetation restoration types on soil quality in Yuanmou dry-hot valley, China. *Soil Science and Plant Nutrition*, *59*(3), 347–360. https://doi.org/10.1080/00380768.2013.785918

Pla, I. (2010). Medición y evaluación de propiedades físicas de los suelos: dificultades y errores más frecuentes. {II}-

propiedades hidrológicas. *Suelos Ecuatoriales*, *40*, 94–127.

Pla, I. (2017). Análisis Crítico de la Calidad de Suelos y de sus indicadores. *Suelos Ecuatoriales*, *43*(1), 1–8.

Pla, S. I. (2010). Medición y evaluación de propiedades físicas de los suelos: dificultades y errores más frecuentes. Propiedades hidrológicas. *Suelos Ecuatoriales*, *40*(2), 94–127.

Rabot, E., Wiesmeier, M., Schlüter, S., & Vogel, H.-J. (2018). Soil structure as an indicator of soil functions: A review. *Geoderma*, *314*, 122–137. https://doi.org/10.1016/j.geoderma.2017.11.009

Reynolds, W., Elrick, D. E., Youngs, E. G., Booltink, H. W. G., & Bouma., J. (2002). Laboratory methods: Falling head soil core (tank) method. In *Methods of soils analysis*, *Part 4* (pp. 802–812).

Safaei, M., Bashari, H., Mosaddeghi, M. R., & Jafari, R. (2019). Assessing the impacts of land use and land cover changes on soil functions using landscape function analysis and soil quality indicators in semi-arid natural ecosystems. *Catena*, *177*, 260–271. https://doi.org/10.1016/j.catena.2019.02.021

Torres, B., Andrade, V., Heredia-R, M., Toulkeridis, T., Estupiñán, K., Luna, M., Bravo, C., & García, A. (2022). Productive Livestock Characterization and Recommendations for Good Practices Focused on the Achievement of the SDGs in the Ecuadorian Amazon. *Sustainability (Switzerland)*, *14*(17). https://doi.org/10.3390/su141710738

Torres, B., Bravo, C., Torres, A., Tipán-Torres, C., Vargas, J. C., Herrera-Feijoo, R. J., Heredia-R, M., Barba, C., & García, A. (2023). Carbon Stock Assessment in Silvopastoral Systems along an Elevational Gradient: A Study from Cattle Producers in the Sumaco Biosphere Reserve, Ecuadorian Amazon. *Sustainability (Switzerland)*, *15*(1), 1–14. https://doi.org/10.3390/su15010449

Torres, B., Herrera-Feijoo, R. J., Torres, A., Bravo, C., & García, A. (2024). Tree diversity and Its Ecological Importance Value in Silvopas-Toral Systems: A Study Along Elevational Gradients in the Su-Maco Biosphere Reserve, Ecuadorian Amazon. *Land*, *13*, 281. https://doi.org/10.3390/land13030281

Torres, B., Vasseur, L., López, R., Lozano, P., García, Y., Arteaga, Y., Bravo, C., Barba, C., & García, A. (2019). Structure and above ground biomass along an elevation small-scale gradient: case study in an Evergreen Andean Amazon forest, Ecuador. *Agroforestry Systems*, *94*(4), 1235–1245. https://doi.org/10.1007/s10457-018-00342-8

Viana, R. M., Ferraz, J. B. S., Neves, A. F., Vieira, G., & Pereira, B. F. F. (2014). Soil quality indicators for different restoration stages on Amazon rainforest. *Soil and Tillage Research*, *140*, 1–7. https://doi.org/10.1016/j.still.2014.01.005

Zhang, Y., Xu, X., Li, Z., Liu, M., Xu, C., Zhang, R., & Luo, W. (2019). Effects of vegetation restoration on soil quality in degraded karst landscapes of southwest China. *Science of the Total Environment*, *650*, 2657–2665. https://doi.org/10.1016/j.scitotenv.2018.09.372