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Evaluating soil quality in silvopastoral systems by the Soil Management Assessment Framework (SMAF) in the Colombian Amazon[1]

Avaliando a qualidade do solo em sistemas silvipastoris pelo Soil Management Assessment Framework (SMAF) na Amazônia Colombiana

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ABSTRACT - Monitoring the influence of livestock systems' on soil quality (SQ) in the Colombian Amazon region is important to ensure the sustainability of those agroecosystems. Here we used the Soil Management Assessment Framework (SMAF) to assess the SQ responses to land-use change associated with the adoption of silvopastoral systems (SPS) at two study sites in the Colombian Amazon region. A chronosequence formed by three land-use systems, reflecting the typical land transition performed in the region, was established at each study site: i) native vegetation (NV), ii) pasture (PAST), and iii) SPS. Soil samples were collected at 10 cm deep increments until reaching 30 cm deep. Then soil pH, potassium, available phosphorus, microbial carbon, soil organic carbon, and bulk density were measured. In addition, data from Visual Evaluation of Soil Structure (VESS) were correlated. Data were interpretated using SMAF algorithms, and a Soil Quality Index (SQI) was calculated. Our data showed an SQ degradation due to land-use change from NV to PAST, with soils reducing their capacity of soils function from 0.72 to 0.62. The establishment of SPS over extensive PAST restored soil quality (SQI = 0.69) compared to PAST (both sites), even reaching similar SQI values to those observed in NV at site 1. The SMAF showed to be a potential tool to monitor the SQ in low-fertility soils from the Colombian Amazon region. The VESS scores were also correlated with SMAF - scores, proving to be a simple and complementary tool for farmers to monitor SQ in the Amazon region.

Key words: Integrated farming systems. Agroforestry systems. Livestock. VESS. Ecosystem services.

RESUMO - O monitoramento da influência dos sistemas de produção pecuária na qualidade do solo (QS) na região amazônica colombiana é importante para garantir a sustentabilidade desses agroecossistemas. Neste trabalho foi utilizado o Soil Management Assessment Framework (SMAF) para avaliar as respostas da QS às mudanças no uso do solo associadas à adoção de sistemas silvipastoris (SPS) em duas localidades da Amazônia Colombiana. Em cada local de estudo foi estabelecida uma cronossequência conformada por três sistemas de uso da terra que refletem a transição no uso da terra típica da região: i) vegetação nativa (VN), ii) pastagem (PAST) e iii) SPS. Amostras de solo foram coletadas a cada 10 cm de profundidade até atingir 30 cm de profundidade. Em seguida, o pH do solo, potássio, fósforo disponível, carbono microbiano, carbono orgânico do solo e densidade aparente foram medidos. Dados da Avaliação Visual da Estrutura do Solo (VESS) foram também correlacionados. Os resultados foram interpretados usando os algoritmos do SMAF e o Índice de Qualidade do Solo (IQS) foi calculado. Nossos dados mostraram uma degradação da QS devido à mudança de uso da terra de VN para PAST, com uma redução na capacidade de funcionamento dos solos de 0.72 para 0.62. O estabelecimento de SPS sobre PAST restaura a QS (SQI = 0.69) quando comparado com a PAST (ambos locais), alcançando valores de IQS semelhantes aos observados em VN no local 1. O SMAF mostrou ser uma ferramenta potencial para monitorar a QS em solos de baixa fertilidade da região amazônica Colombiana. As pontuações do VESS foram também correlacionadas com as pontuações do SMAF, demonstrando ser uma ferramenta complementar e simples para os produtores monitorar a qualidade do solo na região amazônica.

Palavras-chave: Sistemas integrados de produção. Sistemas agroflorestais. Pecuária. VESS. Serviços ecossistêmicos.

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INTRODUCTION

The monitoring of soil quality (SQ) has been increasingly used to evaluate land for a wide range of purposes (BÜNEMANN *et al*., 2018), making it a pivotal aspect to guarantee the sustainability of the agroecosystems. Defined as "the capacity of a soil to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health" (DORAN; PARKIN, 1994; KARLEN *et al*., 1997), the SQ cannot be directly determined, but rather inferred by measuring soil physical, chemical and biological properties (BÜNEMANN *et al*., 2018). Several approaches have been developed to synthesize the soil attribute measurements and create comprehensive SQ indexes (SQI) (BÜNEMANN *et al*., 2018).

The Soil Management Assessment Framework (SMAF) is one of the most relevant SQ assessment tools. Although developed for soil conditions in the USA (ANDREWS; KARLEN; CAMBARDELLA, 2004), recently it has been widely used around the world, including for tropical soils (CHERUBIN *et al*., 2016, 2021; GURA; MNKENI, 2019; LISBOA *et al*., 2019; RUIZ; CHERUBIN; FERREIRA, 2020).

Despite its prominence as an advanced analytical scheme, the literature does not include studies using the SMAF in low-fertility soils from the Amazon region. In the Colombian Amazon region, integrated farming systems, including silvopastoral systems (SPS), have been intensively implemented in the last decade to mitigate the soil degradation process associated with the traditional livestock production system. In those alternative systems, trees or shrub-tree species are intercropped in pastures with the presence of livestock, favoring the yield (biomass, meat, milk) per unit area, efficient resource use, and the provision of ecosystem services (CHARÁ *et al*., 2019; JOSE; WALTER; MOHAN-KUMAR, 2019). Recent studies have indicated the synergic effect of the mix of grasses and trees for silvopastoral management in the Colombian Amazon region, enhancing the cycling and plant availability of soil macro and micronutrients, increasing soil C stocks (OLAYA-MONTES *et al*., 2020), and recovering physical attributes of soil (POLANÍA-HINCAPIÉ *et al*., 2021).

Based on that evidence, integrative approaches are needed that encompass chemical, physical, and biological indicators of soil to test the hypothesis that adoption of silvopastoral systems could restore soil quality and functioning of degraded pastures. The objectives of this study were to quantify the SQ response to land-use change associated with SPS adoption in the Colombian Amazon region and verify the effectiveness of SMAF scoring for function interpretations in this climate and soil management. A secondary objective was to investigate the relationship between the SMAF-SQ scores and the visual evaluation of soil structure (VESS) scores. VESS, a simple and inexpensive methodology to assess soil structural quality (GUIMARÃES; BALL; TORMENA, 2011), which, despite does not consider chemical and biological aspects, has also been considered an integrative indicator that could provide a initial approximation of overall SQ (CASTIONI *et al*., 2018; CHERUBIN *et al*., 2016).

MATERIAL AND METHODS

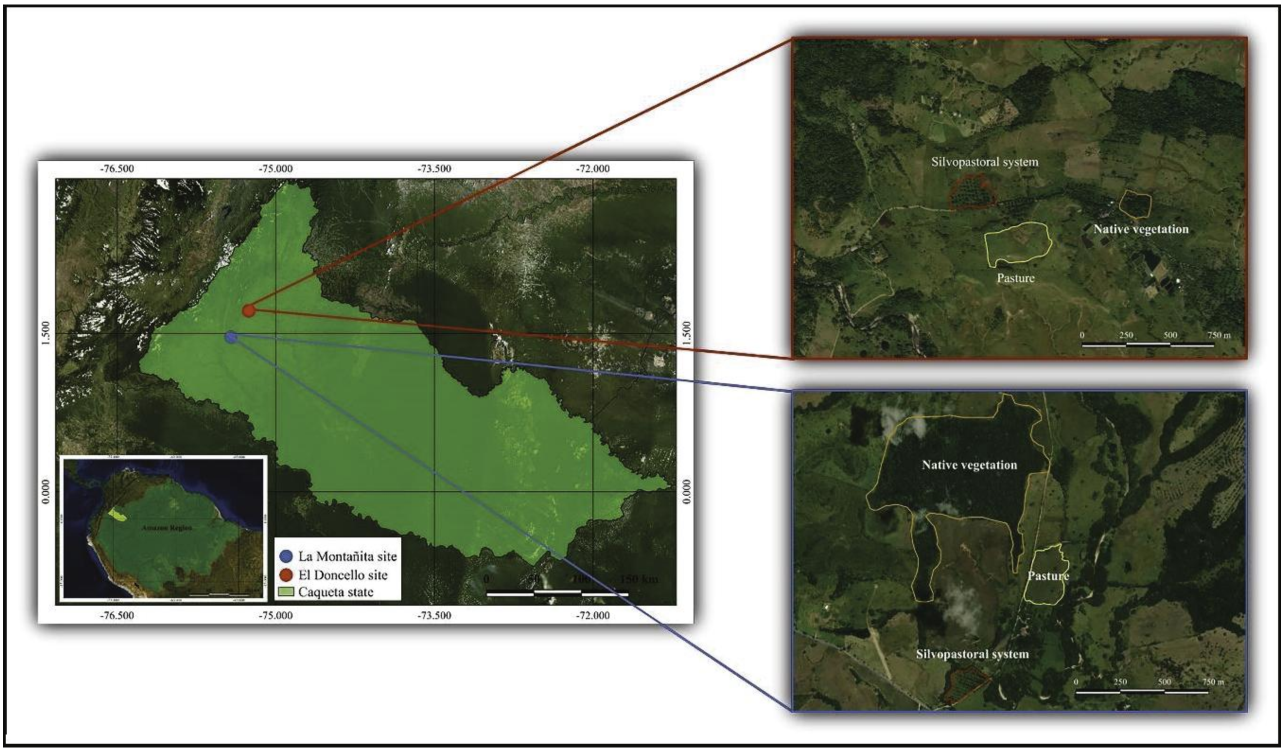
Study site location

The study was performed in the northwestern Colombian Amazon, specifically in two municipalities in Caquetá state: i) La Montañita - site 1 (1°29'15.6" N 75°26'19.3" W) and ii) El Doncello - site 2 (1°44'33.4" N 75°16'05.0" W) (Figure 1). The regional climate is classified as a tropical rainforest—Af type (Koppen classification), with a mean annual temperature of 25.5 °C and annual precipitation of 3793 mm (MURAD; PEARSE, 2018).

Soils in study sites are classified as *Dystrudepts* in La Montañita and *Hapludox* in El Doncello (SOIL SURVEY STAFF, 2014), which were originated from fine alluvial sediments, with particle size distribution of 543 g kg^{-1} sand, 360 g kg^{-1} clay, and 97 g kg^{-1} silt to a depth of -0.30 m in La Montañita site, and 533 g kg^{-1} sand, 381 g kg^{-1} clay and 86 g kg^{-1} silt in El Doncello site respectively.

For each study site, three land-use systems, representative of the typical transition performed in the region, were selected, and evaluated. The synchronic (chronosequence) approach was used, where all areas had similar climatic, topographic, and soil conditions but different historic land-use: i) native vegetation (NV), containing a vegetation community dominated by regularly distributed arboreal elements representing approximately 80% of the total area, forming a discontinuous canopy with a height greater than 15 meters; ii) pasture (PAST) with *Brachiaria sp.*, established 20 years ago after the slash and burn of native forests, and it is managed under rotational grazing systems at an occupation of 7.8 cattle heads per hectare with rotation and rest periods of 15 and 40 days at site 1 and 2, respectively. Likewise, grasses are permanent pastures that have not been fertilized, renovated and/or rotated with other crops. iii) silvopastoral system (SPS), established in 2005 in a traditional ~20-year old pasture. In this land-use system, the pastures were renovated, and then a mixture of *Brachiaria humidicola* and *Arachis pintoi*

Figure 1 - The geographic location of the study sites (La Montañita – site 1 and El Doncello – site 2) in the northwestern region of the Colombian Amazon



was planted in combination with trees including *Gmelina arborea, Erythrina poeppigiana, Tectona grandis,* and *Cariniana pyriformis* following a regular distance of 5 m × 20 m. Before planting, the soil was tilled using a heavy offset disk harrowing perturbing the first 15-20 cm depth. After that, dolomitic lime and phosphoric rock were applied at a rate that provided 274 kg Ca ha^{-1} and 131 kg Mg ha^{-1} and 24 kg P ha^{-1}. Tree component, as well as the Arachis pintoi, were incorporated in the silvopastoral arrangement as permanent crops in order to provide alternative food sources and shadow instead of commercial purposes.

Soil sampling and analysis

A grid containing six plots of 4 m^2 spaced 70 m apart following a completely randomized design was established in each study area. From each sampling plot, disturbed and undisturbed soil samples were collected from March to May 2018 at 10 cm depth increments until reaching 30 cm depth (0-10, 10-20, and 20-30 cm), which were subjected to chemical, physical, and biological soil analyses.

Soil attributes soil pH, potassium content (K), available phosphorus (P), microbial carbon (MBC), soil organic carbon (SOC), and bulk density (BD) - were measured as described by Olaya-Montes *et al.* (2020) and Polanía-Hincapié *et al.* (2021). Briefly, the soil pH was determined in 0.01 M $CaCl_2$ (SPARKS, 1996), potassium content (K) was measured by extraction in a solution of 1 M ammonium acetate and quantified by using atomic absorption spectrophotometer (SPARKS, 1996) and available phosphorus (P) was evaluated by extraction with Bray II method (BRAY; KURTZ, 1945) and determination of the P-molybdate blue color on a visible spectrophotometer at 660 nm wavelength.

Soil organic C (SOC) concentration was determined by the colorimetric method using a UV – visible spectrophotometer as described by Heanes (1984), and microbial C (MBC) was measured according to Vance, Brookes, and Jenkinson (1987) with the extraction of OC from fumigated and unfumigated soils by K_2SO_4 and C determination through a TOC analyzer (Shimadzu TNM-1, Japan). Soil bulk density was determined by collecting an undisturbed sample by a cylinder (98 cm^3) according to Dane and Topp (2002).

On the other hand, visual soil assessment was performed using the Visual Evaluation of Soil Structure (VESS) method, according to the methods proposed by Guimarães, Ball and Tormena (2011). This measurement was performed *in situ* by collecting an undisturbed sample (soil block of ~20 × 10 × 25 cm deep to ~5000 cm^3 volume), which was extracted and gently disaggregated through the natural break up of its structure to analyze the presence of layers of contrasting aggregation, root distribution, and biological activity signs. VESS scores (Sq scores), ranging from 1 to 5, were assigned for each layer identified as a distinct soil structure, where 1 is the best score and 5 the worst.

The results obtained from the different soil layers identified were averaged to have a value corresponding to the top 0-30 cm layer, and then normalized into an ordinal score from 0 to 1 by using non-linear scoring function (eq. 1). Based on agronomic and environmental soil functions, this indicator was scored using a lower asymptote sigmoid curve of "less is better" following the same rationale behind soil quality evaluations (CHERUBIN *et al*., 2016):

$$Score = \frac{\alpha}{\left[1+\left(\frac{LB-LT}{x-LT}\right)^{s}\right]} \quad (1)$$

where, the score is the unitless value of the soil indicator, which range from 0 to 1, a is the maximum score which was equal to 1 in this study, LB is the baseline value of the soil indicator where the score equals 0.5, LT is the lower threshold, x is the measured value, and S is the slope of the equation set to -2.5.

Soil quality assessment

Land-use change effects on SQ were evaluated using the SMAF, which is based on three sequential steps (ANDREWS; KARLEN; CAMBARDELLA, 2004): i) - Selection of a minimum dataset*:* The evaluation of SQ should include physical, chemical, and biological indicators (KARLEN *et al*., 2008). In this study, we considered six SQ indicators (pH, P, K, BD, SOC, and MBC) for the soil layers 0-10, 10-20, and 20-30 cm and 0-30 cm. The selection of those indicators was based on its functionality in the soil. Soil pH, P, and K provide information related to soil acidity and nutrients availability, while BD provides information about soil structural conditions involving aeration, water infiltration, and the ability of the soil to resist soil erosion. SOC and MBC are related to soil C sequestration, nutrient cycling, and microbial activity, providing appropriate data to assess the SQ (ANDREWS; KARLEN; CAMBARDELLA, 2004; BÜNEMANN *et al*., 2018). Moreover, this minimal dataset has been widely tested and validated to evaluate SQ changes induced by land-use change and management practices in tropical regions, such as Brazil (CHERUBIN *et al*., 2016, CHERUBIN *et al*., 2021; RUIZ; CHERUBIN; FERREIRA, 2020).

Since the SMAF algorithms are based on pH in water, the pH values measured in $CaCl_2$ were converted to pH_{water}, as described in Cherubin *et al.* (2016). K values expressed in $cmol_c$ dm^{-3} were converted to mg dm^{-3} as required by the SMAF by multiplying each value by 391 (K atomic weight). Soil C content expressed in g kg^{-1} was converted to % by dividing by 10. ii) - Interpretation of the indicators: The measured values were transformed into scores varying from 0 to 1 using previously published algorithms (ANDREWS; KARLEN; CAMBARDELLA, 2004; WIENHOLD *et al*., 2009) adjusted to tropical conditions by Cherubin *et al.* (2016), and Cherubin *et al.* 2021). Those values were later used to calculate the SQI for each land-use system. Those algorithms consider the type of soil, soil texture, mineralogy, climate, sampling season, slope, crop, and analytical methods (ANDREWS; KARLEN; CAMBARDELLA, 2004). iii) - Integration of indicator scores into an index: Average values were generated based on the scores for chemical (pH, K, and P), physical (BD), and biological (MBC, SOC) components to determine their contribution to overall SQI. Then, the SQI was calculated using the simple additive approach (ANDREWS; KARLEN; CAMBARDELLA, 2004), in which the scores of soil indicators were summed and then divided by the number of indicators. A weighted additive approach (Eq. (2).

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

Where, S_i is the indicator score and W_i the weighted value of the indicators. The indicators were weighted based on chemical (pH, P, and K), physical (BD) and biological (SOC; MBC) components, so regardless of the number of indicators each group had an equal weight (33.33%) in the final index (CHERUBIN *et al*., 2016).

This calculation was performed for each of the layers studied (0-10, 10-20, 20-30 cm) and for the overall 0-30 cm in NV, PAST, and SPS at both study sites.

Data analysis

A Generalized Linear Mixed Model (GLMM) was used for the SQI. We considered land-use systems (NV, PAST, and SPS) and soil depths (0-10, 10-20, 20-30, and 0-30 cm) as fixed factors and plots as random factors. The assumptions of normality and homogeneity of variance were evaluated using an exploratory residual analysis. For each SQI presenting differences, we performed an average test comparison using the Tukey test (p < 0.05). Data that did not show normality and homogeneity of variance was evaluated by a non-parametric test of Kruskal-Wallis (p < 0.05). Finally, Principal Component Analysis (PCA) was performed to understand the relationships of each component of the SQI (chemical, physical, and biological), the SQI scores, and VESS scores at both sites.

All data analyses were conducted in statistical software R version 4.0.3 (R CORE TEAM, 2020), using integrated development environment RStudio version 1.3.1. (RSTUDIO TEAM, 2021). PCAs were performed using the R package FactorMineR and personalized with the R package Performance Analytics.

RESULTS AND DISCUSSION

Soil quality indicators

The mean values of the measured soil chemical, physical, and biological properties are provided in Table 1. In general, the results showed the typical characteristics of weathered soils from the Amazon region were typical of Amazon soils, with low-natural fertility and high biological activity. The effects of land-use change on each individual indicator were presented and discussed in detail by Olaya-Montes *et al.* (2020) and Polanía-Hincapié *et al.* (2021). Here, our objective was to use these individually measured values to perform an integrated evaluation of SQ in different land-use systems through the application of SMAF.

Under this approach, we found that the transition from NV - PAST - SPS generated significant alterations ($p < 0.05$) in the scores calculated for chemical attributes (Table 2). At both study sites, the pH score was higher in NV (*i.e*., scores ranging from 0.9 to 1.0), followed by SPS (0.6–0.9) and finally by PAST (0.49–0.64), evidencing that the implementation of SPS on PAST effectively reduced soil acidity and increase soil pH scores. Changes in P scores were detected in the top layer, with NV having higher values than PAST and SPS. However, the scores were very low (ranging from 0.002 to 0.19) at site 2, which is related to the low-availability of P content in the highly - P - fixing soils of the region (FONTE *et al.*, 2014; SOLTANGHEISI *et al.*, 2019). The SMAF scoring curves for pH and P are gaussian, with indicators having an optimal point after which the values decrease significantly (ANDREWS; KARLEN; CAMBARDELLA, 2004).

A similar pattern was observed for K scores, with NV showing higher scores at both study sites (Table 2), which corroborates the K content decrease caused by the land-use change, as reported by Olaya-Montes *et al.* (2020). The main causes of soil K depletion are related to K losses by leaching and continuous K removal by cattle grazing (FERNANDES *et al.*, 2002).

Table 1 - Mean indicator values of the chemical, physical, and biological properties under native vegetation (NV), pasture (PAST), and silvopastoral systems (SPS) in the 0-10, 10-20, and 20-30 cm depths in the northwestern Colombian Amazon region

Depth (cm)	Land use	Mean indicator values†					
		Chemical			Physical	Biological	
		pH unitless	P	K	BD Mg m^{-3}	SOC g kg^{-1}	MBC mg kg^{-1}
			mg dm^{-3}				
Site 1 - La Montañita							
0-10	NV	4.05 + 0.06	5.83 + 0.77	47.96 + 7.85	1.03 + 0.13	18.90 + 1.67	928.70 + 281.84
	PAST	4.35 + 0.06	5.52 + 0.41	52.21 + 9.92	1.14 + 0.08	24.12 + 1.48	1266.09 + 297.67
	SPS	4.69 + 0.19	4.88+1.02	50.40 + 4.45	0.87 + 0.08	29.19 + 2.89	1294.32 + 136.92
10-20	NV	4.18 + 0.06	3.97 + 0.51	26.64 + 1.72	1.17 + 0.10	11.11 + 0.56	579.20 + 77.10
	PAST	4.31 + 0.07	3.78 + 0.59	35.73 + 5.78	1.34 + 0.09	10.031 + 0.48	506.92 + 32.41
	SPS	4.65+0.12	3.68+0.47	44.46+8.30	1.15+0.11	13.70+1.46	412.22+43.19
20-30	NV	4.24+0.02	3.43+0.10	28.42+8.03	1.15+0.12	8.23+1.92	750.37+135.08
	PAST	4.37 + 0.03	3.41 + 0.40	28.54 + 4.66	1.41 + 0.11	7.95 + 1.06	745.46 + 160.47
	SPS	4.58 + 0.06	3.32 + 0.67	30.31 + 1.85	1.20 + 0.15	7.43 + 0.14	464.76 + 140.11
Site 2 - El Doncello							
0-10	NV	4.52 + 0.06	2.23 + 0.29	98.77 + 8.80	0.89 + 0.09	18.90 + 0.92	1006.34 + 152.04
	PAST	4.49 + 0.05	2.26 + 0.40	75.98 + 7.37	1.06 + 0.10	25.14 + 1.97	1081.32 + 168.64
	SPS	5.03 + 0.04	2.69 + 0.47	56.04 + 11.16	0.95 + 0.07	27.11 + 1.12	1178.55 + 71.93
10-20	NV	4.52 + 0.09	1.13 + 0.07	53.29 + 2.26	1.06 + 0.07	11.24 + 1.18	509.63 + 162.56
	PAST	4.50 + 0.03	0.57 + 0.03	44.68 + 4.13	1.30 + 0.05	12.76 + 0.98	633.48 + 143.43
	SPS	4.92 + 0.15	0.61 + 0.05	52.42 + 3.16	1.24 + 0.03	13.46 + 0.71	652.10 + 118.98
20-30	NV	4.60 + 0.05	1.32 + 0.07	51.23 + 20.35	1.03 + 0.06	7.67 + 0.30	450.94 + 144.61
	PAST	4.54 + 0.04	0.81 + 0.08	33.24 + 6.06	1.24 + 0.10	8.42 + 0.20	387.34 + 26.32
	SPS	4.90 + 0.10	0.67 + 0.19	28.77 + 9.30	1.21 + 0.03	11.92 + 0.46	489.99 + 64.97

† Data adapted from Olaya-Montes *et al.* (2020) and Polanía-Hincapié *et al.* (2021). ± denote standard deviation

Table 2 - Mean indicator scores of the chemical, physical, and biological components under native vegetation (NV), pasture (PAST), and silvopastoral system (SPS) in the 0-10, 10-20, and 20-30 cm soil depth in the Colombian Amazon

Depth (cm)	Land use	Mean indicator scores					
		Chemical			Physical BD	Biological	
		pH	P	K		SOC	MBC
Site 1 - La Montañita							
0-10	NV	0.90 a*	0.77^{ns}	0.51 a	0.95^{ns}	0.99 b	1.00^{ns}
	PAST	0.52 c	0.67	0.42 b	0.99	1.00 a	1.00
	SPS	0.72 b	0.63	0.41 b	0.99	1.00 a	1.00
10-20	NV	0.95 a	0.53 a	0.32^{ns}	0.91^{ns}	0.77 b	1.00^{ns}
	PAST	0.49 c	0.39 ab	0.31	0.88	0.83 ab	1.00
	SPS	0.70 b	0.34 b	0.40	0.99	0.91 a	1.00
20-30	NV	0.97 a	0.42^{ns}	0.34^{ns}	0.83^{ns}	0.46^{ns}	1.00^{ns}
	PAST	0.53 c	0.33	0.26	0.77	0.60	1.00
	SPS	0.66 b	0.31	0.27	0.99	0.53	0.86
Site 2 - El Doncello							
0-10	NV	1.00 a	0.17^{ns}	0.79 a	0.99^{ns}	0.41 b	1.00^{ns}
	PAST	0.59 c	0.12	0.69 b	0.99	0.68 a	1.00
	SPS	0.90 b	0.19	0.56 c	0.99	0.76 a	1.00
10-20	NV	1.00 a	0.02 a	0.55 a	0.98 a	0.14 b	0.95^{ns}
	PAST	0.61 c	0.00 b	0.48 b	0.57 b	0.18 ab	0.97
	SPS	0.84 b	0.00 b	0.54 a	0.69 b	0.20 a	0.97
20-30	NV	0.99 a	0.04 a	0.52 a	0.99 a	0.08 b	0.78^{ns}
	PAST	0.64 c	0.01 b	0.39 ab	0.68 b	0.09 b	0.78
	SPS	0.85 b	0.00 b	0.34 b	0.81 b	0.15 a	0.90

* Means within columns at each site and soil depth followed the same letter do not differ significantly according to Tukey's test ($p < 0.05$), ns: not significant

In contrast, the scores calculated for BD were not affected by the establishment of PAST and/or SPS at site 1 (Table 2). Changes in scores of this soil physical property were detected in subsoil layers at site 2, with lower scores in PAST and SPS than in NV in response to livestock overgrazing which causes compaction through the pressure exerted by the hooves, as well as mechanical injury and loss of the standing pasture. When the animal travels, the pressure exerted on the soil surface may be two to four times the standing load causing soil compaction (BRAZ; FERNANDES; ALLEONI, 2013; MARTÍNEZ; ZINCK, 2004; RITTL; OLIVEIRA; CERRI, 2017).

Alterations in biological scores were observed in SOC, with higher values in PAST and SPS compared to NV soils (Table 2). Those results are aligned with the conclusion of the meta-analysis conducted by Fujisaki *et al.* (2015), who observed increments of soil C in pasture areas studied in the Amazon region. Perennial grasses, such as *Brachiaria*, add more C because of the activity of their root system (BAPTISTELLA *et al.*, 2020; MCSHERRY; RITCHIE, 2013). In the same way, SPS soils have higher capacity to sequester C than NV soils (KAY *et al.*, 2019; OLAYA-MONTES *et al.*, 2020) by adding C through litter deposition, root systems of grasses, and cattle manure (LORENZ; LAL, 2014; ROCHA JUNIOR *et al.*, 2014). Several studies have pointed out the role of agroforestry systems in sequestering C in soil and biomass (DOLLINGER; JOSE, 2018; HOOSBEEK; REMME; RUSCH, 2018).

The MBC scores reached the maximum values in all the soil layers assessed at site 1 and the top layer at site 2. Although the scores were lower in the 10-20 and 20-30 cm soil layers than in the top layer, those scores did not present alterations due to land use. The scores for this soil property are calculated by the SMAF through scoring curves related to the conditional "more is better" in which, according to the textural class of study sites, if the MBC is around 500 mg kg^{-1} the MBC scores will be 1.0 (ANDREWS; KARLEN; CAMBARDELLA, 2004), supporting the scores observed in this study. High precipitation rates, as well as temperature and moisture, promote biological activity in the Amazon biome, favoring the decomposition processes of organic matter by microorganisms (BABUR; DINDAROĞLU, 2020).

Overall soil quality index, and biological, physical and chemical components

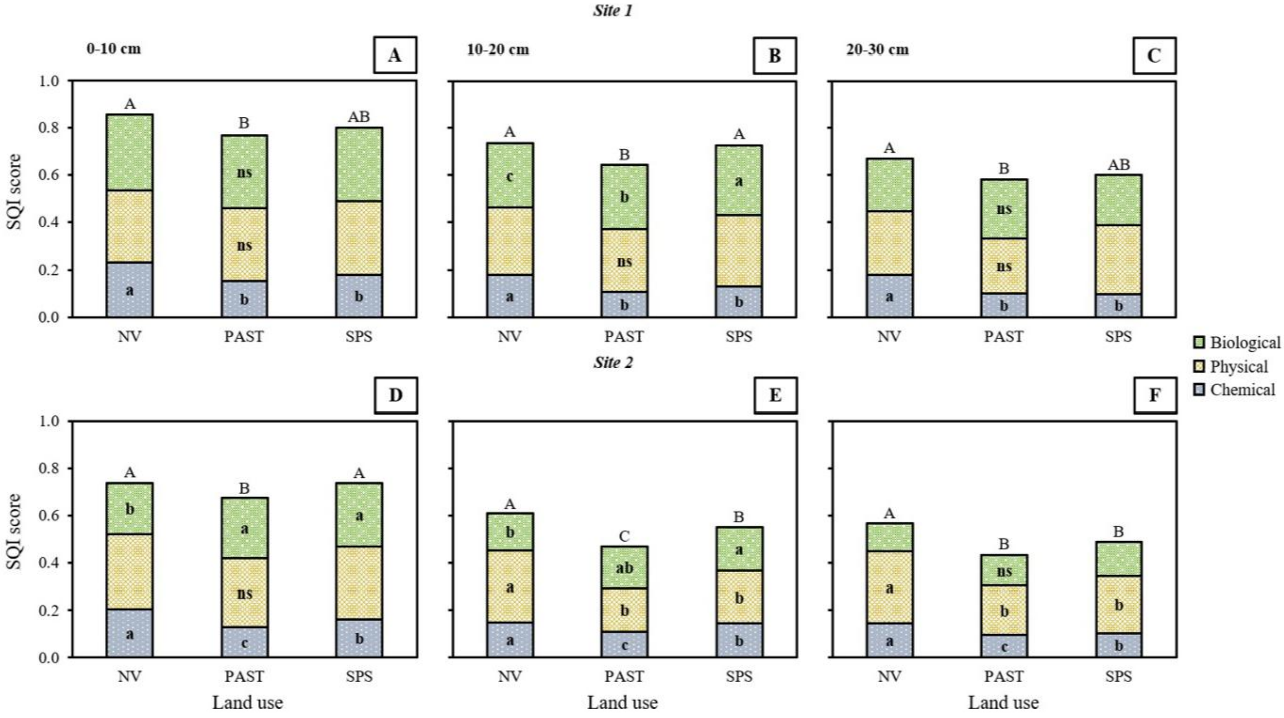
Long-term land-use change from NV to extensive PAST led to SQ degradation in all soil layers assessed (Figure 2). Nevertheless, SQ was restored by implementing SPS reaching values similar to those observed in the top layers (0-20 cm) of NV soils at both study sites. The combination of grasses and trees, and the implementation of agricultural practices, liming and tillage, in SPS enhance the nutrient availability and soil organic matter dynamics, resulting in the recovery of soil physico-chemical properties (OLAYA-MONTES *et al.*, 2020; POLANÍA-HINCAPIÉ *et al.*, 2021).

Soil chemical component had a significant effect in explaining the differences along land-use change process in all soil depths in both study sites ($p < 0.05$), suggesting a degradation in the soil chemical quality due to the transition from NV to PAST, but with reversion under SPS in site 2 (Figure 2). The integration of grasses and legumes (*A. pintoi* and other tree legumes) in SPS promote a synergic effect where grasses can use the N released by the decomposition of legume residues (CONRAD *et al.*, 2017), producing biomass that favor soil organic matter accumulation and the nutrient replenishment enhancing soil chemical quality (ZHONG *et al.*, 2018).

We also found that the biological component had higher scores in PAST and SPS than in NV in the top 20-cm layer, which contains the greatest root system biomass of pastures (GICHANGI; NJARUI; GATHERU, 2017). This result indicates that the biomass from the root system of pastures might play a key role in soil organic matter cycling, favoring the biological activity and SOC sequestration capacity in those livestock systems (MENEZES *et al.*, 2019; RODRÍGUEZ *et al.*, 2021).

Overall, when calculating SQI for the 0-30 cm soil depth, we verified higher scores in NV areas, with values suggesting that soils from those ecosystems are functioning at 78% and 65% of their potential capacity at sites 1 and 2, respectively. PAST establishment and the poor-management implemented in those extensive systems led to a significant decline in the SQ, losing around 10% of its capacity to function (average SQI = 0.70 and 0.53

Figure 2 - Overall soil quality index (SQI) scores and the contribution of chemical, physical, and biological attributes to the overall SQI in native vegetation (NV), pasture (PAST), and silvopastoral system (SPS) for the 0-10, 10-20, and 20-30 cm depths (A, B, C) Site 1, (D, E, F) Site 2, in Colombian Amazon. Mean SQI scores within a site at the same depth followed by the same uppercase letter do not differ significantly among themselves according to Tukey's test ($p < 0.05$). Mean component (chemical, physical, and biological) contributions within a site at the same depth followed by the same lowercase letter do not differ significantly among themselves according to Tukey's test ($p < 0.05$)



at site 1 and site 2, respectively). It has been estimated that more the 50% of pastures in the Amazon region are degraded (MOTTA-DELGADO; OCAÑA-MARTÍNEZ; ROJAS-VARGAS, 2019; SILVA *et al.*, 2017), with inappropriate pasture and animal management being the main driver of this process. Similar results were also reported by Cherubin *et al.* (2016) for Brazilian conditions, in which conversion from native vegetation (Cerrado and Atlantic Forest) to extensive pasture reduced SQI by 17%, from 87 to 70%.

Using a robust framework such as the SMAF, this study revealed that the adoption of SPS over extensive PAST areas helps the recovery of SQ in those livestock systems (Figure 3). Calculated SQ scores for SPS at both sites were similar to NV at site 1 and higher than those estimated in PAST in both locations. Those integrative systems are usually intensively managed by involving cultural operations such as liming, tillage and fertilization, which favor soil acidity reduction and nutrient cycling as well as a decrease in nutrient losses by leaching due to the deeper root systems of trees (JOSE; WALTER; MOHAN-KUMAR, 2019; OLAYA-MONTES *et al*., 2020). Likewise, when grasses and trees are mixed under a SPS management, an increase in above and belowground biomass of the system is expected, resulting then in higher organic residues C inputs to the soils, thus enhancing the SOC stocks (OLAYA-MONTES *et al*., 2020 SARTO *et al*., 2020; WEBSTER *et al*., 2019).

In this sense, the SMAF was able to detect the changes in SQ due to land management in the Colombian Amazon region becoming a strategic tool to monitor SQ alterations over time and to provide scientific support for guiding farmers to make appropriate decisions regarding the sustainable use of their soils. However, as previously pointed out by Cherubin *et al.* (2021), in order to expand the application of SMAF in tropical soils and improve its performance under those conditions, it would be valuable the development of scoring-curves involving key indicators still not considered under this approach such as soil porosity, soil resistance to penetration, aluminum content, abundance and diversity of soil fauna and microorganisms.

Improvements in this area are key aspects for better monitoring the recovering and sustaining healthy soils into the agriculture sector, reducing the pressure of agriculture expansion over the natural ecosystem in the Amazon region, and further reconciling socio-economic development and environmental conservation.

Soil quality index related to the visual evaluation of soil structure scores

The relationship of SQ scores, land-use systems, and VESS scores investigated by PCA analysis is in Figure 4. The first two components explain 83% and 95% of the data variance at sites 1 and 2, respectively. Regardless of site, the data were grouped into three clusters, clearly defined in consonance with the land use for both sites.

The results suggest that SQ is affected by the land-use change, with a positive relationship among the chemical component, VESS, and the overall SQI with NV. It also pointed out the contribution of the biological components of the livestock systems - PAST and SPS, - and the potential role of those systems in soil C sequestration.

We also observed a significant relationship between the overall SQI scores and VESS scores at both sites (r^2 = 0.64 and 0.79 in sites 1 and 2, respectively), indicating that VESS can explain the variation in the overall SQI at 64% at site 1 and 79% at site 2. Recent studies have shown that the VESS is an efficient method to evaluate soil structural quality in a variety of land-uses in the Amazon region (CHERUBIN; CHAVARRO-BERMEO; SILVA-OLAYA, 2019; GUIMARÃES *et al.*, 2017; POLANÍA-HINCAPIÉ *et al.*, 2021). Our data evidenced a positive correlation not only with the physical components, but also with the overall SQ. It corroborates data reported by Cherubin *et al.* (2016), who concluded that VESS scores could provide valuable insights of overall SQ through an inexpensive and quick on-farm evaluation. Therefore, VESS can be easily implemented and interpreted directly in the field by the farmers, becoming a potentially too for monitoring the responses of SQ to management performed in the Amazon region.

Figure 3 - Overall soil quality index (SQI) scores in the 0-30 cm depth at a county scale for native vegetation (NV), pasture (PAST), and silvopastoral system (SPS) in the Colombian Amazon. Error bars denote standard error. Mean SQI scores followed by the same letter did not differ significantly among themselves according to Tukey's test ($p < 0.05$)

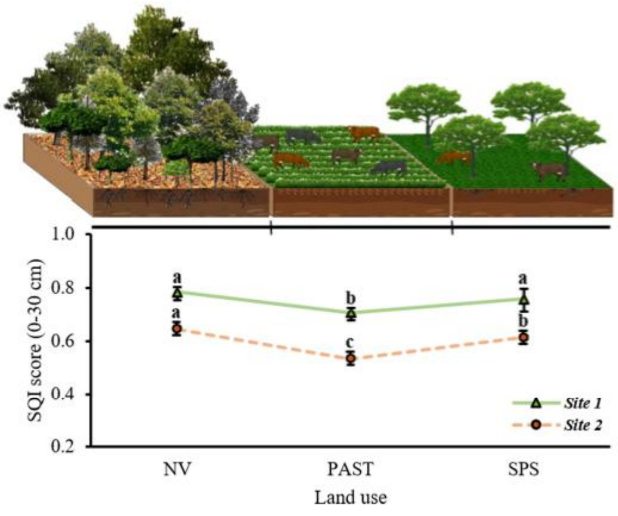
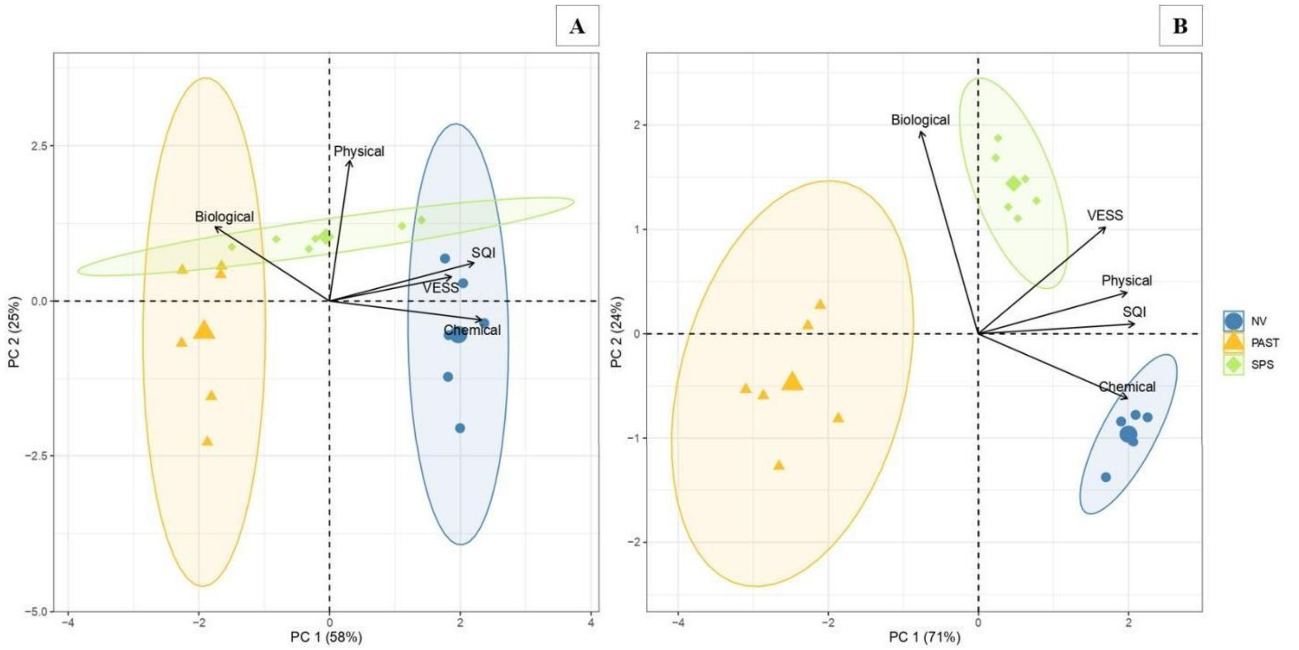


Figure 4 - Principal component analysis (PCA) of the 0-30 cm depth in native vegetation (NV), pasture (PAST), and silvopastoral system (SPS). A) Site 1 - La Montañita, B) Site 2 - El Doncello



CONCLUSIONS

1. Through the SMAF approach, it was possible to detect that the conversion from Amazon forest (NV) to PAST with improper management caused SQ degradation (from SQI = 0.72 to SQI = 0.62), leading to losses of the functional capacity. Moreover, SMAF scores efficiently evidenced the benefits of the silvopastoral systems adoption, derived from reducing soil acidity, improving nutrient cycling and soil organic carbon accumulation, which contribute to recovery the SQI (0.69) to levels similar to those observed in the Amazon forest. Therefore, this study suggests that silvopastoral systems are promising strategies to recover soil health of degraded pasturelands in the Colombian Amazon region.
2. A positive correlation between the visual evaluation of soil structure (VESS) and SQI point out the VESS capacity to provide valuable insights about overall SQ and not just the soil structural quality; aspects that make that simple to perform method a feasible complementary tool for farmers monitoring SQ responses to different land uses in the Amazon region, which could also be further considered into the SMAF approach.

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