Soil quality index using the CASH methodology and Rainforest Alliance Scorecard in the coffee zone of the Caldas department, Colombia

Índice de calidad del suelo utilizando la metodología CASH y Rainforest Alliance Scorecard en la zona cafetera del departamento de Caldas, Colombia

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ABSTRACT

The Comprehensive Assessment of Soil Health (CASH) methodology provides a broad approach to evaluate soil health, helping farmers and researchers to identify management practices that can enhance soil health and increase agricultural sustainability in coffee crops. When integrated with regenerative agriculture strategies such as cover cropping, intercropping, agroforestry, and crop rotation, these practices can effectively enhance soil health and productivity. The aim of this research was to develop a soil health index using the CASH approach adjusted to the conditions of the coffee zone in the Caldas department (Colombia) and to adapt the index of the Rainforest Alliance Scorecard guidelines. A database containing 3,332 soil analyses from different coffee zones in the department was used, carried out between 2005 and 2021. The index obtained with historical data shows that 66% of the properties were classified as Bronze, 18% Silver, and 16% Gold, whereas the validation data showed that 49% of the properties were classified as Bronze, 21% Silver, and 30% Gold. The most important variables identified in soil health were organic matter content, organic carbon stock, CO_2 equivalent, pH, bulk density, and nutrient content related to N, P, K, Ca, and Mg. CASH can be employed to evaluate the soil health status in the field using quantitative indicators linked to the Rainforest Scorecard and is a useful tool to promote regenerative practices in soil adjusted to Caldas coffee zones.

Key words: regenerative agriculture, base line, soil indicator.

RESUMEN

La metodología de la Evaluación Integral de la Salud del Suelo (CASH, por sus siglas en inglés) proporciona un enfoque amplio para evaluar la salud del suelo. Puede ayudar a los agricultores e investigadores a identificar prácticas de manejo que puedan mejorar la salud del suelo y aumentar la sostenibilidad agrícola en los cultivos de café. Cuando se integran con estrategias de agricultura regenerativa como los cultivos de cobertura, cultivos intercalados, la agrosilvicultura y la rotación de cultivos, estas prácticas pueden mejorar eficazmente la salud y la productividad del suelo. El objetivo de esta investigación fue desarrollar un índice de salud del suelo utilizando el enfoque CASH ajustado a las condiciones de la zona cafetera en el departamento de Caldas (Colombia) y adaptar el índice de las directrices del Rainforest Alliance Scorecard. Se utilizó una base de datos que contenía 3332 análisis de suelos de diferentes zonas cafeteras del departamento, realizados entre los años 2005 y 2021. El índice obtenido con datos históricos muestra que el 66% de las propiedades fueron clasificadas como Bronce, 18% Plata y 16% Oro, mientras que los datos de validación mostraron que el 49% de las propiedades fueron clasificadas como Bronce, 21% Plata y 30% Oro. Las variables más importantes identificadas en la salud del suelo fueron el contenido de materia orgánica, el stock de carbono orgánico, el CO_2 equivalente, el pH, la densidad aparente y el contenido de nutrientes relacionados con N, P, K, Ca y Mg. CASH se puede emplear con éxito para evaluar el estado de salud del suelo utilizando indicadores cuantitativos vinculados al Rainforest Scorecard; y se identifica como una herramienta útil para promover prácticas regenerativas en el suelo ajustadas a las zonas cafeteras de Caldas.

Palabras clave: agricultura regenerativa, línea base, indicador del suelo.

Introduction

In coffee-producing regions of Colombia, the Green Revolution (GR) brought significant changes to coffee production, including the introduction of high-yielding coffee varieties, synthetic fertilizers, and pesticides (Osorio-García *et al*., 2020). While these changes have brought benefits, such as increased coffee yields and incomes for farmers, they have

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also had significant impacts on soil health and environmental sustainability (Breitler *et al*., 2022).

The impact of the GR on soil health has been documented, highlighting the changes in soil properties and nutrient cycling associated with the implementation of technologies in coffee production. Manson *et al*. (2022) found that soil pH decreased significantly in coffee farms that used synthetic fertilizers, while organic matter and nutrient availability also decreased over time.

There is growing recognition of the need for more sustainable approaches to coffee production that prioritize soil health and environmental sustainability. Regenerative agriculture (RegAg) (Al-Kaisi & Lal, 2020), for instance, offers a promising approach to enhance soil health, productivity, and environmental sustainability in coffee.

RegAg strategies, such as cover cropping, intercropping, agroforestry, and crop rotation, aim to restore soil organic matter, reduce soil erosion, and enhance nutrient cycling while improving soil structure and promoting beneficial microorganisms (O'Donoghue *et al*., 2022).

RegAg can effectively enhance soil health and environmental sustainability in coffee-producing regions of Colombia. Rekik *et al*. (2020) found that cover cropping and intercropping can effectively reduce soil erosion and enhance soil health in coffee-producing regions in Colombia.

Santos *et al*. (2021) evaluated the soil health of coffee crops in Brazil. Their study compared conventional and organic management practices and found that the organic coffee farm had significantly higher soil health indicators such as microbial biomass, total carbon, and permanganate oxidizable carbon. The study suggests that organic management practices can enhance soil health in coffee crops.

The CASH methodology of a Comprehensive Approach to evaluate Soil Health provides a holistic approach by integrating physical, chemical, and biological indicators, offering a comprehensive view of soil functionality to help farmers and researchers identify management practices that can enhance soil health and increase agricultural sustainability in different crops (Fine *et al*., 2017; Moebius-Clune *et al*., 2017).

Rekik *et al*. (2018) conducted a study in Cauca, Colombia, to develop specific scoring functions to serve as benchmarks for soil health (SH) in coffee production. A total of 3,332 soil samples were collected from coffee farms in six municipalities, analyzing 13 SH indicators including wet aggregate stability, available water capacity, respiration rate, pH, and contents of active carbon, organic matter, protein, and various nutrients (P, K, Mg, Mn, Fe, and Zn). A scoring function was developed for each indicator using the cumulative normal distribution. The results showed that active carbon was the best predictor of soil health.

The Caldas region coffee production is primarily done by small-scale farmers, most of whom own less than 5 ha of area. According to FNC (2021), smallholder coffee farms in the Caldas region have 32,144 farmers and 40,227 farms in 59,282 ha. The intensive use of soils in the department of Caldas due to coffee cultivation has significantly impacted soil health over time. Continuous monocropping and the use of agrochemicals in coffee production have led to soil degradation, including the loss of organic matter, reduced biodiversity, soil compaction, and nutrient imbalances. These practices disrupt the natural processes that maintain healthy, productive soils, ultimately reducing soil resilience, fertility, and long-term sustainability.

Developing soil health indicators using the Comprehensive Assessment of Soil Health (CASH) methodology is essential for evaluating the current state of these soils. Utilizing historical soil analysis data from Caldas allows for the creation of a local Soil Health Index, which is critical for understanding long-term trends in soil degradation and identifying areas for improvement.

This study aimed to provide a tool for interpreting soil analyses, which corresponds to the CASH indices, adjusted to local conditions, to help make decisions that contribute to keeping the soils of the Caldas coffee region in good condition and to adapt the index of the Rainforest Alliance Scorecard guidelines.

Materials and methods

Study area

The study covered seven distinct zones within Caldas, which are critical for coffee production. Each zone presented a variety of soil types, primarily belonging to the Andisol and Inceptisol soil orders, known for their volcanic origin, high organic matter content, and good structure. These soils are conducive to coffee cultivation but present differences in nutrient retention, pH buffering, and susceptibility to erosion. The specific characteristics of each zone are described in Table 1.

TABLE 1. Representative zones of coffee production in the Caldas department.

Zone	Municipality	Number of samples	Modal unit of soils (Gómez *et al.*, 1991)
Aguadas	Aguadas	500	Typic Melanudands
Alto	Marmato, Riosucio, Supía	1,115	Andic Eutrudepts
Anserma	Anserma, Risaralda	157	Typic Melanudands, Typic Hapludands
Bajo Occidente	Belalcazar, San Jose, Viterbo	55	Typic Hapludands, Typic Eutropepts
Centro	Chinchiná, Manizales, Neira, Palestina, Villamaria	976	Typic Melanudands
Norte	Aranzazu, Filadelfia, La Merced, Pacora, Salamina	221	Typic Eutropepts, Typic Melanudands
Oriente	Florencia, Manzanares, Marquetalia, Marulanda, Pensilvania, Samaná	308	Typic Melanudands, Typic Troporthents

Elaboration based on internal data from Fundación Local Partners and Ecotopos cafeteros (Gómez *et al.,* 1991).

Soil inventory and analysis

A database was consolidated with 3,332 soil analyses obtained from seven different zones representing 25 municipalities in the department, located between 1,000 to 2,100 m a.s.l. and specifically conducted for coffee crops collected between 2005 and 2021. The samples were collected from 0 to 15 cm depth and composited.

The following soil variables were measured according to Carrillo (1985): biological: organic matter by Walkley and Black (%), % organic carbon (calculated), and equivalent CO_2 stock (t ha^{-1} year^{-1}) (calculated) using the IPCC parameter (Publications - IPCC-TFI, 2023); chemical: pH (potentiometric), nitrogen (calculated) (Sadeghian, 2010), phosphorus (mg kg^{-1}) by Bray II, potassium, calcium, magnesium (Ammonium acetate 1 N / Atomic Absorption Spectrophotometer (AAS)) and aluminum (cmol(+) kg^{-1}) by KCl 1 N / Volumetric); boron and sulfur (Monobasic calcium phosphate / Turbidimetric), and minor elements Fe, Mn, Zn, Cu (mg kg^{-1}) by EDTA extraction and ammonium acetate / AAS; the effective cation exchange capacity (ECEC) is calculated as the sum of the milliequivalents of the exchangeable bases (Ca, Mg, K, Na) plus exchangeable acidity (often measured separately as Al^{3+} and H^+). ECEC is expressed in cmol(+) kg^{-1} soil and cation saturation of Ca, Mg, K, and Al (%) (calculated)); physical: sand, clay, silt (%) by Bouyoucos-Hydrometer / Gravimetric, bulk density (kg m^{-3}) using a cylinder of known volume, and water aggregate stability (WAS %) by Wet sieving method.

Statistical analysis

Descriptive statistical analysis for each variable, including minimum, maximum, mean, variance (n-1), standard deviation (n-1), and variation coefficient were used. Analysis of variance was conducted for seven regional subsets for all soil parameters. Means separation was computed using the LSD test. Pearson correlation coefficients for physical, biological, and chemical indicators were calculated.

CASH methodology

This article follows the analytical pathway developed by Fine *et al.* (2017) and described in the Manual Comprehensive Assessment of Soil Health: The Cornell Framework (Moebius-Clune *et al.*, 2017). Scoring functions were used to interpret measured physical, chemical, and biological indicator values for CASH. Means and standard deviations for each indicator were calculated and used to determine the scoring function as a cumulative normal distribution (CND) using the following function:

$$\mathrm{Fx}(x) = \int_{-\infty}^{x} \mathrm{N}(z; \mu, \sigma^2)\,dz \qquad (1)$$

where $N(z; \mu, \sigma^2)$ is the normal (Gaussian) probability density function evaluated at z. It is defined by: μ: The mean of the distribution, representing the central value around which the data is distributed; σ^2: The variance of the distribution, representing the spread or dispersion of the data. The square root of the variance, σ, is the standard deviation.

CND represents the probability of a normally distributed random variable being less than or equal to x, e is Euler's number, and t is the standard normal random variable. The CND provides a score on a scale from 0 to 100 (Fine *et al.*, 2017).

CASH - Alignment with sustainability standards of Rainforest Scorecard

The indices were constructed for Bronze, Silver, and Gold levels of the Rainforest Alliance scorecard (2022) using CND values to set thresholds for rating soil health indicators: 1) scores between 0 and 20 are considered very low; 2) scores between 20 and 40 are considered low; 3) scores between 40 and 60 are considered medium (below 60 are all Bronze level); 4) scores between 60 and 80 are considered high (Silver level); 5) scores between 80 and 100 are considered very high (Gold level).

Multivariate statistics (Principal Component Analysis - PCA) were evaluated using the database, including only samples that had measured values for all indicators (n = 640). The first two PCs were visualized in two-dimensional space. The PCA was used to obtain a minimum data set (MDS) described by Mukherjee and Lal (2014). The ranges defined by the index from 0 to 100 were as follows: Bronze: $0 \leq I < 60$, Silver: $60 \leq I < 80$, and Gold: $80 \leq I \leq 100$.

Validation of index

The final index model to measure the soil health index-based CASH – Soil Quality Index (SQI) was applied in farms using the following equation:

$$n = \frac{N * Z_\alpha^2 * p * q}{d^2 * (N-1) + Z_\alpha^2 * p * q} \quad (2)$$

where N = total population (9200 farms), Z_α= 1.96 (95%), p = expected proportion (5% = 0.05), q = 1 – p (1-0.05 = 0.95), d = precision (5% = 0.05).

The chi-square test was used to test for a significant association between CASH and the VALIDATION dataset (frequency table), with the following null hypothesis H_0: There is no association between soil properties and CASH and VALIDATION. All statistics were computed using XLSTAT 2014.5.03 (Addinsoft, New York, USA).

Results

Datasets represent the maximal variability of soil in Caldas department

The diverse array of samples, encompassing varied locations and highlighting the influence of soil-forming factors such as parent material, topography, climate, biological activity, and time, altitudes, time of sampling, sample handling, land use, and land management practices, resulted in a broad spectrum of values (Tab. 2). Each variable presented a considerable standard deviation in comparison to the means, including soil pH, which was influenced by the farmer's practices. The soil analysis revealed significant variability in key physical and chemical properties of soil across the study region, impacting soil health and fertility. The high variability in soil properties, such as aluminum saturation, nutrient availability, and organic matter content, indicates the need for localized soil management practices.

The analysis of variance revealed highly significant differences among the coffee subregions for all soil parameters. The LSD test demonstrated differences among zones for each indicator (Tab. 3), thus highlighting the pronounced soil variability in the coffee-growing regions and the imperative to develop locally focused soil quality indicators.

For aggregate stability, the value of 4.25 suggests that the soil has a moderate level of structural stability. Stable aggregates are vital for resisting erosion and maintaining soil porosity (Lince-Salazar *et al.,* 2020). This value indicates that the region is performing better than zones such as the "Centro" and "Norte" but lags behind "Oriente", which has a superior score of 6.11.

For soil organic matter (OM) content and organic carbon (%), with an organic matter content of 8.80% and organic carbon at 5.10%, "Bajo occidente" shows relatively high fertility. High organic matter supports microbial activity and nutrient cycling, essential for coffee production (González-Osorio *et al.,* 2008). The organic carbon levels also reflect carbon sequestration, an increasingly important metric for soil health (Lal, 2020). This performance is comparable to other regions but still slightly behind "Oriente" (13.11% OM and 7.59% organic carbon).

For soil nutrient content (N, P, K, Ca, Mg), the region demonstrates moderate nitrogen (N) content at 0.73%, phosphorus (P) at 5.89 mg kg^{-1}, potassium (K) at 0.31 cmol kg^{-1}, and calcium (Ca) at 5.07 cmol kg^{-1}. These levels are essential for coffee plants, supporting vegetative growth and coffee bean formation. While the nitrogen levels are at the lower end, phosphorus content is relatively high compared to regions like "Norte" (23.26 mg kg^{-1}). Calcium and magnesium contents in soil were well-balanced, promoting soil pH stability and reducing aluminum toxicity (Sadeghian, 2008).

For effective cation exchange capacity (ECEC), the cation exchange capacity in "Bajo occidente" is 12.68 cmol kg^{-1}, which is among the highest in the region, indicating a strong ability to retain and supply essential nutrients like calcium, magnesium, and potassium. This is a critical factor for long-term soil fertility, especially in tropical regions.

For cation saturation levels (Ca, Mg, K, Al), the region demonstrates a calcium saturation of 47.95%, magnesium saturation of 16.62%, and potassium saturation of 4.02%, suggesting a well-balanced nutrient profile (Sadeghian, 2008). The aluminum saturation, which can be detrimental to root growth, is relatively low at 9.55%, indicating reduced aluminum toxicity, which is crucial for crop performance. This value is significantly better than in zones like "Centro" (13.44% aluminum saturation).

TABLE 2. Descriptive statistics of CASH indicators for all soil samples (total n= 3332) in Caldas coffee zone.

Soil property	Units	Min	Max	Mean	Standard deviation (n-1)	Variation coefficient (%)
Bulk density	(kg m^3)	0.73	1.77	1.01	0.20	20
WAS	%	0.44	12.30	4.27	1.78	42
Sand		2.00	85.90	37.82	16.22	43
Clay		1.50	95.00	35.89	17.55	49
Silt		2.40	67.00	26.91	9.34	35
Organic matter (OM)		0.00	27.40	8.84	4.12	47
Organic carbon (OC)		0.00	15.87	5.12	2.39	47
Organic carbon stock	(t ha^{-1})	0.00	2.39	0.90	0.26	29
eq CO_2	(t ha^{-1} $year^{-1}$)	0.00	8.99	3.38	0.99	29
pH		3.50	7.70	4.97	0.43	09
Al	cmolc kg^{-1}	0.00	13.07	1.48	1.36	92
N	mg kg^{-1}	0.00	1.35	0.38	0.17	45
P	mg kg^{-1}	0.00	303.00	19.79	34.26	173
K	cmolc kg^{-1}	0.00	8.11	0.37	0.38	103
Ca		0.00	28.28	4.20	3.73	89
Mg		0.03	12.76	1.44	1.50	104
Na		0.00	0.58	0.04	0.05	144
Fe	mg kg^{-1}	2.34	3171.00	252.00	188.77	75
Mn		0.00	300.00	38.20	31.98	84
Zn		0.00	82.90	5.44	6.37	117
Cu		0.02	118.60	5.48	5.73	105
S		0.00	212.60	25.26	20.20	80
B		0.00	2.99	0.32	0.20	62
ECEC	cmolc kg^{-1}	0.16	35.84	7.51	5.09	67.7
Ca	% saturation	0.00	95.25	49.96	19.47	39
Mg		0.00	78.81	16.48	8.72	53
K		0.00	100.00	6.52	6.01	92
Al		0.00	94.44	26.49	22.47	84
Na		0.00	23.80	0.52	0.95	180

WAS – water aggregate stability.

The high variability in soil properties across the coffee-growing regions can be attributed to the diverse range of soil types, influenced by volcanic parent material, steep topography, and differential agronomic management practices. Soil acidity and aluminum toxicity are significant constraints in many areas, requiring site-specific interventions such as liming and organic matter amendments. Variability in nutrient availability highlights the need for tailored fertilization strategies to optimize coffee production.

TABLE 3. ANOVA results represented by the p level for subregion group effect. Different letters indicate statistically significant differences at $P = 0.05$ for LSD comparisons between the zones.

Soil property		F-Value (Pr >F***)	AG	B.Oc	AL	N	AN	C	Or
Bulk density		41.52	1.01 ^{B}	1.00 ^{B}	1.02 ^{B}	1.09 ^{C}	1.03 ^{B}	1.02 ^{B}	0.84 ^{A}
WAS		64.90	4.37 ^{C}	4.25 ^{BC}	4.20 ^{BC}	3.83 ^{A}	4.01 ^{AB}	3.86 ^{A}	6.11 ^{D}
Sand		242.86	41.37 ^{E}	39.43 ^{ED}	31.28 ^{B}	38.86 ^{D}	41.62 ^{E}	37.17 ^{C}	56.57 ^{F}
Clay		420.76	32.33 ^{D}	24.25 ^{B}	45.93 ^{F}	30.15 ^{C}	27.12 ^{B}	34.73 ^{E}	16.61 ^{A}
Silt		97.33	26.70 ^{C}	36.32 ^{F}	23.89 ^{B}	31.18 ^{E}	31.39 ^{E}	28.66 ^{D}	26.95 ^{C}
OM		64.90	9.08 ^{C}	8.80 ^{BC}	8.68 ^{BC}	7.84 ^{A}	8.24 ^{AB}	7.91 ^{A}	13.11 ^{D}
% OC		64.90	5.26 ^{C}	5.10 ^{BC}	5.03 ^{BC}	4.54 ^{A}	4.77 ^{AB}	4.58 ^{A}	7.59 ^{D}
OC stock		57.38	0.91 ^{C}	0.89 ^{BC}	0.88 ^{BC}	0.82 ^{A}	0.86 ^{AB}	0.85 ^{A}	1.16 ^{D}
eq CO_2		57.38	3.43 ^{C}	3.36 ^{BC}	3.32 ^{BC}	3.10 ^{A}	3.22 ^{AB}	3.20 ^{A}	4.36 ^{D}
pH		30.52	5.07 ^{D}	5.00 ^{CD}	5.05 ^{CD}	5.08 ^{D}	5.04 ^{CD}	4.86 ^{B}	4.80 ^{A}
Al		192.21	0.88 ^{AB}	0.73 ^{AB}	2.48 ^{D}	0.71 ^{A}	0.85 ^{AB}	1.08 ^{C}	1.01 ^{BC}
N		131.24	0.39 ^{BC}	0.41 ^{C}	0.36 ^{B}	0.35 ^{AB}	0.38 ^{BC}	0.33 ^{A}	0.63 ^{D}
P		69.71	21.63 ^{CD}	5.89 ^{A}	7.35^{A}	23.26 ^{D}	16.24 ^{BC}	36.75 ^{E}	12.05 ^{AB}
K		9.51	0.41 ^{BC}	0.31 ^{AB}	0.34 ^{B}	0.40 ^{BC}	0.43 ^{C}	0.41 ^{BC}	0.24 ^{A}
Ca		87.51	5.03 ^{C}	5.07 ^{CD}	5.45 ^{D}	5.72 ^{D}	4.77 ^{C}	2.69 ^{B}	1.48 ^{A}
Mg		91.64	1.98 ^{D}	2.01 ^{D}	1.92 ^{D}	1.85 ^{D}	1.56 ^{D}	0.79 ^{B}	0.39 ^{A}
ECEC		118.14	8.96 ^{C}	12.68 ^{E}	10.60 ^{D}	11.48 ^{DE}	11.99 ^{E}	5.15 ^{B}	3.18 ^{A}
Saturation	Ca	60.09	54.97 ^{C}	47.95 ^{B}	47.50^{B}	54.86 ^{C}	49.96 ^{B}	58.65 ^{D}	36.07^{A}
	Mg	37.50	20.71 ^{D}	16.62 ^{BC}	16.86 ^{BC}	17.13 ^{BC}	15.48 ^{B}	17.53 ^{C}	10.73 ^{A}
	K	189.11	5.56 ^{B}	4.02 ^{AB}	3.68 ^{A}	4.89 ^{B}	5.89 ^{B}	13.44 ^{D}	8.87 ^{C}
	Al	76.71	15.68 ^{A}	9.55 ^{A}	29.58 ^{B}	10.53 ^{A}	11.79 ^{A}	50.26 ^{D}	41.84 ^{C}
	Na	204.43	0.08 ^{A}	0.48 ^{C}	1.06 ^{D}	0.27 ^{B}	0.25 ^{B}	0.07 ^{A}	0.46 ^{C}

AG = Aguadas; B.Oc = Bajo occidente; AL = Alto; N = Norte; AN = Anserma; C = Centro; Or = Oriente. WAS – water aggregate stability; OM – organic matter; OC – organic carbon; ECEC - effective cation exchange capacity. Pr>F *** indicate significant differences (ANOVA). Averages with the same letter indicate non-significant differences (LSD test).

Correlation analysis between soil health indicators

A correlation matrix (Tab. 4) was created by computing Pearson correlation coefficients for each pair of soil health indicators, including percent sand, silt, and clay. Strong positive correlations were particularly observed among biological indicators, such as percentage of soil organic matter (OM) with % organic carbon (0.99), OM with carbon stock (0.99), and OM with eq CO_2 (0.99), as well as negative correlations between bulk density and OM (-0.91) and carbon stock (-0.92).

Negative correlations ($r \geq 0.2$-0.4) were found between silt and Ca, Mg, ECEC, Fe, Mn, Sand, and Clay with OM, % Organic carbon, and eq CO_2, while Mg showed a negative correlation with OM, % Organic carbon, and eq CO_2.

The correlations between biological, chemical, and physical soil properties provide valuable insights into the key factors that influence soil health. Nitrogen content and organic matter emerge as critical biological indicators, while pH, ECEC, and bulk density serve as important chemical and physical indicators, respectively.

Scoring functions for soil quality index

The best indicators of soil health are described below. The indicators include WAS, OM, organic carbon, eq CO_2, pH, N, P, K, Ca, Mg, ECEC, and saturation of Ca, Mg, and K. These indicators are scored using a "more is better" function, where increasing measured values result in higher scores.

The overall soil health index is calculated as the unweighted mean of individual indicator scores, with nutrients combined into a single metric. The scoring functions for the Caldas department include regional soil health statistics, such as the CND function, mean, and standard deviation, as shown in Table 5.

TABLE 4. Pearson correlation coefficients for CASH indicators for all textural groups (total n = 3,332). Values in bold have absolute correlation coefficients greater than 0.4; ns indicates not statistically significant at $P = 0.05$.

Variable	N	OM	OC %	Bulk density	OC stock	eq CO_2	K	Ca	Mg	Al	P	Sand	Clay	Silt	ECEC
pH	- 0.14	- 0.11	- 0.11	0.12	- 0.12	- 0.12	0.05	0.49	0.40	- 0.37	- 0.13	- 0.18	0.19	- 0.04	0.35
N	1.00	0.95	0.95	- 0.86	0.94	0.94	- 0.05	- 0.30	- 0.33	- 0.05	- 0.09	0.42	- 0.41	0.02	- 0.23
Organic matter		1.00	1.00	- 0.91	0.99	0.99	- 0.04	- 0.31	- 0.32	- 0.02	- 0.09	0.20	- 0.20	0.02	- 0.20
Organic carbon (OC) %			1.00	- 0.91	0.99	0.99	- 0.04	- 0.31	- 0.32	- 0.02	- 0.09	0.20	- 0.20	0.02	- 0.20
Bulk density				1.00	- 0.92	- 0.92	0.03	0.34	0.36	0.03	0.06	- 0.12	0.14	- 0.05	0.23
OC stock					1.00	1.00	- 0.04	- 0.31	- 0.33	- 0.02	- 0.08	0.18	- 0.19	0.03	- 0.21
eq CO_2						1.00	- 0.04	- 0.31	- 0.33	- 0.02	- 0.08	0.18	- 0.19	0.03	- 0.21
K							1.00	0.23	0.13	- 0.04	0.22	0.03	- 0.08	0.08	0.21
Ca								1.00	0.72	- 0.10	0.04	- 0.15	0.18	- 0.06	0.72
Mg									1.00	- 0.04	- 0.07	- 0.21	0.26	- 0.11	0.62
Al										1.00	- 0.05	- 0.23	0.36	- 0.26	0.06
P											1.00	0.11	- 0.18	0.13	- 0.04
Sand												1.00	- 0.83	- 0.18	- 0.38
Clay													1.00	- 0.37	0.17
Silt														1.00	0.36

Values in bold have absolute correlation coefficients that are statistically significant at $P = 0.05$.

TABLE 5. Scoring functions for physical, biological, and chemical CASH indicators and relevant soil processes (n= 3,332 soil analyses). Scoring functions are based on the dataset's cumulative normal distribution (CND) indicated by CND (mean; StdDev).

Type	Soil health indicator (Type of scoring)	CASH scoring function
Physical	Bulk density (LB)	S = 100* 1-CND (1.01; 0.20)
	WAS (MB)	S = 100* CND (4.27; 1.78)
	% Sand (MB)	S = 100* CND (37.82;11.22)
	% Clay (LB)	S = 100*1- CND (35.89; 17.55)
	% Silt (MB)	S = 100* CND (26.91; 9.34)
Biological	% OM (MB)	S = 100* CND (8.84; 4.12)
	OC stock (MB)	S = 100* CND (0.90; 0.26)
	eq CO_2 (MB)	S = 100* CND (3.38; 0.99)
Chemical	pH (MB)	S = 100* CND (4.97; 0.43)
	Al (LB)	S = 100* 1-CND (1.48; 1.36)
	N (MB)	S = 100* CND (0.38; 0.17)
	P (MB)	S = 100* CND (19.79; 34.26)
	K (MB)	S = 100* CND (0.37; 0.38)
	Ca (MB)	S = 100* CND (4.20; 3.73)
	Mg (MB)	Se = 100* CND (1.44; 1.50)
	ECEC (MB)	S = 100* CND (8.25; 6.65)
	Saturation Ca (MB)	S = 100* CND (51.36; 20.14)
	Saturation Mg (MB)	S = 100* CND (17.02; 8.98)
	Saturation K (MB)	S = 100* CND (7.44; 7.68)
	Saturation Al (LB)	S = 100* 1-CND (32.24; 38.51)

Abbreviations: S – score. Type of scoring: MB – more is better; LB – less is better. WAS – water aggregate stability; OM – organic matter; OC – organic carbon; ECEC – effective cation exchange capacity.

Principal component analysis

The analysis revealed that six PCs accounted for 83.4% of the total variability in the raw dataset, with eigenvalues greater than one and a cumulative fraction of total variance of at least 70% (Fig. 1).

PC1 explained 37% of the variance, with twelve variables having high positive loadings (N > WAS > eq CO_2 > bulk density > Mn > Ca > Mg). PC2 had high positive loadings for Sand, Al, and Na, and high negative loadings for Ca saturation, representing 14% of the total variance. The minimum data set (MDS) identified by PCA includes twenty soil variables that are bulk density, WAS, Sand, Clay, Silt, OM, eq CO_2, pH, Al, N, P, K, Ca, Mg, ECEC, saturation of Ca, Mg, K, Al.

Table 6 displays various indicators of soil quality in coffee-growing zones in Caldas. These indicators are categorized into physical, biological, and chemical, each evaluated according to three quality levels: Bronze, Silver, and Gold. The percentages shown correspond to how often the soil properties fall into each of these categories, both for the general database (n = 3332) and for the validation set (n = 400).

Physical properties: For bulk density, in the general database, 53% of the samples fall into the Bronze category, with lower percentages for Silver (24%) and Gold (23%). In the validation set, the Gold category is more frequent (43%), followed by Bronze (38%) and Silver (18%).

WAS (Water aggregate stability): Most soils fall into the Bronze category (66%), with smaller proportions in Silver (17%) and Gold (17%). The validation set shows a similar trend, but with a higher percentage of soils in Gold (35%).

Sand, clay, and silt content: The texture of the soil varied significantly. For sand, the general database shows 79% in Bronze, while the validation set shows a higher proportion in Gold (54%). For clay, the Gold category is predominant in both datasets, with 56% for the general set and 67% for validation. Silt is predominantly found in the Bronze category in the general database (82%), but in the validation set, it is more evenly distributed between Bronze (34%) and Silver (45%).

Biological soil properties: For organic matter (OM), most soils fall into the Bronze category (66% for the general set and 45% for validation), with smaller proportions in Silver and Gold.

Organic carbon stock and eqCO_2: These indicators followed a similar pattern, with the general database having more Bronze-rated soils (~65%), while the validation set shows a strong presence of soils in the Gold category (85%).

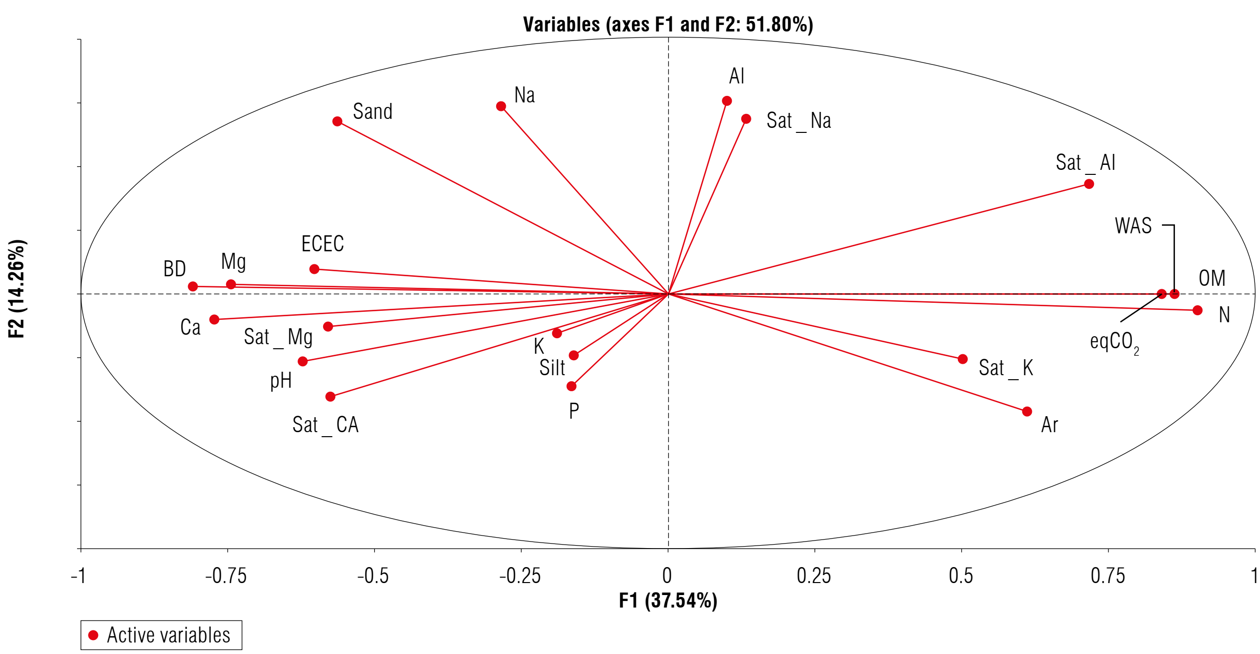

FIGURE 1. Loading plot from the principal components analysis (PCA) performed on CASH indicators presented in Table 5 (n = 640). WAS – water aggregate stability; OM – organic matter; BD – bulk density; ECEC – effective cation exchange capacity.

Chemical properties: For pH, in the general database, 59% of soils fall into Bronze category, with fewer in Silver (23%) and Gold (18%). The validation set shows a shift towards more soils in the Bronze category (62%) compared to the other two categories.

Nutrient content (N, P, K, Ca, Mg): The distribution varies across the Bronze, Silver, and Gold categories. For example, Nitrogen (N) is mainly present in Bronze in both datasets, while Phosphorus (P) is also largely concentrated in Bronze, particularly in the validation set (88%). Potassium (K) and Calcium (Ca) are similarly skewed toward Bronze.

Effective cation exchange capacity (ECEC): The general set shows a predominant Bronze category (69%), similar to that of the validation set (79%).

Saturation levels (Ca, Mg, K, Al): Most soils fall in the Bronze category for saturation of Ca, Mg, and K. Interestingly, for saturation of Al, the general set shows a unique split with a higher percentage of Silver (53%) compared to Bronze (47%), while the validation set has a higher proportion of Silver (61%).

For all indicators, the general database categorizes 66% of soils as Bronze, 18% as Silver, and 16% as Gold. In the validation set, there is a higher distribution of Bronze (49%) and Gold (30%), with fewer soils in Silver (21%).

Table 6 reveals that the majority of soils in the coffee-growing regions of Caldas fall into the Bronze category, especially for chemical properties like pH, ECEC, and nutrient content. The validation set slightly favors Gold in soil properties like bulk density and organic carbon stock, indicating that a subset of soils may be more suitable for high-quality coffee cultivation. However, soil physical properties like texture (*e.g.*, sand, clay, and silt) and biological properties like organic matter are more variable, suggesting that soil management practices could be targeted to improve specific properties in the different regions.

TABLE 6. CASH indicator values for general database (n = 3,332) and validation (n = 400) soil analysis in Caldas department of the Colombian coffee growing zone.

Type of soil properties		Soil property	CASH %			Validation %			Chi^2 (*P*-value)
			Bronze	Silver	Gold	Bronze	Silver	Gold	
Physical		Bulk density	53	24	23	38	18	43	9.38 ***
		WAS	66	17	17	45	20	35	10.44 ***
		Sand	79	8	13	23	23	54	63.09 ***
		Clay	33	11	56	15	18	67	9.42 ***
		Silt	82	10	8	34	45	21	47.96 ***
Biological		Organic matter	66	17	17	45	20	35	10.44 8 ***
		Organic carbon stock	65	20	15	8	6	85	101.04 ***
		eq CO_2	65	20	15	8	6	85	101.04 ***
Chemical		pH	59	23	18	62	22	15	0.36 ns
		Al	51	28	21	26	38	36	13.57 ***
		N	69	14	17	38	12	50	25.38 ***
		P	82	7	10	88	4	8	1.24 ns
		K	77	14	9	74	10	16	2.68 ns
		Ca	67	17	16	72	12	16	1.04 ns
		Mg	72	12	16	79	7	14	1.77 ns
		ECEC	69	15	16	79	11	10	2.67 ns
	Saturation	Ca	53	26	21	50	24	26	0 .69 ns
		Mg	64	18	17	79	10	11	5 .14 ns
		K	74	11	15	72	18	10	2 .71 ns
		Al	47	53	0	39	61	0	1.30 ns
Grand total			66	18	16	49	21	30	7.00 **

*** $P < 0.01$; ** $P = 0.01 – 0.05$; ns indicates not statistically significant at $P = 0.05$. WAS – water aggregate stability. ECEC – effective cation exchange capacity.

For the chemical variables, the Chi^2 results show that only two variables, Al and N contents, are significantly associated with the validation and CASH results, with Chi^2 values of 13.58 and 25.39, respectively (both $P<0.01$).

Discussion

Caldas is a region in Colombia known for its high-quality coffee production (Araque-Salazar & Duque, 2019), which relies heavily on the health and fertility of Andosols and Inceptisols in the area. The management of these soils is essential for the sustainability of coffee production as well as for the preservation of the natural resources of the region. The "Bajo occidente" zone performs well in terms of nutrient availability, organic matter content, and cation exchange capacity. While not the best in every metric, this zone maintains a balance that supports coffee cultivation. Zones like "Oriente" may have higher organic matter and carbon content, but "Bajo occidente" benefits from lower bulk density, better nutrient retention (ECEC), and lower aluminum saturation, which are critical soil health indicators (Rekik *et al*., 2018).

Soil health of Caldas is particularly important for coffee production because it directly affects the quality and yield of coffee crops (Tobasura Acuña *et al*., 2015). Coffee plants require specific soil conditions to grow and produce high-quality beans, including optimal pH, organic matter content, and nutrient availability. Andosols have a high capacity to retain nutrients and water, making them ideal for coffee production (Rekik *et al*., 2019). However, erosion, overuse of agrochemicals, and deforestation can lead to a decrease in soil health, which can ultimately affect the quality and yield of coffee crops (Lal, 2015).

According to a study on soil health assessment for coffee farms on Andosols in Colombia, carbon and organic matter contents are the best predictors of overall soil health and can be used in a simplified test (Rekik *et al*., 2018). The study found that the organic matter contents, organic carbon stock, and CO_2 equivalent stock sequestered in the soil showed the highest values in the defined Gold range.

One of the most critical chemical properties of soil is pH, which affects nutrient availability and soil microbial activity. Coffee crops require acid and moderately acid soils with a pH range of 5.0-6.5 for optimal growth and yield (Manson *et al*., 2022). Soil pH can be managed through the application of lime, which raises the pH, or sulfur, which lowers it. However, excessive use of these chemicals can lead to soil degradation and negatively impact soil health (Krishnan *et al*., 2020).

Lower bulk densities are generally associated with better root penetration and water infiltration (Chalise *et al*., 2019). Organic matter (OM) and organic carbon also reflect carbon sequestration, an increasingly important metric for soil health (Rainford *et al*., 2021). Nutrient content of N, P, K, Ca, Mg should also be well-balanced, promoting soil pH stability and reducing aluminum toxicity (Martins *et al*., 2015).

ECEC is a critical factor for long-term soil fertility, especially in tropical regions (Domingues *et al*., 2020). In our case, we found evidence of soil degradation, particularly in the depletion of nutrient contents and soil acidification, which adversely affects the plant's response in terms of the quality of coffee beans. This calls for changes in the practices in the coffee crops to promote the recovery of soil health under regenerative agriculture practices.

This is the first evidence of using the Rainforest Scorecard (Rainforest Alliance, 2022) to promote regenerative practices and linked to soil health indicators under the CASH methodology, adjusted to tropical zones. The Scorecard evaluates the chemical, physical, and biological characteristics of soils (Mukherjee, 2014), making it an important tool for identifying areas in need of improvement and encouraging best management practices by taking the list of regenerative practices to a quantitative level and applying it to the development of soil quality and health indicators.

Conclusions

The findings of this study were used to develop novel CASH scoring functions that were substantiated by a comprehensive analysis of a diverse dataset. The results indicate that it may be appropriate to create region-specific scoring functions once regional soil health data analyses are more complete.

The results suggest that several soil properties are good predictors of CASH, while others are not. These findings could have important implications for soil management and the Soil Quality Index and soil health.

The CASH approach can be successfully employed to evaluate soil health status in soils managed differently in the field, with the possibility of region-specific parameterization for soils in Caldas that are used to cultivate coffee crops.

The implementation of the Scorecard represents a significant step forward in rainforest scorecard efforts and highlights the importance of adopting regenerative practices to promote soil health and sustainability. Further research is needed to better understand the complex interactions between soil health, management practices, and coffee bean quality in the Caldas department.

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Conflict of interest statement

The authors declare that there is no conflict of interests regarding the publication of this article.

Author's contributions

AMVH contributed to the conceptualization, data collection, analysis and writing of the manuscript; MAAR and JDR organized the data, collected data, analyzed and interpreted the results; EOS and JCAS helped to conceptualize and interpret the results and revised the manuscript. All authors approved the final version of the manuscript.

Literature cited

Al-Kaisi, M. M., & Lal, R. (2020). Aligning science and policy of regenerative agriculture. *Soil Science Society of America Journal*, *84*(6), 1808–1820. https://doi.org/10.1002/saj2.20162

Araque-Salazar, H., & Duque, H. (2019). Variables agronómicas determinantes de la productividad del cultivo de café en fincas del departamento de Caldas. *Revista Cenicafé*, *70*(1), 81–92. https://doi.org/10.38141/10778/70106

Breitler, J.-C., Etienne, H., Leran, S., Marie, L., & Bertrand, B. (2022). Description of an *Arabica* coffee ideotype for agroforestry cropping systems: A guideline for breeding more resilient new varieties. *Plants*, *11*(16), Article 2133. https://doi.org/10.3390/plants11162133

Carrillo, P. I. F. (1985). *Manual de laboratorio de suelos*. https://biblioteca.cenicafe.org/handle/10778/803

Chalise, K. S., Singh, S., Wegner, B. R., Kumar, S., Pérez-Gutiérrez, J. D., Osborne, S. L., Nleya, T., Guzman, J., & Rohila, J. S. (2019). Cover crops and returning residue impact on soil organic carbon, bulk density, penetration resistance, water retention, infiltration, and soybean yield. *Agronomy Journal, 111*(1), 99–108. https://doi.org/10.2134/agronj2018.03.0213

Domingues, R. R., Sánchez-Monedero, M. A., Spokas, K. A., Melo, L. C. A., Trugilho, P. F., Valenciano, M. N., & Silva, C. A. (2020). Enhancing cation exchange capacity of weathered soils using biochar: Feedstock, pyrolysis conditions and addition rate. *Agronomy, 10*(6), Article 6. https://doi.org/10.3390/agronomy10060824

Fine, A. K., van Es, H. M., & Schindelbeck, R. R. (2017). Statistics, scoring functions, and regional analysis of a comprehensive soil health database. *Soil Science Society of America Journal, 81*(3), 589–601. https://doi.org/10.2136/sssaj2016.09.0286

FNC. (2021). Café de Caldas. Federación Nacional de Cafeteros Caldas. https://caldas.federaciondecafeteros.org/cafe-de-caldas

Gómez, L., Caballero, A., & Baldión, J. V. (1991). *Ecotopos cafeteros de Colombia*. https://biblioteca.cenicafe.org/handle/10778/818

Krishnan, K., Schindelbeck, R., Kurtz, K. S. M., & van Es, H. (2020). Soil health assessment. In A. Rakshit, S. Ghosh, S. Chakraborty, V. Philip, & A. Datta (Eds.), *Soil analysis: Recent trends and applications* (pp. 199–219). Springer. https://doi.org/10.1007/978-981-15-2039-6_12

Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustainability, 7*(5), 5875–5895. https://doi.org/10.3390/su7055875

Lince-Salazar, L. A., Castro, A. F., & Castaño, W. A. (2020). Estabilidad de agregados de suelos de la zona cafetera colombiana. *Revista Cenicafé*, *71*(2), 73–91. https://doi.org/10.38141/10778/71206

Manson, S., Nekaris, K. A. I., Rendell, A., Budiadi, B., Imron, M. A., & Campera, M. (2022). Agrochemicals and shade complexity affect soil quality in coffee home gardens. *Earth, 3*(3), 853–865. https://doi.org/10.3390/earth3030049

Martins, L., Machado, L. S., Tomaz, M., & Amaral, J. (2015). The nutritional efficiency of *Coffea* spp. A review. *African Journal of Biotechnology, 14*, 728–734. https://doi.org/10.5897/AJB2014.14254

Moebius-Clune, B. N., Moebius-Clune, D. J., Gugino, B. K., Idowu, O. J., Schindelbeck, R. R., Ristow, A. J., van Hes, H. M., Thies, J. E., Shayler, H. A., McBride, M. B., Kurtz, K. S. M., Wolfe, D. W., & Abawi, G. S. (2017). *Comprehensive assessment of soil health: The Cornell framework* (3rd ed.). Cornell University. https://www.css.cornell.edu/extension/soil-health/manual.pdf

Mukherjee, A., & Lal, R. (2014). Comparison of soil quality index using three methods. *PLoS ONE, 9*(8), Article e105981. https://doi.org/10.1371/journal.pone.0105981

O'Donoghue, T., Minasny, B., & McBratney, A. (2022). Regenerative agriculture and its potential to improve farmscape function. *Sustainability, 14*(10), Article 5815. https://doi.org/10.3390/su14105815

Osorio-García, A. M., Paz, L., Howland, F., Ortega, L. A., Acosta-Alba, I., Arenas, L., Chirinda, N., Martinez-Baron, D., Bonilla Findji, O., Loboguerrero, A. M., Chia, E., & Andrieu, N. (2020). Can an innovation platform support a local process of climate-smart agriculture implementation? A case study in Cauca, Colombia. *Agroecology and Sustainable Food Systems, 44*(3), 378–411. https://doi.org/10.1080/21683565.2019.1629373

Publications – IPCC-TFI. (2023, April 20). 2019 Refinement to the 2006 IPCC guidelines for National greenhouse gas inventories. https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html

Rainford, S., Martín-López, J. M., & Da Silva, M. (2021). Approximating soil organic carbon stock in the eastern plains of Colombia. *Frontiers in Environmental Science, 9*, Article 685819. https://doi.org/10.3389/fenvs.2021.685819

Rainforest Alliance. (2022). *Regenerative coffee scorecard. A Best practices guide*. Rainforest Alliance. https://www.rainforest-alliance.org/resource-item/regenerative-coffee-scorecard

Rekik, F., van Es, H., Hernandez-Aguilera, J. N., & Gómez, M. I. (2018). Soil health assessment for coffee farms on andosols in Colombia. *Geoderma Regional, 14*, Article e00176. https://doi.org/10.1016/j.geodrs.2018.e00176

Rekik, F., van Es, H., Hernandez-Aguilera, J. N., & Gómez, M. I. (2019). Linking coffee to soil: Can soil health increase coffee cup quality in Colombia? *Soil Science, 184*(1), 25–33. https://doi.org/10.1097/SS.0000000000000248

Rekik, F., van Es, H., Hernandez-Aguilera, J. N., & Gómez, M. I. (2020). Understanding soil health and associated farmers' perceptions in Colombian coffee systems. *Journal of Soil and Water Conservation, 75*(4), 499–504. https://doi.org/10.2489/jswc.2020.00107

Sadeghian, S. (2008). Fertilidad del suelo y nutrición del café en Colombia: Guía práctica. *Boletín Técnico Cenicafé*, *32*, 1–44. https://biblioteca.cenicafe.org/handle/10778/587

Sadeghian, S. (2010). *La materia orgánica: componente esencial en la sostenibilidad de los agroecosistemas cafeteros*. Cenicafé. https://doi.org/10.38141/cenbook-0018

Santos, W. P., Silva, M. L. N., Avanzi, J. C., Acuña-Guzman, S. F., Cândido, B. M., Cirillo, M. Â., & Curi, N. (2021). Soil quality assessment using erosion-sensitive indices and fuzzy membership under different cropping systems on a Ferralsol in Brazil. *Geoderma Regional, 25*, Article e00385. https://doi.org/10.1016/j.geodrs.2021.e00385

Tobasura Acuña, I., Obando Moncayo, F. H., Moreno Chavez, F. A., Morales Londoño, C. S., & Henao Castaño, A. M. (2015). De la conservación del suelo al cuidado de la tierra: una propuesta ético-afectiva del uso del suelo. *Ambiente & Sociedade, 18*(3), 121–136. https://doi.org/10.1590/1809-4422ASOC802V1832015