Cienc. Tecnol. Agropecuaria, *23*(3): e2674 ISSN: 0122-8706 ISSNe: 2500-5308
DOI: https://doi.org/10.21930/rcta.vol23_num3_art:2674

Management and Environmental Sustainability

Scientific and Technological Research Article

Conservation Agriculture as a Potential Strategy to Increase Soil Quality in Colombian Agroecosystems

Agricultura de conservación como estrategia potencial para incrementar la calidad del suelo en agroecosistemas de Colombia

Valentina Ardila-Garcia [1] **Leidy Paola Plazas-Navarro** [1]
Victoria Eugenia Vallejo [1 *]

[1] Universidad Central. Bogotá, Colombia.

*Corresponding Author: Victoria Eugenia Vallejo-Quintero Cra. 5 # 21-38, Edificio Lino de Pombo, Segundo piso, Universidad Central, Bogotá, Colombia. evallejoq@ucentral.edu.co

Received: August 19, 2021
Approved: September 22, 2022
Published: December 09, 2022

Subject editor: Oscar Alfredo Forero Larrañaga, (Corporación Colombiana de Investigación Agropecuaria [AGROSAVIA], Bogotá, Colombia.

How to cite this article: Ardila Garcia, V., Plazas Navarro, L. P., & Vallejo Quintero, V. E. (2022). Conservation Agriculture as a Potential Strategy to Increase Soil Quality in Colombian Agroecosystems. *Ciencia y Tecnología Agropecuaria*, *23*(3), e2674. https://doi.org/10.21930/rcta.vol23_num3_art:2674

Abstract: Conservation Agriculture (CA) has been promoted in many Latin American countries as an alternative to sustainable production management because of its ability to prevent soil degradation, enhance crop productivity, minimize climate change impact, and protect soil biodiversity. The main objective of this paper was to evaluate the effects of CA on Soil Quality (SQ) in five agroecosystems from Cachipay (Cundinamarca): Coffee Crop (CC) chronosequences of (1) 5 (CC5) and (2) 10 (CC10) years of establishment; Polyculture Cropping System (PCS) chronosequences of (3) 1 (PCS1) and (4) 6 (PCS6) years, and (5) Fallow (F) systems. A Minimum Data Set (MDS) was determined from principal component analysis. Aggregate stability index, aggregate stability, water holding capacity, geometric mean diameter, electric conductivity, heterotrophic bacterial density, and catalase were finally selected into the MDS and used in the calculation of the Soil Quality Index (SQI). CC5 (0.71), CC10 (0.67), PCS6 (0.66), and PCS1 (0.65) had a higher SQI in the study area than F (0.60). The study demonstrated the positive effect of CA practices based on minimum soil disturbance, lower inputs of agrochemicals, permanent soil organic cover with crop residues, and a diversified cropping system on SQ. The MDS-SQI approach represents a practical, promising, and adequate tool for monitoring SQ in agroecosystems.

Keywords: indicators, minimum data set, soil quality index, sustainable land management, total data set, conservation.

Resumen: La agricultura de conservación (AC) se ha promovido en América Latina como una alternativa para la gestión sostenible del suelo debido a su capacidad para prevenir la degradación edáfica, mejorar la productividad de los cultivos, minimizar el impacto del cambio climático y contribuir a la protección de la biodiversidad edáfica. El objetivo de la investigación fue evaluar el efecto de la AC sobre la calidad del suelo (CS) en cinco agroecosistemas del municipio de Cachipay (Cundinamarca): una cronosecuencia de cultivos de café (CC) de (1) 5 (CC5) y (2) 10 (CC10) años de establecimiento, sistemas de policultivos (SPC) de (3) 1 (SPC1) y (4) 6 (SPC6) años de edad, y (5) un agroecosistema en descanso (F, del inglés *Fallow*). Para lo cual, se determinó un conjunto mínimo de datos (MDS, del inglés *Minimum Data Sets*) a partir de un análisis de componentes principales. El índice de estabilidad de agregados, la estabilidad de agregados, la humedad, el diámetro medio geométrico, la conductividad eléctrica, la densidad de heterótrofos totales y las catalasas se seleccionaron en el MDS. Los mayores valores del índice de calidad se obtuvieron en: CC5 (0,71), CC10 (0,67), SPC6 (0,66), SPC1 (0,65) vs. F (0,60). El estudio evidenció el efecto positivo de las prácticas de AC basadas en una mínima alteración del suelo, una menor dependencia de los agroquímicos, una cobertura orgánica permanente y los sistemas agrícolas diversificados sobre la CS. El enfoque MDS-SQI representa una herramienta práctica, prometedora y adecuada para hacer seguimiento de la CS en agroecosistemas.

Palabras clave: conjunto total de datos, conjunto mínimo de datos, conservación, indicadores, índice de calidad de suelos, ordenación de tierras sostenible.

Introduction

Soil is a finite resource considered a vital part of the natural environment and essential for the existence of life on our planet (FAO, 2015). As a core component of land resources, agricultural development, and ecological sustainability, it is the basis for food, feed, fuel, and fiber production, climate change mitigation, and a critical ecosystem service (FAO, 2015). However, land degradation is proliferating, and 25 % of agricultural soils worldwide are moderately to severely degraded (FAO & ITPS, 2015; Sylvester et al., 2020; Zou et al., 2021). In Colombia, it is estimated that close to 40 % of the soils have some degree of degradation caused by erosion, salinization, nutrient or organic matter depletion, acidification, loss of biodiversity, compaction, and pollution as a consequence of unsustainable agriculture management practices and climate change (Sylvester et al., 2020; Vallejo et al., 2018).

Tropical soils are lost to agricultural use very quickly because the convergence of physical, chemical, or biological degradation will generally lead to detrimental effects on soil properties and processes, implying a decline in Soil Quality (SQ) with an associated reduction in ecosystem functions and services (FAO & ITPS, 2015; Vallejo et al., 2018). Consequently, there has been increased interest in developing sustainable agricultural production practices that would help restore SQ and enhance agroecosystem productivity, particularly in the tropics, where there is a greater risk of forest loss and impact on the global carbon balance (Lerner et al., 2017).

Conservation Agriculture (CA) is a sustainable alternative to conventional agricultural production systems. CA proposes land management practices that involve minimal soil disturbance, such as minimum or no tillage, crop rotation, the intercropping of diversified and high biomass production crops, and permanent soil protection by preserving crop residues as soil organic cover (FAO, 2014). CA has been associated with many environmental benefits, including improvement of SQ, increased biodiversity conservation, increased water and nutrient use efficiency, soil erosion control, enhanced carbon sequestration in agricultural soils, and sustainable crop production (Gura et al., 2022; Morugán-Coronado et al., 2022; Page et al., 2020; Sylvester et al., 2020; Verhulst et al., 2011; Zou et al., 2021).

In recent years, studies from around the world have shown the benefits of CA adoption on SQ in different soils, under various climatic conditions, and across multiple crop types (Gura & Mnkeni, 2019; Sithole et al., 2016). SQ enhancements are about improving Soil Organic Carbon (SOC) content, soil physical status (i.e., aggregate stability, structure, porosity, water infiltration capacity, soil moisture, bulk density), soil nutrient contents, and biological condition, all resulting from the maintenance of organic soil cover, plant diversification, and minimum disturbance. All of these provide a more favorable soil environment for the biological populations, thus contributing to better soil microbiological density and diversity (Das et al., 2021; Ranaivoson et al., 2017; Sithole et al., 2016)

SQ is a complex functional entity that cannot be measured directly but can be calculated or monitored by a combination of SQ indicators and indices that could predict the capacity of soils to function and the overall soil agricultural status (Zhou et al., 2020). The SQ evaluation of key indicators (chemical, physical, and biological) across time can determine whether adopted soil agricultural practices are increasing or maintaining SQ, allowing the design of measures for soil preservation and restoration while improving the decision-making process in soil management (Andrews et al., 2002; Yao et al., 2013). However, given the significant variability of soil properties, even within the same area, the selection of a specific SQ evaluation method or set of SQ indicators could be valid only in particular environments, under given land management conditions, or in certain types of soils or regions (Leite Chaves et al., 2017; Yao et al., 2013; Zhou et al., 2020).

The Total Data Set (TDS) and Minimum Data Set (MDS) approaches have been used to quantify the impact of agricultural management on SQ (Nehrani et al., 2020). The TDS contains an extensive data matrix with measurable soil properties and can provide a comprehensive outcome in evaluating SQ. Nevertheless, if the evaluation sites are extended over a large area, it will inevitably be costly, labor-intensive, and time-consuming. For these reasons, MDS has been introduced to reduce the number of indicators used in SQ assessment and to select critical indicators that contain the most relevant information about SQ based on management goals, reducing data redundancy (Andrews et al., 2002; Qi et al., 2009; Vallejo et al., 2018).

Many methods for SQ evaluation have been proposed and applied successfully. The indexing methods to establish a Soil Quality Index (SQI) have been most widely used (Andrews et al., 2002; Leite Chaves et al., 2017; Qi et al., 2009; Qiu et al., 2019). SQI is a proper and effective tool for synthesizing soil attributes with a single score that allows a better understanding of soil processes and promotes appropriate management. Usually, the SQI method integrates several physicochemical and biological indicators by applying a scoring equation into a single index (Andrews et al., 2002). This method has been successfully employed due to its easy usability, quantitative flexibility, and close relatedness to soil management practices (Kongor et al., 2019; Qiu et al., 2019).

In recent years, numerous studies have been conducted on SQ assessment of different types of soils, agriculture management practices, and cropping across multiple agroecosystems (Askari & Holden, 2015; Qi et al., 2009; Vallejo et al., 2018). However, scarce information about the SQI values in Colombia has been reported in response to sustainable alternatives such as CA. SQI approach can provide an opportunity to support the decision-making process in soil management and improve CA practices previously implemented, considering that CA practices in Colombia are often developed from farmers' empirical knowledge, with low adoption rates on small farms. Therefore, it is urgent to investigate SQ in tropical agroecosystems using holistic approaches (TDS and MDS) while considering all three types of soil properties (i.e., physical-chemical and microbiological) after adoption and conversion to CA.

The present study aimed to evaluate the effect of CA on SQ in the tropical agroecosystems of Colombia. The specific objectives of this study were: (a) to evaluate the SQ in five tropical agroecosystems of Colombia using two indicator selection methods: TDS and MDS, and (b) to calculate SQI using the weighted index method to identify the effect of CA on soils' overall condition. The following hypothesis was tested: CA increases SQ and enhances soil's physical and microbiological status.

DOI: https://doi.org/10.21930/rcta.vol23_num3_art:2674

Material and methods

Study area

This research was carried out on a small farm (04°44'54"N, 74°25'33"W) in a tropical region of Colombia in the municipality of Cachipay (Cundinamarca). The municipality features a varied relief, with a predominance of steep slopes; elevations vary from 650 to 2,400 m above sea level. Most agroecosystems in the crop area (10 ha) follow CA practices based on systematic crop association (polyculture), permanent soil cover by crop residues, minimum mechanical soil disturbance, and limited addition of chemical inputs as alternatives to reduce soil degradation and conserve/improve soil properties (Table 1). Precipitation in the area is bimodal (January-July and April-October) with an average annual temperature of 8-24 °C, with an average annual rainfall of 1,472 mm. The soils within the study area are mainly Andisols, with a dominant loamy sand texture (IGAC, 2014).

Experimental design and soil sampling

Soil samples were taken in July and September 2019. The study had a completely randomized design with five treatments of Coffee Crop (CC) chronosequences of (1) 5 (CC5) and (2) 10 (CC10) years of establishment, Polyculture Cropping System (PCS) chronosequences of (3) 1 (PCS1) and (4) 6 (PCS6) years, and (5) Fallow (F) systems (Table 1). Each treatment had two spatially separated replicates. Within each treatment site, two sampling plots (3 m × 3 m) were delimited per crop type, soil type, and soil management. In each sampling site, 20 subsamples of topsoil (0-15 cm) were randomly collected and mixed thoroughly to obtain one composite soil sample (1 kg). In all, 40 composite soil samples were collected for this study. All soil samples were homogenized through a 2 mm mesh sieve to determine the physicochemical and microbiological properties. One part of the sample (50 %) was air-dried at room temperature to measure physical and chemical properties, and the remaining soil samples were stored at 4 °C for soil microbiological property determination (Vallejo et al., 2010).

Soil analysis

Soil physical properties measured, including soil Bulk Density (BD), were determined using IGAC's (1990) cylinder method. Soil Penetration Resistance (SPR) was measured (three reps) per delimited plots at a depth of 0-20 cm using a concrete Pocket Penetrometer (3/4" - 19 mm day × 7" - 178 mm long). Total Porosity (PR) was calculated from particle density and BD, whereas soil particle-size analysis (sand, silt, and clay) was performed by the modified Bouyoucos method (IGAC, 1990). Water Holding Capacity (WHC) was measured gravimetrically after the soil was oven-dried for 24 h at 105 °C (IGAC, 1990). Water-stable aggregates were determined by the wet-sieving method (IGAC, 1990); dry-stable aggregates were measured by the dry-sieving method with a set of five sieves with the following opening sizes: 4, 2, 1, 0.5, and 0.25 mm, then we calculated the aggregate Stability Index (SI), Aggregate Stability (AS) and Geometric Mean Diameter (GMD) (Nimmo & Perkins, 2002). Soil pH was determined in a 1:1 soil/water (v/v) ratio (EPA, 2004) and Electric Conductivity (EC) in a 1:5 soil/water ratio (Andrades et al., 2015). Soil Organic Carbon (OC) was analyzed using weight loss-on-ignition (Schulte & Hopkins,

DOI: https://doi.org/10.21930/rcta.vol23_num3_art:2674

1996). Heterotrophic Bacterial Density (HBD) and Total Fungal Density (TFD) were determined through a plate count method (Fernández et al., 2006), and Catalase (CAT) was measured with the Johnson and Temple method (1964).

Table 1. Description of the agroecosystems compared in this study

Agroecosystem-Land use	Crop management
PCS1	A one-year polyculture crop production system comprising the following three crops: *Zea mays*, *Arracacia xanthorrhiza,* and *Manihot esculenta* Crop residues and synthetic fertilizer additions at about one-half recommended rates Herbicides used through cultivation and hand hoeing 1 ha
PCS6	A six-year polyculture crop production system comprising the following crops: *Anthurium*, *Musa paradisiaca,* and *Manihot esculenta* Crop residues and synthetic fertilizer additions at about one-half recommended rates Herbicides used through cultivation and hand hoeing 1.3 ha
CC5	Five-year vegetation or organic cover formed by crop farm residues Coffea arabica crop No synthetic herbicides or fertilizers 1 ha
CC10	Ten-year vegetation or organic cover formed by crop farm residues Coffea arabica crop No synthetic herbicides or fertilizers 1 ha
F	The arable land has been left without sowing for one year 1.3 ha This area was previously dedicated to conventional livestock Periodic additions of vegetation residues from crops

Note. Coffee Crop (CC) chronosequences of 5 (CC5) and 10 (CC10) years of establishment, Polyculture Cropping System (PCS) chronosequences of 1 (PCS1) and 6 (PCS6) years, and Fallow (F) systems.
Source: Elaborated by the authors.

DOI: https://doi.org/10.21930/rcta.vol23_num3_art:2674

Selection of Minimum Data Set (MDS)

One-way analysis of variance (ANOVA) was performed on the 14 indicators to assess the land management effects on soil properties in different agroecosystems. The SQ indicators were selected based on the results obtained in previous research in the same geographic area (Vallejo et al., 2018). Only those indicators having a significant difference ($p \leq 0.05$) among the five agroecosystems were included in the TDS. Principal Component Analysis (PCA) was performed on the TDS to select the best representative indicators for the MDS (Andrews et al., 2002). Under each Principal Component (PC), only the variables with eigenvalue ≥ 1 accounting for at least 5 % of the variation in the data were retained. Highly loaded indicators receiving weighted loading amounts within 10 % of the highest weighted factor were chosen for the MDS. When more than one attribute was present within each PC, Pearson's correlation analysis was performed to define redundant attributes. An attribute was kept in the MDS if it was not correlated with the highly loaded attributes. Among the well-correlated attributes ($r \geq 0.60$), the one with the highest factor loading was selected for the MDS (Andrews et al., 2002; Yao et al., 2013).

Soil Quality Index (SQI)

SQI was determined in three separate steps: (1) selecting fundamental soil properties from the TDS for the MDS, (2) scoring and weighting the MDS indicators, and (3) integrating the indicator scores into one comparative SQI value (Andrews et al., 2002). With this approach, after selecting the MDS indicators, each soil parameter was first assigned a unitless score ranging from 0 to 1 by employing linear scoring functions (Andrews et al., 2002, 2004; Liebig et al., 2001). Soil parameters were divided into groups based on three mathematical algorithm functions: (a) "more is better," (b) "less is better," and (c) "optimum." "Optimum" properties have a positive influence up to a certain level beyond which the influence could be considered detrimental.

This study considered the soil EC as "less is better." All other parameters were treated as "more is better," except for WHC considered as "optimum" (Guo et al., 2017). Different SQ variables were sorted according to their function, which was calculated using the equations of linear "more is better" (Equation 1) and "less is better" (Equation 2) functions:

$$Eq1.\ \ S_L = \frac{x}{X_{max}} \tag{1}$$

$$Eq2.\ S_L = \frac{x_{min}}{x} \tag{2}$$

Where: SL is the linear score of the soil indicators, x is the soil indicators value, and X_{max} and X_{min} are the maximum and minimum values of each soil indicator as observed. After soil indicators were scored and weighted, the SQI was calculated using the weighted additive method as follows (Equation 3):

$$SQI = \sum_1^n WiSi \tag{3}$$

DOI: https://doi.org/10.21930/rcta.vol23_num3_art:2674

Where: SQI is the soil quality index, Si is the indicator score (linear), n is the number of soil indicators in the minimum, and Wi is the weighting value of soil indicators. Only potential soil indicators representing the MDS were included in the SQI calculation (Andrews et al., 2002).

The indexing technique used is SQI weighted additive proposed by Karlen and Stott (1994), which has been widely used (Hong et al., 2019; Nabiollahi et al., 2017). Higher SQI values indicate better SQ or superior performance on soil function and process (Andrews et al., 2002).

Statistical analyses

Data were tested for normality using Shapiro-Wilk's ($p \geq 0.05$). An ANOVA ($p \leq 0.05$) was computed using SPSS software (version 25, IBM Corp., Armonk, New York) to test the land management effect on SQ indicators and SQI values. The differences among the means were compared with Tukey's multiple-range test ($p < 0.05$). PCA was performed using Paleontological Statistics (PAST), version 2.17c (Hammer et al., 2001), to select MDS.

Results and discussion

Determination of the MDS for SQ assessment

The analysis of fourteen (14) soil properties evaluated in the five agroecosystems showed no significant differences ($p \geq 0.05$) for BD, PR, OC, and TFD properties at both soil sampling events (Table 2). The results revealed that ten soil properties differed significantly ($p \leq 0.05$) among the agroecosystems (Table 2), and thus, these potential SQ indicators were chosen as part of TDS (SI, AS, GMD, WSA, WHC, SRP, EC, pH, HBD, and CAT) to select the MDS through a PCA. PCA has been commonly accepted as a suitable approach for data reduction in similar studies (Li et al., 2019; Qiu et al., 2019).

The PC score plot (figure 1) showed that both potential physicochemical and microbiological SQ indicators were affected by land management practices in the agroecosystems, as confirmed by ANOSIM (global *R*-value: 0.59; $p < 0.0001$) (Figure 1). PCA was applied to analyze ten potential soil indicators, as shown in Table 3; the first three PCs were selected since they had eigenvalues > 1, each explaining at least 5 % of the data variation and accounting for 72.55 % of the total variance. The first PC explained 32.37 % of the variation, whereas PC2 and PC3 explained 25.24 % and 14.94 %, respectively (Table 3). In general, of the three selected PCs, only the parameters with high factor loadings (≥ 0.60) were retained for indexing to avoid redundancy (Kongor et al., 2019).

DOI: https://doi.org/10.21930/rcta.vol23_num3_art:2674

Table 2. Soil attributes influenced by different land uses in both soil samples

Soil attributes		Agroecosystems				
		PCS6	**PCS1**	**CC10**	**CC5**	**F**
SI (%)	1	2.89 a	2.96 a	3.89 a	2.78 a	2.53 a
	2	2.22 a	3.68 a	6.14 b	4.48 b	2.41 a
AS (%)	1	88.18 a	90.45 a	89.04 a	91.69 a	82.24 a
	2	91.56 b	94.05 b	95.69 b	96.07 b	85.85 a
GMD (mm)	1	1.98 a	2.46 ab	2.50 ab	2.91 b	1.67 a
	2	2.17 b	1.85 a	1.72 a	1.87 a	1.66 a
WSA (%)	1	53.72 b	48.54 b	41.28 a	47.79 b	47.17 b
	2	49.99 a	48.77 a	52.61 a	48.71 a	48 a
WHC (%)	1	32.02 b	35.35 bc	37.17 bc	21.30 a	37.86 c
	2	38.83 b	34.77 b	33.20 b	21.32 a	43.50 b
BD (g/cm^3)	1	0.97 a	0.86 a	1.04 a	1.04 a	0.82 a
	2	0.90 a	0.91 a	0.77 a	0.77 a	0.91 a
PR (%)	1	47.52 a	57.12 a	43.42 a	50.36 a	53.89 a
	2	47.53 a	52.84 a	52.13 a	53.64 a	45.86 a
SRP (MPa)	1	1.58 a	1.55 a	1.51 a	1.83 a	2.30 b
	2	1.90 a	1.83 a	2.08 a	1.90 a	2.00 a
EC (dS/m)	1	0.06 a	0.06 a	0.07 a	0.06 a	0.06 a
	2	0.03 b	0.04 b	0.03 b	0.02 a	0.05 b
pH	1	5.53 b	5.21 a	5.36 a	5.40 a	5.24 a
	2	5.41 a	5.72 a	5.36 a	5.48 a	5.42 a
OC (%)	1	4.89 a	4.82 a	3.58 a	3.60 a	2.93 a
	2	4.52 a	5.03 a	4.18 a	5.41 a	3.43 a
HBD (Log UFC/g)	1	8.55 b	6.63 b	7.07 b	6.66 b	5.32 a
	2	6.87 b	6.77 b	6.53 b	6.55 b	5.97 a
TFD (Log UFC/g)	1	5.55 a	5.28 a	4.67 a	4.73 a	5.56 a
	2	5.43 a	5.98 a	5.73 a	5.54 a	5.98 a
CAT (mmol H_2O_2 / g*h)	1	0.42 a	0.44 a	0.43 a	0.46 a	0.30 a
	2	0.44 a	0.43 a	0.44 a	0.51 c	0.34 b

Note. SI = Stability Index; AS = Aggregate Stability; GMD = Geometric Mean Diameter; WSA = Water-stable Aggregates; WHC = Water Holding Capacity; BD = Bulk Density; PR = Porosity; SRP = Soil Penetration Resistance; EC = Electric Conductivity; OC = Organic Carbon; TFD = Total Fungal Density; HBD = Heterotrophic Bacterial Density; CAT = Catalase. Values followed by different letters within the same parameter under different land uses are significantly different ($p <$ 0.05).

Source: Elaborated by the authors

DOI: https://doi.org/10.21930/rcta.vol23_num3_art:2674

Table 3. PCA summary for measured soil parameters

Principal component	**PC1**	**PC2**	**PC3**
Eigenvalue	3.24	2.52	1.49
Variability (%)	32.37	25.24	14.94
Cumulative (%)	32.37	57.61	72.55
Factor loading			
SI	0.681	-0.123	-0.034
AS	0.943	0.104	-0.155
GMD	-0.150	0.939	-0.195
WSA	0.394	-0.454	0.224
WHC	-0.692	-0.445	0.075
SPR	-0.105	-0.592	-0.512
EC	-0.497	0.684	0.290
pH	0.504	-0.256	0.440
HBD	0.088	-0.044	0.905
CAT	0.841	0.475	-0.127

Note. SI = Stability Index; AS = Aggregate Stability; GMD = Geometric Mean Diameter; WSA = Water-stable Aggregates; WHC = Water Holding Capacity; SPR = Soil Penetration Resistance; EC = Electric Conductivity; HBD = Heterotrophic Bacterial Density; CAT = Catalase. Underlined factor loading corresponds to soil indicators included in the MDS.
Source: Elaborated by the authors

Under PC1, SI, AS, WHC, and CAT were selected; GMD and EC were selected under PC2, while HBD was the only parameter selected under PC3 (Table 3). The selected soil parameters under PC1 were significantly correlated (range (r): 0.68–0.94) (Table 3). AS had the highest factor loading (0.94) in PC1; GMD in PC2 (0.93), and HBD was retained since it had the highest factor loading (0.90) for PC3 (Table 3). In addition, the results showed low correlations between most of the indicators (data not shown). Thus, soil indicators included in the MDS decreased from ten (TDS-from the ANOVA results) to seven (MDS-PCA); in this context, MDS consisted of four soil physical indicators (SI, AS, GMD, and WHC), one chemical indicator (EC) and two microbiological indicators (CAT and HBD).

DOI: https://doi.org/10.21930/rcta.vol23_num3_art:2674

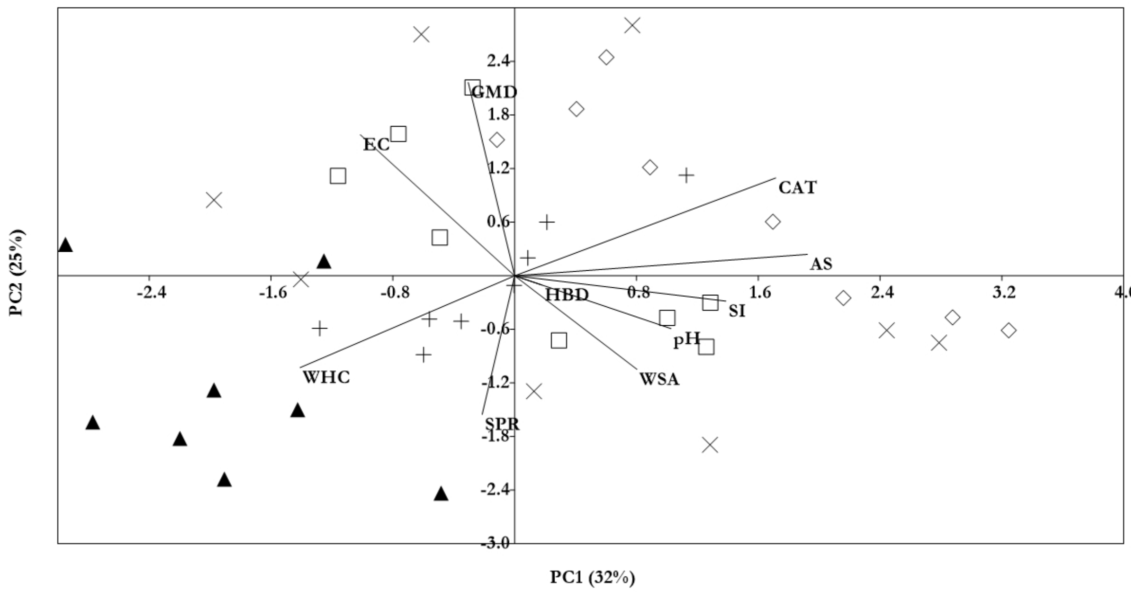

Figure 1. PC ordination of physicochemical and microbiological properties from the PCS and CC chronosequence treatments (CC5, CC10, PCS6, PCS1) and F agroecosystem (filled triangle: F, X-symbol: CC10, square: PCS1, diamond: CC5 and cross: PCS6). The percent variance explained by each PC is shown in parentheses.
Source: Elaborated by the authors

These indicators warned us early about the impact of CA on SQ in the tropical agroecosystems evaluated in this study. It suggests that proper assessment of SQ requires the consideration of physical and microbiological indicators with priority, being these the most responsive and comprehensive to improved management practices in tropical agroecosystems of Colombia. Seven SQ indicators with the MDS method suggested by the literature were also chosen as potential indicators for SQ evaluation (Askari & Holden, 2015; Li et al., 2019).

Additionally, other SQ indicators (BD and SOC) content, usually identified in MDS and found relevant for soil functionality and sensitivity by most previous studies (Shao et al., 2020), were not crucial to indicate the differences in soil management practices between the agroecosystems evaluated here. The results obtained in the present study have shown that CA did not result in any changes in SOC values. It demonstrates the necessity to evaluate other variables associated with the organic carbon stocks, which might be more informative and respond in a short time scale to changes in agricultural soil management.

Similarly, two SQ indicators retained in our MDS (EC and GMD) were reported by other studies (Abd-Elwahed, 2019; Sharma et al., 2018; Udom & Omovbude, 2019). According to Sharma et al. (2014), aggregates play significant roles in several aspects of soil health: the movement and storage of water, soil aeration, physical protection of soil organic matter, prevention of erosion, root development, and microbial community activity. Measuring aggregate stability gives valuable data about soil structural degradation. The key indicator, GMD, ranged from 1.66 mm to 2.91 mm in this study and was considerably moderate-to-high (Diniz et al., 2016; Zhou et al., 2020). Thus, findings from this study suggest that permanent soil cover with organic residues from the crops supports abundant plant diversity in polycultures or intercropping. A lack of or a minimum mechanical soil disturbance improved soil physical structure and specific GMD on most agroecosystems.

Past research has shown that SI and AS are important physical indicators of SQ because they reflect the soil's ability to resist mechanical disruption that may lead to soil erosion, and these have been usually selected into MDS by most studies (Qiu et al., 2019; Yao et al., 2013). Generally, the highest values of soil aggregation indicators (SI and AS) were obtained from PCS and CC (Table 2), independent of agroecosystem age and composition of crops among agroecosystems. These results are consistent with those of other studies, where the positive impact of CA on soil physical condition was also demonstrated (Das et al., 2021). The highest aggregation under CA could be related to C inputs from crop residues on topsoil; the amount and quality of SOC strongly influence the aggregate stability, and fresh crop residues act as a continuous source of labile OC and promote aggregate formation (Li et al., 2019; Sithole et al., 2016). The physical responses indicate that CA practices improve or maintain SQ under tropical conditions (Vallejo et al., 2018).

WHC reflects the water storage capacity of agroecosystems soils, which had been selected into MDS as one of the most common contributors to SQ by most previous studies (Qiu et al., 2019; Thierfelder et al., 2013). WHC is considered an essential indicator since plant growth and soil biological activities depend on water for hydration and delivery of nutrients (Basche et al., 2016; Saurabh et al., 2021). Our SQ assessment suggests an improvement in WHC due to the soil remaining resting to recover from previous agricultural management practices, thus resulting in higher WHC under F conditions for both sampling sets. The accumulation of crop vegetation residues provided a physical barrier on the soil surface that reduced evapotranspiration, improving WHC further.

Apart from the physical and chemical SQ parameters, soil microbiological attributes such as HBD and CAT appeared to be critical indicators for these soils. These parameters are very dynamic or variable and serve as potential early sensitive indicators of soil degradation (Sharma et al., 2014). Therefore, HBD seemed particularly useful for the SQ assessment because of its essential role in maintaining soil fertility and its rapid response to environmental changes. The decrease of soil disturbance and the organic residues input adopted in the agroecosystems could change the soil habitat by affecting the nutrient status, organic matter amount and quality, and the aggregation/microbial habitat, stimulating HBD (Choudhary et al., 2018; Onet et al., 2019; Vallejo et al., 2018). In the present study, the retained crop residues of mixed crops were a perfect substrate that contributed to a proliferation of bacterial density. HBD indicator confirmed that it was significantly higher in PCS and CC (Table 2).

On the other hand, CAT enzyme activity was significantly lower in the F system (Table 2). This type of agroecosystem had previously been subjected to different management practices that negatively affected SQ (Vallejo et al., 2018). In agreement with other studies (Xun et al., 2015; Zhao et al., 2018), stover removal and physical disturbance produced by tillage reduce soil

DOI: https://doi.org/10.21930/rcta.vol23_num3_art:2674

microbial activity, with concomitant consequences for soil functioning. CAT activity is generally higher in high-quality soils, and its activity may be altered when soil pH and nutrients decrease, the temperature reaches extremes, or contaminants pollute the soil, and soil physical status becomes affected by soil compaction (Dubey et al., 2019; Xun et al., 2015).

Effects of land management in agroecosystems and SQI

The results indicated that the SQI values did not differ significantly ($P > 0.05$) among soil sampling events and analyses. In addition, differences in SQI across the studied sites were found among some selected agroecosystems. SQI calculated using our MDS ranged from 0.60 to 0.71 across land management in agroecosystems (Figure 2). Higher and similar SQI values were observed in the agroecosystems: CC5 > CC10 > PCS6 = PCS1 (Figure 2). However, the SQI value of F was slightly lower (0.60) than PCS6 (0.66), PCS1 (0.61), and CC10 (0.67), although there was a statistically significant difference only with CC5 (0.71) ($p < 0.05$) (Figure 2). The relative contribution of each indicator towards the SQI from different agroecosystems (Figure 3) showed that HBD, GMD, and WHC (14.70, 11.16, and 11.15 %, respectively) made the highest contribution towards the SQI, and SI made the lowest contribution (7.80 %).

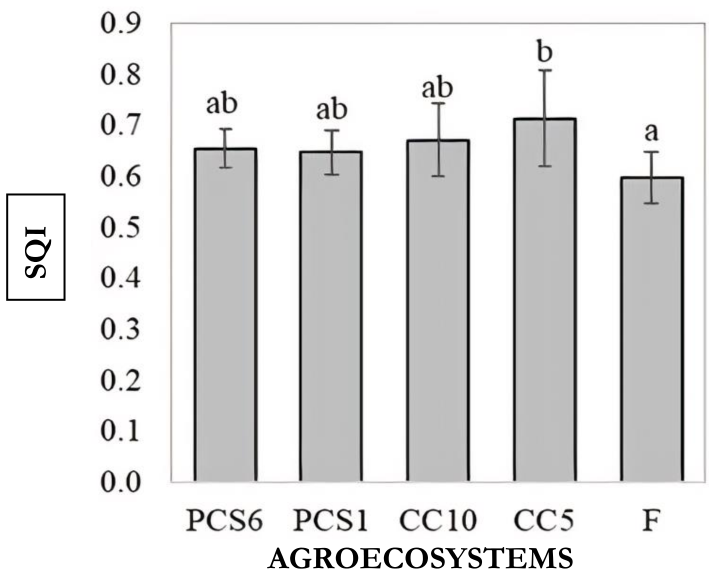

Figure 2. Average effects on soil management in tropical agroecosystems on SQI. SQI values refer to the averages between the two sampling times; averages that do not share a letter are significantly different ($p \leq 0.05$) according to Tukey's test.
Source: Elaborated by the authors

The results regarding SQI showed the positive effects of adopting CA in agroecosystems for sustaining SQ in tropical regions. In this study, CA practices were based on minimum soil disturbances, permanent soil cover, crop diversification, and minimum use of chemical fertilizers, revealing great potential as a sustainable production system without deteriorating SQ (Parihar et al., 2020). Previous studies have shown the positive impact of CA adoption on SQ

DOI: https://doi.org/10.21930/rcta.vol23_num3_art:2674

and an increase in microbial diversity and activity (Page et al., 2020; Verhulst et al., 2011). Additionally, the rest period in agroecosystems previously subjected to conventional management allows an improvement in the natural condition of the soil, which is reflected in the prevalence of some properties.

Improvement of soil OC, CAT activity, AS, SI, and HBD-based management practices under CA might have resulted in higher SQI values for CC and PCS, independent of the agroecosystem's age. On the other hand, the average SQI in this study differed from the SQI values of 0.49 and 0.41 reported in the cacao agroforestry system in the Orinoco Region, Colombia. A similar approach improved cocoa production in six cocoa-growing regions in Ghana (Kongor et al., 2019; Parra-González & Rodriguez-Valenzuela, 2017). Sharma et al. (2014) evaluated the effect of agricultural conservation practices on SQ, comprising conventional and low tillage, as well as conjunctive use of organic and inorganic sources of nutrients in the soils of India. SQIs varied from 0.86 to 1.08 across the tillage, and nutrient-management treatments were practiced for the pearl millet system.

In the case of the F system, the low SQI results from the short period since rest or minimum disturbance from previous intensive grass monoculture was dedicated to livestock for the past 15 years, which may have caused soil degradation and adversely impacted SQ (Cubillos et al., 2016; Vallejo et al., 2010). Another F factor can be related to soil tillage management and continuous agrochemical additions in this agroecosystem, which have adversely affected soil properties, influencing SQ. These results demonstrate that agroecosystems require a longer time to recover their physical, chemical, and microbiological conditions so the SQ can be positively impacted and adequately perform its functions. This result of SQI coincided with a previous study by Leite Chaves et al. (2017), who reported that SQ decreased with the intensity of soil use (i.e., maize, pasture, and 1-y reforestation) in an Oxisol under different land uses in the Brazilian savannah.

Conclusions

Based on sustainable intensification through crop diversification, continuous crop residue addition, and minimum soil physical disturbance, CA improves SQ in agroecosystems. The approach presented here provided an effective, rapid, reproducible, and reliable method for assessing the effects of different management practices on SQ and can help select the best agricultural practices for the benefit of farmers and monitor the changes in SQ after implementing a CA strategy. This study reported improvement in soil physical and microbiological properties under CA independent of the age of establishment of the agroecosystem and the type of crop, which may influence soil ecosystem functioning.

This study improved comprehension of SQ changes induced by sustainable practices such as CA in this tropical region of Colombia. Further investigations using these tools to assess SQ are recommended to validate our findings further, including studies in many sites for different soil types, climates, and cropping systems. These efforts will support decision-making concerning expanding more sustainable agricultural management practices in Colombia.

Acknowledgments

The authors would like to thank the farm owners of "Comunidad Religiosa de las Hermanas de la Caridad Dominicas de la Presentación de la Santísima Virgen" and the farmers for soil sampling support. Thanks to the anonymous reviewers and editors for helping improve the manuscript.

Authors' contributions

Valentina Ardila García: registration of information in the field and laboratory, construction of databases, analysis of information and preparation of manuscript; Leidy Paola Plazas Navarro: registration of information in the field and laboratory, construction of databases, analysis of information and preparation of manuscript; Victoria Eugenia Vallejo: registration of information in the field, construction of databases, analysis of information, supervision of activities and preparation of manuscript.

Ethical implications

There are no ethical implications.

Conflict of interest

The authors declare that there are no conflicts of interest in this study.

Funding

This project has received funding from the Universidad Central.

References

Abd-Elwahed, M. S. (2019). Effect of long-term wastewater irrigation on the quality of alluvial soil for agricultural sustainability. *Annals of Agricultural Sciences*, *64*(2), 151-160. https://doi.org/10.1016/j.aoas.2019.10.003

Andrades, M., Moliner, A., & Masaguer, A. (2015). *Prácticas de edafología: Métodos didácticos para análisis de suelos*. Universidad de Rioja. https://publicaciones.unirioja.es/catalogo/monografias/mdaa15.shtml

Andrews, S. S., Karlen, D. L., & Cambardella, C. A. (2004). The soil management assessment framework: a quantitative soil quality evaluation method. *Soil Science Society of America Journal*, *68*, 1945-1962. https://doi.org/10.2136/sssaj2004.1945

Andrews, S. S., Karlen, D. L., & Mitchell, J. P. (2002). A comparison of soil quality indexing methods for vegetable production systems in Northern California. *Agriculture, Ecosystems & Environment*, *90*(1), 25-45. https://doi.org/10.1016/S0167-8809(01)00174-8

Askari, M. S., & Holden, N. M. (2015). Quantitative soil quality indexing of temperate arable management systems. *Soil and Tillage Research*, *150*, 57-67. https://doi.org/10.1016/J.STILL.2015.01.010

Basche, A. D., Kaspar, T. C., Archontoulis, S. V., Jaynes, D. B., Sauer, T. J., Parkin, T. B., & Miguez, F. E. (2016). Soil water improvements with the long-term use of a winter rye cover crop. *Agricultural Water Management*, *172*, 40-50. https://doi.org/10.1016/j.agwat.2016.04.006

Choudhary, M., Datta, A., Jat, H. S., Yadav, A. K., Gathala, M. K., Sapkota, T. B., & Ladha, J. K. (2018). Changes in soil biology under conservation agriculture based sustainable intensification of cereal systems in Indo-Gangetic Plains. *Geoderma*, *313*, 193-204. https://doi.org/10.1016/j.geoderma.2017.10.041

Cubillos, A. M., Vallejo, V. E., Arbeli, Z., Ter, W., Dick, R. P., Molina, C. H., & Roldan, F. (2016). Effect of the conversion of conventional pasture to intensive silvopastoral systems on edaphic bacterial and ammonia oxidizer communities in Colombia. *European Journal of Soil Biology Journal*, *72*, 42-50. https://doi.org/10.1016/j.ejsobi.2015.12.003

Das, S., Bhattacharyya, R., Das, T. K., Sharma, A. R., Dwivedi, B. S., Meena, M. C., Dey, A., Biswas, S., Aditya, K., Aggarwal, P., Biswas A. K., & Chaudhari, S. K. (2021). Soil quality indices in a conservation agriculture-based rice-mustard cropping system in North-western Indo-Gangetic Plains. *Soil and Tillage Research*, *208*, 104914. https://doi.org/10.1016/j.still.2020.104914

Diniz, L. T., Ramos, M. L. G., Junior, W. Q. R., Cruz, A. F., De Franca, L. V., Diniz, B. T., & Amabile, R. F. (2016). Effect of nitrogen fertilization on soil microbial biomass in an Oxisol cultivated with irrigated barley in the Brazilian Cerrado. *Acta agronómica*, *65*(2), 137-143. https://doi.org/10.15446/acag.v65n2.46432

Dubey, R. K., Dubey, P. K., & Abhilash, P. C. (2019). Sustainable soil amendments for improving the soil quality, yield and nutrient content of *Brassica juncea* (L.) grown in different agroecological zones of eastern Uttar Pradesh, India. *Soil and Tillage Research*, *195*, 1-11. https://doi.org/10.1016/j.still.2019.104418

EPA. (2004). *Method 9045D. Soil and waste pH.*

FAO. (2014). *Agricultura de conservación*. http://www.fao.org/conservation-agriculture/es/

FAO. (2015). *Soil is a non-renewable resource.*

FAO & ITPS. (2015). *Status of the World's Soil Resources (SWSR) - Main Report.*

Fernández, L., Rojas, N., Roldán, T., Carrillo, M., Ramírez, M., Zegarra, H., Hernández, R., Reyes, R., Flores, D., & Arce, D. (2006). *Manual de técnicas de análisis de suelos aplicadas a la remediación de sitios contaminados*. Instituto Mexicano del Petróleo, Secretaría de Medio Ambiente y Recursos Naturales, Instituto Nacional de Ecología.

Guo, L., Sun, Z., Ouyang, Z., Han, D., & Li, F. (2017). A comparison of soil quality evaluation methods for Fluvisol along the lower Yellow River. *Catena*, *152*, 135-143. https://doi.org/10.1016/j.catena.2017.01.015

DOI: https://doi.org/10.21930/rcta.vol23_num3_art:2674

Gura, I., & Mnkeni, P. N. S. (2019). Crop rotation and residue management effects under no till on the soil quality of a Haplic Cambisol in Alice, Eastern Cape, South Africa. *Geoderma*, *337*, 927-934. https://doi.org/10.1016/j.geoderma.2018.10.042

Gura, I., Mnkeni, P., Du Preez, C., & Barnard, J. (2022). Short-term effects of conservation agriculture strategies on the soil quality of a Haplic Plinthosol in Eastern Cape, South Africa. *Soil and Tillage Research, 220* (July 2021), 13. https://doi.org/10.1016/j.still.2022.105378

Hammer, Ø., Harper, D. A., & Ryan, P. D. (2001). PAST: paleontological statistic software package for education and data analysis. Palaeontological association. *Palaeontologia Electronica*, *4*(1), 9. https://palaeo-electronica.org/2001_1/past/issue1_01.htm

Hong, Y., Heerink, N., Zhao, M., & van der Werf, W. (2019). Intercropping contributes to a higher technical efficiency in smallholder farming: Evidence from a case study in Gaotai County, China. *Agricultural Systems*, *173*, 317-324. https://doi.org/10.1016/j.agsy.2019.03.007

IGAC. (1990). *Métodos analíticos del laboratorio de suelos.*

IGAC. (2014). *Códigos para los levantamientos de suelos*. http://igacnet2.igac.gov.co/intranet/UserFiles/File/procedimientos/instructivos/I40100-06-14.V1Codigos para los levantamientos de suelos.pdf

Johnson, J., & Temple, K. (1964). Some variable affecting the measurement of "catalase activity" in soil. *Soil Science Society of America*, *28*, 207-209. https://doi.org/10.1007/s13762-018-1959-5

Karlen, D. L., & Stott, D. E. (1994). A framework for evaluating physical and chemical indicators of soil quality. In J. W. Doran, D. C. Leman, D. F. Bezdicek, & B. A. Stewart (Eds.), *Defining soil quality for a sustainable environment*; *Proceedings of a symposium, Minneapolis*, *MN*, *USA*, *1992* (pp. 53-72). Soil Science Society of America. https://doi.org/10.2136/sssaspecpub35.c4

Kongor, J. E., Boeckx, P., Vermeir, P., Van de Walle, D., Baert, G., Afoakwa, E. O., & Dewettinck, K. (2019). Assessment of soil fertility and quality for improved cocoa production in six cocoa growing regions in Ghana. *Agroforestry Systems*, *93*(4), 1455-1467. https://doi.org/10.1007/s10457-018-0253-3

Leite Chaves, H. M., Concha Lozada, C. M., & Gaspar, R. O. (2017). Soil quality index of an Oxisol under different land uses in the Brazilian savannah. *Geoderma Regional*, *10*, 183-190. https://doi.org/10.1016/j.geodrs.2017.07.007

Lerner, A. M., Zuluaga, A. F., Chará, J., Andrés E., & Searchinger, T. (2017). Sustainable cattle ranching in practice: Moving from theory to planning in Colombia's Livestock Sector. *Environmental Management*, *60*(2), 176-184. https://doi.org/10.1007/s00267-017-0902-8

Li, P., Shi, K., Wang, Y., Kong, D., Liu, T., Jiao, J., Manqiang, L., Huixin, L., & Hu, F. (2019). Soil quality assessment of wheat-maize cropping system with different productivities in China: Establishing a minimum data set. *Soil and Tillage Research*, *190*, 31-40. https://doi.org/10.1016/j.still.2019.02.019

Liebig, M. A., Varvel, G. E., & Doran, J. W. (2001). A simple performance-based index for assessing multiple agroecosystem functions. *Agronomy & Horticulture*, *93*(2), 313-318. https://doi.org/10.2134/agronj2001.932313x

Morugán-Coronado, A., Pérez-Rodríguez, P., Insolia, E., Soto-Gómez, D., Fernández-Calviño, D., & Zornoza, R. (2022). The impact of crop diversification, tillage and fertilization type on soil total microbial, fungal and bacterial abundance: A worldwide meta-analysis of agricultural sites. *Agriculture, Ecosystems and Environment*, *329*, 8. https://doi.org/10.1016/j.agee.2022.107867

Nabiollahi, K., Taghizadeh-Mehrjardi, R., Kerry, R., & Moradian, S. (2017). Assessment of soil quality indices for salt-affected agricultural land in Kurdistan Province, Iran. *Ecological Indicators*, *83*, 482-494. https://doi.org/10.1016/j.ecolind.2017.08.001

Nehrani, S. H., Sadegh Askari, M., Saadat, S., Amir Delavar, M., Taheri, M., & Holden, N. M. (2020). Quantification of soil quality under semi-arid agriculture in the Northwest of Iran. *Ecological Indicators*, *108*, 105770. https://doi.org/10.1016/j.ecolind.2019.105770

Nimmo, J. R., & Perkins, K. S. (2002). Aggregate stability and size distribution. In J. H. Dane & G. C. Topp (Eds.), *Methods of soil analysis: Part 4 physical methods* (pp. 317-328). Soil Science Society of America, Inc. https://doi.org/10.2136/sssabookser5.4.c14

Onet, A., Dincă, L. C., Grenni, P., Laslo, V., Teusdea, A. C., Vasile, D. L., & Crisan, V. E. (2019). Biological indicators for evaluating soil quality improvement in a soil degraded by erosion processes. *Journal of Soils and Sediments*, *19*(5), 2393-2404. https://doi.org/10.1007/s11368-018-02236-9

Page, K. L., Dang, Y. P., & Dalal, R. C. (2020). The ability of conservation agriculture to conserve soil organic carbon and the subsequent impact on soil physical, chemical, and biological properties and yield. *Frontiers in Sustainable Food Systems*, *4*, 31. https://doi.org/10.3389/fsufs.2020.00031

Parihar, C. M., Singh, A. K., Jat, S. L., Dey, A., Nayak, H. S., Mandal, B. N., & Yadav, O. P. (2020). Soil quality and carbon sequestration under conservation agriculture with balanced nutrition in intensive cereal-based system. *Soil and Tillage Research*, *202*, 1-14. https://doi.org/10.1016/j.still.2020.104653

Parra-González, S., & Rodriguez-Valenzuela, J. (2017). Determination of the soil quality index by principal component analysis in cocoa agroforestry system in the Orinoco region, Colombia. *Journal of Agriculture and Ecology Research International*, *10*(3), 1-8. https://doi.org/10.9734/jaeri/2017/31346

Qi Y., Darilek, J. L., Huang, B., Zhao, Y.,, Sun, W., & Gu, Z. (2009). Evaluating soil quality indices in an agricultural region of Jiangsu Province, China. *Geoderma*, *149*(3-4), 325-334. https://doi.org/10.1016/j.geoderma.2008.12.015

Qiu, X., Peng, D., Wang, H., Wang, Z., & Cheng, S. (2019). Minimum data set for evaluation of stand density effects on soil quality in *Larix principis-rupprechtii* plantations in North China. *Ecological Indicators*, *103*, 236-247. https://doi.org/10.1016/j.ecolind.2019.04.010

Ranaivoson, L., Naudin, K., Ripoche, A., Affholder, F., Rabeharisoa, L., & Corbeels, M. (2017). Agro-ecological functions of crop residues under conservation agriculture. A review. *Agronomy for Sustainable Development*, *37*(4), 1-17. https://doi.org/10.1007/s13593-017-0432-z

Saurabh, K., Rao, K. K., Mishra, J. S., Kumar, R., Poonia, S. P., Samal, S. K., Roy, H. S., Dubey, A. K., Choubey A. K., Mondal, S., Bhatt, B. P., Verma, M., & Malik, R. K. (2021). Influence of tillage-based crop establishment and residue management practices on soil quality indices and yield sustainability in rice-wheat cropping system of Eastern Indo-Gangetic Plains. *Soil and Tillage Research*, *206*, 1-9. https://doi.org/10.1016/j.still.2020.104841

Schulte, E., & Hopkins, B. (1996). Estimation of organic matter by weight loss-on-ignition. In F. Magdoff et al. (Eds.), *Soil Organic Matter: Analysis and Interpretation* (pp. 21-31). Soil Science Society of America. https://doi.org/10.2136/sssaspecpub46.c3

Shao, G., Ai, J., Sun, Q., Hou, L., & Dong, Y. (2020). Soil quality assessment under different forest types in the Mount Tai, central Eastern China. *Ecological Indicators*, *115*, 106439. https://doi.org/10.1016/j.ecolind.2020.106439

Sharma, K. L., Grace, J. K., Chandrika, M. S., Vittal, K. P. R., Singh, S. P., Nema, A. K., & Rani, K. U. (2014). Effects of soil management practices on key soil quality indicators and indices in pearl millet (*Pennisetum americanum* (L.) Leeke)-based system in hot semi-arid Inceptisols. *Communications in Soil Science and Plant Analysis*, *45*(6), 785-809. https://doi.org/10.1080/00103624.2013.867048

Sharma, K. L., Srinivasa Rao, C., Chandrika, D. S., Lal, M., Indoria, A. K., Reddy, K. S., & Srinivas, D. K. (2018). Management practices on soil quality indicators and soil quality indices under post monsoon (Rabi) sorghum (*Sorghum bicolor*) in rainfed black soils (Vertisols) of Western India. *Communications in Soil Science and Plant Analysis*, *49*(13), 1629-1637. https://doi.org/10.1080/00103624.2018.1474901

Sithole, N. J., Magwaza, L. S., & Mafongoya, P. L. (2016). Conservation agriculture and its impact on soil quality and maize yield: A South African perspective. *Soil and Tillage Research*, *162*, 55-67. https://doi.org/10.1016/j.still.2016.04.014

Sylvester, J., Valencia, J., Verchot, L. V., Chirinda, N., Romero Sanchez, M. A., Quintero, M., & Castro-Nunez, A. (2020). A rapid approach for informing the prioritization of degraded agricultural lands for ecological recovery: A case study for Colombia. *Journal for Nature Conservation*, *58*, 125921. https://doi.org/10.1016/j.jnc.2020.125921

Thierfelder, C., Mwila, M., & Rusinamhodzi, L. (2013). Conservation agriculture in eastern and southern provinces of Zambia: Long-term effects on soil quality and maize productivity. *Soil and Tillage Research*, *126*, 246-258. https://doi.org/10.1016/j.still.2012.09.002

Udom, B. E., & Omovbude, S. (2019). Soil physical properties and carbon/nitrogen relationships in stable aggregates under legume and grass fallow. *Acta Ecologica Sinica*, *39*(1), 56-62. https://doi.org/10.1016/j.chnaes.2018.05.008

Vallejo, V. E., Afanador, L. N., Hernández, M. A., & Parra, D. C. (2018). Effect of the implementation of different agricultural systems on the soil quality from the municipality of Cachipay, Cundinamarca, Colombia. *Bioagro*, *30*(1), 27-38.

Vallejo, V. E., Roldan, F., & Dick, R. P. (2010). Soil enzymatic activities and microbial biomass in an integrated agroforestry chronosequence compared to monoculture and a native forest of Colombia. *Biology and Fertility of Soils*, *46*(6), 577-587. https://doi.org/10.1007/s00374-010-0466-8

Verhulst, N., Carrillo-García, A., Moeller, C., Trethowan, R., Sayre, K. D., & Govaerts, B. (2011). Conservation agriculture for wheat-based cropping systems under gravity irrigation: Increasing resilience through improved soil quality. *Plant and Soil*, *340*(1), 467-479. https://doi.org/10.1007/s11104-010-0620-y

Xun, W., Huang, T., Zhao, J., Ran, W., Wang, B., Shen, Q., & Zhang, R. (2015). Environmental conditions rather than microbial inoculum composition determine the bacterial composition, microbial biomass and enzymatic activity of reconstructed soil microbial communities. *Soil Biology and Biochemistry*, *90*, 10-18. https://doi.org/10.1016/j.soilbio.2015.07.018

Yao, R., Yang, J., Gao, P., Zhang, J., & Jin, W. (2013). Determining minimum data set for soil quality assessment of typical salt-affected farmland in the coastal reclamation area. *Soil and Tillage Research*, *128*, 137-148. https://doi.org/10.1016/j.still.2012.11.007

Zhou, Y., Ma, H., Xie, Y., Jia, X., Su, T., Li, J., & Shen, Y. (2020). Assessment of soil quality indexes for different land use types in typical steppe in the loess hilly area, China. *Ecological Indicators*, *118*, 1-10. https://doi.org/10.1016/j.ecolind.2020.106743

Zou, X., Zhu, X., Zhu, P., Singh, A. K., Zakari, S., Yang, B., Chen, C., & Liu, W. (2021). Soil quality assessment of different *Hevea brasiliensis* plantations in tropical China. *Journal of Environmental Management*, *285*, 112147. https://doi.org/10.1016/j.jenvman.2021.112147