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Soil quality index of an ultisol under long-term plots in the coastal tablelands in northeastern Brazil

Índice de qualidade do solo de um argissolo sob parcelas de longa duração no tabuleiro costeiro nordestino, Brasil

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ABSTRACT - Soil quality, measured through its chemical, physical and microbiological attributes, changes as a result of anthropic sensations and becomes an important tool to assess environmental quality. The objective of this study was to determine and evaluate the Quality Index of an Ultisol in a long-term (17-yr) plots under different management systems in the Coastal Tablelands of Sergipe State, in Northeastern, Brazil. Main effects were conventional tillage (CT), no-tillage (NT), and minimum tillage (MT) distributed cultivated strips with corn as the main crop. Split-range treatments were randomly distributed and cultivated with cowpea beans (Vigna unguiculata), sunn hemp (Crotalaria juncea), pigeon pea (Cajanus cajan), and millet (Pennisetum glaucum). A forest soil was used as reference, compared to the soil samples of the cultivated area. The Soil Quality Index (SQI) for the 0-0.10 m layer was calculated by the additive method. There were changes in soil properties between the different management systems, and between the experimental soil and the reference area. The highest SQI was obtained from the forest area (67.1) followed by the NT treatment (65.5), MT (65.1) and CT treatment (61.0). The lowest SQI was observed in the CT treatment previously cultivated with pigeon pea (56.5). Among the evaluated soil functions, maintenance of homeostasis had the greatest influence on the SQI. The higher acidity of the forest soil helps to explain the origin of the limitations of the soil in the cultivated area that occupies the same type of soil, tolerated by the adoption of conservationist managements.

Keywords: Conservation systems. No-tillage. Conventional tillage. Minimum tillage. Cover crops.

RESUMO - A qualidade do solo, medida por meio de seus atributos químicos, físicos e microbiológicos, muda em função das interações antrópicas e torna-se uma importante ferramenta para avaliar a qualidade ambiental. O objetivo deste estudo foi determinar e avaliar o Índice de Qualidade de um Argissolo em parcelas de longo prazo (17 anos) sob diferentes sistemas de manejo nos Tabuleiros Costeiros do Estado de Sergipe, Nordeste do Brasil. Os principais efeitos foram plantio convencional (CC), cultivo minimo (CM) e plantio direto (MT) distribuídos em faixas cultivadas com milho como cultura principal. Os tratamentos fracionados foram distribuídos aleatoriamente e cultivados com feijão-caupi (Vigna unguiculata), crotalária (Crotalaria juncea), feijão guandu (Cajanus cajan) e milheto (Pennisetum glaucum). Um solo florestal foi utilizado como referência. O Índice de Qualidade do Solo (IQS) para a camada de 0-0,10 m foi calculado pelo método aditivo. Houve mudanças nas propriedades do solo entre os diferentes sistemas de manejo, e entre o solo do experimento e a área de referência. O maior IQS foi obtido da área de floresta (67,1) seguido do tratamento PD (65,5), CM (65,1) e tratamento CC (61,0). O menor IQS foi observado no tratamento CC previamente cultivado com feijão guandu (56,5). Dentre as funções avaliadas do solo, a manutenção da homeostase teve a maior influência no IQS. A maior acidez do solo florestal ajuda a explicar a origem das limitações do solo na área cultivada que ocupa o mesmo tipo de solo, exigindo a adoção de manejos conservacionistas.

Palavras-chave: Sistemas conservacionistas, Plantio direto, Preparo convencional, Preparo mínimo, Plantas de cobertura.

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INTRODUCTION

Mankind constantly seeks mechanisms to improve and adapt crop production to environmental conditions, aiming at greater agricultural yield (MAIOR et al., 2012). Thus, the soil deserves special attention, once it is responsible for supplying nutrients and water and providing physical support for plants. Thus, the search for agricultural practices to reduce soil degradation and increase plant yield, without losing sight of the various aspects related to sustainability, has become the focus of interest in several study areas (CHENG, 2022). Thus, the search for agricultural soil management practices that do not degrade it and induce high productivity, not losing sight of the various aspects related to sustainability, has become a focus of interest in several areas of study. Soil conservation is one of the main objectives of the sustainability agenda with focus on food security and environmental protection (LAURENTIIS et al., 2019).

Soil management comprises essential practices applied to agricultural lands for proper crop development and production. However, there are variations in soil tillage, intensity related to tillage depth, and level of soil cover. Although there is no soil tillage model that can be successfully applied to all scenarios, the conservation methods are currently preferred over the conventional ones. The conservation systems are based on the adoption of no-till or minimum tillage, where cover crops are previously cultivated to improve the soil environment for the main crop. In addition to the physical protection, cover crops add nutrients to the soil after the decomposition of the organic residues (COSTA et al., 2020). These conservation systems are widely accepted among farmers due to the many benefits on the maintenance or recovery of physical, chemical and microbiological properties (MANSANO, 2020).

Soil quality (SQ) can be understood as the ability of the soil to perform the functions related to yield, biological diversity, environmental quality, promotion of plant and animal health, and support of socioeconomic structures (DORAN; PARKIN, 1996). According to USDA (2001), management systems that improve soil quality also benefit crop yield, increase water use efficiency, increase nutrient availability and sustain the use of these natural resources in the future. Improvement in soil quality benefits air and water quality, with direct positive impact on the quality of life of the inhabitants, thus promoting environmental quality.

The evaluation of soil properties has been suggested as the most effective tool to measure or monitor ongoing degradation processes (SOBUCKI et al., 2019), as they reflect the effects of the adopted management practices. Thus, soil quality has been proposed as an integrated way of assessing environmental quality and agricultural sustainability (ARAGÃO, 2018), being considered a key element for maintaining yield (SILVA et al., 2021).

The soils of the Coastal Tablelands in Sergipe State host the most diverse agricultural activities and play an important economic role in the region. In addition to Ultisols, there are large areas with Oxisols and Entisols. Weak physical properties and low natural fertility (CINTRA, 2011; OLIVEIRA et al., 2017; OLIVEIRA et al., 2020) are very common among these soils, which increase their vulnerability to degradation when used for intensive agricultural practices. The loss of quality is easily identified through changes in the chemical, physical and microbiological properties, and through the reduction in crop production (GONZAGA, 2011).

The objective of this study was to determine and evaluate the Quality Index of an Ultisol in long-term (17-yr) plots under different management systems in the Coastal Tablelands of Sergipe State, in Northeastern Brazil, in a long-term experiment.

MATERIALS AND METHODS

Long-Term Plots have started in 2001, at the Universidade Federal de Sergipe experimental farm – Campus Rural (10° 55' 24”S and 37° 11' 57”W), in the municipality of São Cristóvão, state of Sergipe, Northeastern Brazil (Figure 1). The local soil is classified as ARGISSOLO VERMELHO AMARELO distrófico (SANTOS et al., 2018) or ACRISOLS according to World Reference Base for Soil Resources – WRB of the FAO-UNESCO Soil Classification System (WRB, 2006) and ULTISOLS according to Soil Taxonomy (USDA, 1999), with a 0.27-m-deep A horizon with loamy sand texture (Sand - 82.1%, Silt - 12.5% and Clay - 5.4%), and Bt horizon (0.28 - 0.77 m deep) with clay loam texture (Sand - 15%, Silt - 25% and Clay - 60%). The soil originated from typical sediments from the Barreiras group (SANTOS et al., 2018). The region has annual rainfall of around 1200 mm, with a predominance of the As' climate (classified according to Köppen), characterized as rainy tropical with dry and humid summer and a rainy season concentrated between the months of April and September (70%) (ALVARES et al., 2013), therefore representative of the landscape conditions for the Brazilian northeastern region. The levels of the chemical and physical parameters under the initial conditions of the experiment are, respectively for the A and Bt horizons of the *Argissolo Vermelho Amarelo* (Ultisol): pH in water (1:2.5): 5.6 and 4.8; P ($mg.dm^{-3}$): 1.3 and 0.1; K ($mg\ dm^{-3}$): 6.8 and 5.6; Al ($cmol_c.dm^{-3}$): 0.95 and 1.4; Organic matter ($dag.kg^{-1}$): 1.0 and 0.6; Sand (%): 85.8 and 30.9; Silt: (%): 3.6 and 4.8; and Clay (%): 10.7 and 64.3.

The experiment was set up in a 3 x 4 split-plot design where the main effects were the three different management systems (conventional tillage - CT, no-tillage - NT and Minimum tillage - MT) distributed in 840 m^2 (10 m X 84 m) strips, adopted since the experiment was set up. The secondary effects were the four cover crops in the sequence: From 2001 to 2006, the following cover crops were used: Sunn hemp - *Crotalaria juncea*, Pigeon pea - *Cajanus cajan*, Common beans - *Phaseolus vulgaris* and Peanut - *Arachis hypogea*. From 2006 to 2014, Beans were replaced with Sunflower - *Helianthus annuus* and Peanuts was replaced with Millet – *Pennisetum glaucum*. In 2014, Sunflower was replaced with Cowpea - *Vigna unguiculata*. Thus, from 2014 onwards, as the following cover crops were used: Sunn hemp, Millet, Cowpea and Pigeon pea, distributed in the strips. Each cover crop covered a 60 m^2 area. The experiment had three replications and a total of 12 plots 1 meter distant from each other. Every year, cover crops were planted 90 days before the main crop (corn - *Zea mays*).

The effect of the treatments on the soil quality index was evaluated in 2017, totaling 17 years of long-term plots. The cover crops were sown in February 2017, spaced by 0.5 m x 0.2 m. Soil fertilization was carried out according to Sobral et al. (2007). Ninety days later, the plants were cut and incorporated into the soil.

Soil acidity in the experimental strips was corrected through the application of limestone following the incorporation of the cover crops. Corn seeds (Biomatrix BM hybrid 3061 of dual purpose - commercial green corn cobs and forage) were sown at an average spacing of 0.2 m in the row and 0.8 m between rows, in May 2017. Fertilizer was applied at planting and at 15, 30 and 45 days after planting according to Sobral et al. (2007). Harvest was carried out manually when the corn cobs reached a commercial standard (> 20 cm length and grains at stage R3, from 70 to 85 days after planting). At this stage, the grains had 70-80% moisture, known commercially as Green corn (GC). The corn cobs were counted and weighed to determine the yield. The plant residues were cut and placed on the soil.

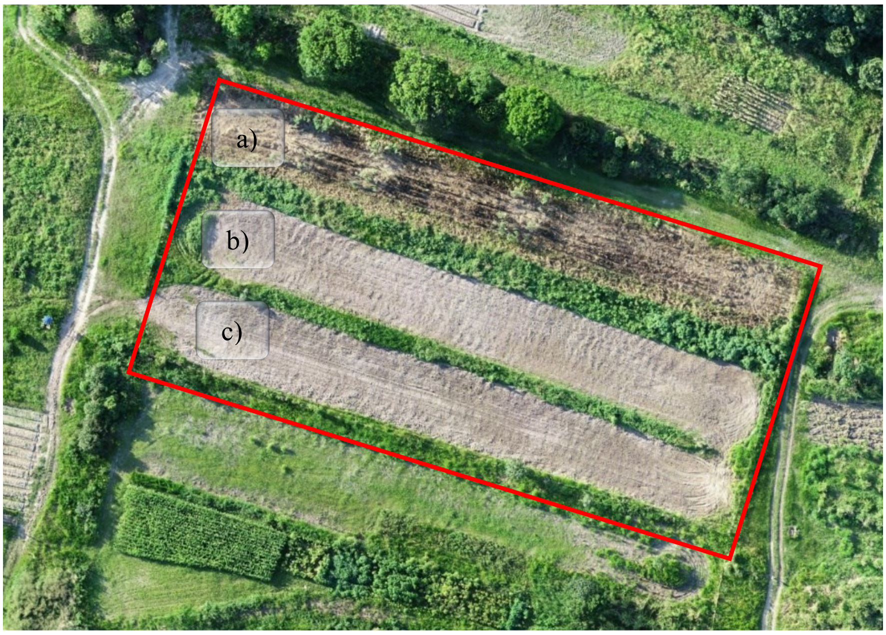


Figure 1. Long-term Experiment (implemented in 2001), located at the Campus Rural (10°55'24" S and 37°11'57" W) of the Federal University of Sergipe (UFS), in the municipality of São Cristóvão, state of Sergipe, Northeastern Brazil, with soil at the site classified as Ultisol, in the Coastal Tablelands of Sergipe: a) Ultisol under no-tillage management; b) Ultisol under Minimum tillage management; Ultisol under conventional tillage management.

Disturbed and undisturbed soil samples were then collected in each experimental plot in the 0-0.10 m layer, and in the native forest area located at approximately 600 m from the experimental area. Undisturbed samples were used to determine bulk density (BD), total porosity (TP), microporosity (Mi), macroporosity (Ma) (TEIXEIRA et al., 2017), soil resistance to penetration (PR), and available water content (AWC). Disturbed soil samples were used to determine soil aggregate stability (HILLEL, 2004), pH_{H2O}, Al, H+Al, available P, extractable K, Ca, Mg, CEC, organic matter, base saturation (v), Al saturation (m), sum of bases (SB) (TEIXEIRA et al., 2017), N stock (N stock), microbial biomass respiration (MBR), microbial biomass carbon (MBC), microbial biomass nitrogen (MBN) (MENDONÇA; MATOS, 2005), metabolic quotient (qCO_2) (ANDERSON; DOMSCH, 1985), and microbial quotient (qMIC) (ALVAREZ et al., 1999). Water infiltration rate (WIR) was tested in situ according to Brandão et al. (2006).

The Soil Quality Index (SQI) was calculated using the model proposed by Karlen and Stott (1994), with modifications. Soil functions considered relevant to the sustainability of agricultural activity were selected as described by Chaer (2001), which are: (1) receiving, storing and supplying water; (2) storing, supplying and cycling nutrients; (3) promoting root growth; (4) promoting biological activity, and (5) maintaining homeostasis. Each function was given a weight of 0.2 so that the sum of the weights of all functions should result in a value of 1.0.

Each soil function was determined according to a given set of indicators or soil attributes. A given weight (Wi) was assigned to each soil indicator, according to its importance to the soil function (Table 1). This assignment was carried out through ad hoc consultation with researchers in the area, assuming that the sum of the weights of the indicators was equal to 1.

Table 1. Framework with functions and indicator weights for the determination of the Soil Quality Index of the Ultisol of the Coastal Tablelands of Sergipe State.

Soil Function	Function weight (Wf)	Indicator	Indicator weight (WI)
Receive, store and supply water	0.2	MGD	0.1
		Bulk density	0.2
		Macroporosity	0.15
		Microporosity	0.15
		WIR	0.1
		SOM	0.1
		Available water/TP	0.2
Promote root growth	0.2	MGD	0.1
		Bulk density	0.1
		Soil resistance	0.1
		Macroporosity	0.1
		SOM	0.1
		pH	0.034
		Al	0.033
		H + Al	0.033
		N stock	0.1
		CEC	0.1
		Base saturation (v)	0.075
		Al saturation (*m*)	0.075
		Sum of bases (SB)	0.05
Store, supply and cycle nutrients	0.2	pH	0.05
		Al	0.05
		H + Al	0.05
		N stock	0.1
		CEC	0.15
		Base saturation (v)	0.1
		Al saturation (*m*)	0.1
		Sum of bases (SB)	0.1
		SOM	0.15
		Microbial activity	0.15
Promote biological activity	0.2	Available water/TP	0.15
		Microporosity	0.075
		Macroporosity	0.075
		pH	0.1
		SOM	0.15
		K	0.02
		Ca	0.02
		Mg	0.02
		Available P	0.02
		N stock	0.02
		Microbial activity	0.15
		Biomass carbon	0.1
		Biomass nitrogen	0.1
Maintain homeostasis	0.2	Microbial activity	0.25
		qCO_2	0.25
		*q*MIC	0.5

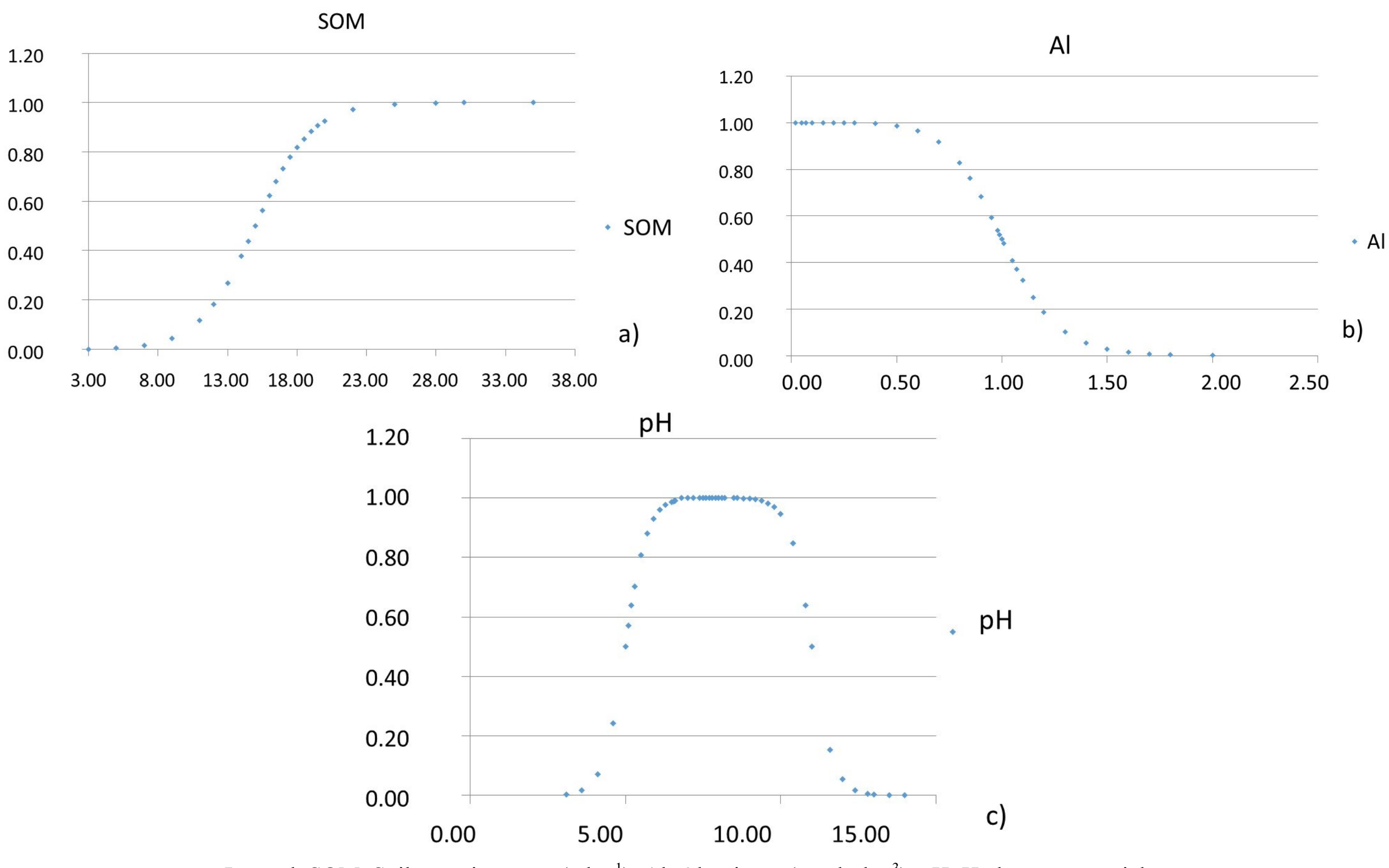
Legend: MGD: mean geometric diameter; WIR: Water infiltration rate; SOM: soil organic matter; TP: Total Porosity; qCO_2: metabolic quotient; qMIC: microbial quotient.

Due to the different units of measurement of the evaluated indicators, they were standardized through the transformation into scores (IS), whose values ranged from 0 to 1, through standardized non-linear scoring functions developed for engineering systems by Wymore (1993) using 3 types of curve (more is better; less is better and optimal) (Equation 1).

$$WWi = \frac{1}{1 + [\frac{B-L}{X-L}]^{2S(B+X-2L)}} \qquad (1)$$

where B is the critical value or base limit of the indicator, whose standardized score is 0.5; L is the initial value or lower limit that the indicator can express, even accepting 0; x is the value of the indicator obtained in the sample; and S is the slope of the curve tangent to the point corresponding to the critical value or base limit.

Limiting and optimum values used as parameters for the standardization of the indicators, as well as the type of the curve, were established through ad hoc consultation or specialized publications, as suggested by Karlen and Stott (1994). For data with specific limits, such as the microbiological ones, or due to the lack of information for sandy soil in tropical regions, the average values obtained in the 12 treatments and in the Native Forest were adopted. Based on the scoring curves of standardized scores, the soil indicators such as bulk density, PR, Al, Al + H, m, and qCO_2 were scored using a “less is better” curve. MGD, AW/TP, P, K, Ca, Mg, SOM, CEC, v, SB, N stock, biomass C, biomass N, and qMIC were scored using a “more is better” curve. Finally, Ma, Mi, WIR, pH, and microbial activity were scored using an “optimum value” curve. The score curves are shown in Figure 2.



Legend: SOM: Soil organic matter ($g.kg^{-1}$); Al: Aluminum ($cmol_c.dm^{-3}$); pH: Hydrogen potential.

Figure 2. Types of standardized point function generated during the transformation of the observed values. a) More is better; b) less is better; c) Optimum value.

The SQI was determined after the multiplication of the ISs by the relative weight of each indicator (Wi) for that given function. The sum of these multiplications constituted the score function (SF) - Equation 2. This SF was multiplied by the weight assigned to the soil function, giving rise to a sub-index for each function, which together constitute the SQI - Equation 3, with values between 0 and 1; the closer to 0, the lower the SQI (CHAER, 2001).

$$SF = \sum(Wi's * IS's) \quad (2)$$

$$SQI = \sum(EF's * PF's) \quad (3)$$

The SQI values were multiplied by 100 to provide a range of values between 0 and 100, instead of 0 to 1, making it easier to understand. For comparison and evaluation of the SQI, the measurement scale proposed by Souza (2005) was used: excellent when SQI is greater than 71 (SQI> 71); regular, when 51 <SQI <71 and bad, when SQI is equal to or lower than 50 (SQI ≤ 50). In addition to the construction of the SQI and evaluation according to Souza (2005), analysis of variance (ANOVA) was also performed, with the means of the treatments decomposed and compared by the Tukey test at 5% probability level with the aid of the STATA® software (STATACORP, 2017). The treatments were also compared with the soil under Native Forest by Dunnett's test, at 5% probability level in the same statistical program.

RESULTS AND DISCUSSION

The SQI values as well as the contribution of the soil functions used for the construction of the SQI are shown in Table 2. In general, the highest SQI values were observed in the sustainable soil tillage systems (MT and NT), whereas the lowest values were observed in the CT system. These results indicate that, in tropical regions, soil management systems that cause minimal or no disturbance in the soil and allow the maintenance of plant residues on the soil surface are important to reduce soil and environmental degradation (LAL, 1999). In addition, management systems that combine sustainable soil practices with previous crops improve soil structure, reduce variation in water content and temperature, increase the quantity and diversity of plant residues in order to increase organic matter content, and contribute to the development of strong and deep root system (PRANDO et al., 2010). Thus, the adoption of these management practices is very important to the development of sustainable agriculture.

Table 2. Soil Quality Index (SQI) and percent contribution of each soil function to the SQI of the dystrophic Ultisol cultivated with corn under different management systems and cover crops in the Coastal Tablelands of Sergipe State. Results from the Dunnett Test at 5% probability level are presented.

Management system	Cover crop	Soil function (%)					SQI
		1	2	3	4	5	
Conventional tillage	Cowpea	19.2	17.4	14.8	20.2	28.3	66.6 ABC
	Sunn hemp	20.8	19.8	16.1	18.1	25.1	59.7 BCD
	Pigeon pea	20.6	19.4	20.6	20.8	18.5	56.5 D
	Millet	19.5	18.4	18.3	22.7	21.1	61.7ABCD
	Mean	20.0	18.7	17.4	20.4	23.4	61.0 b
Minimum tillage	Cowpea	22.5	20.1	21.5	25.1	10.8	58.9 CD
	Sunn hemp	20.1	18.2	19.2	20.7	21.8	69.3 ABC
	Pigeon pea	18.8	18.2	19.4	23.7	19.9	70.7 AB
	Millet	21.9	21.9	21.9	20.4	13.9	61.5 ABCD
	Mean	20.7	19.5	20.4	22.4	16.9	65.1 ab
No-tillage	Cowpea	18.3	18.8	16.8	19.8	26.2	61.1 ABCD
	Sunn hemp	20.8	17.6	17.0	21.1	23.5	65.5 ABCD
	Pigeon pea	22.5	19.4	15.5	20.5	22.1	63.5 ABCD
	Millet	18.9	16.3	14.6	22.3	27.8	71.8 A
	Mean	20.1	18.0	16.0	21.0	25.0	65.5 a
Native forest	NF	25.6	18.0	11.9	20.8	23.6	67,1 ABC

CT - conventional tillage; MT - minimum tillage; NT - no-tillage.
Soil functions: 1- receive, store and supply water; 2- promote root growth; 3-store, supply and cycle nutrient; 4- promote biological activity; 5- maintain homeostasis.

Considering the main effects (tillage systems), the SQI values varied from 61.03 to 65.50 and, according to the scale proposed by Souza (2005), were classified as regular and excellent (Table 2). There was no significant difference between NT and MT systems; however, the NT system was significantly superior to the CT. These results can be attributed to the loss of the quality of the chemical, physical and microbiological properties of the soil, measured by soil functions, as expressed in Table 2, resulting from the intense turning of the soil characteristic of this management system.

As expected, the best SQI was observed under native vegetation, since this soil has a high SOM content and absence of soil disturbance (Table 3). The soil under native vegetation has a greater input of organic material in quantity and quality, due to the biodiversity of the native vegetation, combined with the constant deposition of litter with good nutritional quality, and the absence of soil disturbance stimulates microbial activity and degradation of organic material (OLIVEIRA et al., 2017; SOUZA, 2018; OLIVEIRA et al., 2020 and FAGUNDES et al., 2021), cycling nutrients and altering soil structure.

Table 3. Chemical soil quality indicators of the dystrophic Ultisol cultivated with corn under different management systems and cover crops in the Coastal Tablelands of Sergipe State.

Management system	Cover Crop	K	Mg	Al	H+Al	m	SOM	N stock
		mg kg^{-1}		cmol$_c$.dm^{-3}		%	g kg^{-1}	kg ha^{-1}
CT	Cowpea	31.3 AB	0.54 D	0.05 CE	1.73 ABC	3.17 BE	10.6 C	712 BCD
	S. hemp	28.9 B	0.83 ABC	0.04 DE	1.39 BC	1.94 CF	12.0 BC	658 D
	Pigeon pea	31.9 AB	0.81 ABC	0.06 BCE	1.30 BC	2.44 EF	11.9 BC	798 ABCD
	Millet	42.9 A	0.66 CD	0.05 BCE	1.64 ABC	2.73 E	12.9 ABC	803 ABCD
	Mean	33.7 a	0.71 b	0.05 b	1.51 ab	2.57 b	11.9 c	743 b
MT	Cowpea	21.9 B	0.74 ABCD	0.04 DE	1.48 BC	1.89 CF	14.1 AB	888 AB
	S. hemp	26.4 B	0.94 AB	0.05 CE	1.50 BC	2.36 EF	15.7 A	968 A
	Pigeon pea	24.4 B	0.94 AB	0.04 D	1.37 BC	1.46 D	14.5 AB	902 AB
	Millet	26.9 B	0.99 A	0.04 D	1.39 BC	1.44 D	14.8 AB	898 AB
	Mean	24.9 b	0.65 b	0.04 c	1.43 b	1.78 c	14.8 a	914 a
NT	Cowpea	25.9 B	0.69 BCD	0.04 DE	1.43 BC	1.61 CD	12.7 ABC	668 CD
	S. hemp	32.4 AB	0.67 CD	0.08 ABC	1.91 AB	4.14 AB	13.9 ABC	854 ABCD
	Pigeon pea	33.2 AB	0.55 D	0.11 A	2.08 A	5.92 A	13.5 ABC	8661 ABC
	Millet	29.9 AB	0.69 BCD	0.09 AB	1.64 ABC	4.74 AB	13.1 ABC	823 ABCD
	Mean	30.7 ab	0.90 a	0.08 a	1.77 a	4.10 a	13.3 b	803 b
Reference value								
Native forest		21.6	0.36	0.43	3.59	28.7	21.1	943

Mean followed by the same capital letter in a column do not show a statistically significant difference at 5% probability level by the Tukey test. Means followed by the same lowercase letter in a column do not show a statistically significant difference at 5% probability level by the Tukey test.

These results corroborate those found by Carneiro et al. (2009) and Fernandes et al. (2013), who found higher levels of SOM in forest soils when compared to agricultural systems. Melo Filho, Souza and Souza (2007) used the methodology proposed by Karlen and Stott (1994) and obtained a SQI of 46.2 for a Latossolo Amarelo (Oxisol) under native forest in the Coastal Tablelands of Bahia state. Zeraatpisheh et al. (2020) used the same method to assess soil quality in a deforested area and an intensively cultivated land and found a decrease in the SQI in the cultivated area.

Freitas et al. (2012) investigated the quality of Oxisols and reported SQI values ranging from 48 to 73 under native vegetation and from 44 to 74 under eucalyptus plantation. However, Mota (2015) evaluated the quality of Oxisols cultivated with citrus in the Coastal Tablelands of Bahia state – northeast of Brazil and observed better SQI values as compared with the same soil under native vegetation. Fernandes et al. (2013) also found better values of the SQI in an Ultisol under different uses and management systems as compared to the native soil. Finn, Yu and Penton (2020) reported similar results.

Some anthropogenic activities cause soil degradation in cultivated areas, resulting in reduction in soil quality. Therefore, the adoption of sustainable agricultural practices can improve soil quality and increase agricultural yield (DUBEY et al., 2020). However, under some climatic conditions such as in the tropics, sandy soils are particularly exposed to degradation due to high rates of decomposition of organic residues, resulting in lower carbon storage. The adoption of sustainable tillage systems in those regions is a great challenge, and some time is required to obtain better results (OLIVEIRA et al., 2017; OLIVEIRA et al., 2020). That seems to be the case of our study, in which, after 17 years, the increase in soil quality in the no-tillage system is still minor.

Even though there was no difference in the SQI between the management systems and the native forest soil, a comparison using the Dunnett's test at 5% showed that, when pigeon pea was the cover crop in the conventional tillage system, the SQI was the lowest (56.5) (Table 2), classified as regular according to Souza (2005).

Considering the SQI calculated for each individual function and used to generate the final SQI, it is noticed that, although all of them have the same weight (each contribute with 20% of the total value of the index, with 20 being the maximum absolute value), in general, function 5 (Maintaining Homeostasis) was the most influential, that is, its values were closer to the maximum absolute value (14.39). Thus, we can consider that this function has a greater influence on the SQI, being responsible, on average, for 22.24% of the observed value. The second most influential function was function 1 (Receiving, storing and supplying water), which was responsible for 21.68% of the SQI, followed by function 4 (Promoting biological activity) with 21.17% (Table 2).

Soil functions 4 and 5 are related to the microbiological properties, which are susceptible to changes caused by anthropogenic activities as well as the physical and chemical quality of the soil (MORRIS, 2007). Thus, considering the observed values (Table 2), it seems that the soil microbiota was not significantly altered. However, Function 3 (Storing, supplying and cycling nutrients) was less involved in the SQI, followed by Function 2 (Promoting root growth), showing that the soil probably has chemical and physical limitations to plant development, regardless of the management system. Our results agreed with those of Souza, Souza and Souza (2003), who also observed smaller contribution of Function 3 to the SQI of an *Argissolo Amarelo Distrófico* (Ultisol) cultivated with citrus in the Coastal Tablelands of Bahia state. These results indicate what actions should be taken, in order to primarily improve the supply of soil nutrients, such as increasing the soil organic matter content.

Sobral et al. (2007) point out that the soils of Sergipe state are mostly of low natural fertility and reduced yield due to their parent material. Therefore, these soils need fertilization in order to become productive and economically viable. It is also associated with low levels of soil organic matter and low water and nutrient retention capacity (ANDRADE; FREITAS; LANDERS, 2010). All these characteristics were confirmed in the present study.

In addition, the poor contribution of Function 2 to the overall SQI is probably related to the high values of soil bulk density (1.53 to 1.76 g cm^{-3}) in the experimental area. Bulk density was 1.37 g cm^{-3} in native forest soil. For this soil, a critical limit of soil bulk density of 1.59 g cm^{-3} was adopted. Also, the Mechanical Resistance to Penetration in the experimental area varied from 0.53 to 1.09 kPa, whereas in the native forest soil this value was 0.31 kPa. Considering the adopted critical limit of 2.00 kPa, there was no physical limitation to root growth in the 0-0.10 m layer, justifying its small contribution to the construction of the SQI.

Lower bulk densities have been observed in soils under native forests, which are attributed to the higher levels of soil organic matter, as observed by Cardoso et al. (2013), as we found in this study. Similar results were also reported by Anjos et al. (1994), who studied the effects of crop systems in an Entisol. The authors found an increase in soil bulk density in the No tillage, Minimum tillage and Conventional tillage systems compared to the native forest soil. Camargo (2016), when studying soil quality under different management systems and using native vegetation as a reference, found higher bulk density values, working with a situation similar to the one of this work.

Soil function 1 accounted for 21.68% of the final SQI, showing that the soil had no water storage limitation. Among the indicators used to evaluate this function, the available water / total porosity ratio (17 to 27% for the management systems and 27% for the native vegetation) was higher than the critical limit of 12.50% (Table 4). These results suggest that there was adequate distribution of soil macro and micropores, allowing water infiltration, drainage and storage in the soil and proper plant growth.

Borges, Souza and Melo (2018) used the same method to determine the SQI of 11 profiles of different soils classes under irrigated banana (*Musa* spp.) cultivation in western Bahia and Northern Minas Gerais states and observed that, in the Ultisol, the greatest contributions to the values of the SQI resulted from function 4 (promote root growth). This discrepancy in the SQI in the same soil class in different Brazilian regions may be linked to the indicators selected to compose the soil functions in different studies, which can lead to different behavior and participation in the SQI.

Considering the conventional tillage system (CT), soil functions 2 and 3 were the most important to separate the effects between different cover crops. For soil function 3, microbial activity (1.82%), sum of bases (3.51%) and soil organic matter (5.88%) were the least important indicators. For soil function 2, sum of bases (1.00%) and soil organic matter (3.34%) had the smallest participation. Santiago, Montenegro and Pinheiro (2018) evaluated the SQI in several experimental agricultural units and observed that, for the soil function responsible for nutrient supply and cycling, soil organic matter was one of the most remarkable indicators.

Table 4. Biological soil quality indicators and Physical soil quality indicators of the dystrophic Ultisol cultivated with corn under different management systems and cover crops in the Coastal Tablelands of Sergipe State.

Management system	Cover crop	MBC	qMIC	qCO_2	MA	MGD	WIR	RP
		ug g^{-1}	-	-	%	mm	$mm.h^{-1}$	KPa
CT	Cowpea	93.8 BCD	22.3 BC	4.78 DGF	15.5 ABC	2.02 B	12.0 D	1.31 A
	S. hemp	48.5 FG	12.0 EF	16.3 AB	11.8 DE	1.89 B	11.0 D	0.88 BCE
	Pigeon pea	59.7 DEF	15.4 CDF	5.20 EGF	12.2 CDE	2.48 A	13.5 D	0.92 BCE
	Millet	5 CDE	15.6 CDF	10.1 BC	12.4 CDE	1.85 B	6.00 F	1.09 AB
	Mean	69.1 b	16.3 b	9.08 a	13.0 b	2.05 a	10.6 b	1.05 a
MT	Cowpea	36.4 G	8.00 G	20.8 A	11.2 E	0.85 D	55.0 E	0.64 DE
	S. hemp	106 BC	12.0 EF	5.46 EGF	15.1 ABCD	1.61 BC	93.0 C	0.69 DE
	Pigeon pea	90.7 BCD	13.3 CEF	5.88 EF	13.4 BCDE	0.91 CD	36.0 ED	0.72 DE
	Millet	57.7 EF	11.4 E	12.7 ABC	14.2 BCDE	1.85 B	54.0 E	1.02 BCE
	Mean	72.7 b	12.0 c	11.2 a	13.5 b	1.30 b	59.5 b	0.77 b
NT	Cowpea	100 BC	16.7 CD	3.49 DF	20.4 A	1.33 BC	321 A	0.69 DE
	S. hemp	97.1 BC	15.2 DF	3.14 DH	17.7 AB	1.42 BC	57.0 E	0.76 CDE
	Pigeon pea	139 B	25.8 B	8.34 CE	17.8 AB	1.38 BC	72.0 EC	1.05 ABC
	Millet	325 A	60.8 A	2.02 H	21.3 A	1.27 BD	159 B	0.53 D
	Mean	165 a	29.7 a	4.25 b	19.3 a	1.35 b	152 a	0.70 b
Native forest		175	25.1	1.45	18.7	2.24	182	0.31

Mean followed by the same capital letter in a column do not show a statistically significant difference at 5% probability level by the Tukey test. Means followed by the same lowercase letter in a column do not show a statistically significant difference at 5% probability level by the Tukey test.

The CT-sunn hemp cultivation system showed low levels of soil organic matter (11.93 g kg^{-1}) when compared with the other tillage systems. Soil organic matter accounts for 56 to 82% of the CEC of tropical soils and contributes to the availability of nutrients for plants and microorganisms. Therefore, using sunn hemp as cover crop in the CT system is not the best option.

For the determination of the SQI in the MT system, soil function 5 (Maintaining Homeostasis) had the lowest contribution (Table 2 and Table 4), indicating that the microbial population was under stress, which could have influenced all other functions (CHAER, 2001). Millet and cowpea as cover crops in the MT system had the lowest results, with metabolic quotient scoring less than 0.10% and contributing the least to the partial SQI. Conversely, microbial activity contributed with 51.00 and 78.00%, respectively.

Higher soil organic matter content promotes greater biological activity on the soil surface, which improves soil structure and stimulates plant growth and development (SILVA; REINERT; REICHERT, 2000; OLIVEIRA et al., 2020). Such result can be observed in the present study, in which MT-millet and MT-cowpea systems increased soil organic matter (14.83 and 14.13 g kg^{-1}, respectively) when compared to the other crop systems, justifying the high participation of microbial activity in the determination of the partial SQI.

In the NT system, the soil function 3 was the least influential in the final SQI, whereas soil function 5 was the most important (Table 2), indicating a great role of the soil microbiota. However, despite being under no-tillage system, the soil still has chemical limitations due to its parent material. The best cover crop for the NT system in this soil was millet (SQI = 71.8). Vezzani and Mielniczuk (2011) pointed out that soils that have been under NT system for long periods of time normally have a greater degree of complexity in their structure, generating properties that can benefit their functioning for plant development.

Silva (2010) evaluated the SQI of a soil under NT systems for different periods of time (6, 10 and 15 years) and compared the results with those obtained for a native forest soil. The authors observed that the oldest area under NT had the highest SQI, indicating a long-time effect of conservation practices, which corroborates our results.

In the NT system, there was a great contribution of the microbial quotient to the partial SQI composition of the soil function 5 (50.00%); conversely, the indicators SB (1.07%), CEC (5.42%) and v value (7.21%) were the least important in the soil function 3. Intermediate values of exchangeable bases, T, SB, SOM and pH and high absolute value of Al^{3+} were observed. Melo Filho, Souza and Souza (2007) evaluated the SQI of an Oxisol in the Coastal Tablelands of Bahia and found that the nutrient supply function was the most limiting factor, with great contribution of CEC (94.4%), which differed from our results.

In CT system, the SQI of the pigeon pea treatment (56.50) was significantly different from that of the cowpea treatment (66.60). The same trend was observed between these two cover crops in the MT treatment. In the NT system, there was no statistical difference between the evaluated plants, with the highest absolute value observed in the millet cover crop (71.80), which, according to Souza (2005), is classified as an excellent SQI (Table 2).

There was no statistically significant difference when evaluating only the effect of the previous crops alone, disregarding the effect of the soil management system adopted. It is worth pointing out that Millet was the previous crop that yielded the best value of mean SQI (65.00) to the soil when compared to the other plants evaluated in this study (Cowpea 62.20; Sunn hemp 64.83; Pigeon pea 63.57). Millet is a tropical climate plant with low water and nutritional requirements when compared to corn for example. It has high nutrient cycling capacity, rapid growth and high biomass production, which in tropical regions with nutritional limitations, such as Coastal tablelands, presents itself as a viable alternative to the production of phytomass and consequently of MOS (CAMPOS; ALMEIDA; FERREIRA, 2012). In addition, millet can improve the soil physical conditions due to its abundant root system.

Comparing the results of the experimental area with those of the native forest soil (Table 2 and Figure 3), it was observed that there was a negative change in soil quality, regardless of the management system (CT, NT and MT). Even though the SQI values of MT-sunn hemp (69.32), MT-pigeon pea (70.65) and NT-millet (71.80) were high, they did not differ from that of the forest soil (67.09). The lowest SQI was observed in the CT-pigeon pea system (56.5) (Table 2).

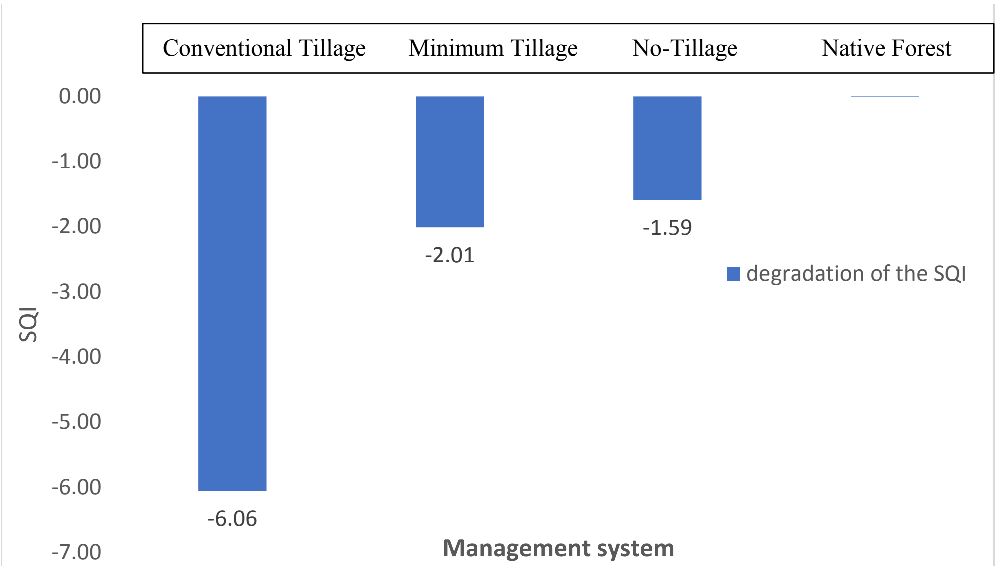


Figure 3. Changes in the SQI of the dystrophic Ultisol under different management systems and cover crops for 17 years in the Coastal Tablelands of Sergipe.

In the forest soil and in the experimental area, function 3 was the least important for the SQI, whereas function 1 seemed to have played a major role (Table 2), demonstrating, as explained in the literature, that in its natural state, this soil has chemical limitations. Such conditions can be improved by management practices as in the MT-sunn hemp, MT-pigeon pea and NT-millet, indicating that soil management can positively alter its characteristics, since in these cultivation systems the SQI was superior to that found for the soil under native vegetation.

The agricultural activities practiced in the Coastal Tablelands of Sergipe must take into consideration the adoption of a regular fertilization program due to the low natural fertility of the soils as well as limitations in the transport of nutrients to the roots, as highlighted by Cintra (2011). Management practices that result in positive changes in chemical properties such as increased nutrient availability lead to improved plant growth and yield (MONTEIRO, 2012; OLIVEIRA et al., 2017; LOPES et al., 2021).

The great challenge of this century regarding the agricultural activities worldwide is the production of food and fiber to meet the demand of a growing population and, at the same time, preserve the environment through the sustainable management of natural resources. Therefore, evaluations of representative soils for a certain agricultural crop and/or agricultural region, such as the Coastal Tablelands of Sergipe State or in the Northeast of Brazil (OLIVEIRA et al., 2017; OLIVEIRA et al., 2020; LOPES et al., 2021), as well as the monitoring of soil quality over time, are considered very important to support agricultural production and face climate changes (VASU et al., 2020; CAVALCANTE et. al., 2021). The results obtained for the SQI reflected the contributions of the physical, chemical and microbiological indicators, determined individually and later integrated through the model used.

CONCLUSIONS

The NT and CT systems promoted, respectively, the highest and lowest SQI values due to the intrinsic practices adopted in the present study, after 17 years.

The soil management systems evaluated in the present study degraded the quality of the soil when compared to the forest soil, because of the edaphoclimatic conditions in the tropical region.

The no-tillage cultivation system associated with the previous millet crop promoted the highest SQI levels, whereas the lowest level was observed in the conventional tillage associated with pigeon pea, contrasting the effect of conservation practices enhanced with positive effects by previous crops.

According to the measurement scale used in the present study, the NT system associated with millet provides great values of SQI, whereas the other cultivation systems evaluated had values classified as regular.

Soil Quality Index (SQI) assessment proved to be sensitive and reliable, constituting an important tool for evaluating agricultural practices aiming at sustainable production with environmental balance and maintaining efficient conditions in the Coastal Tablelands of Sergipe.

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