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Abiotic Soil Health Indicators that Respond to Sustainable Management Practices in Sugarcane Cultivation

Camila Viana Vieira Farhate [1,2,*], Zigomar Menezes de Souza [2], Maurício Roberto Cherubin [3], Lenon Herique Lovera [2], Ingrid Nehmi de Oliveira [2], Marina Pedroso Carneiro [2] and Newton La Scala Jr. [1]

1 School of Agricultural and Veterinarian Sciences, Department of Exact Sciences, Jaboticabal, São Paulo State University, São Paulo 14884-900, Brazil; la.scala@unesp.br
2 School of Agricultural Engineering, University of Campinas, Av. Cândido Rondon, 501, Barão Geraldo, Campinas, São Paulo 13083-875, Brazil; zigomarms@feagri.unicamp.br (Z.M.d.S.); lhlovera@gmail.com (L.H.L.); ingrid.nehmi@gmail.com (I.N.d.O.); marinapedrosoc@yahoo.com (M.P.C.)
3 "Luiz de Queiroz" College of Agriculture, Department of Soil Science, University of São Paulo, Piracicaba, São Paulo 13418-900, Brazil; cherubin@usp.br
* Correspondence: camilavianav@hotmail.com; Tel.: +55-19-98402-0683

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Abstract: Soil quality (SQ) assessments are fundamental to design more sustainable land uses and management practices. However, SQ is a complex concept and there is not a universal approach to evaluate SQ across different conditions of climate, soil, and cropping system. Large-scale sugarcane production in Brazil is predominantly based on conventional tillage and high mechanization intensity, leading to SQ degradation. Thus through this study, we aim to assess the impact of sustainable management practices, including cover crops and less intensive tillage systems, in relation to the conventional system, using a soil quality index composed of abiotic indicators. Additionally, we developed a decision tree model to predict SQ using a minimum set of variables. The study was conducted in the municipality of Ibitinga, São Paulo, Brazil. The experimental design used was in strips, with four cover crops and three tillage systems. We evaluated three sugarcane cultivation cycles (2015/16, 2016/17, and 2017/18 crops). To calculate the SQ index, we selected five abiotic indicators: macroporosity, potassium content, calcium content, bulk density, and mean weight-diameter of soil aggregates. Based on our SQ index, our findings indicated that the soil quality was driven by the production cycle of sugarcane. Although a reduction of soil quality occurs between the plant cane and first ratoon cane cycles, from the second ratoon cane there is a trend of the gradual restoration of soil quality due to the recovery of both the soil's physical and chemical attributes. Our study also demonstrated that the cultivation of sunn hemp and millet as cover crops, during the implementation of sugarcane plantation, enhanced soil quality. Due to the advantages provided by the use of these two cover crops, we encourage more detailed and long-term studies, aiming to test the efficiency of intercropping involving sunn hemp and millet during the re-planting of sugarcane.

Keywords: soil health management; minimum data set; principal component analysis; sustainable management; data mining

1. Introduction

Sugarcane is an important commodity in the Brazilian economy and the state of São Paulo is responsible for about 51% of all national production [1]. However, the mechanized harvesting system currently used in Brazilian sugarcane fields, which is characterized by the increasingly frequent use of larger and heavier machines, has intensified soil compaction and resulted in lower sugarcane yield [2–4]. In parallel, the use of conventional tillage has caused degradation of the soil's physical, chemical, and biological attributes [5] and accelerated global warming, by inducing greater losses of CO_2 to the atmosphere [6].

In this context, there is a need for a tool that provides information on the extent of soil degradation, as well as management practices with the potential for sustainable use [7,8]. Soil quality, in turn, refers to the capacity of a specific soil type to function, within the limits of the natural or managed ecosystem, to sustain the productivity of plants and animals, maintain or improve water and air quality, and support human health and housing [9]. Although currently the terms soil quality and soil health can be used as synonyms, the soil health is more focused on biotic attributes [10]. As the quality index proposed in this study includes only soil abiotic attributes, for this reason, we chose to use the term soil quality in all text.

One of the methods to monitor and assess soil quality is through individual changes in soil attributes [7]. However, the integration of individual indicator responses into a single index can facilitate the decision-making process related to soil management [11].

Currently, there are several studies that have evaluated the sustainability of the sugarcane expansion in Brazil [12–16]. However, all of these studies were carried out in areas without the use of cover crops and with conventional tillage, leaving several gaps on the effects of adopting conservationist practices during the planting of cane fields.

The minimum soil perturbation, permanent soil coverage by crop residues, and diversification of crops in the area are the basic principles of conservationist agriculture [5]. Thus, considering the difficulty of adopting no-till in sugarcane areas [3] and that minimum tillage is related to plowing the soil as minimum as possible, either as to the depth and/or the number of tillage operations [17], this management practice is believed to have potential to minimize the effects of soil degradation in areas cultivated with sugarcane [18]. As well, the use of cover crops during the period between cash crops can improve soil attributes, conserve organic matter, and control erosion and weeds [17,19]. However, as far as we know, there is still no tool that classifies soil quality in sugarcane crops and that enables quick and accurate decision making as to the management practices adopted in the area.

Machine learning is a subfield of computer science, in which intelligent algorithms are able to learn patterns from a set of training data and, through the generated models, it is possible to classify or estimate new cases [20]. Decision tree algorithms are commonly used in data mining, being an efficient non-parametric method for classification and regression [21]. Besides, its tree-like structure provides information that is easily understandable and interpretable [22].

Thus through this study, we aim to assess the impact of using cover crops and less-intensive tillage systems, in relation to the conventional system, using a single soil quality index composed of abiotic indicators. Moreover, we developed a decision tree model to predict soil quality index using a minimum set of variables. To this end, the following hypotheses were tested: (i) the use of cover crops and minimum tillage during the implementation of sugarcane areas increases soil quality in relation to the conventional system; (ii) use of decision tree to predict soil quality using soil abiotic attributes (i.e., physical and chemical) will provide a predictive model with high precision and accuracy.

2. Material and Methods

2.1. Description and History of the Area

The study was conducted in an experimental area of approximately two hectares, located at the Santa Fé Biorefinery, in the municipality of Ibitinga, São Paulo, Brazil (21°83′43″ S, 48°87′50 W and 455 m above sea level). The region's climate is classified as tropical with a dry season (Aw) according to the Köppen climate classification [23] and the soil as an "Argissolo Vermelho distrófico típico" according to the Brazilian Soil Classification System (SiBCS) [24], with a sequence of horizons A, AB, and Bt, or as Ultisols [Udults] according to the Soil Taxonomy System [25]. The soil texture as classified as sandy loam for the 0.00–0.20 m layer and as sandy clayey loam for the 0.20–0.70 m layer, according to the classification proposed by the United States Department of Agriculture [26] (Table 1).

Table 1. Mean ± standard deviation for particle-size fractions, physical and chemical attributes of the experimental area, and soil texture classification.

Layers	Particle-Size Fraction			Texture *	Soil Horizon	
	Sand	**Silt**	**Clay**			
0.00–0.10	736 ± 17	97 ± 2	169 ± 14	Sandy loam	A	
0.10–0.20	694 ± 28	111 ± 2	195 ± 18	Sandy loam	A	
0.20–0.30	631 ± 28	102 ± 6	267 ± 17	Sandy clay loam	AB	
0.30–0.70	571 ± 59	107 ± 9	322 ± 58	Sandy clay loam	Bt	
	Physical Attributes					
	BD	**Pd**	**MaP**	**MiP**	**MWD**	**SRP**
0.00–0.10	1.55 ± 0.05	2.67 ± 0.04	0.11 ± 0.07	0.30 ± 0.05	1.94 ± 0.19	1.01 ± 0.26
0.10–0.20	1.61 ± 0.02	2.69 ± 0.03	0.14 ± 0.05	0.27 ± 0.02	1.83 ± 0.28	1.59 ± 0.59
0.20–0.30	1.66 ± 0.08	2.71 ± 0.07	0.11 ± 0.04	0.27 ± 0.05	1.28 ± 0.23	1.60 ± 0.36
0.30–0.70	1.51 ± 0.01	2.70 ± 0.01	0.10 ± 0.01	0.33 ± 0.01	0.67 ± 0.06	1.79 ± 0.63
	Chemical Attributes					
	pH	**P**	**Ca**	**Mg**	**K**	**TC**
0.00–0.10	4.67 ± 0.06	3.67 ± 0.58	0.97 ± 0.15	0.53 ± 0.12	0.25 ± 0.20	8.83 ± 0.12
0.10–0.20	4.80 ± 0.01	2.00 ± 0.01	1.00 ± 0.10	0.47 ± 0.06	0.08 ± 0.04	6.38 ± 0.36
0.20–0.30	4.93 ± 0.31	2.33 ± 0.58	1.03 ± 0.21	0.50 ± 0.10	0.04 ± 0.01	5.42 ± 0.71
0.30–0.70	5.13 ± 0.06	2.33 ± 1.15	1.33 ± 0.15	0.60 ± 0.10	0.03 ± 0.02	4.66 ± 0.29

* Classification established by the United States Department of Agriculture [26]; Sand, silt and Clay = $g \cdot kg^{-1}$; Layers = m; BD = bulk density ($Mg \cdot m^{-3}$); Pd = particle density ($Mg \cdot m^{-3}$); MaP = macroporosity ($m^3 \cdot m^{-3}$); MiP = microporosity ($m^3 \cdot m^{-3}$); MWD = mean weight diameter of soil aggregates (mm); SRP = soil resistance to penetration (MPa); pH = potential of hydrogen; P = phosphorus content ($mg \cdot dm^{-3}$); Ca = calcium content ($cmol_c \cdot dm^{-3}$); Mg = magnesium content ($cmol_c \cdot dm^{-3}$); K = potassium content ($cmol_c \cdot dm^{-3}$); TC = total carbon content ($g \cdot kg^{-1}$).

The study area was cultivated with brachiaria grass (*Urochloa sp*) for approximately 11 years and, in 2014, the pasture was removed to expand the areas cultivated with sugarcane. In this stage, a characterization of the physical and chemical attributes of the area was performed (Table 1). In addition, at the time of pasture conversion, 2.0 $Mg \cdot ha^{-1}$ of dolomitic limestone was applied with a plowing harrow up to 0.40 m deep, followed by a leveling harrow at 0.20 m depth.

In December 2014, three cover crops were planted: sunn hemp (*Crotalaria juncea* L.), IAC KR1 cultivar; millet (*Pennisetum glaucum* L.), BRS 1501 cultivar; biomass sorghum (*Sorghum bicolor* L.), BD (bulk density) 7607 cultivar; and one commercial crop: peanut (*Arachis hypogaea* L.), Runner IAC 886 cultivar. For sunn hemp and sorghum, the planting took place in rows by means of a no-till seeder using 25 and 10 $kg \cdot ha^{-1}$ of seeds, respectively. The peanut was planted using a four-row seeder using 110 $kg \cdot ha^{-1}$ of seeds. Millet was planted manually, due to the small size of the seed, in rows by means of a manual furrower and 18 $kg \cdot ha^{-1}$ of seeds.

After reaching the point of maximum flowering, the cover crops were sampled in an area of 2 m^{-2} per plot, in which the plants were cut close to the ground for dry mass analysis. A total of 5, 10, 11, and 21 $Mg \cdot ha^{-1}$ of dry matter were produced for peanuts, sunn hemp, millet, and sorghum, respectively. After sampling, the sunn hemp, millet, and sorghum plants were desiccated by applying 200 $L \cdot ha^{-1}$ of a compound composed of 6.0 $L \cdot ha^{-1}$ of a commercial product (CP) based on the active ingredient (ai) glyphosate + 70 $mL \cdot ha^{-1}$ of carfentrazone-ethyl (ai-based CP) + 1.0 $L \cdot ha^{-1}$ of mineral oil. The peanut crop was harvested mechanically with an MF 7140 140 HP 4 × 4 tractor and Double Master peanut harvester.

Sugarcane was planted mechanically in April 2015 with a CTC 4 sugarcane cultivar. On that occasion, planting fertilization was performed with the application of 300 $kg \cdot ha^{-1}$ of NPK fertilizer (10-51-00). In the plots without cover crops (control), tillage used two light harrows. In addition, three other types of tillage were carried out: (i) no-tillage (NT); (ii) subsoiling at 0.40 m depth (MT); and (iii) deep subsoiling at 0.70 m depth (MT/DS). For the first, no-tillage was carried out before planting sugarcane and, for (ii) and (iii), operations were carried out with a 5-tyne subsoiler, at different operating depths.

2.2. Experimental Design

The experimental design used was in strips, with four cover crops (peanuts, sunn hemp, millet, and sorghum) and three tillage systems (no-tillage, subsoiling at 0.40 m depth, and deep subsoiling at 0.70 m depth). For comparison purposes, a control treatment was considered as a reference, without cover crops, and with conventional tillage for planting sugarcane. Each treatment was replicated three times. Table 2 shows the treatments in detail along with the levels of the factors described above.

Table 2. Description of the treatments evaluated in the study area, located in Ibitinga, São Paulo, Brazil.

Cover Crops	Soil Tillage Systems
Peanut	No-tillage (NT) Subsoiling at 0.40 m (MT) Deep subsoiling at 0.70 m (MT/DS)
Sunn hemp	No-tillage (NT) Subsoiling at 0.40 m (MT) Deep subsoiling at 0.70 m (MT/DS)
Millet	No-tillage (NT) Subsoiling at 0.40 m (MT) Deep subsoiling at 0.70 m (MT/DS)
Sorghum	No-tillage (NT) Subsoiling at 0.40 m (MT) Deep subsoiling at 0.70 m (MT/DS)
Control—Sugarcane planted under conventional tillage *	

* Sugarcane planted without cover crops and with conventional tillage. This treatment is the control treatment to assess the effect of management practices in the area under sugarcane cultivation.

2.3. Soil Sampling and Laboratory Analysis

Soil samplings were carried out during the characterization of the pasture area, at the end of the plant cane production cycles (2015/16 crop) (before the harvester traffic), at the end of the first ratoon cane production cycle (2016/17 crop) (cumulative traffic of two sequential harvests), and at the end of the second ratoon cane production cycle (2017/18 crop) (cumulative traffic of three sequential harvests). For sugarcane, the samples were collected between the planting rows up to 0.70 m deep, subdivided into the 0.00–0.05, 0.05–0.10, 0.10–0.20, 0.20–0.30, and 0.30–0.70 m layers. Subsequently, in order to improve the interpretation of the results, the results were grouped according to the soil horizons, that is, A (0.00–0.20 m), AB (0.20–0.30 m), and Bt (0.30–0.70 m) (Figure 1). The soil physical and chemical attributes were analyzed, as described in Table 3.

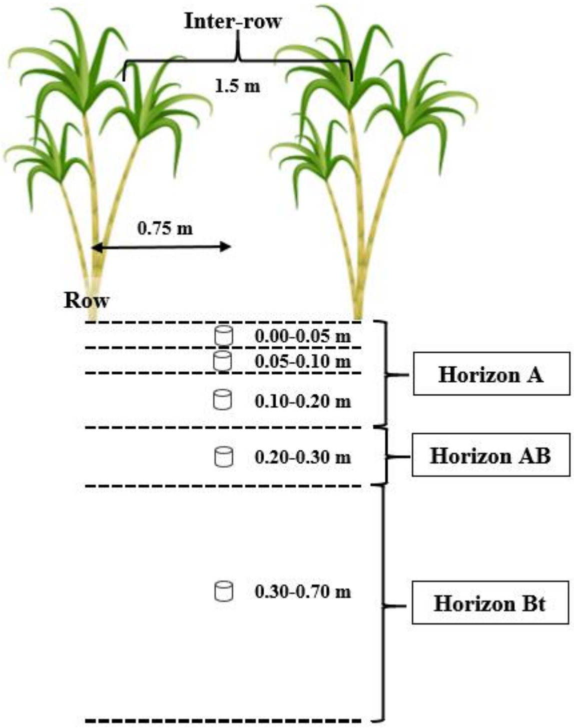


Figure 1. Soil sampling scheme and sequence of horizons in the study area, located in Ibitinga, São Paulo, Brazil.

Table 3. Soil physical and chemical indicators used to compose the database for calculating the soil quality index.

Indicator	Description	Abbreviation	Unit	Method
Physical	Bulk density	BD	$Mg{\cdot}m^{-3}$	[27]
	Macroporosity	MaP	$m^3{\cdot}m^{-3}$	[27]
	Microporosity	MiP	$m^3{\cdot}m^{-3}$	[27]
	Soil resistance to penetration	SRP	MPa	Electronic penetrometer *
	Tensile strength	TS	kPa	[28]
	Mean weight diameter	MWD	mm	[29]
Chemical	Active acidity ($CaCl_2$)	pH	-	[30]
	Phosphorus available (Resin)	P	$mg{\cdot}dm^{-3}$	[30]
	Exchangeable Potassium	K	$mmol_c{\cdot}dm^{-3}$	[30]
	Exchangeable Calcium	Ca	$mmol_c{\cdot}dm^{-3}$	[30]
	Exchangeable Magnesium	Mg	$mmol_c{\cdot}dm^{-3}$	[30]
	Potential acidity	H+Al	$mmol_c{\cdot}dm^{-3}$	[30]
	Total carbon	TC	$g{\cdot}kg^{-1}$	[31]

* electronic penetrometer, model MA 933, MARCONI brand, with a tip of 4.0 mm and with a constant speed of penetration of 10 mms^{-1}.

2.4. Soil Quality Index

The soil quality index was prepared in three stages, as described by Andrews et al. [32], and proceeded by Cherubin et al. [15], these stages being the selection of soil quality indicators, the transformation of the values of the indicators, and integration of the indicators into a single soil quality index. For the selection of indicators, we used principal component analysis (PCA), where only principal components with eigenvalues >1 were selected, according to criteria of Kaiser [33].

Then, for each principal component, we selected the indicator with the highest load value and those with values up to 10% below this maximum value. For those cases where more than one indicator was retained in a principal component, a correlation between them was checked and, if positive ($p < 0.05$), only the one with the highest load value was selected to compose the soil quality index, in order to avoid redundancy.

In the next stage, the soil physical and chemical indicators mean values were normalized on a scale without unit ranging from 0 (worst) to 1 (best soil physical quality). Data transformation was performed using a linear conversion. First, the indicators were classified into ascending or descending order, depending on whether a higher value was considered "good" or "poor" in terms of soil quality. For the indicators that followed the "less is better" score curve, the lowest value observed (in the numerator) was divided by each observation (in the denominator) so that the lowest value observed received a score of 1. For the indicators that followed the "more is better" score curve, each observation was divided by the highest value observed, so that the highest value observed received a score of 1.

Finally, the indicators scores were integrated into a single index considering a weighted additive approach as presented in Equation (1):

$$\mathrm{SQI} = \sum_{i=1}^{n} \mathrm{WiVi} \tag{1}$$

where SQI = soil quality index; n = number of indicators integrated into the index; Vi = normalized indicator value, ranging from 0 to 1; Wi = indicator score obtained according to the proportional variation explained by each principal component (that is, % of variance explained by each component divided by the total accumulated variance of all selected components).

2.5. Categorization of the Soil Quality Index

To determine different soil quality levels, the result obtained for each treatment was categorized into three classes, low, medium, and high, according to the methodology used by Chaves et al. [34], where the limits of each class were calculated using Equations (2)–(4), with the distribution obtained for each class in Table 4.

$$\mathrm{SQI_i} \geq \mathrm{E[SQI]{+}0.5\ s[SQI]} \qquad \text{High soil quality} \tag{2}$$

$$\mathrm{E[SQI]{-}0.5\ s[SQI]} \leq \mathrm{SQI_i} < \mathrm{E[SQI]{+}0.5\ s[SQI]} \qquad \text{Medium soil quality} \tag{3}$$

$$\mathrm{SQI_i} < \mathrm{E[SQI]{-}0.5\ s[SQI]} \qquad \text{Low soil quality} \tag{4}$$

where $\mathrm{SQI_i}$ = soil quality index of the soil of treatment i; E[SQI] = global mean of the SQI of all treatments; s[SQI] = standard deviation of the SQI of all treatments.

Table 4. Soil quality distribution according to the high, medium, and low classes and their corresponding limits, based on our dataset.

Class	Limits
High	≥ 1.52
Medium	1.34 ≤ SQI < 1.51
Low	<1.33

2.6. Decision Tree Induction and Generated Model Validation

For the induction of the decision tree model, we used the J48 algorithm, present in the Weka 3.6 software, which is a version of the C4.5 decision tree construction algorithm introduced by Quinlan [35]. The production cycle, cover crops (peanuts, sunn hemp, millet, and sorghum), tillage systems (NT, MT, and MT/DS), and the categorized soil quality index (high, medium, and low) were used as input parameters.

To assess the quality of a generated model, we used cross-validation with 10 random partitions of the training set, which are mutually exclusive. In addition, we used three metrics: (i) hit rate (accuracy); (ii) the number of rules generated, which are generally associated with the ease of interpretation of the model; (iii) the Kappa statistic, which is a measure of agreement between the classes predicted and observed by the classifier [36].

2.7. Statistical Analysis

Changes in soil quality index induced by the treatments (cover crops and tillage) and the control were determined by Dunnett's test ($p < 0.05$), implemented in the Minitab 19 software.

3. Results

3.1. Selection of Indicators

The results of the principal component analysis performed to select a minimum data set and calculate the soil quality index are shown in Table 5. Following the Kaiser's criterion (components with eigenvalues >1), we selected only five principal components, which together explained 71.61% of the total variance of the original data.

Table 5. Selection of a minimum data set for calculation of soil quality index through principal component analysis.

	Principal Components				
	PC1	**PC2**	**PC3**	**PC4**	**PC5**
Eigenvalues	2.58	2.25	1.96	1.49	1.03
Variance (%)	19.84	17.27	15.09	11.49	7.91
Cumulative (%)	19.84	37.12	52.21	63.70	71.61
Indicator	**Eigenvectors**				
BD	−0.42	0.35	−0.17	**0.67**	−0.20
MaP	**0.82**	0.01	−0.19	−0.28	0.24
MiP	−0.61	−0.32	0.40	−0.27	−0.16
SRP	−0.53	0.29	−0.07	0.36	0.20
TS	−0.49	0.18	0.22	0.12	0.34
MWD	−0.21	0.25	0.11	−0.19	**0.81**
P	0.09	**0.70**	−0.31	−0.37	−0.18
pH	0.49	0.33	0.61	0.30	0.00
K	0.17	**0.78**	−0.26	0.01	−0.09
Ca	0.07	0.29	**0.75**	−0.10	−0.06
Mg	−0.08	0.19	**0.69**	−0.30	−0.19
H+Al	−0.60	−0.20	−0.31	−0.49	−0.07
TC	−0.36	0.69	−0.09	−0.38	−0.10

BD = bulk density; MaP = macroporosity; MiP = microporosity; SRP = soil resistance to penetration; TS = tensile strength; MWD = mean weight diameter of soil aggregates; P = phosphorus; pH = active acidity; K = potassium; Ca = calcium; Mg = magnesium; H+Al = potential acidity; TOC = total carbon. The values in bold and underlined are the indicators selected by the principal component analysis to compose the soil quality index. Values only in bold were selected because the factor loading value was within 10% of the highest values under the same principal component.

The first principal component explained 19.84% of the total variance and the indicator that obtained the highest load value was MaP (macroporosity, 0.82). The second principal component explained 17.27% of the total variance and the indicators K (potassium, 0.78) and P (phosphorus, 0.70) were selected by the principal component analysis. However, as both were correlated ($p < 0.05$) (Table 6), only K was considered for the calculation of soil quality index. As well as Ca (calcium, 0.75) for the third principal component, BD (0.67) for the fourth principal component, and MWD (mean weight diameter of soil aggregates, 0.81) for the fifth principal component. Thus, five indicators were selected to calculate the soil quality index: MaP, K, Ca, BD, and MWD.

Table 6. Pearson's correlation matrix (r) between the chemical and physical variables at depths of 0.00–0.70 m in the sugarcane field expansion area, cultivated with different cover crops and tillage systems.

	BD	**MaP**	**MiP**	**SRP**	**TS**	**MWD**	**P**	**pH**	**K**	**Ca**	**Mg**	**H+Al**	**TC**
BD	**1.00**												
MaP	−0.54 *	**1.00**											
MiP	−0.17 *	−0.63 *	**1.00**										
SRP	0.39 *	−0.37 *	0.08	**1.00**									
TS	0.20 *	−0.30 *	0.18 *	0.25 *	**1.00**								
MWD	−0.04	−0.06	0.06	0.17 *	0.19 *	**1.00**							
P	0.03	0.17 *	−0.21 *	0.05	−0.08	0.06	**1.00**						
pH	−0.03	0.17 *	−0.17 *	−0.09	−0.03	0.00	0.03	**1.00**					
K	0.21 *	0.12 *	−0.33 *	0.05	0.01	0.07	0.54 *	0.17 *	**1.00**				
Ca	−0.07	−0.03	0.14 *	0.01	0.07	0.10	0.00	0.46 *	0.03	**1.00**			
Mg	−0.09	−0.09	0.22 *	−0.06	0.16 *	0.04	0.03	0.28 *	−0.07	0.45 *	**1.00**		
H+Al	0.00	−0.24 *	0.32 *	0.11 *	0.13 *	0.05	0.05	−0.62 *	−0.19 *	−0.17 *	−0.01	**1.00**	
TC	0.15 *	−0.18 *	0.06	0.23 *	0.18 *	0.20 *	0.51 *	−0.10	0.41 *	0.13 *	0.19 *	0.22 *	**1.00**

BD = Bulk density, MaP = Macroporosity, MiP = Microporosity, SRP = Soil resistance to penetration, TS = Tensile strength, MWD = Mean weight diameter of soil aggregates, P = Phosphorus, pH = Active acidity, K = Potassium, Ca = Calcium, Mg = Magnesium, H+Al = Potential acidity, TOC = Total carbon. * indicates the significant Pearson's correlation coefficients ($p < 0.05$). The values in bold indicate the variable correlated with itself.

The score of the variables used to compose the quality index ranged from 0.28 to 0.11 and presented the following order of influence: MaP > K > Ca > BD > MWD, with the soil quality index being obtained through the weighting below (Equation (5)):

$$\mathrm{SQI} = (\mathrm{MaP}*0.28) + (\mathrm{K}*0.24) + (\mathrm{Ca}*0.21) + (\mathrm{BD}*0.16) + (\mathrm{MWD}*0.11) \tag{5}$$

where SQI = soil quality index; MaP = Macroporosity; K = Potassium; Ca = Calcium; BD = Bulk density; MWD = Mean weight-diameter.

3.2. Soil Quality Index

The soil quality index obtained for the three agricultural years comprised in this study, plant cane, first and second ratoon cane cycle, distributed into horizons A, AB, and Bt, are shown in Figure 2. We observed higher soil quality during the plant cane cycle, reaching mean scores in the horizons A, AB, and Bt of 0.58, 0.51, and 0.44, respectively. However, machine traffic between the plant cane and first ratoon cane cycles caused a reduction in soil quality of around 25% in horizon A, 20% in horizon AB, and 11% in horizon Bt, mainly due to the degradation of physical attributes, such as MaP, BD, and MWD. Nevertheless, we observed a gradual restoration of soil quality from the second ratoon cane, where there was an increase in soil quality due to the recovery of both, soil physical and chemical attributes.

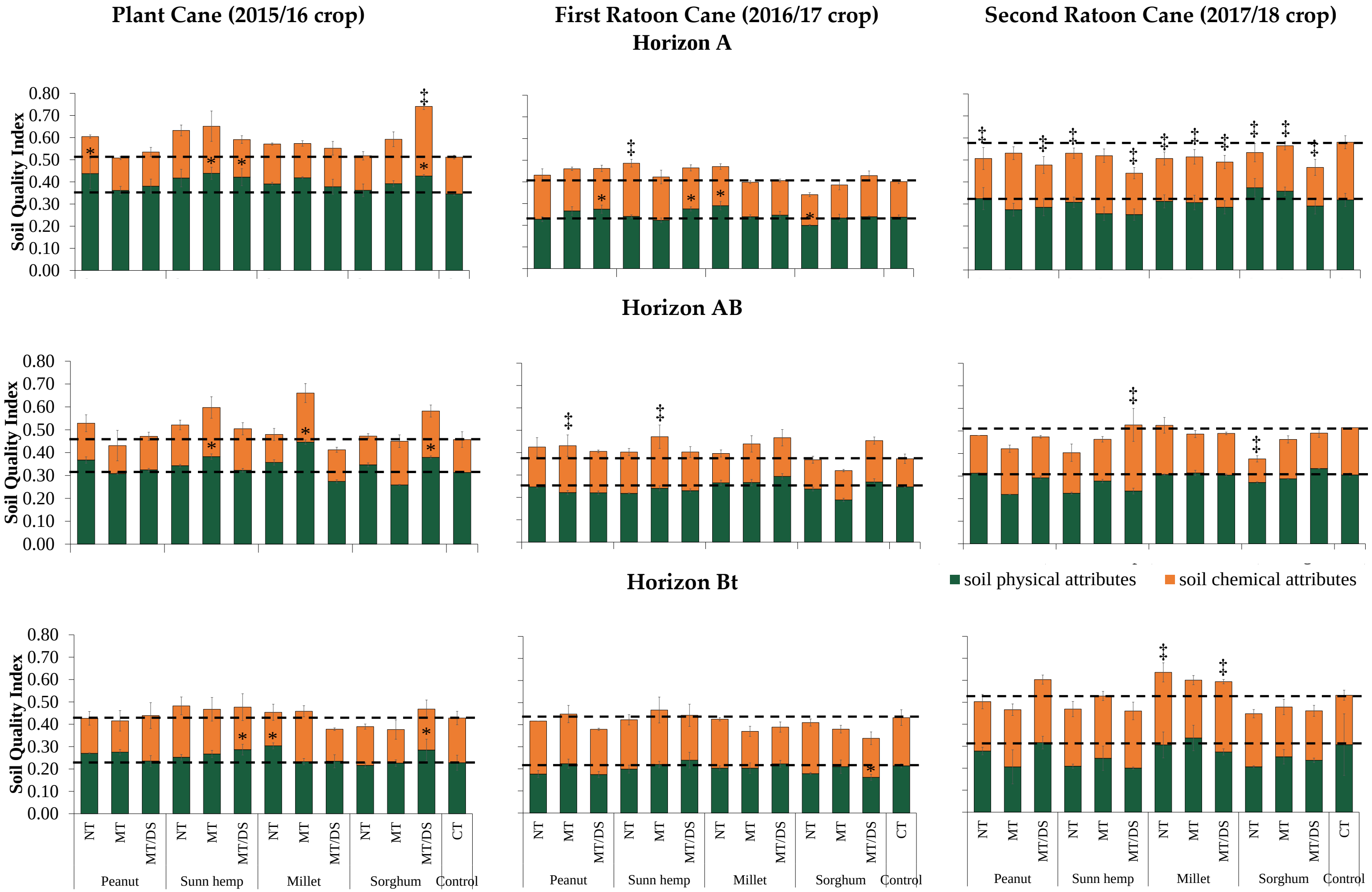


Figure 2. Soil Quality Index (SQI) distributed over horizons A, AB, and Bt in area of sugarcane cultivated under different cover crops and soil tillage systems. NT = no-tillage; MT = minimum tillage; MT/DS = minimum tillage with deep subsoiling; Control = sugarcane grown without cover crops and with conventional tillage. Horizontal dashed line indicates the value obtained by the control treatment. Bars indicate the standard deviation (n = 3). * ‡ indicate physical and chemical attributes significantly different from the control treatment by the Dunnett's test ($p < 0.05$), respectively.

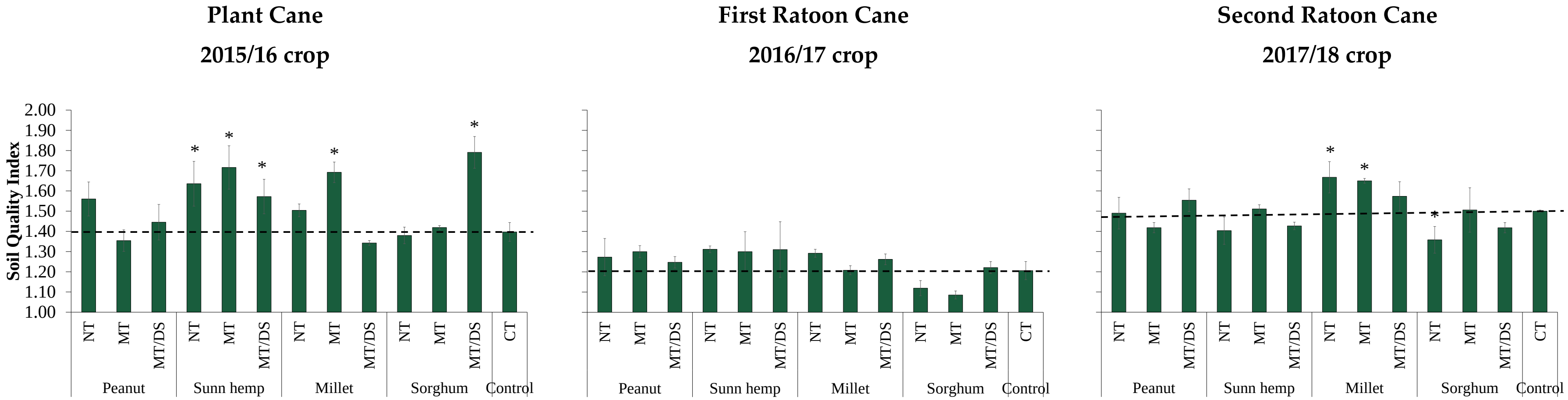
We emphasize that the association of cover crop and tillage system at the time of implementation of sugarcane plantation promoted changes in the quality of the different soil horizons. For example, during the plant cane cycle, the use of peanuts with NT showed higher physical quality than the control treatment (without cover crops and with conventional tillage). In addition, the use of sunn hemp with MT increased the quality of the soil's physical attributes by 26% in horizon A and 23% in horizon AB when compared with the control treatment. Furthermore, the treatment with the use of sunn hemp and MT/DS in horizons A and Bt, which promoted an increase of 20% and 27%, respectively, in soil quality in relation to the control.

On the other hand, grasses increased soil quality, especially in deeper horizons. During the plant cane cycle, the use of sorghum with MT/DS induced an increase in soil's physical quality in all horizons, when compared with the control treatment, with a simultaneous increase in the soil chemical quality in horizon A. For millet, during the same production cycle, there was an increase in the soil's physical quality with the use of MT millet (0.45) in horizon AB and NT millet (0.30) in horizon Bt. In addition, we observed that during the second ratoon cane cycle, the use of millet with NT and MT/DS showed higher soil chemical quality in horizon Bt (0.33 and 0.32, respectively) than the control treatment (0.23) (Figure 2).

The soil quality index obtained for the 0.00–0.70 m layer, in which all soil horizons were considered, also reflected a reduction in soil quality between the plant cane and first ratoon cane cycles, following a trend of increase from the second ratoon cane (Figure 3). In addition, during the plant cane cycle, regardless of the tillage system, the use of sunn hemp increased soil quality in relation to the control treatment. As well as the combinations of millet with MT and sorghum with MT/DS.

During the first ratoon cane, we found no significant differences between the management systems and the control treatment. However, during the second ratoon cane cycle, the use of millet with NT and MT showed scores equal to 1.67 and 1.65, respectively, being higher than the control, which scored 1.50 (increase around 11% and 9%, respectively). Nevertheless, we observed that the combination of sorghum with NT was detrimental to soil quality since it reduced by 9% in relation to the control treatment.

The model generated to predict soil quality, based on abiotic indicators, suggested that the production cycle has an important role in predicting this index since it was selected to compose the root of the decision tree. In total, 15 rules were generated (path from root to leaf), with the formation of three branches from the tree root, one for each cycle. For plant cane, regardless of the tillage system, the use of sunn hemp induced high soil quality. While for the use of peanut, millet, and sorghum, soil quality will depend on the tillage system used, as for peanut only NT will provide high soil quality, for millet only NT and MT, and for sorghum only MT/DS (Figure 4).



Plant Cane 2015/16 crop

First Ratoon Cane 2016/17 crop

Second Ratoon Cane 2017/18 crop

Figure 3. Overall Soil Quality Index (SQI), within the 0.00–0.70 m layer in the area of sugarcane cultivated under different cover crops and soil tillage systems. NT = no-tillage; MT = minimum tillage; MT/DS = minimum tillage with deep subsoiling; Control = sugarcane grown without introduction of cover crops and with conventional tillage. * indicate significantly different value from the control treatment by the Dunnett's test ($p < 0.05$). Bars indicate the standard deviation (n = 3).

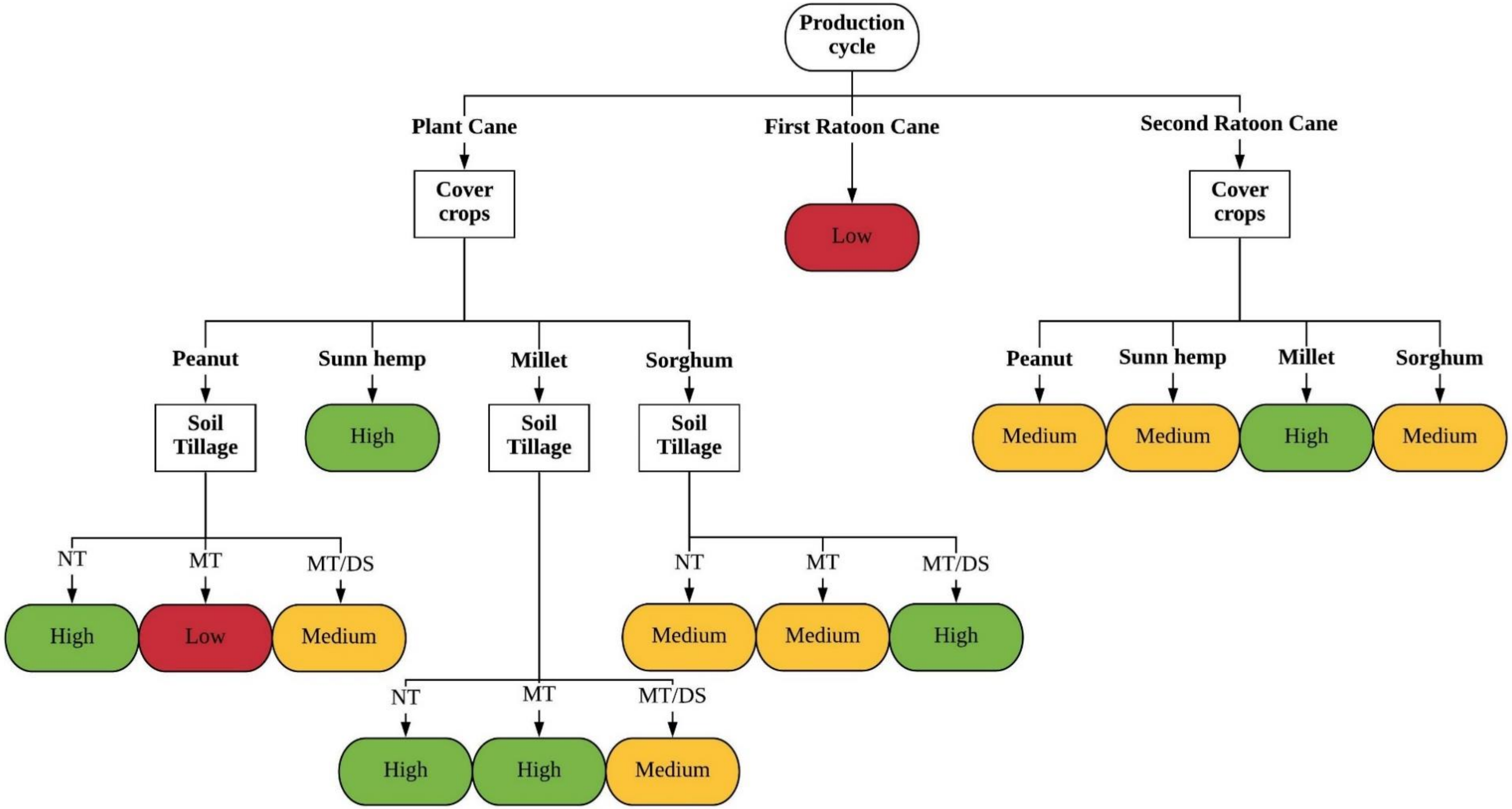


Figure 4. Decision tree for soil quality classification in area of sugarcane cultivated under different cover crops and soil tillage systems. NT = no-tillage; MT = minimum tillage; MT/DS = minimum tillage with deep subsoiling; High = soil quality index ≥ 1.52; Medium = 1.34 ≤ soil quality index < 1.51; Low = soil quality index < 1.33.

For the first ratoon cane, soil quality was low, regardless of the cover crop or soil tillage system. While for the second ratoon cane, only the use of millet will provide high soil quality.

The model developed to classify soil quality had a 73% accuracy rate and a 27% error rate. Of the 32 records belonging to the high class, 39 belonging to the middle class, and 37 belonging to the low class, 20, 27, and 32 were classified correctly, corresponding to a 71%, 63%, and 86% hit rate, respectively. The Kappa coefficient was 0.59 and indicates a "Very good" level of agreement between the lost and observed data according to the classification suggested by Landis and Koch [35] (Table 7).

Table 7. Model parameters and confusion matrix obtained using the J48 algorithm for decision tree induction for classification of soil quality in the sugarcane area.

Model Parameters	**Values**				
Accuracy rate	73%				
Error rate	27%				
Kappa coefficient	0.59				
Observed vs. Predicted	High	Medium	Low	Total	Accuracy by class
High	**20**	12	0	32	71%
Medium	7	**27**	5	39	63%
Low	1	4	**32**	37	86%

Values in bold are the correctly classified observations.

4. Discussion

4.1. Impact of Production Cycles on Soil Quality

Soil physical degradation is one of the main problems that occur in sugarcane areas in Brazil [37,38], mainly due to aspects inherent to the crop and/or related to management. For example, sugarcane is a semi-perennial crop, whose production cycle is normally 5 to 6 years [39]. During this period, a series of mechanized operations take place in the area, which induces changes in soil physical and mechanical attributes, which are reflected in the soil compaction, if the operations are carried out under inadequate water content in the soil or if the pressures applied by the machines were greater than the soil load-bearing capacity [40].

We observed that the productive cycle was the main factor that determined soil quality. During the plant cane cycle, soil quality ranged from medium to high. However, between the plant cane and first ratoon cane cycles, there was a reduction in soil quality, where all treatments were classified as having low quality, mainly due to the degradation of soil physical attributes. Several studies report the degradation of soil physical attributes caused by heavy machine traffic in sugarcane areas [2,3,13,37,40]. However, the results showed that there is a gradual restoration of soil quality from the second ratoon cane due to the recovery of both soil's physical and chemical attributes. After each mechanized harvest event, a large volume of straw is deposited in the area, around 10 and 20 $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ of dry mass [41]. Crop residues act as one of the main sources of carbon (C) and nutrients to the soil [38,39], in addition, the straw from the mechanized harvesting of sugarcane to preserve the quality of soil physical attributes, such as soil resistance to penetration, bulk density, microporosity, and mean weight-diameter of soil aggregates [42].

Straw also behaves as a dissipator of the compression energy caused by traffic, resulting in less structural alteration of the soil [43,44]. According to Vischi Filho et al. [45], straw reduces the pressure of wheel-to-ground contact, due to the increased contact area, which favors the preservation of the structure and minimizes the soil compaction process. Therefore, the presence of straw in adequate quantities can mitigate the soil physical quality degradation caused by intense machine traffic in sugarcane fields [38,42,44].

Despite the beneficial effects provided to soil quality by straw, this important resource is currently being considered for removal from sugarcane fields to produce second-generation ethanol and generate electricity (cogeneration). Although the straw represents an economic opportunity for the sugar-energy sector, its removal must be performed in a sustainable way to prevent drastic impacts on the entrance of C and nutrients into the soil [46], as well as impair the process of restoring soil physical attributes [42,44].

Another factor that affects soil quality is the exploration of the profile by sugarcane roots over consecutive production cycles. The establishment and death of roots throughout the production cycles can create empty round channels called biopores (pores larger than 2 mm in diameter) [47], which contribute to increase aeration and water infiltration in the soil, reduce water runoff and soil erosion, in addition to serving as preferential routes for the subsequent elongation of the roots of subsequent ratoon canes, where they find less resistance to penetration and easier access to water and nutrients [48,49]. Simultaneously, a greater presence of roots significantly increases the stability of aggregates, biological activities, and the entry of organic carbon in the soil, especially in the rhizosphere [48].

In addition, applications of lime and fertilizer improved soil chemical quality throughout the sugarcane cultivation cycles, as previously reported by Cherubin et al. [12]. In addition, there are other management practices that frequently occur in Brazilian sugarcane fields that contribute to improving the chemical quality of these soils. For example, the application of vinasse, which adds some chemical elements to the soil, such as Ca, Mg, and K, in addition to contributing to raising the pH [50]. Another example is the application of filter cake, which improves soil quality by increasing macro- and micronutrient contents and reducing aluminum contents [51].

However, it is essential that adequate tillage is carried out at the time of renewal of the sugarcane field, as excessive tillage of the superficial layers can compromise the agronomic benefits achieved throughout the consecutive production cycles. Studies show that the use of conventional tillage reduces C stocks [52], increases CO_2 losses to the atmosphere [6], in addition to degrading the soil's physical structure [53].

4.2. Impact of Cover Crops and Tillage Systems

During the plant cane cycle, the introduction of sunn hemp as cover crop increased soil quality, regardless of the tillage system used. Sunn hemp is a fast-growing plant with a relatively short-life cycle [54], which is capable of producing a high amount of biomass and fixing atmospheric nitrogen (N) (through biological fixation), thus improving soil nutrient cycling and preventing erosion [55]. In addition, cover crops can grow better in compacted layers than cash crops [56], control weeds [57], and reduce the nematode population [54]. Furthermore, it has great potential to reduce environmental impacts related to sugarcane production, mainly due to the reduction in nitrogen fertilization and in agrochemicals to control nematode infestation in sugarcane [58].

Although the sunn hemp's ability to add N to the soil varies considerably from one region to another, studies carried out under Brazilian edaphoclimatic conditions indicate that on average 323 $kg{\cdot}N{\cdot}ha^{-1}$ can be accumulated. Perin et al. [59] obtained an accumulation of 305 $kg{\cdot}N{\cdot}ha^{-1}$, Teodoro et al. [60] found an accumulation of 514 $kg{\cdot}N{\cdot}ha^{-1}$, and Perin et al. [61] observed an accumulation of 150 $kg{\cdot}N{\cdot}ha^{-1}$. These studies are consistent with Ambrosano et al. [62], who found that sunn hemp was able to completely replace the N required by sugarcane and increase the contents of Ca and Mg, as well as increasing the sum of bases, pH, and base saturation, decrease potential acidity, and ultimately, increase crop yield and farmer's profit.

Although sunn hemp is a legume, its stem, highly lignified and fibrous, can present a C:N ratio above 25 [63]. Therefore, the decomposition and release of nutrients from sunn hemp residues occur in different phases, where the fractions of leaves and flowers are readily decomposable, due to their low C:N ratio, while the stems take longer to decompose due to the large amounts of complex carbon structures [64]. This characteristic is interesting, as it enables rapid nutrient cycling in the early development stages of sugarcane, associated with soil cover and protection for longer periods.

The results indicated that the use of millet induced high soil quality in the long run, and its benefits were manifested up to the second ratoon cane. Millet has stood out especially in no-till areas in the Brazilian *Cerrado*, due to its agronomic characteristics such as high resistance to drought, adaptation to low fertility soils, and rapid growth, in addition to providing efficient soil coverage, creating conditions for the development and maintenance of microbial fauna, inducing greater soil aeration, and improving nutrient distribution, which results in less need for fertilization and liming [65].

The cultivation of millet as a cover crop has high efficiency in recycling nutrients by extracting nutrients in deeper layers of the soil and accumulating in its aerial part [65,66]. However, its straw has a high C:N ratio (around 46) [67], which contributes to relatively slow decomposition and immobilization of nutrients, particularly N in millet plant residues, suggesting lower levels of mineralization of the residues over time. Nitrogen immobilization can generally be considered undesirable in an agricultural production system, as it suggests a potential increase in the need for inputs. On the other hand, plant residues with a high N concentration and, consequently, a low C:N ratio, such as that of legumes, quickly supply the N demand of the microorganisms in the decomposition process and the excess N starts to be released quickly in the soil, in such a way that it supplies nutrients to subsequent crops [68].

To increase the supply of nutrients and at the same time maintain coverage throughout the year, a combination of grass and legume crops is widely encouraged [69]. Cover crop intercropping is a practice that aims to produce phytomass with an intermediate C:N ratio in relation to monocultures, providing soil coverage for a longer time and with better synchronization in the supply and demand of N for commercial crops [61]. Moreover, the use of plants with different root architectures enables the exploration of the soil profile in different layers, inducing the cycling of nutrients in all soil profiles [70].

When considering the results obtained for sunn hemp and millet in our study, intercropping using these two species can provide synergic benefits during the renewal period of sugarcane fields. Perin et al. [61] evaluated the effect of sunn hemp and millet, monocropped and intercropped, on the performance of corn, and found that intercropping resulted in a 67% higher corn grain yield compared with isolated millet. Menezes et al. [71] observed that the intercropped crop that performs better as to the amount of dry phytomass is sunn hemp and millet. Soratto et al. [72] found that sunn hemp shows greater accumulations of N and Ca and millet shows greater accumulations of K, Mg, S, and Si, while intercropping involving both cover crop species shows K, Ca, Mg, and S contents in an intermediate range.

Finally, we highlight that the soil quality index proposed in this study was sensitive to detecting changes associated with different management practices. Although TC is highly recognized as an important indicator of soil quality, in our study this attribute was significantly correlated with most of the attributes available in the dataset and therefore less sensitive to discriminating the differences imposed by treatments, not being included in the minimum dataset for calculating the soil quality index

5. Conclusions

The soil quality index proposed in this study, based on five soil abiotic attributes (i.e., macroporosity, exchangeable potassium and calcium content, bulk density, and mean weight diameter of soil aggregates), was sensitive to detect changes associated with different management practices in a sugarcane cultivation field.

The soil quality was driven by the production cycle of sugarcane. Although a reduction of soil quality occurs between the plant cane and first ratoon cane cycles, from the second ratoon cane there is a trend of the gradual restoration of soil quality due to the recovery of both the soil's physical and chemical attributes.

The introduction of new management practices in sugarcane fields is essential to achieve greater sustainability in the sugar-energy industry. Our study demonstrated that the cultivation of sunn hemp and millet as cover crops, during the implementation of sugarcane plantation, enhanced soil quality. Due to the advantages provided by the use of these two cover crops, we encourage more detailed and long-term studies, aiming to test the efficiency of intercropping involving sunn hemp and millet during the re-planting of sugarcane field under different edaphoclimatic conditions, as well as determine the appropriate proportion of seeds and adapted cultivars. In addition, we encourage research to understand the process of decomposition and nutrient cycling, as well as their effects on soil's physical, chemical, and biological properties and functions.

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