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Assessment of Soil Quality of Smallholder Agroecosystems in the Semiarid Region of Northeastern Brazil

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Abstract: The assessment of soil quality is crucial for the sustainable development of agriculture in semiarid regions. Due to their sensitivity to management practices, soil chemical and physical quality indicators are used for investigating soil quality. This study aimed to assess the soil quality of smallholder agroecosystems from the Brazilian semiarid region. Soil physical and chemical attributes were screened using principal component analysis (PCA) and integrated into a weighted additive soil quality index (SQI). Soil quality was obtained using linear and non-linear scoring methods, a total data set (TDS), and a minimum data set (MDS). The soil quality of the agroecosystems was designated as being of moderate grade. The MDS for soil quality assessment includes cation exchange capacity, C stock, exchangeable sodium percentage, flocculation degree, pH, electrical conductivity, available P, and K^+ from twenty-five indicators of the TDS. This MDS mainly reflects the input of manure and crop residues associated with moderate weathering of easily weatherable minerals given the semiarid conditions. The SQI obtained can be used to synthesize the information of the TDS and is a valuable tool to indicate the soil quality of agroecosystems; thereby, it can be used with indicators of sustainable management for application at a regional scale.

Keywords: soil physical and chemical indicators; minimum data set; agroecosystems services

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1. Introduction

An agroecosystem is a functionally coherent space modified by anthropic activities for agricultural production [1]. However, the agricultural activities of the property are not restricted to the given intrinsic relationships with other ecosystems that make up the landscape (e.g., watersheds and forest systems) [2]. These agroecosystems are considered social–ecological systems, with recognized potential to favor multiple areas of sustainability in relation to climate, land, water resources, and biodiversity. Therefore, they have received considerable attention in relation to sustainable ways of producing food and combating hunger [3].

Agroecosystems provide many ecosystem services, including food production, carbon sequestration, local climate regulation, and nutrient cycling [4]. Nevertheless, in recent years, ecosystem disservices (e.g., excessive use of chemical fertilizers, greenhouse gas emissions, and heavy metal pollution) have been recognized for their negative impact on human well-being [4]. According to these authors, there is an indispensable need to evaluate ecosystem disservices and assess their spatiotemporal distribution.

Reduction in agroecosystem services is also frequently observed in the semiarid region of the Brazilian Northeastern. This mainly results from severe drought in association with inadequate and intense land management (deforestation) that exploits natural resources beyond the ecosystem's resilience capacity [5,6]. Sites with irreversible losses of biodiversity and soil degradation in this region are called "desertification nuclei", with emphasis on the Cariri region, where the tropical forest removal (Caatinga biome) led to changes in soil properties, microclimate, increased bare soils (greater susceptibility to erosion process), and areas with a high water deficit. Such changes can potentially drive plant communities into alternative stable states and increase the areas susceptible to desertification, strongly affecting agricultural practices [6–8].

Thus, land degradation causes high socio-environmental costs for the Cariri local population. It is necessary to maintain large areas of natural or restored vegetation for sustainable agroscapes in combination with production systems (agroecosystems) that use crop diversity, crop rotation, and mixed farming [9]. Currently, the Cariri region needs help to improve its social indicators while managing its low stock of natural resources [10].

Traditional soil management and land use in Brazil's semiarid region also lead to large ecosystem C losses, originating in losses of supporting and regulating ecosystem services [11,12]. Prior studies have mainly assessed changes in physical, chemical, and biological soil properties [6,13], decreases in atmospheric carbon fixation and carbon stock [14], and reductions in soil quality, soil resistance, and resilience, especially in surface soil [15]. However, soil quality changes in Brazilian semiarid agroecosystems are still poorly understood.

Soil quality can be determined from soil quality indices. This parameter can be used to improve knowledge of soil ecosystems, identify land use change, and propose more efficient management [16–18]. The soil management assessment framework is an example designed to follow the following basic steps [19]: (i) indicator selection, (ii) indicator interpretation (scoring), and (iii) integration into a soil quality index (SQI) value using a weighted additive technique. Physical, chemical, and biological soil attributes are determinants of soil functions, which should be combined as indicators of soil quality assessment [20].

Physical attributes such as soil texture, bulk density, and total porosity are mainly suggested for SQI for use assessing aeration, plant root penetration, the retention and transport of nutrients and water, and soil erosion. Chemical attributes such as acidity, electrical conductivity, exchangeable cations, nitrogen, soil carbon stocks (soil organic matter) and available phosphorus are highly sensitivity to changes in the environment (nutrient availability, crop growth, mineralization/immobilization rates, and capacity to support plant growth) [21,22]. Notably, soil carbon stocks are essential for soil fertility due to their relationship with soil biota and processes regulated by living organisms [23]. Owing to the fact that a large number of indicators can increase the collinearity and complexity of the relationships between indicators, previous studies have used minimal data sets (MDS) and principal component analysis (PCA), factor analysis, and multiple correlations for SQI to reduce the extensive use of physical, chemical, and biological attributes that often require high cost of analysis, labor, and time to measure, as well as to adequately represent the total data set [17,24,25].

Thus, analyzing the smallholder agroecosystems in terms of the soil quality of the Cariri region is crucial for promoting sustainable agricultural practices and improving food security and the livelihoods of local communities. However, more information should be reported on the soil quality from smallholder agroecosystems in the Brazilian semiarid region.

In this research, we hypothesized that (i) SQI is strongly affected by management practices and soil weathering and (ii) indicators selected in the MDS can represent all the indicators for soil quality. Thus, the objectives of this study were: (i) to establish an

MDS with proper indicators for soil quality assessment, (ii) to evaluate the soil quality of agroecosystems using the SQI method, and (iii) to identify the individual contribution of selected MDS to the soil quality of smallholder agroecosystems.

2. Materials and Methods

2.1. Site Description

The trial was conducted in the microregion of Cariri Velhos, domain of the Borborema Province, municipality of Boqueirão, Northeastern Brazil. The area is located between the parallels of 7°21′ S and 7°39′ S and between the meridians of 36°3′ W and 36°15′ W (Figure 1). According to Köppen classification, the region's climate is semiarid, with low latitude and altitude (BSh) [26]. Average annual rainfall and temperature are 467 mm and 23.7 °C, respectively. The altitude ranges from 650 to 1.000 m. The native vegetation corresponds to that of a seasonally dry tropical forest (Caatinga vegetation). The local geology is mainly constituted by orthogneisses, with tonalitic to granodioritic composition.

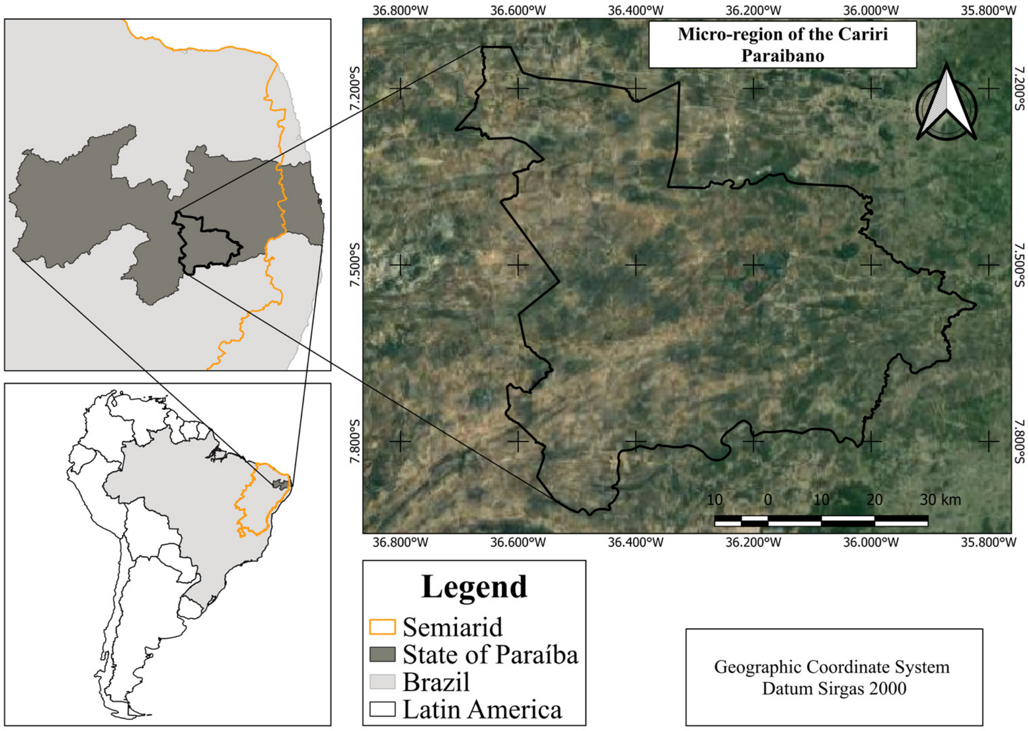

Figure 1. Location map of the study area in the Cariri Velhos micro-region—PB.

The major soils include Abruptic Chromic Luvisols (Loamic) [27], which is highly susceptible to erosion owing to the abrupt textural changes associated with sloping to strongly sloping relief. Damage to surface horizons caused by active water erosion is a common occurrence of in approximately 5% of the evaluated area. Thus, subsurface horizon (textural B) or saprolite can currently be found on the surface. These saprolites derived from orthogneisses present visible occurrences of quartz and weatherable minerals, such as biotite, microcline, amphibole, and muscovite, at different stages of weathering.

We studied 10 smallholder agroecosystems representative of the Brazilian semiarid region due to their production systems, which are widely used throughout the region. The historical management of the agroecosystems studied was similar. From 2000–2012, the agroecosystem experienced deforestation, and vegetation was burned, representing the agricultural practice used in the region. Initially, the deforestation gave way to papaya (*Carica papaya*), passion fruit (*Passiflora edulis*), sweet potato (*Ipomoea batatas*), tomato (*Solanurn lycopersicum*), maize (*Zea mays*), beans (*Vigna unguiculata* and *Sorghum bicolor*), and cactus cultivation (*Opuntia ficus-indica*). Mechanized soil preparation was carried out with a tractor using a disc harrow, and planting and harvesting were carried out manually. The soil was first fertilized with 400 kg of NPK (10-28-20), 400 kg of urea, and 200 kg of ammonium sulfate, and leaf fertilizers were sprayed (micronutrients). Pests, diseases, and weeds ware controlled with herbicides and insecticides. Irrigation was performed via drip irrigation, with 2–4 m space between plants and distances between single and double rows of 2.0 and 4.0 m, respectively. Goat manure was applied as organic fertilizer (201/plant/week/). In the last five years, beans (conventional method) and maize were rotated. During the rainy season, the aerial part of crops and the material from regrowth were cut and incorporated into the soil.

2.2. Soil Sampling and Analysis

The experimental design was completely randomized. In each agroecosystem (2–3 ha), 15 samples were randomly collected at the soil depth of 0.0–0.2 m with the aid of soil auger. These samples were mixed to form three composite samples (three repetitions). At the same time, three undisturbed soil samples were collected with 100 cm^3 cores. These were used to determine physical properties such as bulk density (BD) and total porosity (TP). The other samples were homogenized, dried at room temperature, and passed through a 2 mm sieve for physical and chemical analyses. These analyses were performed according to standard methods from Brazil [28].

The pipette method was used to perform particle size analysis and to produce water-dispersed clay (WDC), using NaOH and H_2O as dispersants, respectively. BD was obtained using the volumetric cylinder method after the sample was dried at 105 °C until a constant weight was reached. Electrical conductivity (EC) was determined using a direct-reading conductivity meter (1:5.0, *w:v*). The pH in water was determined by mixing the soil samples with deionized water (1:2.5, *w:v*). Potential acidity (H + Al) was extracted with $CaC_4H_6O_4.H_2O$ 0.5 mol L^{-1} pH 7.0. The exchangeable cations Ca^{2+} and Mg^{2+} were extracted with KCl 1 mol L^{-1}, while available P, K^+, and Na^+ were extracted with Mehlich-1 solution (HCl 0.05 mol L^{-1} + H_2SO_4 0.0125 mol L^{-1}). Ca^{2+}, Mg^{2+}, K^+, and Na^+ were determined via microwave plasma atomic emission spectroscopy (MP-AES). Available P was determined via UV–visible spectrophotometry, and potential acidity was determined via titration. Total carbon (TC) and total nitrogen (TN) were obtained via dry combustion in a CHNS elemental analyzer. Total carbon stock (C stock) and total nitrogen stock (N stock) also were calculated [29].

From these data, the following parameters were determined: flocculation degree (FD), total porosity (TP), exchangeable bases (EB), cation exchange capacity (CEC), effective CEC (ECEC), base saturation (BS), and exchangeable sodium percentage (ESP) [28]. Soils' physical and chemical parameters were interpreted according to the general guide of Interpretations of Soil Results [30].

2.3. Soil Quality Index

The SQI was calculated using the soil management assessment framework [19], following three steps: (i) identification of a minimum data set (MDS), (ii) normalization of the MDS indicators, and (iii) integration of the indicator cores into an overall index of soil quality. Twenty-five measured attributes were used in a total data set (TDS) and were selected for their sensitivity in soil quality evaluation. Principal component analysis (PCA), the most suitable indicator for the MDS, was used as a data reduction technique [21]. The principal components (PCs) were large eigenvalues and factor-loading indicators. Therefore, only PCs with eigenvalues > 1 and soil attributes with values within 10% of the highest factor loadings were selected for the MDS [17,25].

Each soil indicator was transformed and normalized to a value ranging from 0 to 1 (with 1 representing the indicator's optimum level) using the standard scoring function method [31]. The scoring functions "more is better" (increasing the level of the indicator increases the quality of the soil), "less is better" (indicator increment negatively affects the soil quality), and "optimum" (indicators with positive association with soil quality up to an optimal level) were used based on the contribution of each indicator to soil functions [19]. The equations of the scoring functions "more is better" (Equation (1)) and "less is better" (Equation (2)) are as follows (Shao et al., 2020) [25]:

$$f(x) = \begin{cases} 0.1 & x \leq L \\ 0.9 \times \frac{x-L}{U-L} + 0.1 & L \leq x \leq U \\ 1 & x \geq U \end{cases} \quad (1)$$

$$f(x) = \begin{cases} 1 & x \leq L \\ 1 - 0.9 \times \frac{x-L}{U-L} & L \leq x \leq U \\ 0.1 & x \geq U \end{cases} \quad (2)$$

where $f(x)$ is the linear score of the soil indicator, x is the soil indicator value, and L and U are the indicator's lower and upper threshold values, respectively. For the "optimum" function, indicators were considered suitable for the soil quality of the increasing (more is better) or decreasing part (less is better).

We applied the "more is better" function to K^+, available P, CEC, C stock, and FD due to its positive effects on plant growth [17,25]. The scoring function "less is better" was used for ESP due to its adverse effects on aeration, plant root penetration, and soil porosity [22]. The "optimum is better" function was applied to pH and EC [17,32]. The threshold value of seven was applied for pH, and optimal ranges from 0.2 to 2 dS m^{-1} were applied for EC [17]. For the TDS and MDS, the weight values of each indicator resulted from the ratio of their commonality to the sum of commonalities found in the TDS and MDS methods [18,25]. The scores were then combined into an overall weighted-additive *SQI* as follows (Equation (3)):

$$SQI = \frac{\sum_1^n Ni}{n} \quad (3)$$

where Ni represents indicator scores and n indicates the number of indicators.

The *SQI* classification was evaluated using a scale of six categories: none (<0.00), poor (<0.00–0.19), weak (0.20–0.39), moderate (0.40–0.59), strong (0.60–0.79), and excellent (0.80–1.00), with specific limits for each category [17].

2.4. Statistical Analysis

Data were subjected to one-way analysis of variance (ANOVA) to verify the influence of management practices on soil's physical and chemical attributes, with the aid of the statistical software R, version 4.2.3. PCA was used to select the most appropriate soil indicators for assessing soil quality. The indicators retained with PCA were then subjected to correlation analysis. Finally, additional ANOVA was performed on the overall SQI and MDS score soil quality indicators to reveal the effect of soil attributes on soil quality.

3. Results

3.1. Soil Quality Assessment

The mean, standard error, coefficient of variation, and minimum and maximum values of the selected indicators are shown in Table 1. Substantial variability was found in terms of potential acidity, available P, K^+, CEC, and ESP, while FD, BS, pH, and sand exhibited a lower variability. The soils ranged from neutral (pH 6.86) to strongly alkaline (pH 8.53). The EC values between 0.38–1.38 dS m^{-1} indicated non-saline soils. The average levels of P were considered very high (50.99 mg kg^{-1}).

The average Ca^{2+} contents were considered high (17.07 cmolc kg^{-1}), but soils with low (7.19 cmolc kg^{-1}) and very high (26.48 cmolc kg^{-1}) contents also were observed (Table 1). Similarly, the average Mg^{2+} contents were considered moderate (2.83 cmolc kg^{-1}), but soils with low (0.64 cmolc kg^{-1}) and high (4.52 cmolc kg^{-1}) contents were found. The average K^+ and Na^+ contents were high (K^+: 0.73; Na^+: 0.77; cmolc kg^{-1}). The average contents of CEC were high (21.81 cmolc kg^{-1}), although low (10.62 cmolc kg^{-1}) to very high (32.21 cmolc kg^{-1}) values were also observed. The average BS content was high (98%).

Table 1. Descriptive statistics (mean, standard error, coefficient of variation, minimum and maximum) of soil characteristics in the agroecosystems studied.

Parameter	Dimension	Mean	SE	CV—%	Min	Max
pH	-	7.94	0.30	6.96	6.86	8.53
H + Al	cmolc kg^{-1}	0.42	0.21	107.34	0.06	1.10
EC	dS m^{-1}	0.84	0.27	88.54	0.38	1.88
Available P	mg kg^{-1}	50.69	25.85	94.93	12.40	163.09
Ca^{2+}	cmolc kg^{-1}	17.07	3.70	42.56	7.19	26.48
Mg^{2+}	cmolc kg^{-1}	2.83	0.72	47.13	0.64	4.52
K^{+}	cmolc kg^{-1}	0.73	0.30	88.28	0.40	2.08
Na^{+}	cmolc kg^{-1}	0.77	0.15	47.15	0.38	1.28
CEC	cmolc kg^{-1}	21.81	3.95	35.28	10.69	32.21
ECEC	cmolc kg^{-1}	21.39	3.80	34.85	10.47	31.38
EB	cmolc kg^{-1}	21.39	3.80	34.85	10.47	31.38
BS	%	98.18	0.66	1.67	96.14	99.73
ESP	%	4.01	1.15	65.57	1.86	8.18
BD	kg dm^{-3}	1.30	0.07	10.95	1.16	1.53
TC	g kg^{-1}	15.43	1.90	25.29	10.60	19.63
NT	g kg^{-1}	1.26	0.17	28.08	0.89	1.70
C stock	Mg ha^{-1}	200.25	24.55	26.34	135.80	269.59
N stock	Mg ha^{-1}	16.35	2.26	29.80	10.81	23.26
CN ratio	-	12.43	0.96	14.37	10.84	23.26
Sand	g kg^{-1}	585.42	33.75	11.38	513	691
Silt	g kg^{-1}	167.92	19.79	24.27	96	213
Clay	g kg^{-1}	246.67	21.85	18.97	187	300
WDC	g kg^{-1}	20.60	2.11	23.11	13	25
FD	%	96.36	0.54	1.23	95	98
TP	m^3 m^{-3}	0.51	0.03	10.59	0.42	0.56

3.2. Correlations between Soil Quality Indicators

The linear correlation matrix of chemical and physical indicators is shown in Figure 2. A significant and strong correlation was found between Ca^{2+} x CEC, ECEC, and EB ($r > 0.97$; $p < 0.05$), sand x FD ($r > -0.97$; $p < 0.05$), clay x FD ($r > -0.87$; $p < 0.05$), and C stock and N stock ($r > 0.86$; $p < 0.05$). Significant but moderate correlations were observed between ESP and Ca^{2+} ($r > -0.74$; $p < 0.05$), FD and Mg^{2+}, Na^{+} and silt ($r > -0.75$, -0.71; -0.69, respectively; $p < 0.05$), ESP and silt, sand and TN ($r > 0.79$, -0.67; 0.65, respectively; $p < 0.05$), except for Ca^{2+} and ESP and between TN and N stock ($r > -0.74$, -0.71; -0.66, respectively; $p < 0.05$) (Figure 2).

3.3. Indicators for MDS

The principal component loading matrix is shown in Table 2. Five components had eigenvalues over 1, ranging from 1.61 to 8.42 and accounting for 89.50% of the total variance. Thus, the first five PCs were used for the MDS. The percentage of variance explained was 33.67% for the first PC, while it was 29.43%, 11.84%, 8.12%, and 6.45% for the other four PCs, respectively. Communalities showed that the five components explained over 90% of the variance in Ca^{2+}, CEC, ECEC, EB, ESP, BD, TC, TN, C stock, N stock, CN, sand, clay, WDC, FD, and TP, over 80% of the variance in H + Al, Mg^{2+}, K^{+}, and silt, and over 70% of the variance in pH, Na^{+}, and BS (Table 2).

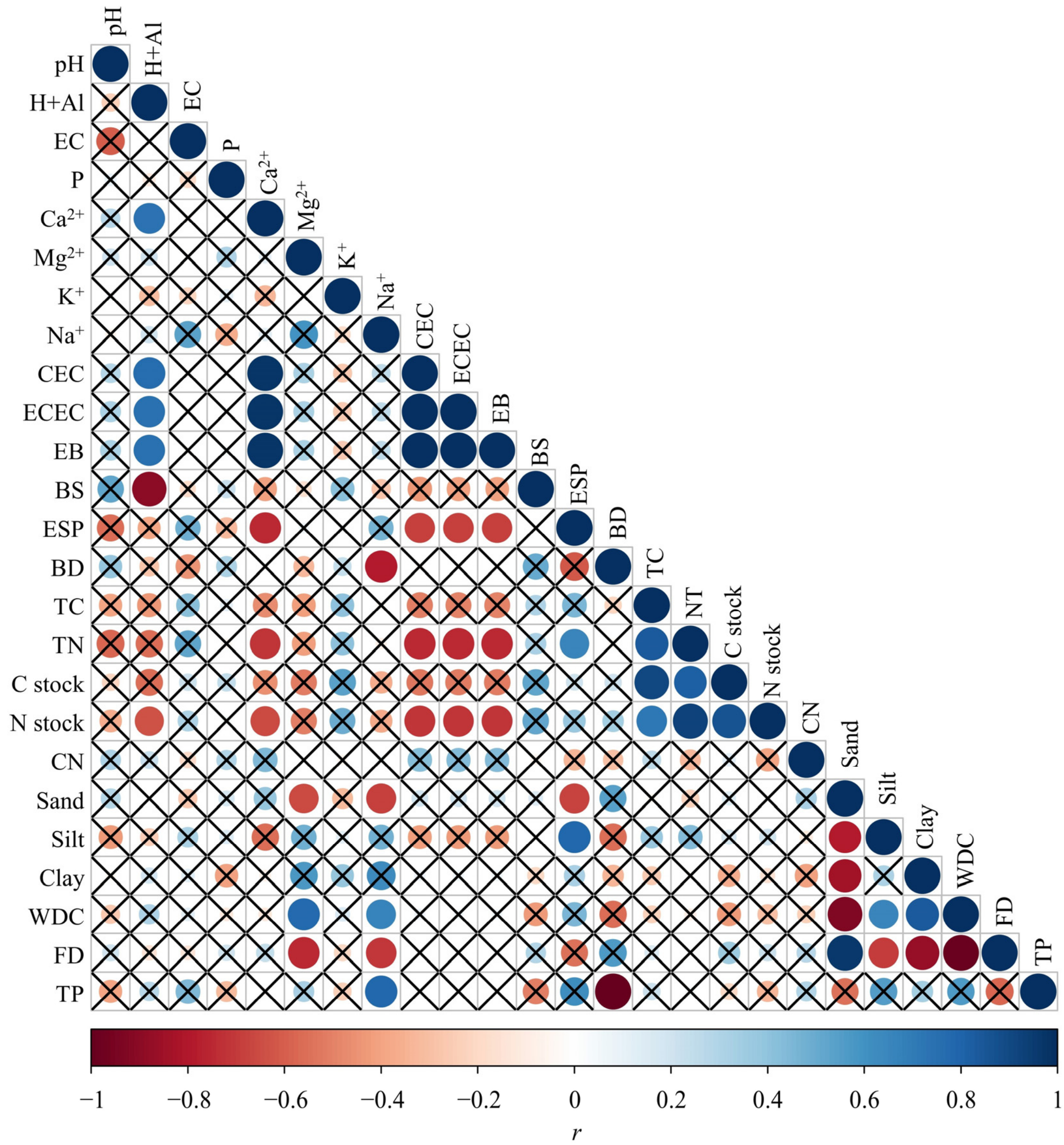

Figure 2. Pearson correlation coefficients between soil indicators. The color of each circle indicates the correlation direction—blue for positive, red for negative. The intensity of the color corresponds to the correlation strength: the darker the shade, the stronger the correlation. The circle's size denotes the correlation coefficient's magnitude, with larger circles representing higher absolute values. The "X" denotes a non-significant correlation.

In PC1, the absolute factor loading values ≥ 0.50 were H+Al, Ca^{2+}, CEC, ECEC, EB, BS, ESP, TC, TN, C stock, and N stock, where CEC and N stock had the highest norm value at 2.74, while norm values within 10% of the highest value were obtained for Ca^{2+}, CEC, ECEC, EB, ESP, TN, C stock, and N stock. Given that the Ca^{2+}, CEC, ECEC, EB, ESP, TN, C stock, and N stock showed significant correlations ($p < 0.05$), CEC and N stock were maintained in the MDS.

In PC2, Mg^{2+}, Na^{+}, ESP, BD, sand, silt, clay, WDC, FD, and TP had absolute factor loading values ≥ 0.50, ESP had the highest normal value at 2.71, and ESP, sand, WDC, and FD had norm values within 10% of the highest value. Significant correlations ($p < 0.05$) were obtained between ESP and sand ($r = -0.67$), sand and FD ($r = -0.97$), and between WDC and FD ($r = -0.82$). Thus, ESP and FD were maintained in the MDS.

Table 2. Principal component analysis of selected soil indicators plus each soil property's estimated communality and weight values.

Soil Properties	PC1	PC2	PC3	PC4	PC5	Norm	Communality	Weight
pH	0.376	−0.397	**−0.550**	0.308	−0.304	1.89 [a]	0.79	0.118
H + Al	**0.770**	0.235	0.324	−0.163	0.315	2.43	0.88	
EC	−0.239	0.405	**0.601**	−0.072	0.264	1.70 [a]	0.66	0.099
Available P	−0.005	−0.298	−0.155	**0.589**	−0.016	1.20 [a]	0.46	0.069
Ca^{2+}	**0.902**	−0.187	0.245	0.087	0.232	2.72	0.97	
Mg^{2+}	0.368	**0.631**	−0.463	0.349	−0.083	2.23	0.88	
K^+	−0.419	−0.018	−0.408	0.386	**0.570**	1.67 [a]	0.82	0.122
Na^+	0.211	**0.837**	0.128	0.149	−0.073	2.37	0.79	
CEC	**0.930**	−0.017	0.135	0.172	0.258	2.74 [a]	0.98	0.147
ECEC	**0.927**	−0.030	0.123	0.188	0.252	2.73	0.97	
EB	**0.927**	−0.030	0.123	0.188	0.252	2.73	0.97	
BS	**−0.509**	−0.446	−0.429	0.342	−0.123	2.11	0.77	
ESP	**−0.670**	**0.677**	0.146	−0.121	−0.221	2.71 [a]	0.99	0.149
BD	−0.058	**−0.798**	−0.467	−0.150	0.267	2.35	0.95	
TC	**−0.726**	−0.028	0.486	0.441	0.145	2.36	0.98	
NT	**−0.922**	0.077	0.264	0.012	0.259	2.74	0.99	
C stock	**−0.756**	−0.342	0.253	0.399	0.273	2.51 [a]	0.99	0.148
N stock	**−0.893**	−0.234	0.052	−0.016	0.352	2.71	0.98	
CN ratio	0.367	−0.178	0.405	**0.713**	−0.252	1.73	0.90	
Sand	0.213	**−0.908**	0.301	−0.105	−0.151	2.60	0.99	
Silt	−0.457	**0.722**	−0.028	0.294	−0.150	2.41	0.84	
Clay	0.085	**0.749**	−0.440	−0.105	0.369	2.24	0.91	
WDC	0.119	**0.916**	−0.301	0.036	0.138	2.57	0.96	
FD	−0.005	**−0.930**	0.341	−0.052	−0.093	2.59 [a]	0.99	0.149
TP	0.075	**0.800**	0.457	0.165	−0.269	2.36	0.95	
Eigenvalue	8.42	7.36	2.96	2.03	1.61			
% of variance	33.67	29.43	11.84	8.12	6.45			
Cumulative % of variance	33.67	63.10	74.94	83.06	89.50			

Bold font values are considered highly weighted. [a] Norms correspond to the indicators included in the minimum data set.

In PC3, pH and EC had absolute factor loading values below 0.50, where pH had the highest norm value at 1.89, and pH and EC had norm values within 10% of the highest value. There was no significant correlation between pH and EC ($p < 0.05$), so these soil attributes were maintained in the MDS. Available P and CN had absolute factor loading values $\geq$ 0.50 in PC4, where the available P presented the highest norm value at 1.73. No norm values were observed within 10% of the highest value. Thus, P was maintained in MDS. Lastly, only K^+ had absolute factor loading values $\geq$ 0.50 in PC5, presenting a 1.67 norm value. Thus, K^+ was maintained in MDS.

3.4. Soil Quality Index

The SQI and the individual contribution of selected minimum data set indicators are presented in Figure 3. Except for agroecosystems V and VI, with strong (0.60) and weak (0.39) SQI values, respectively, the other agroecosystems showed moderate SQI values (0.40–0.59). The highest SQI values were observed in agroecosystems IV, VI, VIII, and IX. Nonetheless, these agroecosystems statistically differed from only agroecosystems I and V ($p < 0.05$). EC, available P, pH, K^+ values, and C stock are essential attributes in agroecosystems with higher SQI values. At the same time, the FD strongly contributes to the agroecosystem with the lowest SQI values (Figure 3).

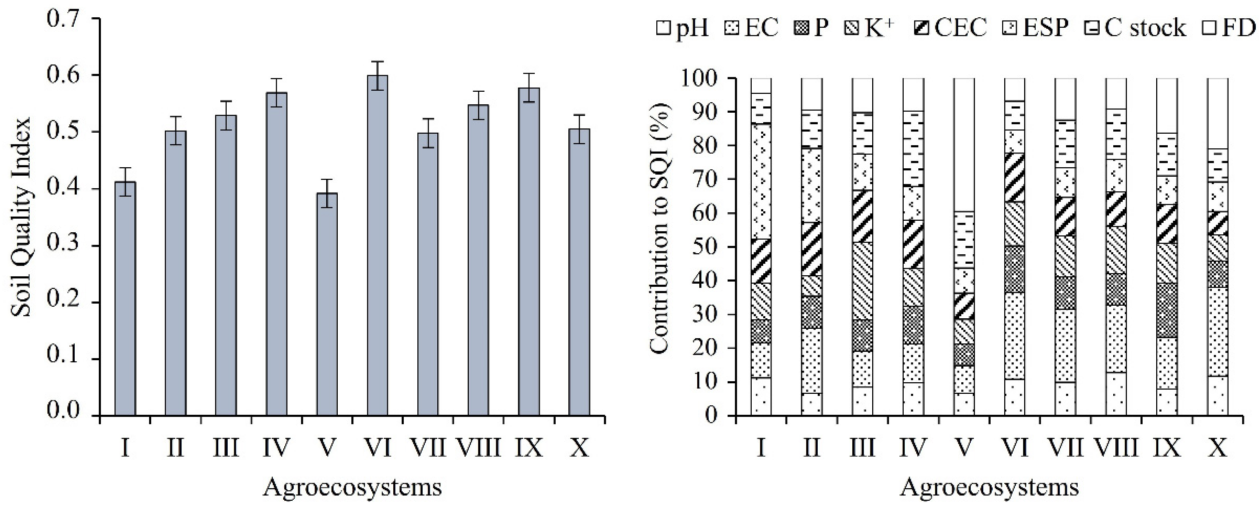

Figure 3. Soil quality index and the individual contribution of selected minimum data set indicators in agroecosystems evaluated.

4. Discussion

4.1. Indicators from Soil Quality

Functions and soil quality can be interpreted according to land use and environmental conditions, meaning that their intercorrelations should be considered [24]. Many researchers have used different chemical attributes as indicators of soil quality because their work involved the cycling of nutrients and the activity of organisms. In this context, pH has been pointed out as a critical indicator of soil quality owing to its high sensitivity to changes in land use and because pH directly affects nutrient availability [33].

Our results corroborate these studies because, under the semiarid conditions analyzed, the soils' predominantly neutral-to-alkaline reaction permitted an adequate availability of Ca^{2+}, Mg^{2+}, K^+, and P. The alkaline reaction of soils is indirectly related to the presence of considerable levels of Ca^{2+} in the exchange complex ($r = 0.97$; $p < 0.05$) that displace H^+ ions from adsorption sites, favoring its leaching, as well as the presence of carbonate anions and bicarbonates (pH 7.0–8.4) that dissociate and release hydroxyls. It is also necessary to consider the crucial effect of $CaCO_3$ on soil alkalinization, where Ca ions replaces H^+ in the exchange complex, while carbonate reacts with soil acidity to form water and carbon dioxide [34].

Although our results did not indicate the presence of sodic soils (sodification process), Na^+ was a vital chemical attribute in the evaluated soils. The positive correlation found between WDS and Na^+ ($r = 0.66$; $p < 0.05$) and the negative correlation between Na and DS, besides Na and FD ($r = -0.78$ and -0.71, respectively; $p < 0.05$), indicate that Na^+ can favor the dispersion of clays, since its higher ionic radius promotes greater distancing and less interaction between the soil particles, consequently increasing destabilization of soil structure and deterioration of soil hydraulic properties. The Na^+ levels reflect the low rainfall levels in the region, contributing to the partial hydrolysis of easily weatherable minerals, such as plagioclase [35]. Under semiarid conditions, the Na^+ remains in the soil because of the reduced leaching rate and the incipient process of altering parent material (incipient pedogenesis).

Thus, our results warn about using these soils to avoid sodification and salinization processes in the soil surface layer, since Na^+ and Cl^- are potent contributors to soil degradation in irrigated agriculture in semiarid regions [36]. This mainly occurs when high Na^+ concentrations enhance colloidal dispersion, reduce soil permeability, and deteriorate the soils structure, indicating a regressive process of pedogenesis. This mechanical dispersion of clay from soil into water also may avoid considerable losses of the surface layer of these Luvisols, which are highly susceptible to erosion, with consequent exposure on the soil surface of horizons with high levels of salts (salinization) and sodium (sodification) [37].

Available P has been included in the minimum data set for a soil quality assessment [24,32]. Despite the soils having high P contents, the neutral-to-alkaline conditions of soils indicate that alkalization can reduce the availability of P through its precipitation with Ca ions (inorganic P-Ca fraction) of low solubility [38,39] as these soils have low iron and aluminum oxides contents. This fact is essential for agriculture in the region because it can lead to an increase in the frequency of fertilization in the soil and an increase in production costs necessary to reach adequate productivity levels.

Most of the TC and C stock is likely constituted by organic carbon, although the soils in the studied region present considerable levels of $CaCO_3$, where its formation is favored by the increase in the concentration of Ca bicarbonates (plagioclase as the main source of Ca) in the soil solution due to water evaporation or by pCO_2 deceasing [40]. Furthermore, in agricultural systems, organic nitrogen constitutes 80–90% of the total soil N stock [41]. The strong positive correlation found between TC and TN ($r = 0.83$; $p < 0.05$) also confirms the decisive contribution of organic carbon as an indicator of quality in the evaluated soils.

Due to the dynamics of soil organic matter (SOM) being related to soil N transformations (mineralization or immobilization), the C and N as components of SOM are subject to transformation via the activity of microorganisms [42]. Thus, the strong negative correlation found between TN x CEC and BS ($r = -0.75$; $p < 0.05$) and TN x Ca^{2+} ($r = -0.71$; $p < 0.05$) indicates that the mineralization process of SOM is essential in the regulation of soil chemical quality in the evaluated agroecosystems. The C: N ratio of 10:1 in the soils confirms that an adequate quantity of nitrogen offsets the carbon amount, dominating the mineralization process [43].

Physical indicators were less responsive to management practices and pedogenesis than the chemical parameters. However, the FD was an essential physical indicator of the quality of the evaluated soils. The strong negative correlation between Mg^{2+} and FD ($r = -0.75$; $p < 0.05$) suggests that the Mg ions influence the mechanisms of flocculation and dispersion of soil colloids. In this process, Na^{+} also plays an essential role in the dispersion of soil colloids (Na^{+} x FD: -0.71; $p < 0.05$). Colloid surfaces rich in Mg and Na ions tend to absorb less water due to the notable hydrated radius of Mg^{2+} and Na^{+}, weakening intermolecular forces that keep soil particles together and increasing clay dispersion [44]. The reduction in FD with increments of Mg and Na can cause deleterious effects on soil structure, such as a reduction in soil hydraulic properties, a decline in soil infiltration, increased surface sealing, and triggering soil erosion [45].

4.2. Soil Quality Index—SQI

The attributes CEC, C stock, ESP, FD, pH, EC, available P, and K^{+} were retained in the MDS. Thus, our study confirms previous research which showed that the SQI requires soil chemical and physical indicators [18,24]. These indicators were also selected for SQI in other studies, including ESP and EC in semiarid regions [24].

The PC1 demonstrates that Ca^{2+} contents are crucial for the CEC, while Na^{+} and TN contents play an important role in BS. The considerable Ca^{2+} contents in the agroecosystems reflect both management practices commonly used in the semiarid region, such as manure application and incorporation of crop residues in soils [15], and the hydrolysis of easily weatherable primary minerals, such as feldspars and plagioclase, present in the leucocratic layers of the gneiss parental material [35]. These plagioclases are also the primary source of Na^{+} release in soils, and their importance in BS can be explained by agricultural practices occurring directly in the subsurface horizon (textural B), especially given the occurrence of erosion processes [37].

Total nitrogen is often used as an indicator in agricultural and forest systems due to its important role in nutrient cycling and biochemical reactions in vegetation [25,33,46]. Our results indicated that the contribution of TN in soils (PC1) mainly reflects intercropping system using legumes, with consequent incorporation of the aerial part of these species into the soil [15]. Intercropping legumes with crops increases N availability, promoting litter and organic carbon deposition, favoring nutrient cycling and mineralization, and improving soil chemistry [47], which explains the substantial contribution of carbon and Ca^{2+} contents in soils.

The significant and negative correlation found between TN and Ca^{2+} ($r > -0.71$; $p < 0.05$) confirms that the mineralization of organic matter contributes to increased Ca^{2+} contents in soils, while the significant and positive correlation obtained between TN and CT ($r > 0.83$; $p < 0.05$) demonstrates the great participation of organic N in maintaining soil fertility. Thus, PC1 determined the availability of nutrients in soils and, consequently, the productivity of family agroecosystems.

The PC2 showed that the granulometric composition directly influences the release of Mg^{2+} and Na^{+} in soils and regulates critical physical attributes of soils, such as TP, DB, WDC, and FD. The moderate and negative correlations between sand and Na^{+}, in addition to that between sand and Mg^{2+} ($r > -0.68$; -0.65, respectively; $p < 0.05$), indicate that the hydrolysis of plagioclase (leucocratic layer) and biotites (melanocratic layer) of the gness parent material is an important process in soils of agroecosystems in the Brazilian semiarid region. These results corroborate other studies emphasizing the importance of mineralogical composition for soil fertility and productivity in the region [35,48–50].

The PC2 also points out that the colloidal inorganic fraction (clay) also plays a fundamental role in the availability of Na^{+} and Mg^{2+}, given their entrapment in the interlayer of 2:1 clay minerals (e.g., smectites), whose genesis is credited to partial desilicatization and the permanence of basic cations given moderate weathering under semiarid conditions [34,39]. This process directly influences the physical attributes of soils, mainly because the high charge density of clay minerals can increase clay dispersion and reduce soil FD [51].

Under these conditions, there are losses of important services provided by inorganic colloids, such as water retention, aggregation, aeration, and nutrient retention, and consequently, an increase in the susceptibility of these layers to erosion processes and a reduction in the quality of the soils. Finally, our data also showed that the strong participation of Na^{+} in PC1, mainly related to BS, plus its association with the clay fraction, EC, and ESP in PC2, indicate that Na^{+} adsorption in the exchange complex in these soils is a viable process. Thus, caution is recommended when using these soils to avoid the installation of the sodification process.

PC3 indicates that acidity and alkalinity are controlled by EC values, which in turn are predominantly constituted by the Mg and K salts released from the weathering of silt fraction minerals. Salt contents also control the pH of Central European arable soils [24]. PC4 shows that the availability of P in soils is strongly influenced by the mineralization of organic material (C:N) (Table 2), primarily because organic fertilization with manure is widely adopted for supplying phosphorus in family farming in the semiarid region of Brazilian Northeast [52]. Finally, PC5 isolated the K^{+} contents, which did not show any relation with other attributes analyzed.

4.3. Soil Quality in Agroecosystems

Overall, EC values made the highest mean contributions to the SQI (17%), followed by FD > ESP = TC > K^{+} = CEC > available P = pH. The EC represents the levels of salts, mainly from mineral weathering. K, pH, P, and CEC were also properties selected for the MDS to discriminate the effects of slope gradient and land use change in semiarid soils [17]. The pH, available K, and P also were soil quality indicators in Central European arable soils [24]. Available K was also retained in MDS under different forest types in Eastern China [25]. Phosphorus and pH can also be indicators in temporal soil quality monitoring programs under forest plantations [33]. Thus, our results corroborate those of other studies by showing that SQI is made up of indicators that (i) characterize nutrient retention (CEC and TC) and (ii) available nutrients (K and available P). Additionally, there are (iii) indicators related to base saturation (pH, CEC). In addition, our results point out that mineral weathering—CE and ESP (Na^{+}: plagioclase; Mg^{2+}: biotite; [35,50])—and soil structure (FD) play essential roles in maintaining soil quality.

The neutral-to-alkaline reaction of the soils indicates that Ca and Na salts must predominate in the soil solution. A substantial contribution of the ESP in the SQI indicates that the concentration of diluted solutions with Na carbonates must be active in soils. The less soluble salts and carbonates easily precipitate under semiarid conditions, increasing the proportion of Na^+ ions in solution and, consequently, replacing Ca^{2+} and Mg^{2+} of the exchangeable complex (increases ESP values) [53]. The strong and significant correlation between Ca^{2+} and ESP ($r = -0.74$; $p < 0.05$) confirms the antagonistic effect of these cations in the soil solution. In this context, Na^+ and Mg^{2+} ions can impair the physical quality of soils. The significantly negative correlation between BD and Na^+ ($r = -0.78$; $p < 0.05$) and between DF and Na^+ ($r = -0.71$; $p < 0.05$) implies that high levels of Na^+ may cause deleterious effects on the aggregation, aeration, and infiltration of water in the soils [54].

Finally, the considerable contribution of C stocks in the SQI, as well as its significant correlation with TC and NT, evidences the role of organic matter mineralization in maintaining the quality of agroecosystems, owing to the strong influence of OM on the CEC, BS, and EB of the soils.

4.4. Effects of Indicators of Soil Quality in Ecosystems Services

Agroecosystems may provide a specific supply service in which agricultural practices affect the ecosystem services, but they also can cause ecosystem disservices (adverse effects on human well-being) [55]. This fact assumes crucial importance in the Brazilian semiarid region since predictions indicate increments in agropastoral activity, combined with a decrease in the native vegetation areas for the next 21 years, an increase in aridity in the region due to reduced rainfall, increased temperature and water deficits, in addition to longer dry periods. Such dry and arid conditions may remain until the middle of the 21st century [56,57].

Although most agroecosystems presented SQI values considered moderate, the average levels of nutrients in soils are considered high to very high, with solid contributions from available P, K^+ values, and C stock. Such results allow us to emphasize that agroecosystems can provide critical regulating services, such as maintenance of soil fertility and erosion prevention, which are directly regulated by adequate chemical and physical soil conditions. Consequently, agroecosystems are related to the provision of services, with direct implications for increasing local food security.

Our results also showed that the evaluated soils present C stocks in the first 20 cm, corresponding to 25% of what is found, and up to 1 m in Luvisols under dense and open Caatinga conditions in the Brazilian semiarid region [11], confirming that these agroecosystems also can contribute to the provision of regulating services (e.g., global/local climate regulation), reductions in soil losses (increased soil aggregation), and conservation of biodiversity [58]. These results were mainly found when employing crop rotations that present high-value C fixation coefficients in arable crops [59].

Maintaining soil quality means improving the agroecosystems' resilience and confronting the negative impacts of water deficits and longer dry periods on the agricultural landscape, in addition to enhancing the correlated socioeconomic systems.

P and N are essential quality indicators of the evaluated agroecosystems. Agricultural practices, especially manure application and cover crops, are responsible for inputting these macronutrients crucial to sustainable soil fertility and crop production, and thereby providing agroecosystem services. However, the application of manure with high rates of phosphates and nitrogenous compounds, followed by runoff and leaching, can contribute directly to the salinization of groundwater, primarily due to the greater susceptibility to erosion processes in the region due to the occurrence of Luvisols, with abrupt textural changes associated with sloping to strongly sloping relief [37]. In this sense, it is still important to conduct research defining the critical environmental limit of these nutrients for the Brazilian semiarid soils to avoid the pollution of natural resources.

It has been found in previous studies that the reservoir sediments of the region are susceptible to the P bound to aluminum release concomitant with high temperatures and alkaline water pH, which intensifies eutrophication and increases cyanobacteria population, rendering waters unsuitable for consumption and use in irrigation [60,61]. This fact could lead to the provision of agroecosystem disservices on a regional scale (e.g., water resource consumption) given that the supply of water from the Epitácio Pessoa reservoir (surrounding the evaluated agroecosystems) allows the carrying out of the main economic activities in the nearby municipalities, which form an essential economic hub in the northeast region of Brazil (industry, commerce, schools, hospitals; ≈ 500,000 inhabitants).

5. Conclusions

The chemical attributes CEC, C stock, ESP, FD, pH, EC, available P, and K^+ were selected as quality indicators for soil quality assessment. Such a data set reflects specific pedogenetic processes and mainly indicates the management practices commonly used in the Brazilian semiarid region.

Physical indicators were less responsible for management practices and pedogenesis than the chemical parameters. However, soil properties must be interpreted together and correlated because they do not affect soil quality independently.

Principal component analysis is an adequate technique for selecting the most suitable indicators for the MDS of soils in smallholder agroecosystems under the evaluated conditions.

The soil quality maintenance of agroecosystems can provide temporary products (e.g., food). Soils can support essential ecosystem services related to the sustainability of agricultural landscapes (e.g., nutrient cycling and carbon sequestration), constituting an alternative to reducing the vulnerability of family farmers to climatic adversities in the region.

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