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Comparative approach for assessing the soil quality in an urban conservation unit

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Abstract. This study aimed to verify the quality of the soil according to different stages of forest regeneration. Urban conservation units can be of great importance in land management and in the sustainable development process of cities. Monitoring soil quality in these spaces can help to define strategies in the forest recovery process. A management performance evaluation method and consequent soil quality was applied, using data envelopment analysis (DEA). Soil was collected in the three stages of forest regeneration observed, land with established forests, reforested land, and open land, at three different depths. In the set of 54 analyzed observations, soils with low levels of fertility were verified. However, an area with reforested land showed the best performance in maximizing the selected variables and consequently better soil quality scores. The open lands showed the lowest performance in soil conservation. In this way, the revealed performance scores accompanied the Sum of Exchangeable Bases and Organic Matter values. This quality score can help to define soil management strategies, which may be applicable to a wider audience and wider contexts in environmental management.

Key words: degraded area, environmental management, forest regeneration, quality scores, soil management, sustainable development.

INTRODUCTION

Globally, the forested area decreased by 420 million hectares (ha) between 1990 and 2020 (FAO, 2020). Changes in land use such as conversion of forests to agriculture, human settlements and other infrastructure developments are the main causes of forest loss (Fekete & Nehren, 2023). However, recent global initiatives to reforest degraded lands considerably reduce these losses to 4.7 million ha per year during 2010 and 2020 (Ahirwal et al., 2021).

Tropical forests stored 55% of the total carbon (C) stocks, where the soil is responsible for about 32% of the total, and the conversion of forests to non-forest land generally results in low quality, loss of C reservoir and soil biodiversity (Sarvade et al., 2016; Das et al., 2021).

Therefore, it is important to develop a good knowledge of these changes, mainly to understand how they affect soil functioning and losses of natural forest ecosystems (Xiao et al., 2022). These degradations are a potential generator of changes, which can have one of the most adverse consequences in the forest ecosystem (Huang et al., 2019), where soil properties can be altered by changes in land use and can act as an indicator parameter of soil quality.

For this, it is interesting to study the physical and chemical characteristics of soils that are in different stages of forest regeneration and, consequently, different vegetation cover, in order to understand their relationship with soil quality in these environments. Through an evaluation method that reveals a performance score of forest regeneration and consequent soil quality, using data envelopment analysis, the present study can contribute to soil conservation and improvement in the reforestation process, which among many others benefits through increases the carbon stock, establishes the earth's ecological flow, supports the biogeochemical cycle of water, meets part of the Sustainable Development Goals of the United Nations and mitigates the impact of climate change (FAO, 2020). These modifications are reflected sensitively by considerable alterations in soil formation and degradation processes, in soil properties and soil functions (Várallyay, 2010).

According to Maróstica et al. (2021), an index of green areas can be adopted as a decision-making parameter for the expansion of green areas in the city, such as the implementation of parks, seeking greater environmental equity. Thus, this study can help define management strategies in a conservation unit, applying an evaluation and monitoring system for land use and management in forest regeneration. Espada et al. (2018) draw attention to forest management as a tool for environmental conservation and for improving people's quality of life, contributing to the development of sustainable territories. Therefore, the objective of this study was to verify the quality of the soil in function of different stages and managements of forest regeneration through the evaluation of the physical and chemical attributes of the soil in the Conservation Unit Parque Natural Municipal da Água Escondida, in Morro da Boa Vista, in Niteroi, RJ.

MATERIALS AND METHODS

This study was carried out in Morro Boa Vista, Niterói, State of Rio de Janeiro, which is part of the Água Escondida Municipal Natural Park Conservation Unit, coordinates UTM, 22º53'22"S 43º06'22". Study in the Conservation Unit has Authorization from the Secretary of Environment, Water Resources and Sustainability - SMARTH, for Scientific Research in a Municipal Conservation Unit, under number Nº01/2022, Process Nº 250000056/2022.

The climate of the study site is characterized as Aw (tropical savannah climate), according to the Köppen classification (Gorthi et al., 2022), with two well-defined seasons, a hot and rainy summer; a dry winter with lower temperatures, with January being the rainiest month (average of 147 mm) and August the driest (41 mm) (Aragão et al., 2022). At the highest point of this Hill there is a structure with 6 (six) transmission antennas of the State Security Secretariat, which is 209 meters above sea level. The soils are shallow in the most rugged areas and in areas with low slopes they are moderately developed and deep (Wang et al., 2022).

In the study area there are three different soil cover compositions, called treatments(T), being: T1. lands with established forests; T2. reforested lands; T3. open land, where soil samples were later collected (Fig. 1).

Figure 1. Aerial view of the study site located in the Conservation Unit Parque Natural Municipal da Água Escondida, in Morro da Boa Vista, Niterói, RJ, Brazil.
Source: The authors.

The soil had the following characteristics at the time of collection: normally not very thick, yellowish to pinkish yellow in color, sandy in appearance on the surface, sometimes saprolite, permeable, weakly developed soils and can be classified as Acrisol (WRB, 2022), with greater stability on the slopes, and quite stable to excavations, even on steeper terrain. Showing shallow variations in the most rugged areas, but moderately developed in areas with low slopes. The presence of colluvial slopes with talus deposits was also observed, which are strongly inclined depositional surfaces, consisting of hillside deposits, with sediments primarily medium sands to silts, as also verified in a study carried out by Rowell et al. (2018).

Regarding soil analysis, in each of the three treatments, six soil samples were collected at three different depths: 0–10; 20–30 and 40–50 cm, making a total of 54 samples. The samples, for each treatment, were collected close to tree individuals, in the planting line of the seedlings and between the planting lines.

After collection in the field, samples were weighed and sent to the IBRA Agronomic Testing Laboratory in Sumaré, SP. Chemical and physical analyses were performed, including Calcium, Magnesium, Sodium, Phosphorus, and pH. The organic carbon was determined by the volumetric method of potassium dichromate ($K_2Cr_2O_7$). The carbon in the organic matter in the sample was oxidized to CO_2, and the chromium (Cr) in the extracting solution was reduced (from Cr^{+6} to Cr^{+3}). Excess dichromate was titrated with ammonium ferrous sulphate. The results were expressed in g dm^{-3} (Li et al., 2022). To calculate the soil organic matter content, the value of C (%) was multiplied by

1.724 (assuming that the soil organic matter contains 58% carbon). In the evaluation of the soil texture, the organic fraction was not considered, since this presents less stability compared to the mineral fraction and can be altered with the change of land use. Thus, in addition to allowing assessments of the ionic exchange capacity, soil texture is of great relevance in the mechanisms of nutrient uptake by the roots, such as nutrient diffusion and mass flow (Freire et al., 2013).

To compare the performance of each treatment, the DEA (Data Envelopment Analysis) methodology was chosen. This methodology incorporates multiple variables for the calculation of a single score, with a value between 0 and 1, where the higher, the better the treatment performance, facilitating the intended analysis (Banker et al., 1984). Based on the results of the soil analysis, 6 variables were selected (Hydrogen Potential (pH), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg) and Soil Organic Carbon (SOC), as they are essential elements, as intrinsic components in the structure and metabolism of plants, essential for growth, development, or reproduction in their life cycle (Taiz et al., 2017). Neimane et al. (2019) also highlighted the quantitative variables referring to the levels of Ca, Mg, P and K in the monitoring of soils in reforested areas. The dynamics of organic carbon and mineral macronutrients are influenced by several factors including vegetation cover. Forest species have a greater capacity for nutrient cycling than annual cycle plants, as the root system is permanent and deep, absorbing elements from subsurface layers and returning them to the soil through litter (Mafra et al., 2008). Although these nutrients go through a continuous cycle through all organisms, they predominantly enter the biosphere through the root systems of plants, therefore, they were considered as outputs because they are identified as products to be maximized.

In the DEA methodology, the observations were called DMUs (Decision Making Units). Each observed point, where soil samples were collected, was considered a DMU, in a total of 54. Thus, we chose to use the DEA BCC model of unitary input directed to outputs. Where the unit input indicates the existence of the DMU. Functioning as a multicriteria tool, not as a classic efficiency measurement technique (Gomes et al., 2012; Oliveira et al., 2014). To apply the DEA model, the SIAD version 3.0 program - Integrated Decision Support System (Angulo Meza et al., 2005) was used.

The analyzed variables Sum of Exchangeable Bases, Sand Content and Organic Matter (OM) were not included in the model used to generate the performance score but were considered as explanatory variables. The Sum of Exchangeable Bases (V value) refers to the sum of the bases (calcium, magnesium, potassium, and sodium) in exchangeable form expressed as milligram equivalents per 100 g of soil, can be expressed in percentage (V%) and is already an indicative index of soil quality, where a value above 50% characterizes eutrophic soil. Organic matter (OM), in turn, plays an important role in the maintenance and sustainability of natural ecosystems, as it is responsible for storing a good part of soil nutrients, including SOC, and is a source of diverse transformations, mediated by soil organisms (Sales et al., 2018). In the evaluation of the texture, soils with a sandy texture may present less water retention and adsorption of ions when compared to soils with a clayey texture. For these reasons, the use of these variables in the DEA model can cause inconsistencies or mathematical distortions (Dyson et al., 2001).

Then, the generated scores were related to variables, also extracted from the results of soil analysis, however, external to the DEA model; through dispersion diagrams, similar to those applied in Lin et al. (2022), in order to assist the intended analysis. These diagrams were divided into four quadrants. Where, the points observed in quadrant 1 have the highest and in quadrant 3 the lowest, scores and values linked to the external variables in question, in each of the 54 points observed (Fig. 2).

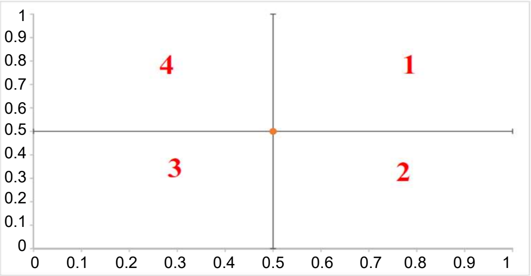

Figure 2. Representation of the applied dispersion diagram.

Adapted from Lin et al. (2022).

RESULTS AND DISCUSSION

Each observed point was considered a DMU, resulting from the combination between the treatment, the planting sector, distance between the planting row and the collection depth, for each of the 54 analyzed soil samples. Among the scores generated by SIAD, the standard score was considered as the performance soil quality score analyzed (Table 1).

The macronutrients calcium (Ca), magnesium (Mg), potassium (K), phosphorus (P) and soil organic carbon (SOC) showed their maximums in Treatment 2, reforested land, indicating the best soil quality in this treatment (Table 2).

Average of the performance score of the set of observations was 82.3%, the minimum was 61%. Sectors with a performance score of 100% include in Treatment 1, DMU 09; in Treatment 2, DMUs 20 and 23 and in Treatment 03, DMUs 34 and 37 (Table 3). However, treatment 2 had the best average quality score (86.3%) (Table 2).

Table 1. Performance scores revealed by the DEA method applied to each of the 54 DMUs

DMU*	Depth (0–10 cm)		Depth (20–30 cm)		Depth (40–50 cm)	
	score	(%)	score	(%)	score	(%)
1SFAB	0.84	84	0.84	84	0.94	94
1SFC	0.87	87	0.81	81	0.89	89
1SFlAB	0.61	61	0.69	69	1.00	100
1SFlC	0.83	83	0.70	70	0.78	78
1S17AB	0.86	86	0.71	71	0.70	70
1S17C	0.89	89	0.73	73	0.73	73
2SAAB	0.71	71	1.00	100	0.85	85
2SAC	0.85	85	1.00	100	0.86	86
2SEAB	0.86	86	0.83	83	0.83	83
2SEC	0.85	85	0.80	80	0.78	78
2S2AB	0.95	95	0.82	82	0.88	88
2S2C	1.00	100	0.81	81	0.84	84
3S9AB	1.00	100	0.89	89	0.92	92
3S9C	0.98	98	0.84	84	0.89	89
3S13AB	0.84	84	0.80	80	0.90	90
3S13C	0.74	74	0.71	71	0.70	70
3S19AB	0.83	83	0.69	69	0.67	67
3S19C	0.74	74	0.71	71	0.64	64
Minimum	0.61	61	0.69	69	0.64	64
Average	0.85	85	0.80	80	0.82	82
Maximum	1.00	100	1.00	100	1.00	100
SD	0.10	10	0.10	10	0.10	10

* Numbers 1, 2 and 3 (treatments); SF, SF1 and S17 (sectors); SA, SE and S2 (sectors); S9, S13 and S19 (sectors); AB (planting row) and C (between rows).

Table 2. Variables (outputs) and performance scores in each treatment

	Ca, (cmolc dm^{-3})	Mg, (cmolc dm^{-3})	K, (cmolc dm^{-3})	P, (mg dm^{-3})	SOC, (g dm^{-3})	pH	Scores, (%)
Treatment 1							
Minimum	4.0	1.0	0.4	0.2	4.0	2.0	61.0
Average	7.8	4.2	1.0	1.4	9.0	4.0	80.2
Maximum	20.0	12.0	1.7	4.2	16.0	6.0	100.0
S D	4.1	2.8	0.5	1.1	3.9	0.7	10.2
Treatment 2							
Minimum	4.0	2.0	0.2	0.2	4.0	3.9	71.0
Average	16.4	10.8	2.0	2.6	10.7	4.1	86.3
Maximum	29.0	20.0	5.1	9.0	18.0	4.5	100.0
S D	7.2	5.1	1.5	2.5	4.0	0.2	7.9
Treatment 3							
Minimum	4.0	1.0	0.2	0.1	4.0	3.7	64.0
Average	11.0	7.0	1.1	1.5	8.1	4.1	80.4
Maximum	24.0	18.0	4.1	8.1	14.0	4.7	100.0
S D	6.6	6.3	1.2	2.0	3.1	0.3	11.0
T1. T2 e T3							
Minimum	4.00	1.00	0.20	0.10	4.00	2.00	61.0
Average	11.74	7.35	1.36	1.86	9.28	4.06	82.3
Maximum	29.00	20.00	5.10	9.00	18.00	6.00	100.0
S D	6.99	5.58	1.23	2.02	3.78	0.47	10.0

T1– established forest; T2 – forest in regeneration; T3 – open area.

Table 3. Variables selected as outputs for the applied DEA model and DMU performance score

DMU*	Ca, cmolc dm^{-3}	Mg, cmolc dm^{-3}	K cmolc dm^{-3}	P, mg dm^{-3}	SOC, g dm^{-3}	pH	Score, %
1	14	12	1.3	1.4	6	4.2	84
2	7	3	1.4	2.0	4	4.0	84
3	20	7	1.7	3.5	14	4.6	94
4	8	4	1.3	1.2	15	4.0	87
5	5	2	0.5	0.3	10	3.9	81
6	4	1	0.4	0.2	9	3.8	89
7	6	2	0.5	1.1	4	2.0	61
8	7	3	0.6	2.2	5	4.0	69
9	8	4	0.7	4.2	6	6.0	100
10	13	6	1.3	2.3	10	4.3	83
11	7	3	0.8	1.0	6	4.0	70
12	6	3	1.6	1.2	5	4.3	78
13	7	6	1.4	1.0	15	3.9	86
14	5	3	0.6	0.4	9	3.7	71
15	4	3	0.4	0.7	8	3.7	70
16	9	9	1.7	1.9	16	3.8	89
17	5	3	0.6	0.4	10	3.7	73
18	5	2	0.4	0.2	10	3.7	73
19	4	2	0.2	0.2	7	3.9	71
20	23	16	4.3	7.2	17	4.4	100
21	17	11	2.0	1.5	7	4.2	85

Table 3 (continued)

22	12	12	1.2	1.0	4	4.2	85
23	29	20	4.0	9.0	18	4.5	100
24	19	13	2.3	3.6	9	4.2	86
25	13	8	0.9	5.1	13	4.2	86
26	10	6	0.7	4.9	12	4.1	83
27	15	5	0.5	2.8	12	4.1	83
28	10	9	0.9	2.0	14	4.0	85
29	12	7	0.6	1.3	12	3.9	80
30	6	5	0.4	1.3	11	3.9	78
31	26	17	4.2	3.8	13	4.3	95
32	13	13	2.5	0.6	9	4.0	82
33	25	10	1.3	0.3	5	4.0	88
34	25	20	5.1	2.1	15	4.5	100
35	16	11	3.0	0.6	9	4.0	81
36	21	10	2.3	0.2	6	4.0	84
37	24	18	4.1	4.7	12	4.7	100
38	19	15	1.8	0.9	7	4.3	89
39	19	17	0.9	0.1	4	4.3	92
40	22	18	3.9	0.3	12	4.6	98
41	16	10	2.1	0.1	5	4.2	84
42	16	13	1.4	0.2	4	4.4	89
43	10	6	0.6	2.2	14	3.9	84
44	9	5	0.5	1.1	13	3.8	80
45	9	4	1.0	8.1	8	3.9	90
46	8	4	0.7	2.2	9	3.9	74
47	6	2	0.3	1.0	9	3.7	71
48	6	2	0.2	0.7	8	3.7	70
49	10	4	0.6	2.7	8	4.5	83
50	6	2	0.4	0.8	6	3.9	69
51	4	1	0.3	0.2	6	3.8	67
52	6	3	0.5	1.3	9	3.9	74
53	4	1	0.3	0.4	8	3.8	71
54	4	1	0.2	0.3	4	3.8	64
Minimum	4	1	0.2	0.1	4	2.0	61
Average	11.7	7.3	1.36	1.86	9.3	4.06	82.3
Maximum	29	20	5.1	9.0	18	6.0	100
S D	7.0	5.6	1.23	2.02	3.8	0.47	10

*1 to 18, Treatment 1 (T1); 19 to 36, Treatment 2 (T2) and 37 to 54; Treatment 3 (T3). Ca (calcium), Mg (magnesium), K (potassium), P (phosphorus), SOC (soil organic carbon), pH (hydrogen potential).

Among the observations performance score showed an average of 82.3%while the average pH was 4.06, proving to be strongly acidic. Regarding the texture, we can observe the classification in Table 4.

The area with established forest had the highest level of total sand (84%), with an average of 64.3% and soil with a sandy texture. Treatment 2 presented the lowest sand content 54.6% (Table 4). The mean, across all 54 observations of the performance score is 82.3%, and the sand content is 59.7%, these define the quadrant divisions of the diagram in Fig. 3, A (Table 5).

Table 4. Soil textural classification

T1			T2			T3		
DMU*	Sand, %	Texture Type	DMU	Sand, %	Texture Type	DMU	Sand, %	Texture Type
1	53	Medium	19	66	Medium	37	54	Medium
2	84	Sandy	20	68	Medium	38	32	Clay
3	72	Medium	21	62	Medium	39	43	Clay
4	78	Medium	22	58	Medium	40	52	Medium
5	71	Medium	23	63	Medium	41	48	Medium
6	63	Medium	24	53	Medium	42	43	Clay
7	73	Medium	25	58	Medium	43	62	Medium
8	76	Medium	26	56	Medium	44	62	Medium
9	79	Medium	27	46	Clay	45	60	Medium
10	68	Medium	28	55	Medium	46	60	Medium
11	80	Sandy	29	50	Medium	47	61	Medium
12	74	Medium	30	58	Medium	48	60	Medium
13	58	Medium	31	53	Medium	49	78	Sandy
14	51	Medium	32	50	Medium	50	75	Medium
15	45	Clay	33	43	Clay	51	78	Medium
16	58	Medium	34	57	Medium	52	76	Medium
17	30	Clay	35	37	Clay	53	71	Medium
18	46	Clay	36	51	Clay	54	74	Medium
Minimum	30.0			36.9			32.3	
Average	64.3			54.6			60.3	
Maximum	84.2			67.9			77.9	
S D	14.8			7.9			13.4	

* T1 – established forest; T2 – forest in regeneration; T3 – open area.

Table 5. Means of performance scores, V% value, sand content and available organic matter (OM), in each treatment

T1	V%	Sand, g kg^{-1}	OM, g dm^{-3}	Scores, %
Minimum	11.0	300.0	7.0	61
Average	34.1	643.1	15.5	80
Maximum	57.0	842.0	27.0	100
S D	15.65	147.97	6.44	10
T2				
Minimum	5.0	369.0	7.0	8
Average	23.1	545.8	18.4	80
Maximum	53.0	679.0	31.0	100
S D	16.1	79.40	6.80	24
T3				
Minimum	14.0	323.0	7.0	64
Average	30.1	603.3	13.9	79
Maximum	51.0	779.0	24.0	98
S D	10.75	133.52	5.40	10
T1, T2 and T3				
Minimum	5.0	300.0	7.0	61
Average	29.1	597.4	15.9	82.3
Maximum	57.0	842.0	31.0	100
S D	14.8	128.0	6.4	10

T1 – established forests; T2 – forest in regeneration; T3 open area.

The analysis of the performance score in relation to the sand content is shown in Fig. 3, (A), where quadrant 2, with the highest concentration of points (35.2%), shows that the observations with the best performance are in regions with lower sand contents. Quadrant 4, which has the highest sand content and lowest performance scores, has 29.3% of the observed points. Pointing out the influence of sand content in the process of conservation of these soils.

The analysis of the performance score in relation to organic matter (OM) is shown in Fig. 3, (B). The average of the performance score is 82.3%, and the average of the OM is 15.9 g dm^{-3} and define the quadrants of this diagram. Quadrants 1 and 3, with 61.1% of the observations, points to the best performance of the soil regeneration process, in places with higher levels of organic matter. In forest ecosystems, a variety of abiotic and biotic soil-forming factors drive soil organic matter and nutrient cycling with a profitable outcome in mitigating climate change (Camponi et al. 2022).

The relationship between the performance score and the V% value is revealed in Fig. 3, (C). The quadrants of this diagram are defined by the mean of the performance score (82.3%) and by the mean of the V% value (29.1). The observations contained in the first quadrant represent 27.8% and in the third quadrant 29.6%, making up 57.4% of the total points observed. Confirming the positive relationship between the revealed performance score and the V% value.

Like the studies by Mafra et al. (2008) and Sales et al. (2018), this study used the applied DEA model, serve to discriminate the treatments evaluated in the set of 54 observations, in which both authors obtained analysis of soil nutrients in reforested areas. These authors evaluated soil organic carbon and macronutrient elements to analyze soil characteristics in terms of their ability to store nutrients in response to the different management conditions adopted. Lehocká et al. (2009) also evaluated soil quality through indicators extracted from chemical and physical analysis, in different management systems.

This study corroborates the work of Neto et al. (2007), who also use DEA to evaluate the biological performance of intercropped planting systems and concludes that the DEA method is effective in discriminating the best cultivation systems.

When collecting and analyzing the soil in layers, Mafra et al. (2008) revealed the carbon stock is more present in reforestation areas than in field or forest areas and the levels of P, K, Ca and Mg, also, obtained the highest averages in the regenerating sector, as well as in the present study. It can be seen in the T2 treatment that the enrichment with plant species from different strata, herbaceous, shrubby, and arboreal, in the forest restoration process carried out, may have provided interactions that favored better availability of nutrients and consequent soil quality detected, on soil profile analyzed in this study. An approach involving the diversity and distribution of plant species, within each studied area, could help to understand this trend.

In Table 3, which shows the variables and scores revealed, an average performance was 82.3%, in the treatment of regenerating forest. This result indicates that among the three treatments, treatment in the process of regeneration presents the best soil quality, corroborating with the studies of Mafra et al. (2008) and Sales et al. (2018). Thus, this quality score can help define soil management strategies, which may be applicable to other soil assessment situations in environmental management (Espada et al., 2017).

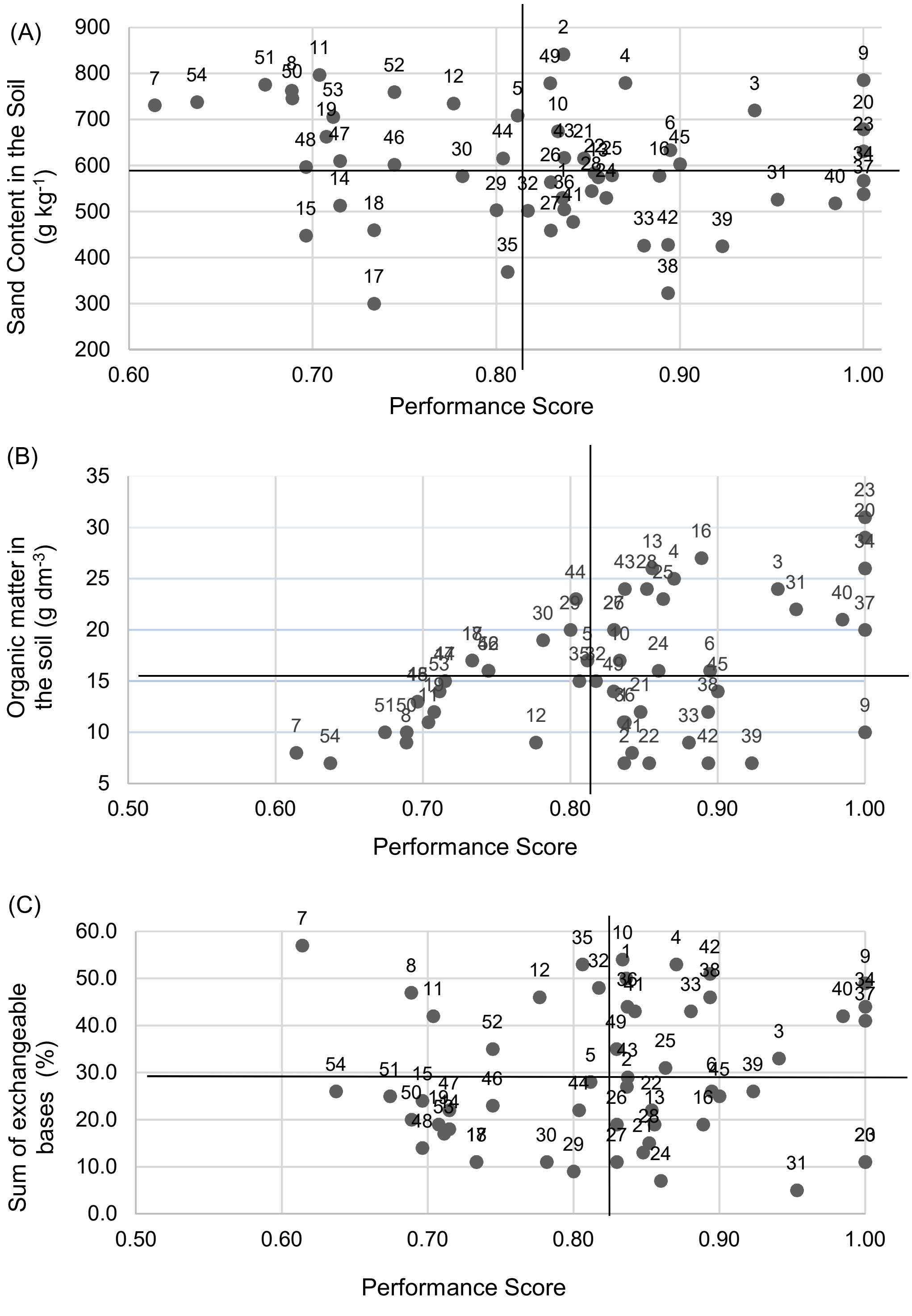

Figure 3. Scatter diagram of the performance score in relation to the explanatory variables: (A) Sand Content, (B) Organic Matter and (C) Sum of Exchangeable Bases.

Source: prepared by the authors.

It was considered that there may have been influence of the slope in relation to the loss of organic carbon and macronutrients. The treatment with an open area and with a higher percentage of sand content showed the lowest levels of the variables studied, in agreement with the work by Rocha (2021) who found a greater loss of soil nutrients through leaching in areas with greater slope. Lowe et al. (2021), also found that a soil with a steeper slope may have a greater loss of macronutrients, correlated with the loss of silt and clay.

CONCLUSIONS

The analyzed soils, in general, presented low levels of fertility. However, the treatment with regenerating area (T2), obtained the highest average in the performance score and consequent higher soil quality, obtaining the highest levels of SOC and macronutrients in the soil. In addition, the revealed performance scores accompanied the V % and organic matter values. The treatment with the worst performance was the one with open land (T3), which presented the lowest levels of the analyzed variables. The initiative of aggregating representative variables of the soil analysis in a single quality score can contribute to directing actions and defining strategies for soil management (Espada et al., 2018).

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