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Applying the Soil Management Assessment Framework (SMAF) to Assess Mangrove Soil Quality

Laís Coutinho Zayas Jimenez, Hermano Melo Queiroz, Maurício Roberto Cherubin and Tiago Osório Ferreira *

Luiz de Queiroz College of Agriculture, University of São Paulo (ESALQ-USP), Av. Pádua Dias 11, Piracicaba 13418-900, SP, Brazil; lais.jimenez@usp.br (L.C.Z.J.); hermanomelo@usp.br (H.M.Q.); cherubin@usp.br (M.R.C.)
* Correspondence: toferreira@usp.br; Tel.: +55-19-3417-2147

Abstract: Soil quality (SQ) refers to its capacity to perform its functions. Thus, the SQ index (SQI) is a potentially useful tool for monitoring soil changes induced by mangrove restoration initiatives. Although the soil management assessment framework (SMAF) is a well-developed tool for SQ assessments in diverse ecosystems, it has never been tested on mangrove soils. In this study, we tested the SMAF to evaluate the shifts in the SQ of mangroves in a reforestation initiative using three- and seven-year plantations, which were compared with degraded and mature mangroves. A minimum dataset, composed of the pH and available P as chemical indicators, bulk density as a physical indicator, and soil organic carbon as a biological indicator, was used to calculate the SQI. The SMAF scores facilitated the monitoring of improvement in the mangrove SQ with vegetation development, mainly driven by physical and biological indicators. The SMAF may be a useful tool for monitoring SQ in mangroves under protection and recovery initiatives. Nevertheless, we suggest the inclusion of additional biological and chemical indicators in the minimum dataset for future studies to better represent specific processes and functions (e.g., microbial redox reactions and contaminant immobilization) that can alter the SQ of mangroves.

Keywords: environmental recovery; ecosystem services; wetlands; carbon dynamics

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1. Introduction

Different forest biomes at a global scale provide significant ecosystem service (ES) diversity. Recognizing their importance and the mechanisms controlling their occurrence are pivotal for sustainable decision-making [1]. Mangroves are estuarine ecosystems that provide a wide diversity of ESs, such as regulation, support, and culture for human livelihood [2–5]. Despite this recognition, mangroves are one of the ecosystems most threatened by human activities, i.e., mainly aquaculture, sewage and industrial disposal, and deforestation [6,7]. Mangrove degradation is mainly related to the total or partial suppression of mangrove vegetation, which has declined by 30–50% over the past half century, triggering a loss in soil quality, which in turn affects ES provisions (e.g., carbon accumulation and metal immobilization) [8,9].

Additionally, many of the ESs provided by mangroves are directly associated with soil processes and soil quality (SQ) [10–12]. Accordingly, SQ can be conceptualized as a soil's capacity to perform its functions, such as sustaining its productivity, improving water quality, and providing ESs. This ability to perform specific functions is associated with the inherent characteristics of each soil type [13,14]. As tidal activity influences mangroves, this flooded environment has soil characterized by intrinsic geochemical characteristics, such as a high salinity, low oxygen diffusion, and predominance of anaerobic metabolism [15,16]. Moreover, the geochemical features of mangrove soils lead to low organic matter decomposition rates and iron sulfide formation, which favor the sequestration of large amounts of carbon (reaching ~five-fold that of terrestrial ecosystems) and contaminant immobilization in the soil [9,17]. In this sense, evaluating SQ is pivotal for ensuring the maintenance of ESs.

However, SQ cannot be measured directly in the field or laboratory, but can be indirectly inferred by soil indicators (e.g., soil chemical, physical, and biological properties) sensitive to changes in soil functions [13,14,18–20]. The use of a soil quality index (SQI) may be a strategic tool in providing useful information that can promote sustainability in highly threatened environments [18].

The SQI approach has been used in mangrove ecosystems to understand the magnitude of the effects of land-use changes; for example, the removal of mangrove forests for rice cultivation [21] and the clearing of mangrove vegetation [22]. These previous studies focused on developing region-specific SQIs. From this perspective, there is a need for standardized SQI studies that can be replicated for comparisons and quantifications of the environmental impacts on mangrove soils. In this study, we innovatively tested mangrove soils using the soil management assessment framework (SMAF), a widely used tool for assessing the SQI in agricultural soils [18]; however, to the best of our knowledge, this tool has never been tested on mangrove soils.

The SMAF uses integrative measurements related to ecosystem processes and functions, which are reflected in the SQI based on the chemical, physical, and biological properties of soils [19,23,24]. It is a cost-effective framework that uses selected indicators and a reduced number of measurements (i.e., a minimum dataset) to reliably detect the changes in SQI [14].

Although the SMAF was developed for North American soils [18], it is suitable for assessing the SQI of tropical soils [25–28]. A recent study also showed that is useful for human-made soils [29]. The SMAF is a three-step framework that includes (1) indicator selection, (2) indicator interpretation, and (3) integration into an overall SQI [18]. The first step includes the chemical, physical, and biological indicators to accurately assess the SQ. In the second step, the SMAF implements non-linear scoring curves to interpret 13 indicators (i.e., the pH, soil aggregation stability, bulk density (BD), available plant water, water-filler pore space, electrical conductivity, sodium adsorption rate, extractable phosphorus and potassium, microbial biomass, soil organic carbon (SOC), potentially mineralizable nitrogen, and β-glucosidase). In the third step, within these individual scores, the SMAF integrates them into an overall SQI ranging from 0 to 1, which represents the functioning rate of the soil compared with its potential capacity.

Although SMAF has been applied worldwide, to the best of our knowledge, no studies have yet evaluated the sensitivity of SMAF scores for detecting changes in mangrove soils. We evaluated the applicability of the SMAF to assess the SQ changes in mangroves subjected to a reforestation initiative (i.e., plots at three- and seven-year-old plantations) and compared them with degraded and mature mangroves. Based on these analyses, there is an actual need for the recovery of coastal areas that provide a large range of ESs, which demand both public and private investors [30,31]. Quantitative proxies of the ecological evolution, as exposed by soil indicators, may be strategic tools to support the recovery of mangrove projects and monitor their evolution [28,29]. Therefore, we tested the following hypothesis: the development of mangrove forests increases SQ scores, and the SMAF can effectively detect changes in SQ.

2. Materials and Methods

2.1. Study Area

The study area was located in Ceará State, northeast Brazil (Figure 1). The region has a semi-arid climate (BSh, Köppen climate classification), with well-defined wet (February to May) and dry seasons (June to January), a mean annual precipitation <900 mm, and a mean annual temperature of 27 °C [32,33]. The mangrove soils in the study area are characterized by sand–clay textures originating from the sedimentary deposits of the Barreiras Formation, as well as influence from the surrounding dunes [34–36]. Additionally, mangroves experience a daily to diurnal mesotidal regime, ranging from 0.75 to 3.25 m [37].

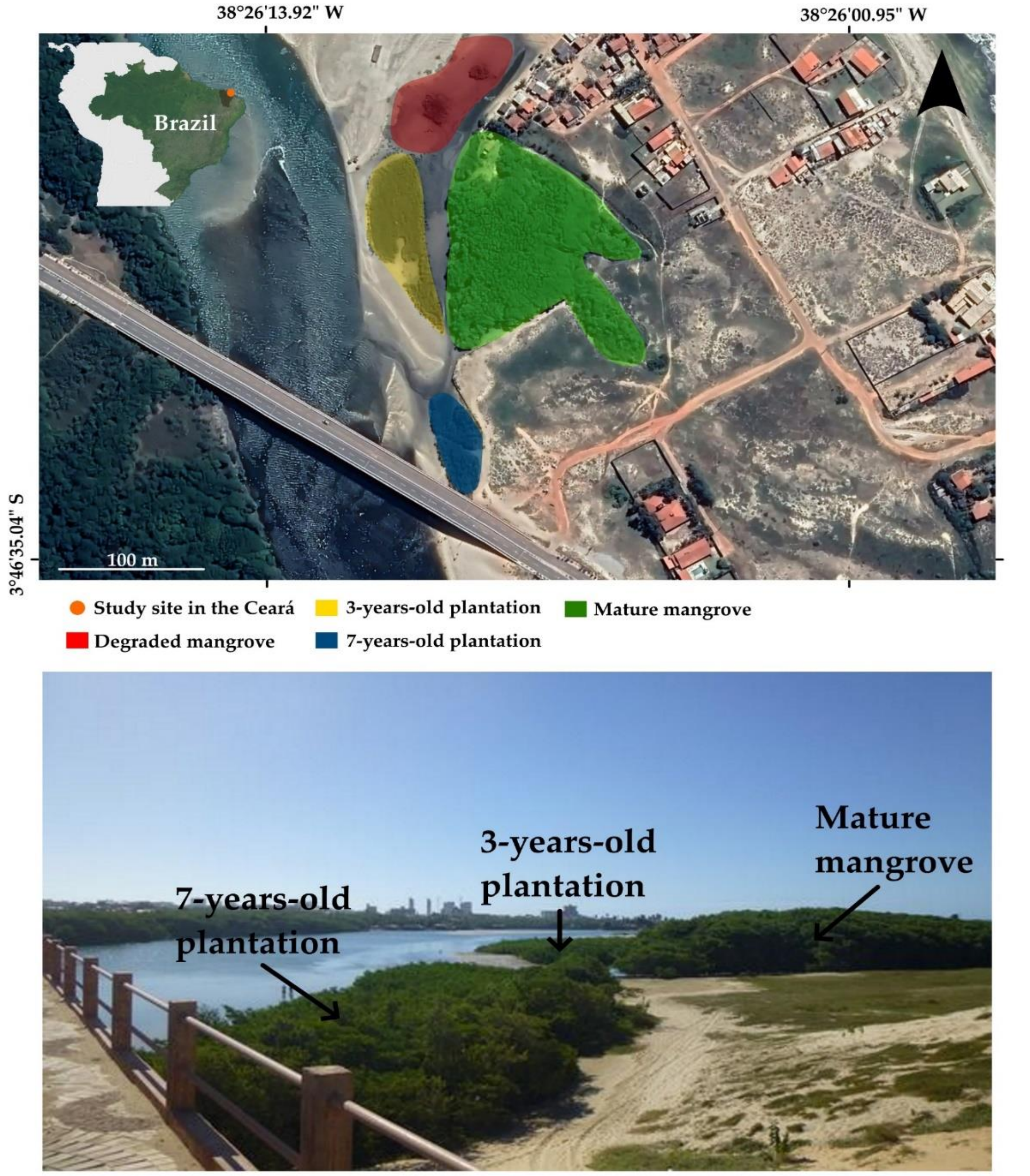

Figure 1. Location of the studied mangrove in the Cocó River estuary, and the degraded (red area) and mature (green area) mangrove and plots with 3-year-old (yellow area) and 7-year-old plantations (blue area). The satellite image was obtained from Google Earth^{TM}. In the satellite image, the XY axes represent latitude and longitude. In the detail (bottom photo) are the plots with 3- and 7-year-old plantations compared with mature mangroves, showing the vegetation development differences. Photo credits: Claudia Albuquerque, Igor de Melo, and Michele Boroh.

Changes in the SQ were investigated in a mangrove reforestation initiative with three- (3Y) and seven (7Y)-year-old plantations, a degraded mangrove forest (DM), and a mature mangrove forest (MM; Figure 1). Each plot was separated by approximately 100 m. Additionally, the MM and DM covered an area of approximately 13,000 and 1000 m^2, respectively. The plantation areas of 3Y and 7Y were 3500 and 1000 m^2, respectively. The study plots were located within the Sabiaguaba Environmental Protection Area, which is a conservation unit created through municipality decrees in February 2006 for mangrove reforestation initiatives, sustainable use practices, and educational and tourism activities [38]. The MM plot was a well-developed forest free from disturbances for at least 30 years, composed of *Avicennia germinans* (L.) L., *Laguncularia racemosa* (L.) C. F., and *Rhizophora mangle* L. After the creation of the conservation unit, previously deforested areas were replanted with

Rhizophora mangle propagules, as occurred in areas 3Y and 7Y. There was a total absence of vegetation in the DM plot owing to urban occupation and deforestation.

2.2. Soil Sampling

Four undisturbed soil cores (n = 16) were obtained during low tide within 1 × 1 m areas in each scenario (i.e., DM, 3Y, 7Y, and MM) using polyvinyl chloride tubes (0.05 m in diameter and 0.6 m in length) attached to a stainless-steel auger for flooded soils. To avoid chemical and biological alteration, the tubes were hermetically sealed and transported (vertically) under refrigeration (~4 °C) to the laboratory soon after sampling. Analyses were performed in triplicate using subsamples collected from the soil cores at depths of 0–30 cm.

2.3. Determination of Soil Quality Indicators

The soil pH values were obtained in situ using portable meters (HANNA, model HI98121, Hanna Instruments, Woonsocket, RI, USA) equipped with a glass electrode, which was previously calibrated with standard solutions (pH values of 4 and 7).

In the laboratory, the SOC content was determined via dry combustion using an elemental analyzer (LECO SE-144 DR). Soil samples for the SOC determination were treated with 1 mol L^{-1} HCl for carbonate removal, dried at 45 °C until a constant weight was maintained, and then re-weighed [39]. The available P content in the mangrove soils was extracted using a Mehlich-1 instrument and quantified using calorimetry [40].

The undisturbed soil cores (i.e., collected with minimal compaction) were used to determine the soil BD. Thus, the soil BD was calculated using the mass of the soil solids and total soil volume (depth and tube diameter of 30 cm) [39].

2.4. Soil Quality Assessment Using SMAF

The SMAF was used as a tool to evaluate the effects that mangrove replanting had on the SQ compared to degraded and mature mangroves. The minimum dataset consisted of four soil indicators, i.e., the pH, available P, SOC, and BD.

The soil pH and available P were selected as the chemical indicators. The soil pH is an environmental physicochemical variable that indicates the acidity of mangrove soils [41]. Accordingly, soil pH values may reveal certain geochemical processes, such as acid drainage, which may be caused by the degradation and drainage of mangrove soils [42–44]. Additionally, pH measurements can be easily obtained in situ using portable meters, which facilitate replicability. The SOC was used as a biological indicator because carbon plays a key role in the biological activity of mangrove soils [18,45]. Phosphorous is a limiting nutrient in mangrove soils; therefore, it was selected as a key indicator to provide information on soil nutrient availability [46]. The soil BD provides information on soil compaction and aeration; it is also a necessary variable for soil carbon stock calculations [18,22,47].

The biological, physical, and chemical scores calculated by the SMAF scoring curves were based on site-specific algorithms for several factor classes, including the inherent soil characteristics (i.e., the soil texture, mineralogy, and weathering class), climate, topography (slope), crop system, and analytical methods. To calibrate these curves (i.e., establish the upper and lower limits or optimal values on the curves), different codes were selected in the SMAF spreadsheet [27]. Thus, we created SMAF algorithms according to the conditions of this study; Table 1 lists the codes for the indicators.

Table 1. Factor codes selected in the soil management assessment framework (SMAF) spreadsheet to interpret the soil quality (SQ) indicators according to the conditions of this study.

Parameter	Factor Codes	Indicator Scoring Curve Affected by Class Factor
Soil type	3 (medium–low SOC)	SOC
Texture	1 (low clay content)	SOC, BD, available P
Soil mineralogy	3 (other)	BD
Weathering class	3 (other)	Available P
Slope of field	1 (flat)	Available P
Climate	2 (high temperature and low rainfall)	SOC, available P
Crop	Mangrove 117 *	pH, available P
P method	1 (Mehlich-1)	Available P

SOC: soil organic carbon; BD: bulk density. * Mangrove 117 was a created crop factor whose optimal values for the pH and available P were set as follows: pH = 7; available P = 30.47 mg kg^{-1}.

Additionally, in the SMAF spreadsheet, the “crop factor” reflects the scores of soil pH and available soil P associated with the current crop at the time of sampling. In this study, the “Mangrove 117” crop was created (Table 1). In the “Mangrove 117” crop factor, we set up the optimum pH value and available P content to adjust the nonlinear scoring curves of these two chemical factors. We adopted pH = 7 as the ideal pH value because healthy mangrove soils usually present a high capacity for buffering acidity [41,48], and for available P we considered the contents registered in the MM plot (i.e., 30.47 mg kg^{-1}; see Table 2).

Table 2. Mean contents of the SOC and available P, mean values of the pH and BD, and their corresponding soil quality (SQ) score in the degraded and mature mangrove plots and replanted areas (3 and 7 years).

Plot	SOC (%)	pH	Available P (mg kg^{-1})	BD (g cm^{-3})
		Means		
DM	0.44 ± 0.06 c	7.68 ± 0.22 a	19.67 ± 2.74 b	1.51 ± 0.08 a
3Y	0.91 ± 0.10 b	6.98 ± 0.15 b	4.34 ± 0.81 d	1.33 ± 0.03 b
7Y	0.92 ± 0.34 b	6.95 ± 0.10 b	8.44 ± 0.71 c	1.35 ± 0.11 b
MM	1.85 ± 0.07 a	6.33 ± 0.05 c	30.47 ± 1.04 a	1.08 ± 0.02 c
		SMAF Scores (0 to 1.00)		
DM	0.13 ± 0.02 d	0.79 ± 0.12 b	0.95 ± 0.02 a	0.81 ± 0.16 b
3Y	0.40 ± 0.08 c	0.99 ± 0.01 a	0.17 ± 0.08 c	0.99 ± 0.01 a
7Y	0.59 ± 0.14 b	1.00 ± 0.01 a	0.60 ± 0.06 b	0.97 ± 0.03 ab
MM	0.99 ± 0.01 a	0.80 ± 0.03 b	1.00 ± 0.00 a	0.99 ± 0.01 a

DM: degraded mangrove; 3Y: 3 years after replanting; 7Y: 7 years after replanting; MM: mature mangrove; SOC: soil organic carbon; BD: bulk density. Means followed by the same lowercase letters did not differ among the study plots according to Tukey’s test ($p < 0.05$).

Individual scores of the indicators were calculated and grouped into chemical (pH and available P), physical (BD), and biological (SOC) components. The SQI was calculated using the weighted additive approach (Equation (1)). Regardless of the number of indicators, the groups (i.e., chemical, physical, and biological) were integrated and had an equal weight (33.33%) in the final index, i.e., the SQI [14,26]:

$$SQI = \sum_{i=1}^{n} S_i W_i \quad (1)$$

where S_i is the indicator score and W_i is the weighted value of the indicators.

2.5. Statistical Analysis

The differences between the means of the soil parameters (i.e., SOC, pH, available P, and BD), SQ indicators, and SQI in the study plots (i.e., DM, 3Y, 7Y, and MM) were tested using analysis of variance (ANOVA). When significant, the means were compared using Tukey's test ($p < 0.05$).

3. Results

The SOC content varied significantly between the study plots, indicating a gradual increase with vegetation development (Table 2). Higher SOC contents were observed in the MM plot (1.85 ± 0.07%), whereas lower contents occurred in the DM plot (0.44 ± 0.06%; Table 2). No significant differences were observed in the SOC content between the 3Y (0.91 ± 0.10%) and 7Y plots (0.92 ± 0.34%). Gradual increases in the SOC content were also observed in the SMAF score, which was attributed to the biological indicator of SQ (SOC; Table 2). The SMAF scores for the SOC were significantly higher in the MM (0.99 ± 0.01), followed by a significant decrease in 7Y (0.59 ± 0.14), 3Y (0.40 ± 0.08), and DM (0.13 ± 0.02) (Table 2).

For the chemical indicators, the soil pH values varied significantly between the study plots, ranging from slightly alkaline (7.4–7.8) in the DM plot (7.68 ± 0.22) to acidic (6.1–6.5) in the MM plot (6.33 ± 0.05; Table 2). In the 3Y (6.98 ± 0.15) and 7Y (6.95 ± 0.10) plots, the soil pH values were close to neutral (6.6–7.3), yielding no significant differences (Table 2). For the SQ scores, the higher significant values were attributed to the 3Y (0.99 ± 0.01) and 7Y (1.00 ± 0.01) plots, whereas lower values occurred in the DM (0.79 ± 0.12) and MM plots (0.80 ± 0.03; Table 2). The available P content did not show a gradual increase with vegetation development (Table 2). The MM plot had a significantly higher available P content (30.47 ± 1.04 mg kg^{-1}), whereas the 3Y plot (4.34 ± 0.81 mg kg^{-1}) presented lower content (Table 2). The available P content was also significantly higher in the DM plot (19.67 ± 2.74 mg kg^{-1}) compared to the 7Y plot (8.44 ± 0.71 mg kg^{-1}; Table 2). The SQ score for the available P in the DM plot (0.95 ± 0.02) did not differ significantly from the MM plot (i.e., optimum SQ score: 1.00 ± 0.00; Table 2). In contrast, the SQ score for available P in the 7Y plot (0.60 ± 0.06) was significantly higher than the SQ score in the 3Y plot (0.17 ± 0.08; Table 2).

The physical indicator (i.e., BD) in the replanted plots (3Y: 1.33 ± 0.03 g cm^{-3}; 7Y: 1.35 ± 0.11 g cm^{-3}) differed significantly from that of the degraded mangrove (DM: 1.51 ± 0.08 g cm^{-3}). Higher BD values were observed in the MM plot (1.08 ± 0.02 g cm^{-3}; Table 2). Accordingly, the highest significant SQ score for the BD occurred in the MM (0.99 ± 0.01) and 3Y (0.99 ± 0.01) plots, whereas the lowest was in the DM plot (0.81 ± 0.16; Table 2). The SQ score for the BD in the 7Y (0.97 ± 0.03) plot did not differ from the 3Y and DM plots (Table 2).

The SQI score obtained from the integrated SMAF scores for the biological (i.e., SOC), chemical (i.e., pH and available P), and physical (i.e., BD) components gradually and significantly increased with vegetation development. According to the observed SQI (DM: 0.60 ± 0.04; 3Y: 0.66 ± 0.04; 7Y: 0.74 ± 0.09; and MM: 96 ± 0.01), the mangrove SQ gradually increased following vegetation development (Figure 2).

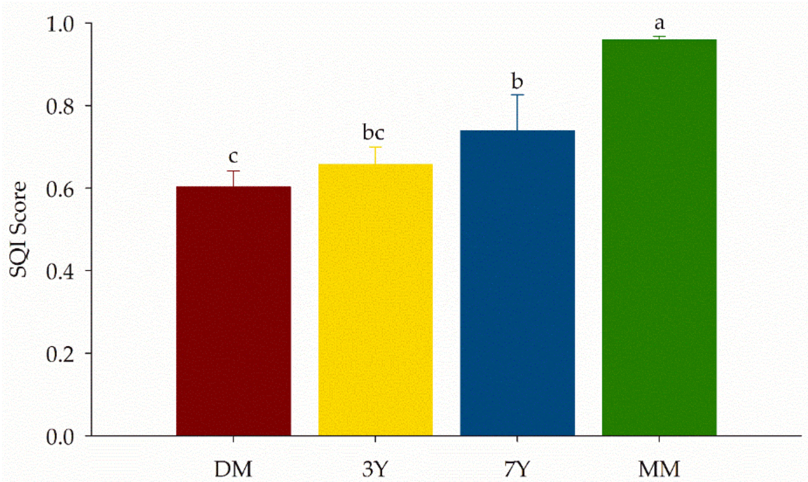

Figure 2. Soil quality index (SQI) score for each stage of mangrove development in Ceará state, northeastern Brazil: degraded mangrove (DM); 3- and 7-year-old plantations (3Y and 7Y, respectively) and mature mangrove (MM). Means followed by the same lowercase letters did not differ among studied plots according to Tukey's test ($p < 0.05$).

4. Discussions

Several available methodologies focus on integrating physical, chemical, and biological indicators to assess the quality of mangrove soils [21,45]. Thus, in this study, we tested the SMAF, a widely used international tool [49,50], to assess SQ in two replanted mangrove plots, which were compared with degraded and mature mangroves. In this study, we observed a gradual increase in the SQI scores with mangrove vegetation development. The SQI scores were between 0.74 $\pm$ 0.09 and 0.66 $\pm$ 0.04 for the three- and seven-year-old plantation plots, respectively (Figure 2).

The increase in the SQI score with replanting reflects shifts in the chemical, biological, and physical indicators. However, the chemical SQ scores showed different tendencies among the degraded, replanted, and mature mangroves (Table 2). For example, the soil pH values observed in the study plots ranged from 6.3 to 7.7 (Table 2). These soil pH values are common for mangrove soils [22,33,51]. Within mangrove soils, the constant influence of seawater via tidal activity, root exudates, bioturbation, biogenic carbonates, and redox oscillations results in soil pH values that can vary between ~6.5 and 7.0 [22,33,51,52]. Thus, despite the significant pH variation, this did not reflect significant variations in the SQ score associated with the pH; the observed values are plausible for mangrove ecosystems. However, the SQ score for the pH ranged from 0.77 to 1.00, yielding significant differences (Table 2). Additionally, as the chemical indicator was composed of only two components (pH and available P), the SQ score associated with the soil pH values strongly influenced the chemical component. A potential contribution from this study for the future use of the SMAF for mangrove ecosystems is that adjustments to the pH scoring curves should be made to better represent these specific soil environments. Furthermore, the scoring curves for interpreting the electrical conductivity and sodium adsorption rate available in the SMAF spreadsheet should be tested in future studies such that they can represent other important processes that occur in mangrove soils, such as salinization and microbial redox processes.

The available P, which is a chemical indicator for nutrient availability, did not follow the conservation gradient for mangrove plots. Although P is a key nutrient for vegetation in mangrove soils, it is usually a limiting nutrient [53,54]. In plantation plots (i.e., 3Y and 7Y), P is a limiting nutrient; plants require large quantities of P, which may explain the lower available P content [46]. In contrast, in the MM plot, a significantly higher available P content was likely associated with nutrient cycling [54]. For example, the atypical values observed in DM may be related to sewage disposal or other anthropogenic effluents [55]. Therefore, in mangrove forests exposed to P-rich waste, we recommend the use of additional chemical indicators in the minimum dataset. Nevertheless, P should not be substituted with other indicators because it is an important nutrient for plant species [54,56]. Furthermore, as mangroves are one of the ecosystems most affected by anthropogenic activities (e.g., effluent discharge and urban waste disposal) [9,57,58], P as a chemical indicator must be carefully analyzed to avoid positive scores at eutrophication or organic pollution sites.

In contrast, the biological indicator (SOC) increased with plantation development (Table 2). This result indicates that mangrove reforestation initiatives have successfully restored the soil carbon stocks in degraded mangrove forests and improved the SQ. Vegetation development mainly enhances organic matter inputs into mangrove soils through dead roots, microbial biomass, litterfall, wood debris, and fauna activity [59,60]. Additionally, vegetation development and, ultimately, root system development of *Rhizophora mangle* L. decreased the turbulence kinetics and favored a higher water residence time, enhanced fine particle trapping, decreased oxygen diffusion, and stimulated anaerobic metabolism [61,62]. These changes may favor carbon accumulation [63–68]. A recent study in this region showed that an increase in fine particles enhanced organomineral interactions, increasing the SOC with vegetation development [69], which may be enhanced by anaerobic metabolism with low organic matter degradation rates [63–68]. Owing to the reforestation initiative [5,70], the increase in the SQ associated with the SOC may indicate an improvement in one of the most important ESs provided by mangrove soils (i.e., carbon sequestration).

Moreover, SOC is a soil variable that directly or indirectly has a strong influence on the overall SQI owing to its relationship with other variables (e.g., BD and available P). Although the biological SQ corresponded to 33.3% of the SQI, it gradually increased with plant development. The increased SOC content also directly affected the BD results and its SQ scores [71,72]. Additionally, soil organic matter is an important source of P in mangrove soils [55,73,74], which can indirectly affect the chemical SQ scores.

However, soil health and the development of soil functions are not the sole responses to the presence of SOC; thus, asserting that the variations in the integrated SQ depend on a particular aspect of the soil may be inaccurate [22,72,75]. For example, SOC in mangrove soils depends on several factors (e.g., climate, soil texture, tidal regime, plant species, and redox potential), which leads to significant variations in the SOC content in mangrove soils (>1000%) [22,76–78]. Therefore, adjustments regarding the optimum SOC content in mangrove soils in the SMAF could avoid overestimations of the SQ at the expense of the SOC content.

Additionally, we used a small dataset to generate a SMAF score that is accessible and replicable. However, for mangrove soils, our findings indicate that more indicators could ensure soil function development and increase the relevance of the SQ scores. Therefore, the use of SOC as a biological indicator may limit inferences on soil biological health. One of the most important functions of mangrove soils is their potential to immobilize contaminants [79,80]. This soil function is closely associated with microbial activity, iron and sulfate reduction processes, and the formation of metallic sulfides, pyrite, and acidic volatile sulfides [16,81–83]. Given the importance of anaerobic metabolism in the diverse soil functions of mangrove soils [84–86], future studies should consider other biological indicators in the minimum dataset, such as microbial biomass carbon and the enzymatic activity of β-glucosidase, both of which already have scoring curves in the algorithms within the SMAF spreadsheet. Additionally, other chemical indicators (e.g., the Fe and S content) may play a key role in predicting soil functions because the quantity of these elements directly affects important soil processes within mangrove soils (e.g., pyritization) [51,87]. These indicators are not available in the current version of the SMAF spreadsheet; therefore, developing reliable scoring curves for new indicators such as these is a challenging task for future soil quality research in mangrove soils.

5. Conclusions

This study used the SMAF tool to monitor the effect of a mangrove reforestation initiative on SQ. Using the SMAF scores, we observed an increase in mangrove SQ with vegetation development, which was mainly driven by physical and biological indicators (e.g., SOC and BD). Our findings provide novel information on the use of the SMAF as an effective tool for monitoring SQ in mangrove forests under protection and recovery initiatives. Despite the encouraging results obtained using SMAF in mangrove soils, we suggest that future studies include additional biological and chemical indicators in the minimum dataset to better represent specific processes and functions (e.g., salinization, microbial redox reactions, and contaminant immobilization), which can alter the quality of mangrove soils.

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